Development of circular solutions for a sustainable agricultural sector in Africa

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General abstract

This PhD thesis focuses on the development of circular agriculture solutions to enhance sustainability in African farming. The first chapter examines the broader potential of circular agriculture, particularly in maize farming, across Africa. Agriculture is essential to the continent's development, but the challenge remains in balancing productivity with sustainability. Circular agriculture, with its emphasis on restoring soil fertility, reducing dependency on chemical fertilizers, and minimizing ecological footprints, presents a promising solution. Through a literature review using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology, this chapter identifies successful case studies and underscores the need for effective indicators to measure circularity, specifically in maize production. Building on this foundation, Chapter 2 explores a practical application of circular agriculture in Morocco, where a composting station dedicated to recycling date palm by-products was established. This chapter investigates the economic viability of such circular solutions, analyzing the compost's impact on soil fertility and its adoption by local farmers in the Figuig Oasis. A detailed cost-benefit analysis reveals that, despite challenges, the project offers significant environmental and socio-economic benefits, with potential for replication in other similar agro-ecosystems. Finally, Chapter 3 focuses on maize productivity in the Haut-Katanga and Lualaba provinces of the Democratic Republic of Congo (DRC). Using a data-driven approach, this chapter assesses the socio-economic and environmental factors that influence maize yields in these regions. The study emphasizes the role of data in informing on agricultural practices and suggests that circular solutions, informed by predictive modeling, could play a crucial role in improving productivity and food security in the DRC. Together, these chapters highlight the potential of circular agriculture to transform African farming into a more sustainable and productive system.

Aknowledgements

"Commit your way to the Lord; trust in Him, and He will act."
(Psalm 37:5)

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Table of Abbreviations

Abbreviation	Full Term
ANDZOA	National Agency for the Development of Oasis and Argan Areas
ARES	Académie de Recherche et d'Enseignement Supérieur
CA	Circular Agriculture
DRC	Democratic Republic of Congo
DSSAT	Decision Support System for Agrotechnology Transfer
ENABEL	Belgian Development Agency
EUR	Euro
FAO	Food and Agriculture Organization
Field. Exp	Field Experiment
GDP	Gross domestic product
IF	Impact factor
LR	Literature review
MM	Millimetter
NPK	Nitrogen, phosphorus, and potassium
OLS	Ordinary least squares
PPT	Push-Pull Technology
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RF	Random Forest
SD	Standard deviation
SOC	Soil organic carbon
SSA	Sub Saharan Africa
WOS	Web of Science

1 General introduction

Agriculture plays a central role in Africa's socio-economic development, providing livelihoods for the majority of rural populations, contributing significantly to food security, and supporting national economies. However, agricultural systems in Sub-Saharan Africa are facing unprecedented challenges that threaten their productivity and long-term sustainability. Population growth, land degradation, climate variability, and resource scarcity converge to create intense pressures on farming systems, while poor infrastructure, limited access to inputs, and inadequate research and extension services exacerbate existing vulnerabilities. As a result, smallholder farmers — who represent more than 80% of agricultural producers in the region — struggle to achieve sufficient productivity while preserving natural resources and maintaining viable livelihoods.

In this context, two complementary conceptual frameworks have gained prominence in recent literature: sustainable agriculture and circular agriculture. While closely related, these concepts differ in their scope and operational focus. Sustainable agriculture (SA) provides a strategic vision for meeting present food and fibre needs without compromising the ability of future generations to meet theirs. It rests on three interdependent pillars: environmental sustainability — including biodiversity conservation, soil and water management, and climate change mitigation; economic sustainability — ensuring farm viability, income stability, and market access; and social sustainability — improving food security, equity, and rural well-being (FAO, 2018). However, while SA establishes overarching goals, it does not prescribe specific mechanisms for achieving resource efficiency or reducing environmental impacts.

Circular agriculture (CA) emerges as a complementary operational pathway within the broader framework of sustainable agriculture. CA focuses on how resources are managed, reused, and reintegrated within production systems in order to close resource loops and reduce waste. It aims to limit the reliance on synthetic fertilizers, pesticides, and fossil-based energy by promoting practices such as composting organic residues, recycling water and nutrients, integrating crops and livestock, adopting intercropping systems, and valorising agro-industrial by-products (Velasco-Muñoz et al., 2021; Poponi et al., 2022). By maximising the value extracted from locally available resources and reducing dependence on costly external inputs, CA supports the restoration of soil functionality, enhances ecosystem services, improves productivity, and mitigates greenhouse gas emissions. In regions like Sub-Saharan Africa — where resource constraints are severe, soils are increasingly degraded, and chemical inputs are often scarce or unaffordable — the integration of CA practices could represent both an economic opportunity and an ecological necessity.

This doctoral research situates itself at the intersection of these two frameworks, focusing specifically on circular agriculture as a scientific, operational, and policy-oriented approach to improving agricultural productivity and environmental sustainability in Africa. The objective is to design, evaluate, and test data-driven solutions that harness circular practices to address three interrelated challenges:

1. Resource efficiency — making optimal use of locally available inputs;
2. Environmental preservation — reducing soil degradation and closing nutrient cycles;
3. Agricultural productivity — supporting sustainable intensification in smallholder farming systems.

To achieve these objectives, the research combines a comprehensive literature review, empirical case studies, controlled agronomic experiments, and data-driven modelling approaches. Particular attention is given to two emblematic farming systems: maize cultivation — a staple crop and strategic food security driver in Sub-Saharan Africa — and date palm farming in semi-arid regions, where agro-residue management presents significant challenges but also important opportunities for circular solutions.

The originality of this thesis lies in its integrated approach, which combines conceptual analysis, experimental validation, and predictive modelling within a single research framework.

Another contribution of this research lies in the extent and difficulty of its fieldwork. Data were collected across multiple provinces and regions, often in remote rural areas with limited infrastructure, poor road accessibility, and minimal health and sanitation facilities. Research teams were frequently exposed to extreme climatic conditions and elevated risks of vector-borne diseases such as malaria. Despite these constraints, the study produced datasets and replicable experimental protocols attempting to provide a solid foundation for future research and policy design.

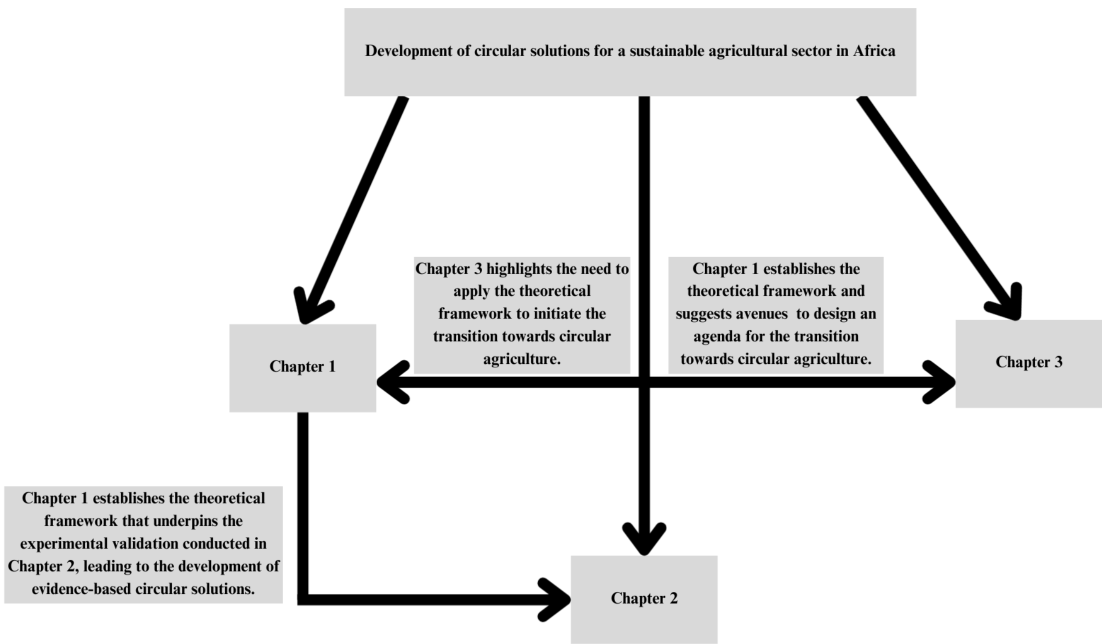

Figure 1. Thesis conceptual framework

The thesis is organised into three interlinked chapters (Figure 1), each contributing a distinct layer of understanding to the integration of circularity into African agricultural systems. Chapter 1 provides the theoretical foundations and proposes indicators for transitioning towards circular agriculture. Chapter 2 validates these concepts through an experimental case study on date palm composting, demonstrating the agronomic and economic viability of circular practices. Chapter 3 integrates empirical data and predictive modelling to identify productivity determinants and develop policy insights supporting sustainable agricultural transitions. Together, they form a progressive research pathway.

Chapter 1 attempted to establish a conceptual and analytical framework by reviewing the state of circular agriculture in Sub-Saharan Africa, with a particular focus on maize-based systems.

It identifies key challenges faced by smallholder farmers — including climate variability, soil degradation, and dependency on costly chemical inputs — while exploring opportunities offered by circular solutions such as composting, nutrient recycling, intercropping, integrated pest management, and agroforestry. By positioning CA as an operational pathway within sustainability transitions, this chapter provides the theoretical foundations necessary for the subsequent empirical analyses.

Chapter 2 is adapted from an article published in Sustainability:
Kalukuta Mahina, L., Gagou, E., Chakroune, K., Hakkou, A., El Jaziri, M., & Lamkami, T. (2025). Turning Waste into Wealth: The Case of Date Palm Composting. *Sustainability, 17*(17), 7980. This chapter translates some of these insights into practical application through a detailed case study on date palm composting in Morocco's Figuig oasis. Conducted under challenging field conditions, this chapter examines the potential of waste-to-wealth models to improve soil fertility, enhance maize productivity, and generate economic value. It combines controlled agronomic experiments — testing different compost application rates on eggplant (*Solanum melongena*), pepper (*Capsicum annuum*), and barley (*Hordeum vulgare*) — with a cost-benefit analysis assessing the economic viability of compost production and commercialisation. The findings demonstrate that composting could not only improves soil health and crop yields but also offers a scalable, profitable, and environmentally sustainable solution for smallholder farming systems.

Chapter 3 builds on these experimental results to conduct a data-driven assessment of maize productivity determinants in the Haut-Katanga and Lualaba provinces of the DRC. It develops a synthetic yield model to overcome the limitations of self-reported production data and applies econometric regression techniques to quantify the impacts of soil management, fertiliser use, climatic variability, and socio-economic factors on maize yields.

2 Chapter 1: Challenges for a circular agriculture in Africa: a literature survey on maize

Abstract Agriculture is vital for sustainable development, impacting environmental conservation, human health, biodiversity, and social well-being. Africa faces challenges in achieving adequate agricultural productivity while maintaining sustainability. Circular agriculture offers a solution by restoring soil fertility, reducing soil erosion, nutrient loss, and the use of chemical fertilizers. It also decreases the ecological footprint of agriculture. This article reviews circular agriculture implementation in Africa using the PRISMA methodology, with searches in Scopus and Web of Science databases. The review highlights successful case studies and opportunities for transitioning to a circular economy, emphasizing the need for suitable indicators to measure circularity in agriculture. This review underscores the importance of advancing circular agriculture in Africa for sustainable agricultural practices on maize.

2.1 Introduction

Circular Agriculture (CA) is pivotal for Africa's sustainable development, addressing critical environmental, social, and economic challenges inherent to the continent's agricultural landscape. Velasco-Muñoz et al. (2021) underscore the detrimental impacts of conventional agricultural practices in Africa, including water pollution and human health risks from chemical inputs like fertilizers and pesticides. These issues are exacerbated by climate change, manifesting in heat waves, droughts, and disruptions in agricultural productivity and public health (Webber et al., 2014). In response to these challenges, there is a pressing need for a paradigm shift in agricultural practices, aligning with global sustainability frameworks such as the Paris Agreement (Kpadonou et al., 2019).

As Africa's population is projected to surpass Asia's in the coming decades, the growing pressure on land resources and food demand is intensified by erratic rainfall patterns, limited access to agricultural inputs, and recurrent pest outbreaks (Kpadonou et al., 2019). To address these challenges, transitioning from the traditional linear "take–make–dispose" agricultural model to CA practices has become imperative. Circular agriculture refers to a set of agricultural practices aiming to limit the use of inorganic fertilizers and pesticides in order to stimulate agricultural productivity, restore the soil's original properties, maximize economic and social benefits, and minimize global emissions. Essential components include recycling plastics, reducing packaging, and reusing crop and water residues to close resource loops.

According to the Food and Agriculture Organization (FAO), CA further emphasizes the sustainable management of natural resources to ensure environmental integrity while fostering socio-economic equity. This shift reflects the intrinsic interconnection between environmental, social, and economic dimensions of agricultural development, highlighting the urgent need for sustainable alternatives that reconcile productivity with resource preservation (Poponi et al., 2022).

Key themes in CA include optimizing resource efficiency through closed-loop systems, reducing waste, promoting biodiversity, and fostering economic viability (Janker et al., 2018; Velasco-Muñoz et al., 2022). Janker et al. (2018) discuss these themes comprehensively, highlighting the potential of CA to transform agricultural systems towards sustainability. The integration of biological and technical nutrients aims to enhance productivity while minimizing environmental degradation. Waste reduction strategies, such as recycling agricultural residues and converting organic waste into valuable inputs, contribute to self-sustaining agricultural systems (Feleke et al., 2021).

Biodiversity conservation and ecosystem resilience are critical aspects, emphasizing agroecological principles to maintain soil health and support essential ecosystem services. Economic viability is also central, as CA reduces production costs and mitigates financial risks associated with resource scarcity and environmental regulations. Effective policy frameworks and innovation pathways are necessary to mainstream CA practices across agricultural sectors, ensuring scalability and impact (Ulukan et al., 2022).

CA offers transformative solutions for economic revitalization, poverty alleviation, food security, and job creation, particularly benefiting rural women and smallholder farmers (United Nations, 2021). The interconnectedness of agricultural industries—encompassing farming, forestry, fisheries, and processing—supports agroecological industry chains through circular economy principles (Jun and Xiang, 2011). Maximizing resource efficiency and sustainability through differentiated nutrient cycles and closed-loop systems is foundational to CA (Feleke et al., 2021; Ellen MacArthur Foundation, 2013).

Despite historical reliance on intensive farming practices, the shift towards smallholder and mixed farming practices is crucial for reducing ecological footprints and enhancing food security (Boon & Anuga, 2020; Velasco-Muñoz et al., 2021). CA promotes minimal chemical input usage, waste repurposing, and closed-loop product life cycles to optimize resource utilization and environmental impact (Lohman et al., 2020).

Maize, a staple crop in Africa, plays a vital role in food security and economic development (Ranum et al., 2014; FAO, 2023). Maize production faces challenges from climate variability and soil fertility decline exacerbated by intensive cultivation practices (Adjei-Nsiah et al., 2004). Adopting CA strategies for maize production emphasizes regenerative practices, reducing chemical inputs, and enhancing resilience to climate stresses (Grote et al., 2021). Maize residues contribute to soil enrichment and livestock feed, exemplifying circularity in agricultural production systems (Peter et al., 2017).

This literature review emphasizes the scientific advancements and practical applications of CA in Africa, aiming to bridge the gap between research and implementation. The compilation of studies from 1993 to 2022 highlights innovations tested under real conditions to promote farmer adoption and sustainability. Progress towards CA in Africa is advancing through tailored approaches that integrate scientific knowledge with practical farming experiences, fostering sustainable agricultural practices essential for future food security and environmental resilience.

2.2 Methodology

The PRISMA approach refers to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (Liberati et al., 2009). It is an evidence-based minimum set of items for reporting in systematic reviews and meta-analyses. The PRISMA statement was developed to help authors improve the reporting of systematic reviews and meta-analyses, providing a structured framework to ensure transparency and completeness in reporting such studies. Transparency allows readers to assess the strengths and weaknesses of the reported study as well as the quality of the review itself. The PRISMA statement includes a 27-item checklist and a four-phase flow diagram to guide authors in reporting the different stages of a systematic review or meta-analysis: identification, screening, eligibility, and inclusion. Adhering to the PRISMA guidelines enhances the quality and transparency of reporting, making it easier for readers to assess the validity and reliability of the review or meta-analysis (Ololade et al., 2019; Nadaraja et al., 2021).

The PRISMA approach is widely recognized and endorsed in the scientific community as a valuable tool for improving the reporting quality of systematic reviews and meta-analyses across various disciplines. This method was originally developed in the field of health care and medical sciences (Liberati et al., 2009) but since then, it has already been successfully applied in other fields of research such as sustainable agriculture research (Martinho & Guiné, 2021; Nadaraja & Islam, 2021). The innovativeness and quality of PRISMA, as an approach for conducting systematic literature reviews, result from its elaboration process relying on repeated enhancements based on deliberation among review experts. They are also related to the transparency of this approach, as well as its recognition by review authors and journal editors. PRISMA and its extensions are detailed on a dedicated website[1].

Articles were selected from two online databases - Web of Science (WOS) and Scopus – recognized among the scientific community as the most complete databases in terms of scientific articles. This study employed rigorous inclusion criteria at different stages to select

[1] https://www.prisma-statement.org

relevant research on CA practices in Africa. The inclusion criteria considered factors such as keywords, crop relevance, geographical area, study type, data output, language, year of publication and journal impact factor (Stathers et al., 2020).

- Relevant crop: only studies having maize as a main crop were considered
- Relevant geographical area: only studies taking place in Africa were selected
- Relevant study type: only studies that were published in a peer reviewed journal were selected
- Relevant data output: Studies describing practices perceived as stemming from circular agriculture
- Studies reporting only CA practices
- Language: only studies written in English were included
- Year of publication: articles published during the last 30 years (from 1993 to 2022) were considered

Specific inclusion criteria were applied, retaining only studies published in journals with an Impact Factor (IF) ≥ 3.0 to ensure scientific rigor. While IF is widely used as a quality proxy (Saha et al., 2003; Garfield, 2006), this approach has limitations. It may introduce selection bias by excluding relevant francophone studies, particularly those focused on African contexts, often published in journals with lower IF or not indexed in Scopus/WOS. Although this choice supports methodological consistency, the omission of high-quality regional literature could affect long-term interpretation. Future studies should integrate broader sources to improve representativeness.

2.3 Results

The first part of the results section presents the findings derived from the iterative stages of the PRISMA approach applied to the systematic literature review on CA in Africa. While the PRISMA methodology provides a rigorous framework, it is important to acknowledge potential biases that may influence the scope and interpretation of findings. First, the limited availability of research specifically focused on CA in African contexts may lead to an overrepresentation of certain regions, practices, or perspectives, potentially skewing overall conclusions. Second, language barriers and publication biases—such as the exclusion of relevant studies published in French-language journals or non-indexed outlets—may restrict the inclusiveness of the review, especially given the predominance of francophone agricultural research in Central and West Africa. Finally, methodological heterogeneity among the included studies, as well as context-specific cultural and environmental factors, can influence data collection and interpretation. Recognizing these limitations is essential to ensure transparency and guide more informed conclusions.

Three steps were undertaken to identify 33 articles most relevant to this review. The first phase consists of formulating the list of keywords. The inclusion and exclusion criteria made it possible to focus on articles published in English between 1993 and 2022 and having at least one of the keywords linked by the appropriate Boolean operator (OR, AND): *((circular AND economy) OR (GHG AND emissions) OR (life AND cycle AND analysis) OR (farm* AND system) OR (regeneration AND farm*) OR (regeneration AND agriculture*) OR (carbon AND sequestration) OR (power AND security) OR (circular* AND indicator) OR (regeneration AND design) OR (sustainable* AND agri*) OR (circular AND system) OR (ingenious AND firm* AND practical) OR (power AND security) OR (productivity) OR (circular AND system)) AND Africa (All areas)*.

The second phase consisted of eliminating the 194 duplicates among the 598 articles selected from the Scopus and WOS databases (Figure 1). The last phase was carried out in 2 parts using manual reviews on EndNote, the first made it possible to exclude 78 articles by means of filtering article titles. These articles were excluded either because the main targeted crop was not maize or because the fertilization practices were chemical. The second part consisted of a selection of the full texts of the remaining 326 articles and made it possible to eliminate 293 articles. Only research that did not involve the use of chemical inputs and focused on current or past practices was retained. For example, preliminary interviews used to prepare a survey or climate change forecasts were not considered. Articles are classified according to the data on the country, the research method and the classification of CA practices were put in Table 1 and Table 2.

The classification of practices was made according to the definition of CA and the need to reduce the use of external and chemical inputs in commonly used agricultural practices. Data synthesis included meta-analysis at the study and intervention level, with adjustments for sustainable agricultural interventions. The final list is made up of 33 articles including 26 quantitative analyzes such as field experiments or case studies and 7 qualitative analyzes such as literature reviews or surveys.

This list is divided into Table 1, which encompasses literature reviews, and Table 2, which comprises quantitative and descriptive analyses. These tables include articles that document various tillage practices, soil management strategies, intercropping methods, sustainable soil fertility strategies, and sustainable fertilization practices across different regions and communities in Africa. The tables integrate qualitative studies, field experiments, and surveys, with each category representing approximately one-third of the total number of articles. Surveys offer the advantage of encompassing a large number of farms (over one hundred), whereas field experiments are conducted at fewer than 50 sites.

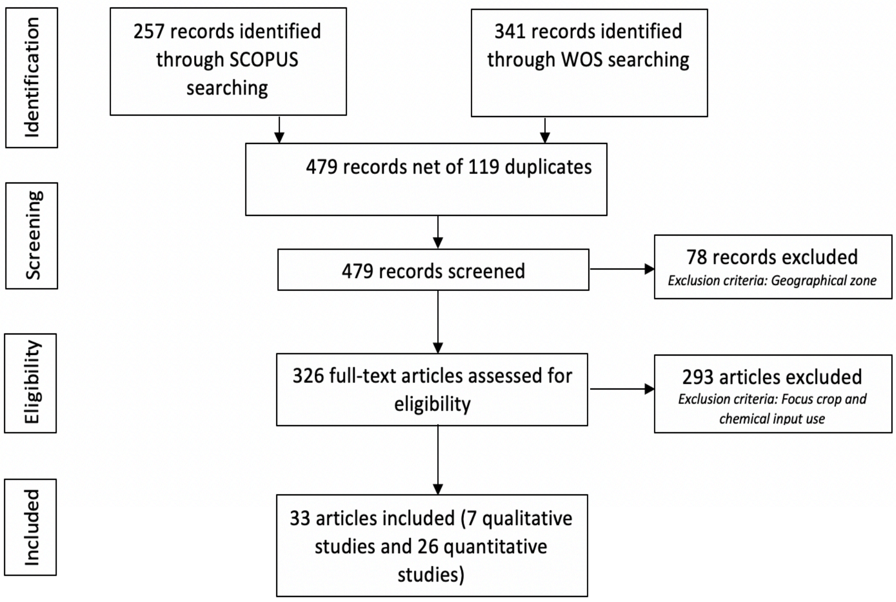

Figure 1. The Flow diagram

Authors	Study Year	Research method	Sample Size	Country/ Region	Topic

Babalola and Oparanadi, 1993	1961-1990	LR	113	West Africa	Effect of tillage practices on soil chemical properties
Snapp et al., 1998	1993-1996	LR	67	Malawi, Zimbabwe	Organic matter technologies
Snapp and Silim, 2002	1996-1999	LR	28	Kenya, Malawi	Legume-based technologies for intercropping and fertilization
Kuyah et al., 2019	1945-2018	LR	126	Sub-Saharan Africa	Effects of agroforestry intercropping
Daryanto et al., 2020	1970-2018	LR	180	Africa	Effects of grain legumes intercropping

Table 1. Distribution of literature reviews by author, year, research method, sample size, geographical zone and topic

Note: LR=Literature review

Authors	Study Year	Sample size	Empirical method	Country/ Region	Topic
Odunze et al., 2004	2000-2002	5	Field. Exp	Nigeria	Impact of forage legume and maize intercropping on soil fertility
Guzha et al., 2005	2002	4	Field. Exp	Zimbabwe	Human excreta as a fertilization practice
Tian et al., 2005	1989-2000	10	Field. Exp	Nigeria	Fallow crops as a fertilization practice
Adjei-Nsiah et al., 2007	2003-2004	44	Field. Exp	Ghana	Intercropping management practices' relevance in social context
Doraiswamy et al., 2007	1985-2000	17	Field. Exp	Mali	Soil management practices to ameliorate soil carbon sequestration
Mapfumo et al., 2007	2007	6	Field. Exp	Zimbabwe	Soil organic matter formation
Khan et al., 2008	2005	478	Survey	Kenya	Impact of push-pull practice on parasites
Enfors et al., 2011	2005-2008	6	Field. Exp	Tanzania	Conservation tillage practice
Makurira et al., 2011	2006-2008	4	Field. Exp	Tanzania	Farming system innovations
Adgo et al., 2013	2009	60	Survey	Ethiopia	Soil and water initiatives' impact on economic measures and their relevance in social context
Adjei-Nsiah et al., 2004	2002	78	Survey	Ghana	Soil management practices' relevance in social context
Waha et al., 2013	2002-2004	8697	Survey	Sub-Saharan Africa	Spatial distribution of sequential cropping systems
Midega, Bruce, Pickett and Kahn, 2015	2009	400	Survey	East Africa	Impact of push-pull practice on parasites
Midega et al., 2015	2012-2014	395	Field. Exp	East Africa	Impact of push-pull practice on parasites
Murage, A. W., et al., 2015	2014	461	Survey	East Africa	Gender specific perspectives and adoption patterns of push-pull practice
Atandi et al., 2017	2015-2016	5	Field. Exp	Kenya	Effects of organic and conventional farming on plant parasitic nematodes
Chepchirchir et al., 2017	2014	560	Survey	Uganda	Impact of adoption of push-pull technology (PPT) on household welfare
Lalani et al., 2017	2014	197	Survey	Mozambique	Consequences of adopting conservation agriculture
Smethurst et al., 2017	1996-2003	7	Field. Exp	Kenya, Malawi	Effects of agroforestry intercropping
Nkomoki et al., 2018	2016	400	Survey	Zambia	Impact of implementing sustainable agricultural practices on food security
Katterer et al., 2019	2006	3	Field. Exp	Kenya	Impact of incorporating biochar into maize and soybean crop rotations
Roobroeck et al., 2019	2016-2017	60	Survey	Uganda	Impact of biochar on carbon sequestration
Amadu et al., 2020	2000-2014	808	Survey	Malawi	Effects of agroforestry intercropping and climate-smart agriculture practices

Diallo, A., et al., 2020	-	308	Survey	Mali	Impact of climate change adaptation strategies on maize productivity and household food security
Amann et al., 2021	2014	506	Survey	Kenya, Uganda	Impact of implementing sustainable agricultural practices on food security and soil fertility
Schader et al., 2021	2014-2017	700	Survey	Ghana and Kenya	Agronomic and economic impacts of organic farming
Tanga et al., 2022	2019	6	Field. Exp	Kenya	Impact of black soldier fly frass fertilizer on maize crop performance
Adetoyinbo et al., 2022	2022	54	Survey	Nigeria	Pathways for enhancing the bioeconomy

Table 2. Distribution of quantitative and descriptive article by author, year, empirical method, sample size, geographical zone and topic

Note: Field. Exp = Field Experiment

Closer analysis of article distribution in space (Figure 2) reveal that scientists carried out more experiments in Kenya, with 9 studies. There are 7 articles where the exact regions were not specified, because the authors either referred to the whole continent or to a broader region (e.g. sub-Saharan Africa, East Africa or West Africa). Uganda and Malawi come next, with half as many studies conducted on their territory as Kenya. Meanwhile, Zimbabwe, Ghana, Zambia, Tanzania and Nigeria come third, with three publications each. Ethiopia, Mali and Mozambique have published the least, with two and one articles respectively. The geographical distribution of unselected articles was also examined (Figure 2). It turns out that when the hypothesis of strict circularity is lifted, the geographical coverage expands. This is an indication that the concept of circularity is in a discovery phase as far as scientific research is concerned. However, the countries that are most advanced in this area already have a high level of research into sustainable agriculture, solutions for improving soil fertility in the short or long term, improving irrigation systems and improving seed quality.

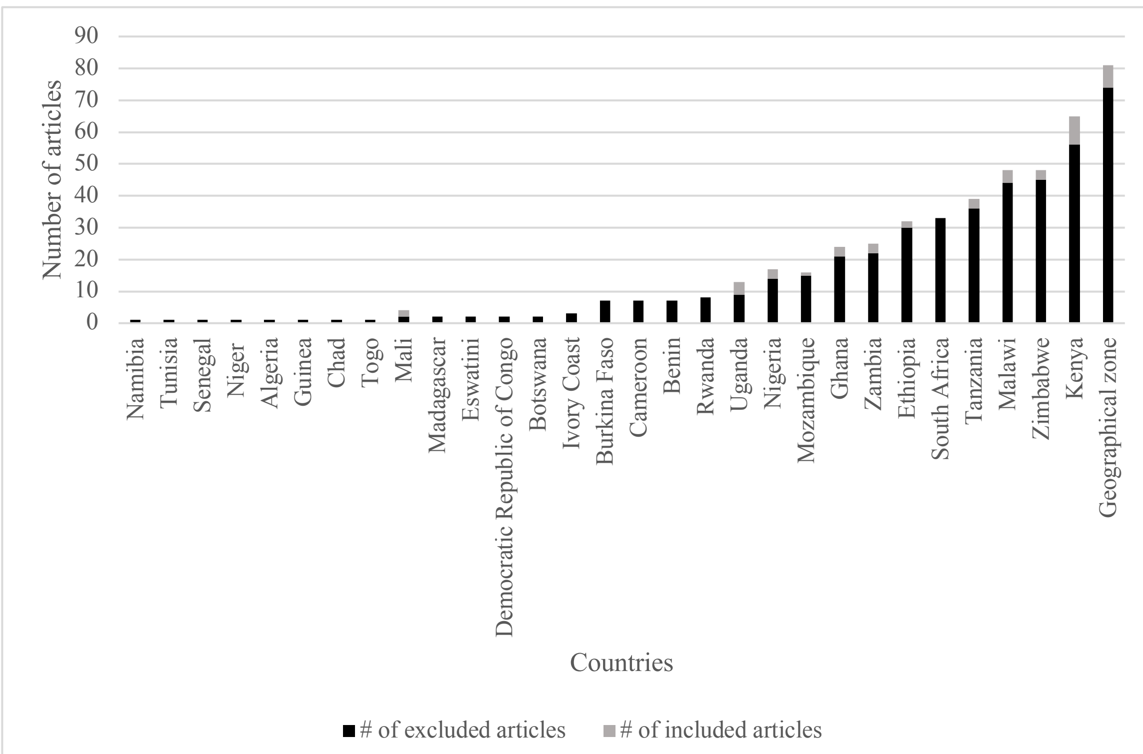

Figure 2. Distribution of articles by country
Note: Geographic zone represents China, East Africa, Sub-Saharan Africa, West Africa and North Africa.

The second part of this section synthesizes the findings from the 33 selected studies, which reveal that CA implementation strategies converge around three main thematic axes: (i) tillage practices and soil management, (ii) intercropping and soil fertility strategies, and (iii) fertilization practices. These represent the core research priorities and action pathways for promoting sustainable and resilient agricultural systems in African contexts.

i. Tillage practices and Soil Management

Tillage practices play a crucial role in shaping soil physical properties, influencing crop growth, and ultimately determining agricultural productivity. Within the framework of CA, these practices are central to improving soil health, enhancing nutrient cycling, and reducing environmental degradation. However, in West Africa, appropriate tillage systems have not yet been fully recognized as an integral part of sustainable land and resource management strategies, despite their potential to alleviate soil and environmental constraints weighing on agricultural production (Babalola & Oparanadi, 1993).

Among the most widespread practices, in West Africa, traditional tillage involves the use of cutlasses, hoes, axes, and shovels to prepare mounds, piles, or ridges. This approach aims to increase soil depth, recycle organic matter by burying residues, improve tuber development, enhance aeration, and control erosion. Mulching is often integrated into this system and has proven effective in reducing nutrient losses. From a circular perspective, traditional tillage contributes to resource recycling by reintegrating biomass into soils and improving nutrient retention. However, under marginal precipitation conditions, this system can also lead to supraoptimal soil temperatures, unstable moisture levels, and accelerated erosion, which may counteract its intended benefits. Assessing its circularity requires monitoring soil organic matter content, nutrient retention efficiency, and soil erosion control (Babalola & Oparanadi, 1993).

In contrast, plow-till systems, which use mechanized equipment such as moldboard plows, discs, and harrows, increase short-term productivity but can negatively affect soil structure and carbon storage if residues are not managed properly. While plow-till offers operational efficiency, its circular benefits are limited unless combined with crop residue retention strategies. Evaluating its sustainability involves measuring soil compaction, energy consumption, and greenhouse gas emissions linked to mechanized operations (Babalola & Oparanadi, 1993).

Minimum tillage reduces the intensity of soil disturbance by limiting mechanical operations to preserve soil structure and increase macroporosity. As a result, this practice enhances water retention and promotes biodiversity, thereby improving the soil's ability to store and recycle nutrients while reducing energy use (Enfors et al., 2011). Its contribution to circularity can be quantified by measuring bulk density, infiltration rates, soil moisture content, and energy savings compared to conventional plowing systems.

Similarly, no-till systems, which avoid plowing altogether, rely on the retention of crop residues on the surface and herbicide use for weed control. By leaving a protective mulch, these systems improve soil organic carbon, reduce erosion, and enhance water retention. No-till therefore fosters closed nutrient cycles and contributes directly to carbon sequestration (Babalola & Oparanadi, 1993). Monitoring soil organic carbon levels, residue recycling ratios, and greenhouse gas reduction allows for evaluating the degree of circularity achieved through this approach.

Complementary practices such as puddling and soil compaction are designed to regulate soil permeability and water retention, which is particularly relevant in water-scarce contexts. By optimizing infiltration and reducing evaporation losses, these techniques enhance water use efficiency and overall resource sustainability (Babalola & Oparanadi, 1993). Evaluating circular benefits here requires monitoring water retention capacity, evapotranspiration reduction, and yield stability under dry conditions.

Recent research highlights that combining tillage with integrated practices, such as mulching, cover cropping, runoff diversion, and manure application, enhances circularity outcomes. Makurira (2011) demonstrated in Tanzania and Zimbabwe that this integration significantly improves maize yields by optimizing water use and nutrient recycling, particularly under average rainfall conditions. However, these benefits decrease in extreme droughts, underscoring the importance of water availability and conservation for sustaining productivity in rainfed systems (Makurira, 2011; Enfors et al., 2011).

Simulation studies by Doraiswamy et al. (2007) conducted in Mali revealed that optimal management of ridge tillage combined with improved irrigation and increased nutrient inputs can enhance soil carbon sequestration and significantly raise economic returns. Similarly, research in Nigeria's Anjenie catchment demonstrated the long-term benefits of terracing for improving yields, ensuring food security, and reducing household poverty by enhancing water retention and reducing erosion (Adgo et al., 2013). These findings underline the importance of measuring runoff reduction, soil erosion control, and changes in household income to capture the full circular contribution of terracing practices.

Beyond soil and water management, innovative agroecological systems such as push-pull strategies offer promising results. Midega et al. (2015) showed that integrating legumes and pest-repelling plants improves soil fertility, reduces striga and stemborer infestations, and increases maize grain yields. These systems are inherently circular, as they minimize pesticide use while promoting biological nitrogen fixation and biomass recycling. Measuring pest incidence reduction, nitrogen fixation rates, and yield gains provides a robust basis for evaluating their effectiveness.

The adoption of conservation agriculture, which combines residue retention, crop rotation, and cover cropping, has also demonstrated significant potential. Thierfelder et al. (2013) reported that CA systems implemented in Zambia enhance water infiltration, increase soil moisture, improve carbon storage, and progressively raise crop yields compared to traditional systems. These improvements are directly linked to recycling organic matter, preserving ecosystem services, and stabilizing production across variable climatic conditions.

Recent developments in bioresource recycling complement these advances. Tanga et al. (2022) highlighted the potential of black soldier fly frass fertilizer, which converts organic waste into sustainable biofertilizers, closing nutrient loops while reducing dependency on chemical inputs. Integrating this innovation into CA systems enhances nutrient efficiency and lowers environmental impacts.

However, several systemic challenges remain. As noted by Adetoyinbo et al. (2022), the indiscriminate disposal of maize residues can cause environmental pollution and lead to conflicts between farmers and livestock herders. Lalani et al. (2017) further emphasized that successful implementation of CA relies on social learning mechanisms, tailored training, and inclusive management systems. Programs that integrate risk management strategies and targeted farmer education are therefore essential to encourage widespread adoption, particularly among resource-constrained smallholders.

ii. Intercropping and Soil Fertility Strategies

Intercropping, defined as the cultivation of two or more different crops within the same planting space, represents another key practice in promoting CA. A typical example is maize intercropped with legumes such as groundnuts or beans, enabling farmers to harvest two crops within a single season and improve household income (Nkomoki et al., 2018). This practice plays a central role in smallholder systems across Malawi and Zimbabwe, particularly where access to synthetic fertilizers is limited. By promoting biological nitrogen fixation and soil regeneration, intercropping directly contributes to reducing external inputs and improving agroecosystem sustainability (Snapp et al., 1998; Snapp & Silim, 2002).

Several intercropping strategies illustrate the diversity of circular contributions. First, grain legumes cultivated in rotation with cereals supply nitrogen to subsequent crops, reducing dependence on mineral fertilizers and closing nutrient loops. Second, although intercropping maize with food legumes mitigates production risks, maize competitiveness often limits legume biomass production, resulting in minimal soil nitrogen contributions. Third, the use of perennial legumes as improved intercrops or fallows enhances biological nitrogen fixation and deep nutrient uptake, improving long-term soil fertility (Tian et al., 2005). Fourth, relay intercropping using deep-rooted species such as *Sesbania sesban* combines the benefits of improved fallows (e.g., *Pueraria* or *Leucaena*) and green manures, enhancing nitrogen use efficiency and providing soil cover to prevent erosion (Snapp et al., 1998).

These systems also improve phosphorus solubilization and soil structure while promoting diversified diets and increased market opportunities through the integration of short- and long-cycle crop varieties, balancing immediate food needs and long-term soil restoration (Snapp & Silim, 2002). To measure the degree of circularity of intercropping systems, relevant indicators include (Velasco-Muñoz et al., 2021):

- Nutrient cycling efficiency: quantity of N fixed biologically (kg N/ha) and phosphorus availability;
- Soil quality enhancement: changes in soil organic carbon content and aggregate stability;
- Resource-use efficiency: reduction in synthetic fertilizer dependency (% decrease);
- Diversity metrics: number of functional species cultivated simultaneously.

Forage legumes integrated into cropping cycles further enhance circularity by enriching plant-available nitrogen and improving soil moisture retention (Odunze et al., 2004). In Ghana, cowpea fixed more than 50% of its nitrogen through biological processes, supplying up to 200 kg N/ha to subsequent crops (Adjei-Nsiah et al., 2004). Beyond nitrogen contributions, cowpea disrupts pest cycles, improves soil structure, and increases arbuscular mycorrhizal colonization, fostering greater microbial diversity (Mapfumo et al., 2007; Smethurst et al., 2017). Such benefits demonstrate the multifunctional role of legumes in promoting nutrient self-sufficiency and reducing external inputs, aligning closely with the principles of CA.

The introduction of Push-Pull Technology (PPT) represents a particularly innovative approach to achieving circularity in East African smallholder systems by reducing dependence on herbicides (Midega et al., 2015; Chepchirchir et al., 2017). This habitat management system integrates drought-tolerant crops like *Brachiaria brizantha*, *Cenchrus purpureus*, and *Desmodium intortum* to repel stemborers (“push”) while attracting them to trap plants (“pull”), simultaneously controlling *Striga hermonthica* through suicidal germination and allelopathy. PPT enhances soil fertility, reduces reliance on pesticides, and provides livestock fodder, creating a closed-loop system between crops, pests, and livestock. Farmers adopting PPT report increased maize and fodder yields, improved milk production, and higher household incomes (Murage et al., 2015; Khan et al., 2008). Indicators of circular performance include (Velasco-Muñoz et al., 2021):

- Pest suppression rates (% reduction in stemborer and striga incidence);
- Integration of livestock and cropping systems (livestock feed production per hectare);
- Adoption intensity (land area under PPT relative to total farm size);
- Household livelihood impacts (income diversification indices).

Furthermore, sequential and rotational cropping systems offer complementary strategies to enhance circular flows of nutrients and resource efficiency. Waha et al. (2013) showed that the highest-yielding sequential cropping systems, involving two short-cycle crops per year, optimize land productivity while preserving soil integrity. Similarly, integrating cassava/maize rotations with nitrogen-fixing species like *Mucuna pruriens* or pigeon pea increases soil nitrogen content and improves maize yields in subsequent seasons (Adjei-Nsiah et al., 2007). These practices reduce nutrient losses and increase carbon sequestration potential, reinforcing CA’s environmental objectives.

iii. Fertilization Practices

The global consumption of fertilizers has risen steadily over the past decades, and if this trend continues, it risks leading to an unsustainable food production model. To ensure long-term food security, it is essential to optimize resource efficiency so that nutrients remain available for future generations (Guzha et al., 2005). Within the framework of CA, fertilization practices aim not only to improve crop yields but also to maintain soil health, recycle nutrients, and reduce environmental pressures. Conventional nitrogen (N) fertilization, while widely used, presents significant challenges such as nitrous oxide (N_2O) emissions, nitrate leaching, and soil acidification.

Transitioning towards CA promotes organic and bio-based fertilization strategies, which close nutrient loops and reduce dependency on synthetic inputs. Organic farming, for example, embodies circularity by recycling organic matter, reducing pesticide and mineral fertilizer use, and enhancing biodiversity. However, challenges like yield declines must be carefully managed to prevent trade-offs between environmental benefits and food security (Schader et al., 2021). In Mali, Diallo et al. (2020) demonstrated that combining biofertilizers with short-duration maize varieties improves productivity, empowers rural communities, and reduces climate vulnerability, thereby strengthening farmers' livelihoods.

One promising CA pathway is the integration of biochar, derived from crop residues, into fertilization systems. Kätterer et al. (2019) found that biochar significantly improves soil water-holding capacity and increases maize yields, particularly in low-input systems. Furthermore, Roobroeck et al. (2019) highlighted biochar's potential to sequester carbon and reduce greenhouse gas emissions. Using cereal-legume biomass waste from maize, sorghum, rice, millet, and groundnut, biochar contributes to both energy production and soil fertility restoration. However, Adetoyinbo et al. (2022) note that industrial demand for maize residues from breweries, textile companies, and food processors can destabilize residue availability, requiring coordinated resource planning.

To measure circularity within biochar systems, several indicators are recommended:

- Carbon sequestration potential (t CO_2e ha^{-1} yr^{-1}) through bulk density sampling;
- Residue recycling rates (% of maize biomass converted into biochar);
- Energy recovery efficiency (MJ kg^{-1} of dry residue gasified);

Agroforestry systems represent another essential CA practice by integrating trees into cropping systems to enhance nutrient cycling, stabilize soils, and diversify production. According to Kuyah et al. (2019), selecting appropriate tree-crop combinations maximizes ecosystem services while minimizing shading or resource competition. Nitrogen-fixing "fertilizer trees," such as *Gliricidia sepium*, improve soil fertility and increase maize yields across Sub-Saharan Africa (Amadu et al., 2020). However, performance varies significantly depending on soil type, climate, and farmer capacity, underscoring the need for site-specific recommendations.

The circular contributions of agroforestry can be quantified using indicators such as:

- Nitrogen fixation by trees (kg N ha^{-1} yr^{-1})
- Soil organic carbon gains (%) through belowground biomass incorporation;
- Household food security index via dietary diversity and yield stability metrics.

Atandi et al. (2017) demonstrated the potential of organic amendments—such as composted manure or plant residues—in controlling root-knot and lesion nematodes while improving soil structure. Similarly, Tanga et al. (2022) revealed that black soldier fly (BSF) frass compost enriches soil nutrients and enhances maize yields, representing a low-cost, circular biofertilizer. By recycling organic waste into agricultural inputs, BSF-based fertilizers close the loop between waste management and soil fertility restoration, offering significant environmental and economic benefits.

Measuring the circularity of these organic inputs requires:

- Nutrient recovery efficiency (% of nutrients from waste assimilated by crops);
- Yield response factor;
- Reduction in synthetic input use (% replacement of mineral fertilizers).

Furthermore, combining mineral fertilizers with locally available organic resources like compost, vermicompost, and ecofert—fertilizers derived from treated human excreta—improves nutrient efficiency while mitigating environmental risks. Guzha et al. (2005) demonstrated that integrating human waste-based amendments into fertilization systems not only improves yields but also reduces pollution from untreated waste streams. Ecofert thus presents a dual benefit: sustainable nutrient recycling and improved sanitation. However, policy interventions are required to classify human excreta as a resource rather than waste, enabling its safe integration into CA frameworks.

Finally, Amann et al. (2021) highlighted that urine collection, composting, and vermiculture are promising options for smallholder farmers to close nutrient cycles sustainably. Linking these practices to CA principles enables simultaneous improvements in soil fertility, sanitation, and farm profitability.

2.4 Blocking factors to transition

While this study of CA in Africa provides valuable insights into sustainable agricultural practices, it is not without limitations. These blocking factors affect a full transition to a CA and the applicability of the findings to a larger scale. Here are some of the most important factors that should be considered:

1. Regional differences: CA practices may vary significantly between countries in Africa due to different agro-ecological conditions, socio-economic factors and cultural differences. Therefore, the results of the study may not be universally applicable and should be interpreted with caution in the context of the specific regions mentioned.

2. Scale of implementation: The study may have focused on a specific scale of implementation of CA, such as smallholder farms or community-based initiatives. It may be difficult to extrapolate the results to larger farming systems or industrial-scale agriculture. The scalability and feasibility of CA at different scales needs to be considered, as it could accelerate the transition of the agricultural sector towards a more competitive and sustainable sector. It is recommended to focus on medium and large farms. In recent years, these types of farms have gained more interest and

share in the distribution of farms in most African countries (Muyunga & Jayne, 2019). An approach to test the relationship between farm size and productivity could also provide solutions to the adaptability of farms to climate change and their potential in the transition (Sheng et al., 2019; Verschelde et al., 2012; Sorgho et al., 2020; Muyunga & Jayne, 2019).

3. Temporal dynamics: Agricultural systems are subject to temporal dynamics influenced by seasonal variations, climate change and changing socio-economic conditions. The results of the study may reflect a specific time frame and may not capture long-term impacts or changing trends in CA practices over time.

4. Infrastructure and technology constraints: CA often relies on advanced technologies and infrastructure for efficient waste management, resource recycling and renewable energy integration. Limitations in technology adoption and inadequate infrastructure in certain areas can hinder the widespread adoption of CA practices. However, during this transition, SSA countries will have to overcome several challenges, such as adapting regulations and decision-making processes, enforcing adequate infrastructure, developing new technologies, changing consumer and farmer attitudes, and providing incentives to attract new investors. (Velasco-Muñoz et al., 2021).

5. Social and cultural factors: The success of CA is determined not only by technical and environmental factors, but also by social and cultural aspects. Local traditions, beliefs and social structures can influence the acceptance, pace and adoption of circular farming practices, and these nuances should be thoroughly explored. Particular attention will be paid to the expectations of the target audience (local agricultural producers) by positioning these products in relation to existing competing products (synthetic pesticides and plant extracts) (De Groote et al., 2001).

6. Policy and regulatory framework: The study may not fully account for differences in policy frameworks and regulatory environments in different African countries. Differences in governance structures and policies related to agricultural and environmental management could affect the feasibility and success of CA initiatives.

Given these limitations, researchers and policymakers should be cautious in applying the study's findings to broader contexts and work to address these limitations in future research to ensure a more comprehensive understanding of the potential of CA in Africa. As mentioned above, the concept of CA has long been ignored in favour of other areas. An in-depth analysis of the list of keywords would make it possible to identify those that would enable the final list to be obtained and to optimise the PRISMA process of selecting key articles. This approach could also be used in future research.

2.5 Discussion and Concluding remarks

This review attempted to demonstrate that CA can provide a viable pathway toward sustainable and resilient agricultural systems in Africa, particularly for maize-based production. However, fully realizing its potential requires addressing data gaps, testing CA practices across diverse agro-ecological zones, quantifying environmental and economic impacts using standardized indicators, and exploring scalable models for smallholder and medium-scale farms. By integrating evidence-based policy, technological innovation, and farmer-driven approaches, African countries can leverage CA to simultaneously improve productivity, enhance resource efficiency, and ensure long-term food security while mitigating environmental degradation.

This study provides a systematic synthesis of 33 peer-reviewed articles using the PRISMA approach to assess the state of CA research in Africa, with a particular focus on maize-based systems. Rooted in the principles of the circular economy, CA offers an integrated framework for minimizing waste, optimizing resource efficiency, and regenerating ecosystems while enhancing agricultural productivity. The findings indicate that, although interest in CA is growing, research in African contexts remains fragmented and unevenly distributed, with significant gaps for several countries — particularly in Central Africa. This underlines both the urgency and the opportunity to further develop empirical and context-specific studies on CA for sub-Saharan Africa.

Across the reviewed literature, CA practices in Africa converged around three main thematic areas: tillage and soil management, intercropping and soil fertility strategies, and fertilization practices. Collectively, these approaches contribute to closing nutrient loops, enhancing resource efficiency, and restoring ecosystem services.

Methodologically, this review acknowledges several limitations. A potential selection bias arises from the scarcity of African-focused CA studies indexed in major databases such as Scopus and Web of Science, which leads to an underrepresentation of French-language publications and relevant studies from local journals with lower impact factors. Furthermore, significant data gaps persist, particularly in countries such as the Democratic Republic of Congo (DRC), constraining the ability to generalize findings and design robust monitoring frameworks. Addressing these gaps requires targeted data collection and the inclusion of non-indexed literature to better reflect Africa's diverse agricultural realities.

From a practical perspective, the findings demonstrate that scaling CA practices requires integrated policy actions across several dimensions. First, promoting organic amendments such as compost, biochar, and black soldier fly (BSF) frass shows strong potential to improve soil organic carbon and crop productivity. Second, the adoption of agroforestry systems and push-pull technologies enhances nutrient cycling, reduces pest pressures, and improves household food security. Third, diversified cropping systems through intercropping and rotations are essential for maintaining soil fertility and stabilizing yields. Collectively, these practices embody the core principle of circularity: optimizing resource use while maintaining ecological resilience.

Despite its promise, the transition towards CA faces structural challenges requiring coordinated interventions. Public policies should invest in extension services, capacity-building programs, and financial incentives to accelerate farmer adoption. Strengthening financing mechanisms for cooperatives and farmer associations would reduce barriers to accessing organic inputs, innovative technologies, and diversified markets. Additionally, the high climatic variability typical of African agro-ecological zones leads to heterogeneous and sometimes inconsistent impacts compared to regions with more stable conditions, underscoring the need for localized and context-specific strategies.

To systematically evaluate the degree of circularity achieved by these practices future research should be dedicated to the construction of a composite circularity indicator combining three main dimensions:

1. Biophysical indicators
2. Resource-use indicators
3. Socio-economic indicators

Integrating these indicators would enable policymakers, researchers, and practitioners to monitor progress towards sustainable agricultural transitions, compare systems across contexts, and prioritize effective strategies for scaling CA. Such tools are particularly relevant for African decision-makers seeking to reconcile food security objectives with environmental conservation and climate resilience.

3 Chapter 2 : Turning waste into wealth: The case of Date Palm Composting (published in *Sustainability*)

Abstract: This study investigates the economic viability of a new composting station dedicated to the recycling of date palm by-products. A field experiential analysis was performed in the Figuig Oasis (Morocco), providing the first evidence on the agronomic quality of the compost. The compost produced from date palm by-product was *c*ompared to cattle manure and unamended soil and can be considered as a good-quality amendment demonstrating its ability to enhance soil fertility. Second, a socio-economic survey was conducted to explore farmers' perceptions and adoption of sustainable agricultural practices. A total of 201 farmers out of 450 farmers registered in Figuig's municipal administration, were surveyed. In terms of fertilisation, farmers preferred locally produced organic fertiliser when available in order to improve soil organic matter content and reduce dependence on chemical inputs. The selling price for the compost was set at 0.14 EUR/kg to reflect the current market price for compost and the willingness of about 38% of the farmers surveyed to buy it. Third, a detailed cost/benefit analysis was performed, with a breakdown of the station's operational and investment expenses. This illustrates the minimum scale needed to generate a viable business model. Financial projections show that increasing production capacity from 350 tonnes/year to 3500 tonnes/year reduces unit production costs while increasing profits. As illustrated by the application of the Ecocanvas framework, the socio-economic analysis reveals the potential to generate positive environmental, economic, and social impacts, as the circular approach could be replicable and scalable in similar oases agro ecosystems.

2.1 Introduction

Oases are unique agro-ecosystems, intensively managed in desert areas and often located in river deltas, alluvial–diluvial plains, and along the edges of alluvial fans, where irrigation is typically sourced from rivers (El Janati et al., 2021). In Morocco, oases cover about 15% of the national territory (107,324 km² out of 446,500 km²) and are home to 1.6 million inhabitants, representing 5% of the population. They host a large share of the country's phoenicicole heritage, with date palm (*Phoenix dactylifera* L.) cultivation playing a central role in their ecological and socio-economic fabric (FAO, 2017; Sedra, 2003).

As of 2019, date palms in Morocco were cultivated over approximately 60,000 hectares (Ibrahimi et al., 2023). While historically valued for food and carpentry, date palm residues now often accumulate, causing several problems: they occupy arable land, foster pests and diseases such as Bayoud (caused by the soil-borne fungus *Fusarium oxysporum* f.sp. *albedin*is), increase fire hazards, and contribute to visual pollution (Janati et al., 2022).

Date palm waste in Morocco is estimated at 104,000 tonnes annually (Khardi et al., 2024). Rich in organic carbon, it holds significant potential for compost production to enhance soil fertility and crop yields in arid and semi-arid regions (El Janati et al., 2021; FAO, 2017; Sedra, 2023; Ibrahimi et al., 2023; Janati et al., 2022). Desert-based agricultural systems are characterised by acute constraints in soil fertility, water scarcity, and waste management. These limitations are particularly visible in oasis farming systems, where maintaining productivity under resource scarcity requires innovative solutions. Footprint assessments of Medjool date value chains have underscored the importance of developing circular approaches to close nutrient loops, reduce waste, and sustain production under desert conditions (Ravitz Wyngaard & Kissinger, 2022). Within this context, the valorisation of date-palm residues through composting emerges as a promising pathway to simultaneously manage agricultural waste and improve soil health.

A growing body of research demonstrates that compost derived from date-palm residues has the capacity to improve nutrient availability and support crop productivity in arid agro-ecosystems. For instance, it has been shown that date palm compost application enhanced nutrient release and promoted silage corn growth in desert soils, confirming its agronomic value (Janati et al., 2022). Additionally, it was reported that date palm compost improved germination and seedling vigour in barley (Ghouili et al., 2023). Importantly, when composting processes are rigorously monitored following physico-chemical and spectroscopic assessments to confirm compost maturity and safety, the resulting product meets agronomic quality standards (Vico et al., 2023; Abid et al., 2020).

Beyond nutrient enrichment, date palm compost influences biological dimensions of soil fertility. Its application was documented as it increased soil microbial diversity in barley fields, highlighting its potential to sustain soil health beyond short-term nutrient cycling (Ghouili et al., 2023). In parallel, research has shown that combining date palm residues with biochar further improves soil physical properties, including water retention and structural stability—critical levers for resilience in sandy soils with low organic matter content (Kavvadias et al., 2024; Le Guyader et al., 2024). Such results align with broader evidence demonstrating the long-term benefits of organic amendments for soil fertility and sustainability in diverse agro-ecosystems (Diacono & Montemurro, 2024).

The objective of this study is to evaluate whether establishing a composting station for date palm waste can serve as a viable circular business model. The research was conducted in three main stages:

- Agronomic assessment: Production of compost from date palm residues and evaluation of its effect on crop productivity in field trials with crop species commonly grown in oases.
- Farmer survey: Assessment of local farmers' perceptions and willingness to use locally produced compost to assess market acceptance.
- Socio-economic viability and business modelling: Evaluation of the production capacity, potential pricing, investment and operational costs, and long-term sustainability of the composting station, combined with the development of a circular business plan using the Ecocanvas tool (Daou et al., 2020) to visualise the potential added value.

Although previous studies have examined the composting of date palm residues—either alone or combined with other organic inputs—in oasis environments (El Janati et al., 2021), this study is, to our knowledge, the first to integrate agronomic validation of compost quality through field trials with a comprehensive socio-economic feasibility assessment, including circular business modelling, within an oasis agro-ecosystem.

2.2 Materials and Methods

2.2.1 Date Palm By-Product Compost as Fertiliser for Oasis Crops

The compost used in this study was produced at the Figuig Oasis production plant using the process mentioned in Souna et al. (2015). A full-scale field experiment was conducted to assess the agronomic value of compost derived from date palm by-products. The effects of compost application were compared with those of cattle manure and a control (untreated soil) on two vegetable crops commonly cultivated in the Figuig oasis: pepper (*Capsicum annuum L.*) and eggplant (*Solanum melongena L.*). Growth performance was evaluated through measurements of fresh and dry biomass for both aboveground and root parts. In addition, the effect of compost on seed productivity was evaluated for barley (*Hordeum vulgare L.*), a widely grown cereal in the region.

C. annuum and *S. melongena* trials - The experimental plot covered 51 m² and consisted of five rows: two treated with 80 kg of compost, two with 80 kg of cattle manure, and one left untreated as a control. Each row was 0.25 m wide and 17 m long, with 0.5 m spacing between rows. The application rate for both compost and manure was 9.41 kg/m². This amount was selected to reflect local agronomic practices in the Figuig oasis, ensuring realistic field conditions and comparability between treatments rather than testing different application gradients. For statistical analysis, all plants were considered, corresponding to n = 32 for compost and cattle manure treatments and n = 16 for the control.

Planting took place on 22 April 2020, and harvesting occurred on 26 July 2020 (three months after planting). Drip irrigation was applied every three days for three hours to maintain consistent soil moisture. At harvest (flowering stage), both aerial parts (stems and leaves) and root systems were measured. Roots were carefully removed from the soil to assess below-ground biomass. Fresh weight was recorded immediately after harvest using a precision balance. Dry weight was obtained by drying samples at 70°C for 48 hours in a ventilated oven until a constant weight was reached.

Barley trial: This experiment consisted of 30 plots of 2 m² each, arranged in three complete randomised blocks of 10 plots. Each plot was sown with 133 g of barley seeds and irrigated every 15 days using a gravity-fed system. Of the 30 plots, 10 received 60 kg of compost, 10 received 60 kg of fresh cattle manure (uncomposted), and 10 served as an unamended control, corresponding to an application rate of 30 kg/m². Irrigation was applied every 15 days using a gravity-fed system. This application rate also reflects common local practices, allowing results to be directly comparable with farmers' current fertilisation methods. Planting took place on 3 December 2022 and harvesting on 30 April 2023 (after five months of cultivation). At harvest, the plants were dry and bearing spikes at maturity, and grain yield was determined separately for each treatment.

All data were expressed as mean ± standard deviation (SD). Differences between treatments were assessed using one-way analysis of variance (ANOVA) followed by Tukey's HSD post hoc test at a significance level of $\alpha = 0.05$. Normality and homogeneity of variances were verified using Shapiro–Wilk and Levene tests, respectively. Statistical analyses were performed using IBM SPSS Statistics software, Version 21.0 (IBM Corp., Armonk, NY, USA).

2.2.2 *Field surveys to assess the uptake of compost by farmers*

A socio-economic survey was conducted to explore farmers' perceptions and adoption of sustainable agricultural practices (Gwara et al., 2023). The analysis focused on the palm sector and growers in the oasis environment of Figuig city. The Figuig municipal administration share that there are approximately 450 farmers registered across the different ksours (i.e fortified districts). We surveyed 201 farmers, which corresponds to 44.6% of the total farming population. The sample size ensures a 95% confidence level with an acceptable error margin (<5%).

The key objectives were to identify the factors influencing the adoption of date palm compost as a fertiliser, assess perceptions of compost compared with other fertilisers, and determine farmers' willingness to pay for compost. The survey form used for this study is provided in the Appendix A (English translation).

2.2.3 *Composting station economic model*

The Ecocanvas framework (Daou et al., 2020) was applied as a predictive tool to develop and structure a circular business model for the Figuig composting station. Rather than limiting the analysis to a description of existing practices, the Ecocanvas was adapted to integrate environmental, social, and economic parameters, enabling an assessment of the potential impacts of managing date palm by-products through composting in fragile oasis ecosystems.

2.3 Results

2.3.1 *Evaluation of date palm compost as an amendment*

The results indicate that the compost mixed with soil was the most efficient growing substrate for *C. annuum* and *S. melongena*, outperforming cattle manure and the control (Figures 1 and 2).

For pepper plants (Figure 1), compost application significantly improved root and shoot growth compared to cattle manure and the control. Regarding root development (Figure 1A), the fresh root weight was 39.2 g with compost compared to 27 g with cattle manure and 3.92 g in the control. Similarly, dry root weight was 10.8 g with compost compared to 4.34 g with cattle manure and 0.95 g in the control. Aboveground biomass (Figure 1B) also showed significant improvement with compost. The fresh aerial part weight was 332.2 g with compost, while cattle manure resulted in 86.01 g and the control only 3.63 g. The dry aerial part weight was 75.54 g with compost, 17.68 g with cattle manure and 0.54 g in the control.

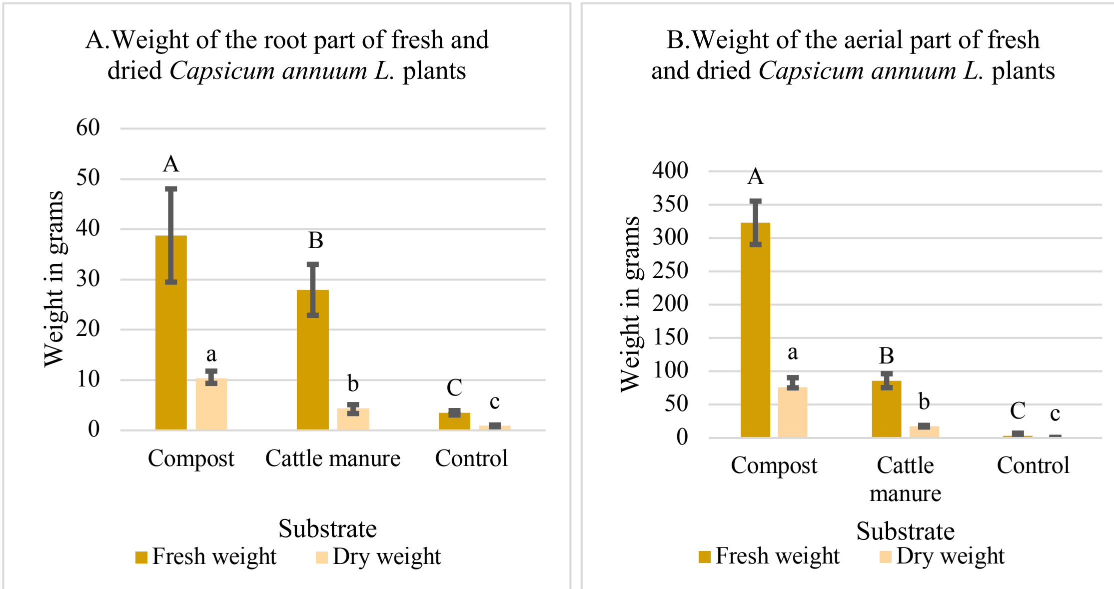

Figure 1. Effects of compost on the growth (grams/plant) of *Capsicum annuum L.* after 3 months of field cultivation. Bars represent mean ± SD (n = 32 plants per treatment for the compost and the cattle manure; n = 16 plants per treatment for the control). Different uppercase and lowercase letters above the bars indicate significant differences between treatments (one-way ANOVA followed by Tukey's HSD test, $p < 0.05$).

Similar trends were observed for *S. melongena* plants (Figure 2), with compost significantly improving biomass accumulation. In root development (Figure 2A), the fresh root weight reached 290 g with compost compared to 36 g with cattle manure and 3.67 g in the control. Dry root weight was 136.18 g for compost treated plants, compared to 13.31 g for those treated with cattle manure and 1.46 g for the control. Aerial biomass (Figure 2B) followed the same pattern. The fresh aerial weight was 290 g for compost, 36 g for cattle manure and 3.67 g for the control. The dry aerial weight was 136.18 g for compost treated plants, 13.31 g for those treated with cattle manure and 1.46 g for the control.
As shown in Figures 1 and 2, compost application significantly improved plant growth and biomass accumulation compared to cattle manure and unamended soil.

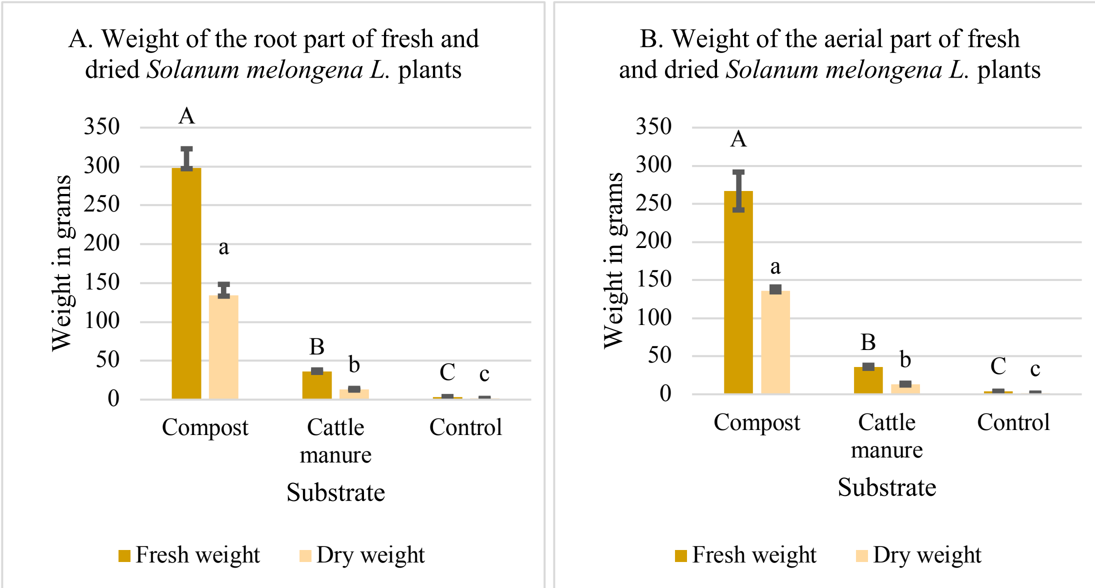

Figure 2. Effects of mature compost on the growth (grams/plant) of *Solanum melongena L.* after 3 months of field cultivation. Bars represent mean ± SD (n = 32 plants per treatment for the compost and the cattle manure; n = 16 plants per treatment for the control). Different uppercase and lowercase letters above the bars indicate significant differences between treatments (one-way ANOVA followed by Tukey's HSD test, $p < 0.05$).

The harvested grain weight of H. vulgare varied between the different substrate treatments (Figure 3). The application of compost resulted in the highest grain yield, followed by cattle manure, while the control treatment (unamended soil) produced the lowest yield. Specifically, compost application significantly increased grain yield compared to the control, producing 472 g/m² compared to 257 g/m² in the control treatment. Similarly, cattle manure resulted in a significant improvement in grain yield compared to the control, with a harvested grain weight of 396 g/m². Furthermore, compost application resulted in higher grain production compared to cattle manure, with yields of 472 g/m² and 396 g/m² respectively, highlighting its superior ability to improve barley grain productivity.

In conclusion, compost produced from date palm by-product can be considered as a good-quality amendment for the investigated crops that are commonly cultivated in oases environments.

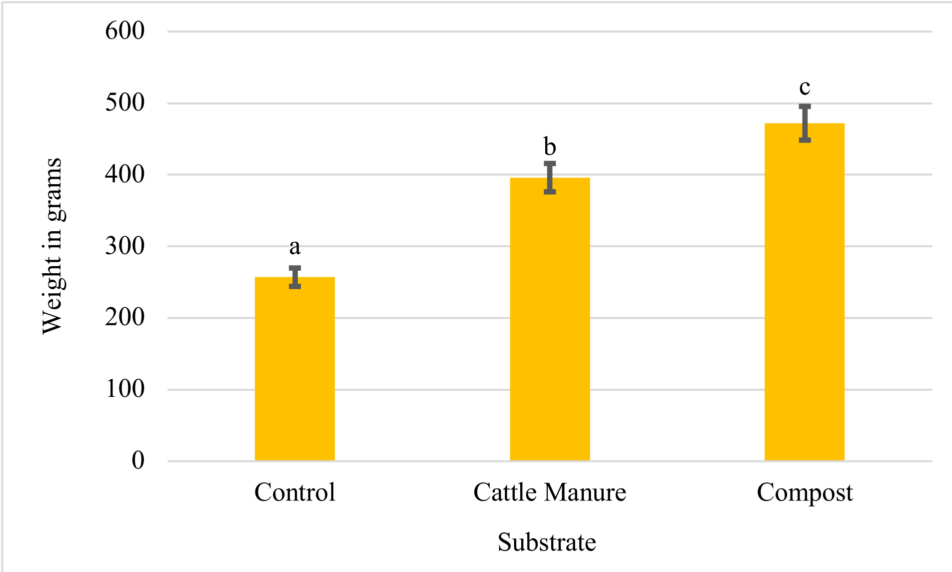

Figure 3. Impact of compost and cattle manure on *Hordeum vulgare L.* grain production (g/m^2). Bars represent mean ± SD (n = 10 plots per treatment; each plot contained 133g of barley seeds). Different lowercase letters (a, b, c) indicate statistically significant differences between treatments based on one-way ANOVA followed by Tukey's HSD test, $p < 0.05$.

2.3.2 *Field survey findings on the uptake of compost by farmers*

A total of 201 farmers were interviewed within Figuig town, which consists of seven ksours. Originally, Figuig was divided into ksours that controlled their own date palm groves. Figure 4 shows their distribution across the ksours, reflecting the size of the different ksours in Figuig. It is clear that the majority of farmers come from Zenaga (74%), followed more or less equally by Loudaghir (6%), Lamâiz (6%), Hammam Foukania (5%), Oulad Slimane (2%), Hammam Tahtani (2%) and Laâbidate (1%).

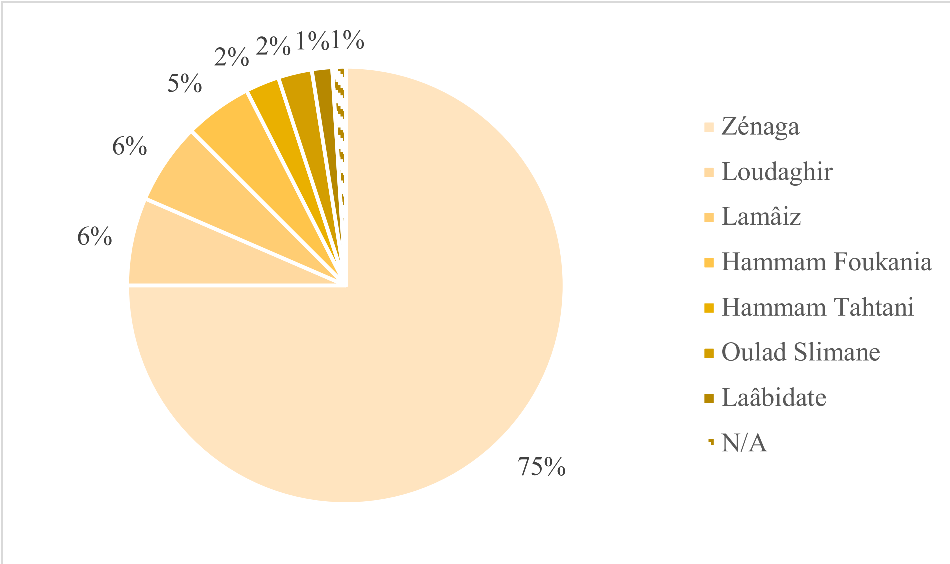

Figure 4. Distribution of interviewed farmers (n=201) within Figuig Ksours

This survey was conducted in June 2023. It allowed us to draw a typical portrait of figuigui farmers. They come from old traditional palm groves, are on average 39 years old on average, and live in Zénaga. They have been farmers all their entire lives and have a secondary school degree. Their farm, with an average area of 0.9 hectares, are mainly devoted to the cultivation of date palms, with around 52 trees, although they also grow other crops. They employ at least one seasonal worker and spend an average of three hours a day farming. One of the main challenges they face is pest pressure, especially Bayoud which they fear the most. This disease is a major constraint, with an average of two infected trees per farm. They consider the overall quality of Figuig's soils to be average, highlighting the challenges associated with the sustainability of oasis farming systems. In terms of fertilisation, they prefer locally produced organic fertiliser when available, often combined with commercial chemical fertiliser.

Farmers use a variety of soil fertility management practices, with all respondents using manure, 30% combining manure with chemical fertiliser and 7% relying solely on compost, including homemade or industrial composts. The widespread use of manure underlines its critical role in maintaining soil health, while its combination with chemical fertilisers is intended to increase crop yields by providing immediate nutrient availability. The exclusive use of compost by 7% of the surveyed farmers reflects a growing interest in sustainable agricultural practices that improve soil organic matter content and reduce dependence on chemical inputs.

The use of compost remains limited as it is neither a traditional practice nor readily available on demand. These findings highlight the need for balanced nutrient management strategies and increased awareness of sustainable farming practices to optimise agricultural productivity and maintain soil health.

Farmers choose soil amendments based on various factors, with 94% prioritising availability, indicating a preference for easily accessible options (Figure 5). Soil quality is a consideration for 47% of farmers, highlighting the importance of maintaining soil health. Nutrient content, particularly nitrogen, phosphorus, and potassium (NPK), influences the choice of 36% of the farmers, reflecting the perceived importance of these macro-elements for plant growth. Environmental impact is a concern for 34% of farmers, highlighting a growing awareness of sustainable practices. This awareness is especially crucial in regions like oasis ecosystems, where climate change is exacerbating soil degradation through rising temperatures, erratic rainfall, and disrupted water cycles (Lal, 2018).

Economic considerations also come into play, with 31% of farmers factoring in cost when choosing soil amendments. Organic matter content, valued by 16% of farmers, is another key factor for improving soil quality, particularly as higher temperatures accelerate the breakdown of soil organic carbon (SOC), weakening soil fertility and resilience (Lal, 2018). Interestingly, only 13% of farmers are influenced by proximity to the purchase point, suggesting that most are willing to travel farther to secure the right amendments. Trust in the seller matters to just 7% of farmers, indicating that while reliable supplier relationships are important to a small group, the majority prioritise other factors when acquiring soil nutrients.

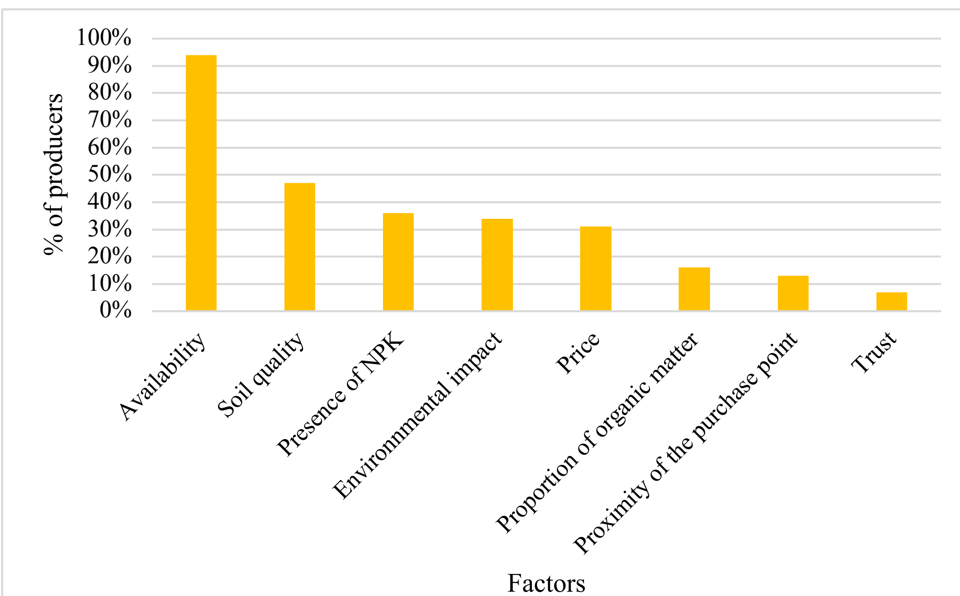

Figure 5. Factors influencing the choice of soil amendments as expressed by Figuig's farmers, (n=201).

Among the farmers surveyed, 55% provided an opinion on the price they were willing to pay for compost produced from date palm residues. Their willingness to pay (Figure 6) ranged from 0.02 to 0.57 EUR/kg of compost.

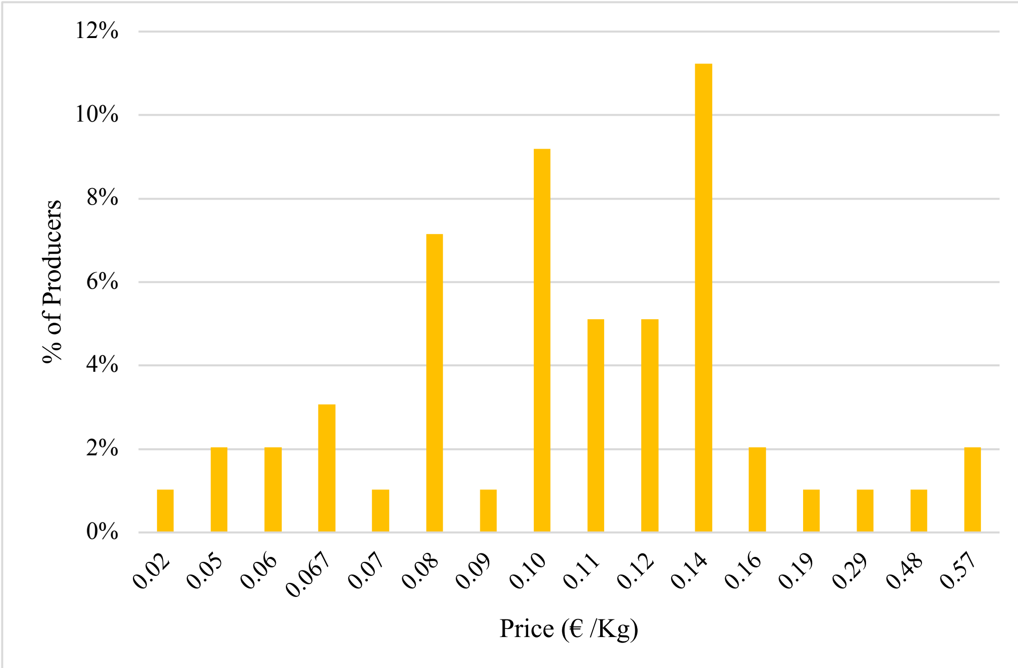

Figure 6. Figuig farmers' willingness to pay for compost made from date palm waste in Figuig station, (n=201).

2.3.4 Economic Analysis and Viability Assessment of the Figuig composting station

The compost produced in this study was developed in an experimental composting station consisting of three composting lanes, each measuring 5 m x 35 m. Additionally, it is possible, on each track, to set up a windrow of 100 m^3 on each track, producing 30 tonnes of compost. The production station currently has a production capacity of 350 tonnes of compost per year. Its maximum capacity can be reached after three production batches, each batch consisting of compost production spread over the three tracks described above. To establish the cost structure for this experimental composting station using date palm by-products, initial investment costs were calculated at EUR 238,26. These costs include land acquisition, construction of composting lanes, procurement of equipment (e.g. shredders) and other infrastructure-related costs. Operating costs include consumables, raw materials (by-products and manure), water, grinding fees and labour costs for two workers. These costs amount to EUR 1916 per 30 tonnes, which corresponds to a unit cost of 0.06 EUR/kg of compost (Table 1).

Table 1. Breakdown of operating costs (in EUR) for the production of 1 windrow of 30 tonnes of compost

	Unit	Quantity	Unit price (in EUR)	Total price (in EUR)
By-product	m^3	75	7	525
Manure	m^3	25	19	475
Grinding costs	tonne	30	14	420
Water	m^3	50	0.4	20
Workforce	workers	2	238	476
Total cost for a windrow of 100 m^3 with 30 tonnes of production				1916
Cost per Kg				0.06

The selling price for the compost was set at 0.14 EUR/kg to reflect the current market price for compost and the willingness of about 38% of the farmers surveyed to pay within this price range (0.08-0.14 EUR/kg, see Figure 6). At this price, the sale of 350 tonnes per year generates an annual income of EUR 49,000. After deducting operating costs, the profit is estimated at 26,647 EUR/year. The initial investment of EUR 238,261 can therefore be depreciated over a minimum period of 9 years, which is a considerable period. Two solutions can be envisaged to factor in a faster payback. The first is the involvement of public authorities, which should help such entrepreneurial venture, based on the important secondary effects and spillovers. The second is the growth in scale, so that economies of scale can be reached, reducing the payback period of the initial investment.

Field surveys conducted in 2018 by the National Agency for the Development of Oasis and Argan Areas (ANDZOA) in Morocco estimated that the Figuig oasis contains approximately 259,250 date palm trees (Baba et al., 2022). Based on agronomic recommendations provided by local figuigui farmers, each tree requires an average of 15 kg of compost per year to ensure optimal growth. Consequently, the annual compost demand in the Figuig oasis is projected to be around 3889 tonnes. Given this potential demand, it is crucial to project the scalability of the station from an experimental unit to a production facility. Four scenarios are proposed for different production scales (see Table 2):

- Production scale: 350 tonnes/year:
  - 2.6 Workforce of two people
  - 2.7 Three composting lanes
  - 2.8 Under these conditions, the initial investment could be recovered in at least nine years.
- Production scale: 1000 tonnes/year:
  - o Increase the workforce from 2 to 6, increasing the operating costs by 953 EUR/year.
  - o Increase the number of composting lanes from 3 to 10, requiring an additional EUR 33,357 in investment costs.
  - o Under these conditions, the initial investment could be recovered in at least 6 years.

- Production scale: 2000 tonnes/year:
  - Invest in more advanced and efficient machinery (shredders and windrow turning) at an additional cost of EUR 238,261.
  - Increase in workforce from 2 to 6 people, increasing operating costs by 953 EUR/year.
  - The initial investment could be recovered in a minimum of 6 years.
  - Increase the number of composting lanes from 10 to 20, requiring an additional investment of EUR 47,652.
  - Under these conditions, the initial investment could be recovered in at least 6 years.
- Production scale: 3500 tonnes/year:
  - Invest in modern machinery, adding EUR 47,652 to the capital cost.
  - Maintaining 20 composting lanes.
  - Maintain a workforce of six people.
  - Under these conditions, the initial investment could be recovered in a minimum of 4 years.

Economies of scale play a crucial role in profitability. Financial projections show that increasing production capacity from 350 tonnes/year to 3500 tonnes/year reduces unit production costs while increasing profits. One of the main factors explaining these efficiency gains is the allocation of fixed costs (infrastructure, equipment, installation of composting stations) over a larger production volume. For example, initial investment increases from EUR 238,261 for 350 tonnes/year to EUR 605,183 for 3500 tonnes/year, but profitability increases with a reduction in the payback period from 9 years to just 4 years. In addition, variable costs (labour, transport, energy) increase at a slower rate than production, allowing an improvement in the profit margin as capacity increases.

Table 2. Estimated costs (in EUR) as a function of the production capacity of the composting station.

	350 tonnes/year	1000 tonnes/year	2000 tonnes/year	3500 tonnes/year
Investment costs (in EUR)	238,261 3 composting lanes	271,617 10 composting lanes	557,530 20 composting lanes and additional equipment	605,183 20 composting lanes and additional equipment
Operating costs for 30 tonnes (in EUR)	1916 (2 workers)	2869 (6 workers)	2869 (6 workers)	2869 (6 workers)
Total operating costs (in EUR) (B)	22,353	95,633	191,266	334,716
Income after sales at 0,14 EUR/kg of compost (EUR/year) (A)	49,000	140,000	280,000	490,000
Profit (A-B) (in EUR)	26,647	44,367	88,734	155,284
Minimum years return on investment (=investment costs/profit) (in Years)	9	6	6	4

The price of amendments is calculated annually per palm tree and reveals significant shifts in the cost-effectiveness of different amendment sources when adjusted for the quantities required per tree (Table 3). In particular, manure, previously considered a low-cost option, becomes more expensive than composted alternatives at EUR 2.5 per tree. Fertiliser, although less costly on a financial basis in this calculation, remains the least environmentally sustainable option due to its significant environmental footprint (Ravitz Wyngaard & Kissinger, 2022). With fertiliser currently in short supply, farmers show a preference for natural products over chemical fertilisers, as indicated by 89 out of 201 farmers surveyed. Despite the lower financial cost of chemical fertiliser (Table 3), farmers are aware of its long-term effects, including increased soil salinity and accelerated soil degradation (Valenzuela Ruiz et al., 2024). This awareness positions compost as a viable alternative in line with farmers' long-term sustainability goal.

Table 3. Amending requirement per palm foot

Amendment	Unitary price (EUR/kg)	Requirement (Kg/year)	Cost (EUR/year)
Commercially available chemical fertiliser (NPK)	0.40	1.00	0.40
Compost produced in the Figuig station	0.14	15.00	2.10
Commercially available compost	0.14	15.00	2.10
Cattle Manure	0.10	25.00	2.50

In this study, the Ecocanvas framework was applied as a predictive tool (Figure 7) to develop and structure a circular business model for the Figuig composting station. Rather than merely describing existing practices, Ecocanvas enabled the anticipation of potential impacts by integrating environmental, social, and economic parameters. Its application provides a comprehensive understanding of how managing date palm by-products through composting can contribute to sustainability in fragile oasis ecosystems.

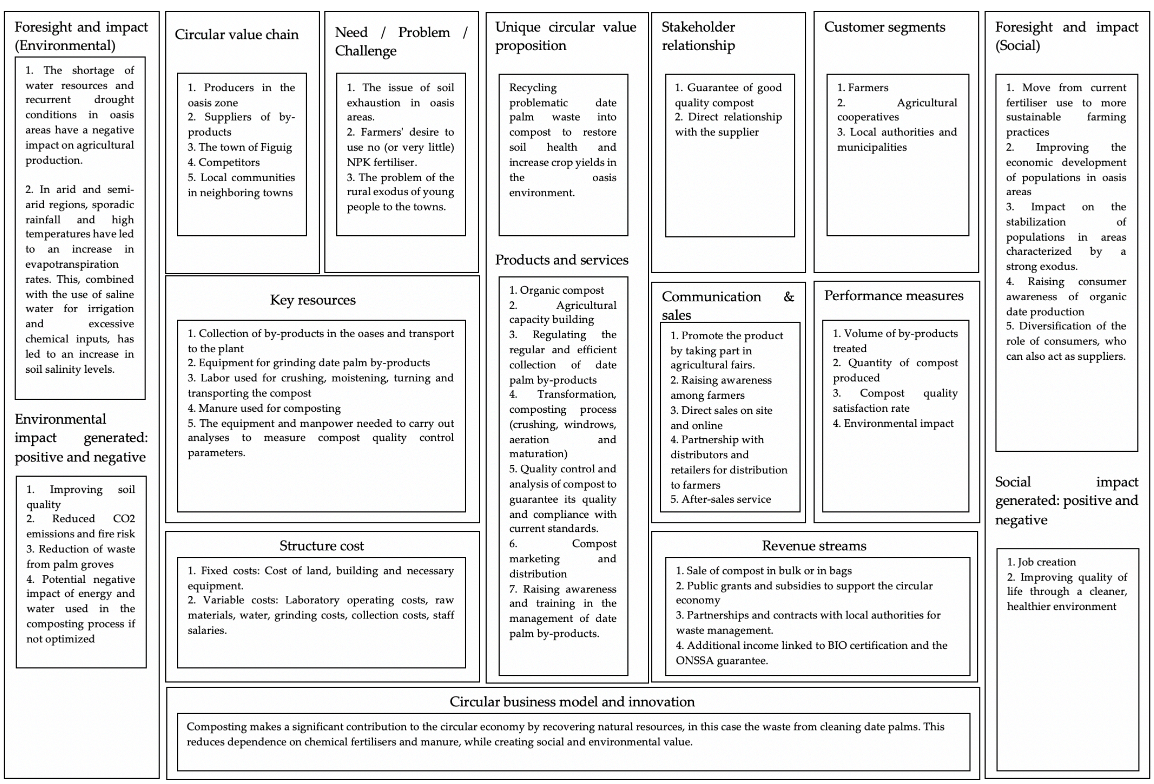

Figure 7. The oasis Ecocanvas of Figuig’s compost production facility. Source: Own computation inspired by Daou et al. (2020).

The Ecocanvas review reveals the following main dimensions:

- Adaptation of the Ecocanvas to the Local Context
  The generic Ecocanvas framework was adjusted to reflect the specificities of the Figuig oasis. Localised parameters were incorporated, including the availability and management of date palm residues, the participation of farmers and cooperatives, and institutional support from local authorities. This adaptation allowed the model to reflect realistic operational conditions and anticipate the station's sustainability potential.
- Integration of Environmental, Social, and Economic Dimensions
  The Ecocanvas was used to map the value creation process by identifying how by-product collection, compost production, and distribution interact with broader sustainability objectives:
  - Environmental dimension: Assessing potential contributions to soil fertility restoration, reduced dependence on chemical fertilisers, mitigation of CO_2 emissions from residue burning, and improved waste management.
  - Social dimension: Predicting the creation of local employment opportunities, capacity building through farmer training, strengthened partnerships between cooperatives and institutions, and stabilisation of rural populations by reducing youth migration.
  - Economic dimension: Analysing the market potential for compost in the Figuig oasis, assessing pricing strategies, and identifying collaborative mechanisms to improve market penetration and long-term financial viability.

The Ecocanvas operates not only as a visualisation tool but also as a predictive decision-support framework. It provides a comprehensive understanding of how the Figuig composting station can enhance soil fertility, strengthen local socio-economic structures, and support the transition to a sustainable circular economy in oasis ecosystems.

2.4 Discussion

This study evaluated the feasibility and sustainability of adopting a circular business model for managing date palm by-products to produce high-quality compost in the Figuig oasis, Morocco.

From an agronomic perspective, the results confirm that the compost produced in Figuig is of high agronomic quality and has demonstrated positive effects on crops commonly cultivated in oasis environments, such as eggplant, pepper, and barley.

The application of compost resulted in significantly higher crop productivity, which can be attributed to several complementary mechanisms. The controlled composting process stabilises organic matter and reduces phytotoxic compounds, producing a safer and more effective soil amendment. In addition, compost enhances humification, improving the cation exchange capacity and gradually increasing the availability of essential nutrients such as nitrogen, phosphorus, and potassium (Janati et al., 2022; Kavvadias et al., 2024). This slow and sustained nutrient release supports continuous plant uptake throughout the growing season, unlike cattle manure, which often results in variable nutrient release and temporary nitrogen immobilisation during early decomposition.

Furthermore, compost improves soil physical properties, including aggregation, porosity, and water-holding capacity, which together enhance root development and plant access to water and nutrients—critical advantages under semi-arid conditions (Diacono & Montemurro, 2011; Ghouili et al., 2024). The application of compost also stimulates beneficial soil microorganisms involved in nutrient mineralisation and plant growth promotion (Ben Zineb et al., 2024; Barkat et al., 2025), thereby fostering a biologically active and resilient soil system. These combined effects on soil fertility, structure, and microbial dynamics explain the superior agronomic performance of compost over cattle manure or chemical fertilisers and underlines the potential of locally produced compost to serve as a sustainable alternative for soil regeneration, water retention, and ecosystem stability (Janati et al., 2022).

The socio-economic survey highlights a strong willingness among farmers to adopt composting practices, revealing significant potential for scaling up circular agriculture within the region.

The predictive analysis highlights significant potential environmental benefits resulting from the adoption of a circular composting model. By transforming date palm by-products into compost, the station can contribute to improving soil quality through the restoration of organic matter and better nutrient availability, helping to counteract the widespread issue of soil exhaustion in the oasis environment. This approach promotes sustainable soil management by reducing reliance on chemical fertilisers and limiting the associated risks of salinisation and land degradation.

Additionally, composting may prevent the open burning or uncontrolled dumping of palm residues, thereby mitigating fire risk. However, the Ecocanvas also identifies that these environmental gains depend on optimised energy and water management, highlighting potential areas requiring careful monitoring to maximise benefits.

Moreover, by replacing chemical fertilisers with organic compost, the initiative raises consumer awareness of sustainable agricultural practices and strengthens confidence in local organic production systems.

From a social perspective, the Ecocanvas predicts substantial positive impacts associated with the integration of local actors, fostering social cohesion by strengthening partnerships between cooperatives, producers, and local institutions while simultaneously stabilising rural populations in regions vulnerable to youth migration and rural exodus.

At the economic level, the Ecocanvas analysis demonstrates that the systematic collection and transformation of date palm by-products into compost respond to a substantial market demand in the Figuig oasis. With an estimated average selling price of 0.14 EUR/kg, the model anticipates the possibility of covering operational costs while generating revenue for local producers. Furthermore, the tool underscores the importance of strategic partnerships with cooperatives, local authorities, and private distributors to improve compost accessibility and market penetration. These collaborative mechanisms are expected to enhance the station's economic resilience and contribute to the long-term sustainability of the oasis farming system. In addition, the composting station is expected to create local jobs and improve household incomes by generating new economic opportunities in the oasis.

2.5 Conclusion

This study shows that the recovery of date palm waste, generated each year by the exploitation of the Figuig oasis, into quality compost should make it possible to remedy the problems of soil degradation in oasis environments. The adoption of a circular business model for managing date palm by-products offers significant environmental, agronomic, and social benefits in oasis ecosystems. The Figuig composting station represents a successful integration of sustainable resource management and community-based practices, reducing residue mismanagement, improving soil fertility, and fostering local collaboration through cooperatives and farmer training.

However, achieving long-term sustainability requires scaling up compost production to meet regional demand and fostering wider farmer adoption through targeted awareness campaigns and capacity-building programs. These measures will ensure that the Figuig model can serve as a replicable framework for other oasis regions in Morocco and beyond, promoting sustainable agriculture while addressing environmental challenges in semi-arid agro-ecosystems.

4 Chapter 3: More maize, less hunger: A data-driven approach to sustainable farming in Haut-Katanga and Lualaba (DRC)

Abstract

Maize (*Zea mays L.*) is a cornerstone of food security and rural livelihoods in Sub-Saharan Africa (SSA), yet yields in the Democratic Republic of Congo (DRC)—particularly in Haut-Katanga and Lualaba—remain far below their agronomic potential despite favorable agroecological conditions. Structural challenges, including limited access to quality inputs, insecure land tenure, and climate variability, hinder productivity, while broader sustainability concerns arise from input-dependent intensification. Against this backdrop, government initiatives like the "Villages Agricoles" program aim to modernize agriculture but face implementation gaps, including technical and institutional constraints. This study investigates the factors influencing maize productivity in these regions and explores how data-driven approaches can support sustainable, circular agricultural systems. Using a novel two-stage framework, we first generate synthetic yield estimates to mitigate biases in farmer-reported data, then apply econometric analysis to identify key productivity determinants. Our findings reveal the role of socio-economic, agronomic, and environmental factors in shaping yields while demonstrating the potential of predictive

modeling to enhance policy precision. By bridging critical data gaps and offering practical insights, this research attempt to contribute to evidence-based strategies for improving food security and agricultural circularity in the DRC and similar contexts.

4.1 Introduction

Maize (*Zea mays L.*) stands as a cornerstone for food security and livelihoods across rural Sub-Saharan Africa (SSA). Despite its critical role, maize yields in the Democratic Republic of Congo (DRC), particularly within the Haut-Katanga and Lualaba provinces, consistently fall short of their agronomic potential. This paradox is particularly striking given the rich endowments of these regions, which boast fertile soils, favorable rainfall patterns, and vast expanses of arable land. Historically, progress in enhancing maize productivity has been inconsistent, with yields remaining suboptimal and national demand increasing (Shiferaw et al., 2011). Nevertheless, governmental initiatives, such as the "Villages Agricoles" program, have been implemented with the aim of alleviating rural poverty and modernizing agricultural production systems.

The persistent productivity gap in the DRC can be attributed to a confluence of structural challenges. Access to quality agricultural inputs, including fertilizers, improved seeds, and pesticides, is often limited. Furthermore, issues surrounding secured land tenure and consistent technical support exacerbate these challenges (Otchia, 2014). The situation is further complicated by high climatic variability, which introduces significant risks to agricultural planning and execution. Beyond these immediate concerns, broader questions related to environmental sustainability emerge. Many intensification efforts heavily rely on external inputs, raising critical questions regarding long-term soil health, nutrient balances, and overall environmental impact (Pretty and Bharucha, 2014). Consequently, there is a growing recognition of the importance of ecological management in conjunction with productivity gains (Velasco-Muñoz et al., 2021). The adoption of circular economy principles, such as nutrient recycling and waste minimization, is increasingly being considered as a viable pathway towards more sustainable agricultural practices. Recent studies also highlight the utility of yield predictions in guiding cultivar selection and planting strategies, thereby contributing to more precise and climate-resilient interventions (Han et al., 2024).

The context of the DRC underscores the urgent need for agricultural transformation. The country remains highly food insecure, with approximately 105 million inhabitants, roughly 70% of whom are dependent on agriculture in rural areas. It is estimated that 27.3 million people face acute food insecurity (IPC, 2021). This situation is particularly perplexing given the DRC's immense agricultural potential, encompassing nearly 80 million hectares of arable land, extensive natural pastures, abundant water resources, and vast agro-biodiversity—conditions that, theoretically, could sustain billions. Despite this inherent potential, the agricultural sector currently contributes only around 20% to the national GDP and 11.2% to GDP growth (Institut National de la Statistique, 2021; Otchia, 2014). This stark contrast underscores the critical importance of boosting agricultural productivity as a fundamental pillar for fostering a more sustainable Congolese economy. As articulated by Velasco-Muñoz et al. (2021), concerted efforts are imperative to expand cultivated areas and enhance productivity on existing farmland, thereby meeting escalating food demand while simultaneously preserving ecological balance.

Staple foods, including cereals (such as maize), legumes, and vegetables, constitute the predominant components of Congolese diets. In the Haut-Katanga and Lualaba provinces, maize holds particular significance as the most affordable staple on local markets, directly influencing household food security (Nyembo et al., 2018). This dual importance—as both a subsistence crop and a market commodity—positions maize as a strategic entry point for interventions aimed at mitigating food insecurity and stimulating rural economies (Tabu et al., 2023). However, despite their pivotal role, maize production systems in these provinces are hampered by a scarcity of reliable field-level productivity data. This data deficit severely restricts opportunities for implementing tailored management practices, generating accurate forecasts, and conducting comprehensive sustainability assessments.

In response to these challenges, the Haut-Katanga government initiated a ministerial decree in 2016 to establish 'Villages Agricoles'—farmer village schemes meticulously designed in collaboration with local chiefs, non-governmental organizations such as APEFE, and academics from the University of Lubumbashi. These villages are integral to broader agricultural subsidy programs that also target large-scale farmers, cooperatives, religious groups, customary leaders, and local dignitaries. While innovative in its conception, the program has encountered several operational challenges, including technical extension gaps, weak collaboration with the provincial agricultural inspection agency, land conflicts stemming from the absence of cadastral systems, issues related to storage and post-harvest handling, and limited financial literacy among participating farmers.

Under this scheme, for instance, local households cultivate an average of 1 hectare under technical supervision and receive essential inputs, such as seeds and other resources, in exchange for a portion of their harvest. While this model effectively subsidizes production costs—estimated at $750/ha—it also results in a net financial shortfall for the province, as only an estimated $300/ha is recovered through maize sales. Furthermore, concerns have been raised regarding the quality of inputs, particularly the seeds provided. In contrast, the province of Lualaba currently lacks comparable governmental programs, highlighting a notable disparity in institutional support structures that could significantly impact maize productivity (Otchia, 2014).

In light of these critical observations, the overarching aim of this study is to address the following research question: *What factors influence maize productivity in Haut-Katanga and Lualaba, and how can data-driven approaches set the path to the transition a circular agricultural system?* To comprehensively address this question, we propose a novel two-stage modeling framework. In the initial stage, we will compute a synthetic yield to predict maize yields based on a comprehensive dataset encompassing climatic, agronomic, and household socio-economic variables. This methodological approach is designed to provide more precise yield estimates by mitigating the well-documented biases inherent in farmer self-reporting. In the subsequent stage, classical econometric analysis will be employed to regress these synthetic yields on a diverse range of socio-economic, land, and input factors.

This analytical approach will enable us to quantitatively determine the key drivers of maize productivity.

The objectives of this research are threefold:

1. To generate robust estimates of maize productivity, thereby addressing common measurement errors associated with self-reported yields.
2. To identify and quantify the socio-economic, technical, and environmental factors influencing maize productivity in tropical regions such as Haut-Katanga and Lualaba.
3. To demonstrate the potential of predictive modeling frameworks to inform policy decisions aimed at enhancing agricultural sustainability.

The article will be structured as follows: it will begin with a comprehensive literature review, providing a foundational understanding of existing research. This will be followed by a detailed methodological section, outlining the two-stage modeling framework. Subsequently, the results of the synthetic yield calculation and the econometric analysis will be presented and discussed. The article will conclude with a summary of key findings and actionable policy recommendations.

4.2 Literature Review

Accurate crop yield prediction is pivotal in modern agriculture. Accurate yield forecasts can alert farmers and crop managers to potential issues, such as nutrient deficiencies, water stress or climatic anomalies, before they result in significant losses. Yield predictions also inform optimal cultivation decisions, ensuring that fields reach their full productive potential. Beyond the farm level, these forecasts are essential for coordinating the distribution of aid, planning imports and exports, managing crop insurance schemes and allocating government resources.

However, estimating agricultural yields is inherently challenging. Crop productivity depends on the complex interplay of biological, environmental and management factors. These include cultivation practices, crop rotation patterns, irrigation regimes, fertiliser and seed choices, soil characteristics, weather variability, and the incidence of pests and diseases. While some models can predict yields with remarkable precision at sub-regional scales, many struggles to capture the full complexity of these interconnected drivers, particularly given the non-linear responses of cropping systems to ecological pressures.

Historically, researchers have used a variety of methods to predict crop yields, including classical statistical models, crop growth simulations, field surveys and remote sensing technologies. Each of these approaches emphasises a different aspect of the yield puzzle. As awareness grows of the multifaceted, nonlinear interactions between environmental factors and crop responses, the limitations of traditional models become increasingly evident. While deep learning models show promise, recent works have demonstrated that their effectiveness often depends on the availability of high-quality features, and their ability to navigate complex, nonlinear mappings remains variable (Nirosha & Vennila, 2025).

Forecasting crop yields is not just an academic exercise; it is central to global efforts to ensure food security, especially in the context of accelerating climate change. Accurate predictions empower farmers to make better-informed management and investment decisions, support strategic interventions to prevent famines and stabilise food markets. At its core, predicting yield addresses one of biology's most enduring challenges: understanding how phenotypes emerge from the interplay of genotype, environment, and management practices. The intricate relationships between genetics, weather, soil conditions and farming techniques have therefore been the focus of extensive investigation. As Chang et al. (2023) emphasise, the pursuit of more accurate crop yield forecasts continues to drive innovation at the intersection of plant science and data analytics — a convergence that is likely to remain pivotal in agricultural research for years to come.

Identification of the factors that influence yield are critical for enhancing agricultural policies and practices. Understanding these factors is essential to improving agricultural output, especially in regions where maize serves as the backbone of food security. Ordinary Least Squares (OLS) regression is one of the most widely used techniques for estimating agricultural productivity. It is a linear regression method that helps determine the relationship between maize yields (the dependent variable) and various independent variables, such as fertilizer use, labor input, land size, and other socio-economic and environmental factors.

For instance, Ntiamoah and Acheampong (2022) used OLS regression to assess the impact of climate variables, such as rainfall and temperature, and fertilizer consumption on maize productivity in Ghana. The study found that both climate conditions and fertilizer use had significant effects on maize yields. The authors emphasized that rainfall variability, along with the efficient use of fertilizers, was critical in determining maize productivity in the region.

Despite its simplicity, OLS can sometimes oversimplify the complexities of agricultural systems. As Lone and Patra (2025) point out, applying OLS in heterogeneous environments, where different regions may have varying soil types, climate, and socio-economic conditions, may lead to biased estimates. They suggest that more complex models, such as the Just and Pope production function, may be more appropriate in these cases to account for differences in data across heterogeneous regions.

While OLS provides useful insights, it has several limitations. One of the primary challenges is the assumption of homoscedasticity, meaning that the variance of errors remains constant across all levels of the input variables. This assumption may not hold in agricultural data, where variability in soil quality, water availability, and input use can lead to heteroscedasticity. Additionally, OLS assumes a linear relationship between dependent and independent variables, which may not always be appropriate for agricultural systems where non-linear effects are common. The work of Midamba (2025) highlights that gender disparities in agricultural productivity can complicate OLS estimates, as different socio-economic groups may experience varying impacts from the same set of agricultural inputs.

Several factors affect maize productivity, including agronomic practices, socio-economic conditions, and environmental variables. This section reviews the key determinants influencing maize productivity, as identified by studies that use econometric models like OLS.

1. Agronomic Factors
    - Fertilizer Use: Fertilizer application is widely recognized as a critical determinant of maize productivity. Gheith et al. (2022) found that nitrogen and phosphorus application levels significantly influenced maize yields in Egypt. Similarly, the study by Ntiamoah and Acheampong (2022) in Ghana confirmed the positive role of fertilizer use in improving maize yields. Their OLS regression analysis revealed that fertilizer use had a direct and significant impact on the productivity of maize, especially in areas with moderate rainfall.
    - Seed Variety: The use of hybrid maize varieties has been shown to significantly enhance maize productivity. Hybrid seeds are generally more resistant to pests and diseases and are more resilient to adverse environmental conditions compared to traditional varieties. Several studies, including Midamba (2025), have highlighted that hybrid seeds contribute to improved maize yields, especially when combined with proper agronomic practices such as timely fertilization and pest management.
2. Socio-Economic Factors
    - Access to Credit: Access to financial resources is a key socio-economic factor influencing maize productivity. Farmers with access to credit are more likely to purchase inputs such as fertilizers and improved seeds, which can lead to higher productivity. Asante et al. (2024) found that access to credit and agricultural subsidies significantly affected the adoption of climate-smart agricultural technologies, which in turn boosted maize yields. Similarly, Lone and Patra (2025) observed that farmers in India who had access to financial resources were able to adopt modern farming techniques and increase their yields.
    - Education and Training: The level of education and agricultural training is another significant socio-economic factor. Farmers with higher levels of education are more likely to adopt new technologies and improve their productivity. Studies have shown that agricultural extension services play a critical role in disseminating knowledge and skills related to modern farming practices. Midamba (2025) noted that farmers in Uganda with access to agricultural training had higher maize productivity than those without formal education.
3. Environmental Factors
    - Climate Conditions: Climate variables, particularly rainfall and temperature, significantly affect maize productivity. Studies, including those by Ntiamoah and Acheampong (2022), have shown that maize yields are sensitive to changes in temperature and rainfall patterns. The timing and distribution of rainfall, especially during the growing season, are critical for optimizing maize productivity.

- Soil Fertility: Soil quality is another important factor. Fertile soils with balanced pH levels, adequate organic matter, and proper drainage systems promote better growth and higher yields. Asante et al. (2024) found that maize productivity in Ghana was highly dependent on soil fertility, with more fertile soils leading to higher maize yields when combined with appropriate fertilizer use.

4.3 Methodology

Using agronomic models to predict crop yields has become an effective strategy for mitigating the classical measurement errors that are often encountered in household surveys. These errors can obscure the true relationships between farming practices and productivity outcomes, resulting in biased estimates in econometric analyses. Using predicted yields as dependent variables therefore provides a more reliable basis for examining the determinants of productivity (Suri & Udry, 2022; Lobell et al., 2009; Shahhosseini et al., 2021).

4.3.1 Study Area

The study was conducted in rural areas spread across the provinces of Haut-Katanga and Lualaba in the south-eastern region of the DRC. These provinces have a subtropical highland climate, characterised by a distinct rainy season from October to April, which supports an annual cycle of maize cultivation.

Data were collected from around 2,000 farming households operating predominantly under smallholder conditions. The area's soils consist mainly of ferralsols and acrisols, which are moderately acidic and often require nitrogen and phosphorus intakes to increase productivity. The key agronomic inputs recorded were the application rates of nitrogen–phosphorus–potassium (NPK) and urea fertilisers (kg/ha), seed density (kg/ha) and binary indicators for herbicide and insecticide use.

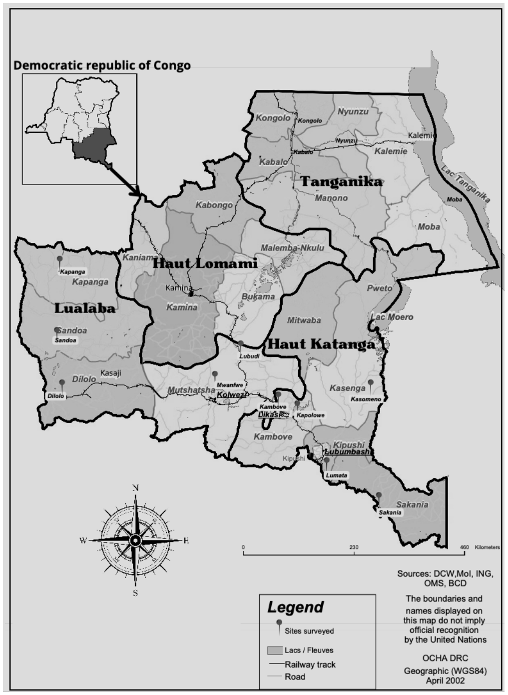

Figure 1. Study Area and Localities in Haut-Katanga and Lualaba, Democratic Republic of the Congo

Source: OCHA, 2018 ; own computation

The surveyed localities situated in the south-east part on DRC (Figure 1) included:

- Haut-Katanga province: Lumata, Kapolowe, Kambove, Mwaiseni, Kasomeno and Sakania.
- Lualaba province: Kolwezi, Musumba, Kapanga, Nganga, Sandoa, Komeisha, Dilolo and Lubudi.

The dataset comprised detailed records of farm management practices, such as fertiliser and seed use, as well as household socio-economic characteristics. Climate data were integrated from the CHIRPS dataset (for precipitation) and long-term WorldClim 2.1 records, while soil types were classified according to the FAO/WRB 2015 system. In the absence of direct yield measurements on the ground, an indirect estimation is proposed using a synthetic yield constructed according to agronomic rules derived from scientific literature and validated by local data. This yield is then used in a classical econometric regression to quantify marginal effects.

4.3.2 Construction of a Synthetic Yield Proxy

In the absence of direct field yield measurements and given the well-documented measurement errors associated with self-reported yields in smallholder settings (Suri & Udry, 2022), this study adopted an indirect estimation strategy to approximate maize productivity. In line with recent literature recommendations (Shahhosseini et al., 2021;

Morán-Figueroa et al., 2024), a synthetic yield variable was constructed using a data-driven agronomic function designed to serve as a robust proxy for actual yield outcomes in conditions where data is scarce.

This function was initially derived from local agronomic norms reported by field extension officers and village site coordinators. They stated that a combination of 25 kg of hybrid seed, 250 kg of NPK fertiliser and 250 kg of urea per hectare usually yields approximately 3,500 kg/ha. This simplified rule of thumb was then refined using the documented marginal responses of maize to key inputs, aligning with the best practices identified in recent research on predictive crop modelling in environments with limited data (Morán-Figueroa et al., 2024).

To enhance agronomic realism, the synthetic function incorporated several key constraints identified in the literature.

Minimum effective thresholds: Studies by Campbell et al. (2014) and Nyembo et al. (2014) suggest that mineral fertilisers only have a significant impact on maize yield when application rates exceed 100 kg/ha. Below this threshold, nutrient availability may be insufficient to overcome soil limitations or crop nutrient demands, rendering fertiliser ineffective.

Interaction effects: Evidence also highlights the importance of input complementarities. Specifically, the combined application of NPK and herbicides, or urea and insecticides, has a positive impact on yield as the effectiveness of each input is enhanced by the other (Pimentel et al., 2019). These interactions likely reflect improved nutrient use efficiency under weed- and pest-controlled conditions, which reduce competition and stress during critical growth stages.

By incorporating these agronomic insights into the synthetic yield formula, the resulting proxy variable captures the quantitative intensity and qualitative interaction of input use, providing a more ecologically valid estimation of field productivity. This approach ensures that the synthetic yield remains sensitive to real-world constraints and reflects the processes by which yield is formed in smallholder systems.

Specifically, the function was defined as follows:

$$Y_i = \beta 0 + \beta 1 \times NPK_{eff} + \beta 2 \times Urea_{eff} + \beta 3 \times Seed + \beta 4 \times Herb + \beta 5 \times Insect + \beta 6 \times Interaction + \epsilon \quad (1)$$

With a cap set at 6,000 kg/ha, extreme outliers are limited. This specification reflects non-mechanised systems in Haut-Katanga and Lualaba undergoing modest intensification.

In the absence of field measurements, a synthetic yield function was developed to predict maize yield using agronomic parameters derived from peer-reviewed literature and meta-analyses in SSA. The model is specified as a deterministic agronomic function with input thresholds and interaction effects, plus a normally distributed stochastic error term. The model is as follows:

$$Y_i = 800 + 2.5\times\max(0,NPK-100) + 2.5\times\max(0,Urea-100) + 20\times Seed + 400\times Herb + 300\times Insect + 0.5\times\max(0,NPK-100)\times Herb + 0.3\times\max(0,Urea-100)\times Insect + \epsilon \quad (2)$$

Where:

- Yi is the predicted maize yield (kg/ha).
- NPK and urea are the application rates of mineral fertiliser (kg/ha).
- 'Seed' is the quantity of maize seed used (kg/ha).
- 'Herb' and 'Insect' are binary variables indicating herbicide and insecticide use, respectively.
- The error term, ϵ, is normally distributed with a standard deviation of 200 kg/ha.

The intercept (β_0 = 800 kg/ha) represents the average maize yield in the absence of modern inputs. This is consistent with empirical observations in SSA, where baseline yields without inputs typically range between 600 and 1,000 kg/ha (FAO, 2018; IFPRI, 2020).

The marginal productivity of mineral fertilisers is estimated at 2.5 kg of maize for every additional kg of nutrients applied beyond a threshold of 100 kg/ha. Below this threshold, fertiliser is assumed to have no measurable effect, consistent with findings that low input doses often fail to overcome basic nutrient deficiencies in SSA soils. The effective fertiliser components are defined as follows:

$$NPK_{eff} = \max(0,NPK-100),\ Urea_{eff} = \max(0,Urea-100) \quad (3)$$

This calibration is based on recent meta-analyses (Snapp et al., 2019; Kihara et al., 2020). These studies report marginal returns of 2–3 kg/kg for both NPK and urea under field conditions in SSA.

The coefficient for seed use is set at 20 kg of maize yield per kg of seed, based on the assumption of an optimal seeding rate of around 25 kg/ha. This estimate is consistent with the findings of Mafouasson et al. (2018), who observed significant yield increases with increased planting density and improved seed.

The binary variables for pesticide use capture the discrete productivity gains from controlling weeds and pests: Herbicide use is associated with an increase in yield of 400 kg/ha, based on evidence from Coulibaly et al. (2017). Insecticide use contributes an additional 300 kg/ha, consistent with the findings of Affognon et al. (2015). These effects are treated as additive step functions under the assumption of proper application practices and moderate pest or weed pressure.

To account for the synergistic effects of chemical fertilizers and crop protection products, the model incorporates two interaction terms. An NPK × herbicide interaction, which results in a marginal yield increase of 0.5 kg per kg of effective NPK when herbicide is used. This interaction is supported by agronomic studies, including those of Pimentel et al. (2019).

The second interaction is between urea and insecticide, with a marginal gain of 0.3 kg of yield per kg of effective urea applied when insecticide is used. This interaction is supported by empirical insights from Abouziena et al. (2007).

These interactions reflect the complementarity between input types, such as improved nutrient uptake when weed competition is suppressed or better biomass accumulation when insect damage is controlled.

Finally, a stochastic error term $\epsilon \sim N(0,200^2)$ captures unobserved heterogeneity, environmental noise and measurement errors. The standard deviation of 200 kg/ha reflects the typical variability observed within farms in smallholder systems across the region. $\epsilon \sim N(0,200^2)$.

4.3.3 Econometric model

In order to investigate the household-level drivers of maize productivity, a semi-logarithmic OLS regression model was estimated (Equation 4), with the natural logarithm of the predicted yield acting as the dependent variable. This specification stabilises variance and allows the coefficients to be interpreted as approximate percentages.

$$\ln(Y_i) = \beta_0 + \sum_{k=1}^{K} \beta_k X_{ik} + \epsilon_i \quad (4)$$

Y_i represents the synthetic maize yield for household i and serves as a robust proxy for productivity. The explanatory variables encompassed:

Land indicators, including field size and ownership status, which capture the scale of operations and the security of land rights, factors that often influence long-term investments in soil health and sustainable practices.

Input use and agronomic practices, such as the quantities of total fertiliser applied, the use of hybrid seeds and the adoption of pest control measures through herbicides and insecticides, are also included.

Labour and human capital variables covering manual preparation, agricultural training, labour hours and educational attainment levels reflect technical know-how and readiness to implement improved or circular practices.

Socio-demographic variables include age, sex of the household head, household size, financial constraints and whether support was received.

Market access and environmental conditions were also considered, including distance to roads and markets, total and seasonal rainfall, solar radiation and soil type codes.

Table 1 provides a detailed description of various factors that influence maize productivity in Haut-Katanga and Lualaba provinces in the DRC. The synthetic maize yield, with a mean of 1,483 kg/ha and a standard deviation of 981, demonstrates considerable variation in productivity across the sample. The range of 62 to 6,000 kg/ha reflects both the potential for high yields in some instances and the lower productivity levels in others. These values highlight the variability in maize farming practices and outcomes in the region.

Regarding the land variables, the sample reveals that 63% of the fields are located in Haut-Katanga, while the remaining fields are in Lualaba. The mean plowed area is 327,758 m^2, with a large standard deviation of 4,675,850 m^2, indicating significant differences in farm sizes. The mean size of the maize field is 216,771 m^2, showing that farms vary widely in terms of the land dedicated specifically to maize cultivation. Land ownership is relatively high, with 84% of farmers owning their land, which may contribute to greater land tenure security and encourage investment in agricultural improvements. However, the distance to roads (average of 6,864 meters) and distance to markets (average of 8,989 meters) indicate that accessibility to resources and markets may be a challenge for many farmers, potentially affecting their productivity and access to inputs.

In terms of socio-demographic factors, 96% of households report financial difficulties, which likely limits their ability to invest in fertilizers, seeds, or other agricultural inputs. The average household size is 9 members, with a range from 1 to 25, suggesting significant variability in labor availability. In terms of education, 12% of household heads have no formal education, while 45% have completed primary education and 30% have completed secondary education. This distribution points to the potential need for agricultural training programs to improve productivity and adoption of advanced farming techniques.

Looking at the input variables, 77% of the households use fertilizers, with an average application of 334.2 kg (combined NPK and urea). The large standard deviation (532.7 kg) indicates that fertilizer use varies significantly across farms, with some households using very high amounts while others use minimal or no fertilizer. Hybrid seed usage is relatively high, with 73% of farmers using hybrid seeds, suggesting an adoption of improved seed varieties that can contribute to higher productivity. However, insecticide and herbicide use are limited, with only 18% and 25% of households using these chemicals, respectively, indicating that pest control may not be a priority or that farmers face challenges in accessing these inputs. The use of solar energy is relatively low (10%), while 70% rely on wood energy, pointing to limited access to more sustainable energy sources.

Finally, the climate and environmental variables show that the region receives sufficient rainfall, with an annual average of 1,189 mm and 533 mm during the critical November to January period, which supports maize growth. The solar radiation value of 18.97 $kWh/m^2/day$ indicates favorable conditions for photosynthesis, contributing to crop development.

Table 1. Descriptive statistics of variables used in the analysis.
Source: Authors' computation from household survey data (Haut-Katanga & Lualaba, DRC).

	Sample size (n)	Mean	Std. Dev.	Min	Max	Description
Dependent variable						
Synthetic yield (kg/ha)	1 959	1 490	981	61	6000	Synthetic maize yield
Land variables						
Plowed area (ha)	1 776	33	468	0	18000	Total area plowed by the household, indicating farm scale.
Size of maize field (ha)	1 895	22	266	0	8000	Area specifically under maize cultivation.
Field ownership	1 937	0.84	0.37	0	1	Indicates land tenure security (1=owned, 0=other).
Distance to road (m)	1 809	6 864	96 543	0	4000000	Proximity to nearest main road.
Distance to market (m)	1 628	8 989	15 633	0	350	Proximity to nearest market.
Socio-demograpgic variables						
Household has financial problems	1 936	0.96	0.21	0	1	Whether the respondant currently has financial problems
Household size	1 925	8.68	4.43	1	25	Number of persons living in the household.
No formal education	1 893	0.12	0.32	0	1	Head of household has no formal schooling.
Primary education	1 893	0.45	0.5	0	1	Completed primary level.
Secondary education	1 893	0.30	0.46	0	1	Completed secondary level.
Received agri training	1 922	0.35	0.48	0	1	Attended agricultural training or extension programs.
Member of agri association	1 924	0.3	0.45	0	1	Belongs to a cooperative or farmers' group.
Input variables						
Fertilizer use (dummy)	1 931	0.77	0.42	0	1	Whether any chemical fertilizer was applied.
Urea quantity (kg)	1 218	257.1	292.6	0	6480	Amount of urea applied on maize plots.
NPK quantity (kg)	1 259	271.2	311.8	0	6500	Amount of NPK fertilizer applied.
Total fertilizer (kg)	1 959	334.2	532.7	0	13	Combined Urea + NPK application.
Hybrid seed use	1 885	0.73	0.44	0	1	Whether hybrid maize seeds were used
Insecticide use	1 913	0.18	0.39	0	1	Whether any insecticide was applied
Herbicide use	1 695	0.25	0.44	0	1	Whether any herbicide was applied
Uses solar energy	1 853	0.10	0.30	0	1	Household uses solar panels for energy needs.
Uses wood energy	1 853	0.70	0.46	0	1	Household relies on wood (firewood, charcoal).
Weekly water spending (CDF)	1 341	9 744	67 148	0	1500000	Money spent weekly on irrigation or domestic water.

Manual technical prep	1 951	0.93	0.25	0	1	Received technical pre-planting advice.
Climate & environment variables						
Annual rainfall (mm)	1 951	1 189	90.4	1050	1400	Total yearly precipitation at location.
Solar radiation (kWh/m²/day)	1 706	16.52	6.40	17.80	20	Average daily solar radiation, affecting photosynthesis.
Rainfall Nov-Jan (mm)	1 706	464.37	183.37	0	630	Rainfall in critical early growth period.
Soil type code	1 951	1.26	0.88	0	3	Categorical soil classification.

This methodological framework was designed to systematically explore how technical inputs, socio-economic conditions and environmental constraints collectively influence maize productivity. The synthetic yield serves as a robust proxy, integrating multiple dimensions of farm management. This allows for an econometric analysis of marginal effects that is less susceptible to the biases arising from the measurement errors commonly encountered in self-reported yields. These insights support the overarching aim of the research, which is to identify better ways to increase maize productivity in Haut-Katanga and Lualaba, while simultaneously laying the groundwork for transitions towards more sustainable and circular agricultural system.

4.4 Results

4.4.1 Predictive insights from the synthetic yield model

Synthetic yield enables the agronomic structure of yield to be captured, even when it is simulated. However, using it as field truth introduces a form of modelling bias. Therefore, the structural error was considered during interpretation.

The comparative analysis of synthetic maize yields between the provinces of Haut-Katanga and Lualaba (Figure 1) reveals significant regional disparities.

In Haut-Katanga, the average yield is approximately 1,631 kg/ha. The median maize yield exceeds 2,000 kg/ha, with an interquartile range (IQR) spanning from approximately 1,500 kg/ha to 3,500 kg/ha. This suggests that while the region has the potential for high productivity, there is considerable variability. The presence of outliers indicates instances of exceptionally high yields, possibly due to optimal conditions or advanced farming practices. However, the wide spread also points to disparities in access to inputs, knowledge, and infrastructure among farming communities in the Village Agricole Program.

In contrast, Lualaba exhibits a lower average yield (1,257 kg/ha) and a lower median yield of approximately 1,500 kg/ha, with an IQR between 1,000 kg/ha and 3,000 kg/ha. The narrower spread suggests more uniformity in productivity levels across the province. However, this uniformity is at a suboptimal level, indicating that the region is not fully exploiting its agricultural potential.

The consistent yet low yields may be attributed to several factors, including limited access to quality inputs, inadequate extension services, and challenges related to climate variability. Addressing these issues requires targeted interventions that focus on improving resource access, enhancing farmer knowledge, and promoting the adoption of climate-smart agricultural practices.

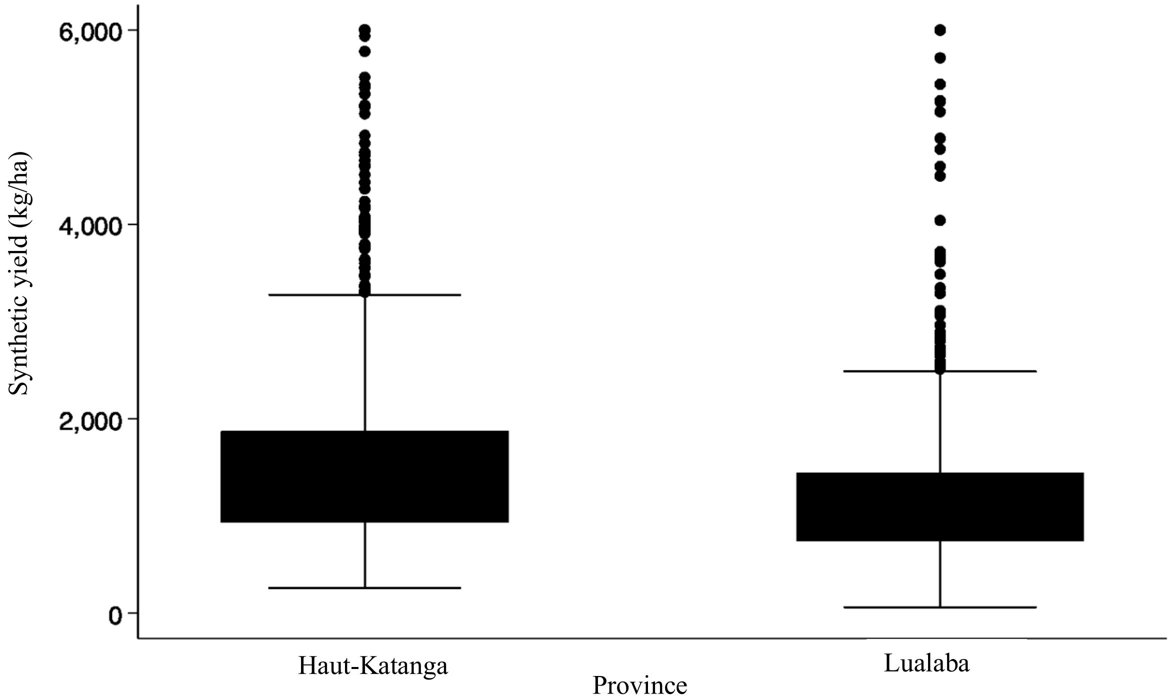

Figure 2. Distribution of synthetic maize yield by province

The plot clearly shows a positive correlation between fertilizer use and synthetic maize yield. As fertilizer use increases, the synthetic yield also tends to increase. However, this relationship appears non-linear; the yield increases more significantly at moderate levels of fertilizer application, and the rate of increase diminishes as fertilizer use exceeds certain thresholds.

At lower fertilizer application rates (up to approximately 1,500 kg/ha), the yield remains relatively low, with a concentration of data points around 0 to 2,000 kg/ha for synthetic yield. However, once fertilizer use exceeds 1,500 kg/ha, there is a noticeable increase in yield, with values rising steeply, indicating that fertilizer application positively impacts yield beyond a certain threshold. This suggests that farmers who apply higher amounts of fertilizer could see significantly higher yields, but the gains diminish as the fertilizer quantity increases further.

There are several outliers where synthetic yield exceeds 5,000 kg/ha, often corresponding to higher fertilizer use. These cases suggest that under optimal conditions (e.g., better soil management, appropriate pest control, and timely irrigation), high fertilizer application can result in exceptionally high yields. However, these outliers represent extreme cases and should not be generalized as typical farming conditions. They emphasize the potential for achieving high yields through effective fertilizer management, but they also highlight the potential variability in farming conditions and input efficiency.

The non-linear relationship observed in the plot reflects the classic principle of diminishing returns. Initially, as fertilizer use increases, yield increases sharply. However, as fertilizer use continues to rise beyond a certain point (around 2,500 to 3,000 kg/ha), the increase in yield becomes less pronounced. This diminishing return suggests that there is an optimal level of fertilizer application, beyond which further input may not significantly enhance yield and could even lead to inefficiencies or environmental issues like soil degradation or nutrient imbalances.

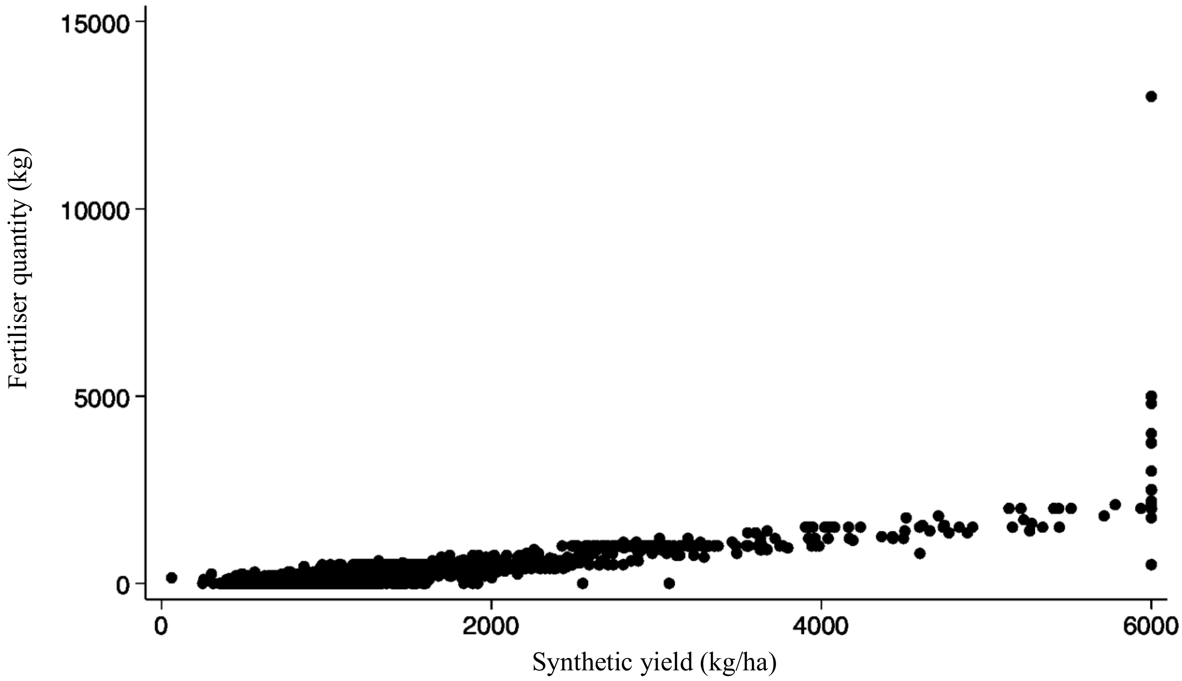

Figure 3. Relationship between synthetic maize yield and fertilizer application

4.4.2 Econometric insights on productivity drivers

This section presents and interprets the findings of a linear regression analysis which aims to explain variations in synthetic maize yield (log-transformed) across households in the provinces of Haut-Katanga and Lualaba. The dependent variable is a synthetic approximation of maize productivity (in kilograms per hectare) derived from agronomic assumptions and key input data, including fertiliser usage, seed type and crop protection practices.

Initial diagnostic tests revealed substantial multicollinearity when quadratic terms were included, with variance inflation factors (VIFs) exceeding critical thresholds (>10) and thus jeopardising the stability of the coefficients. Applying natural logarithmic transformations offered a more parsimonious approach, capturing diminishing marginal returns without exacerbating collinearity. Log transformations also stabilised variances and aligned residuals with the homoskedasticity assumptions of OLS (Wooldridge, 2010), while rendering the coefficients interpretable as elasticities. The Breusch–Pagan test indicated significant heteroskedasticity ($\chi^2 > 300$, $p < 0.001$). To address this, robust (White) standard errors was applied.

Table 3 reports the semi-log regression results, providing information on the marginal impact on maize yields. The model explains approximately 42% of the variation in synthetic maize yield.

The positive impact of fertilizer use on maize yield, reflected by a 33% increase in yield for every additional kg/ha of fertilizer applied, aligns with widely established agronomic theory. This result emphasizes the importance of nutrient availability for maize productivity. However, the small magnitude of the effect suggests that while fertilizer use is beneficial, it might not be the sole driver of productivity. This modest increase could be attributed to the efficiency of fertilizer application and the fact that diminishing returns to fertilizer might set in at higher application levels. Additionally, optimal fertilizer use needs to be coupled with improved soil health, proper timing, and efficient water management to maximize its impact on maize yields.

The use of insecticides significantly enhances maize productivity, with a 23% increase in yield when insecticides are applied. This finding emphasizes the importance of pest management in enhancing agricultural productivity, as insect pests, such as the fall army worm can severely reduce crop yield and quality (Goergen et al., 2016). The strong impact of insecticide use suggests that pests, particularly those affecting maize, are a significant constraint on yield in the studied regions. The application of herbicides also has a strong positive effect, with a 41% increase in synthetic maize yield when herbicides are used. This result underscores the importance of weed control in maize farming, as weeds are known to compete with crops for essential resources such as light, water, and nutrients. The significant impact of herbicides suggests that weed management is crucial for optimizing maize productivity, particularly in areas with high weed pressure.

A slightly positive effect of household size on maize yield is observed, with a 2% increase in yield for each additional household member. This result suggests that labor availability is an important factor for smallholder farms. Larger households are likely to provide more hands for farm work, which could lead to increased labor input, particularly during the planting and harvesting seasons.

The negative coefficient for solar radiation indicates that increased solar radiation is associated with a 6% decrease in yield. This is likely due to the detrimental effects of heat stress on maize crops, which can hinder photosynthesis, reduce grain formation, and increase water demand.

Both distance to market and distance to road show minimal effects on synthetic maize yield, with coefficients close to zero. This suggests that, while infrastructure is important for facilitating access to markets and inputs, other factors such as access to fertilizers, seeds, and extension services may have a more immediate effect on yield.

The coefficient for rainfall during the critical period from November to January shows a positive impact, with a 0.02% increase in yield for each additional millimeter of rainfall. This is expected, as adequate rainfall during the early maize growth phase is crucial for crop establishment and development. This result highlights the importance of timing and distribution of rainfall for optimizing yield.

The results suggest that soil type plays a meaningful role in shaping maize productivity. Households farming on certain soils, such as Ferralsols or Lixisols, tend to achieve yields that are on average 13.7% higher, all else being equal. Likewise, the positive and significant coefficient for province implies that farmers located in Haut-Katanga benefit from 23.6% higher yields on average. This likely reflects broader structural differences across provinces, including soil characteristics, access to markets, and the availability of agricultural support services.

Variables like field ownership, hybrid seed use, and manual technical prep show insignificant effects on synthetic maize yield, suggesting that these factors may not directly influence the yield in this model, though they might contribute indirectly over time or through technological adoption.

Independent Variables	Coefficient
Size of maize field	-4.55e-09
Field ownership	-0.0169
Total fertilizer	0.3286***
Insecticide use	0.2253***
Herbicide use	0.4084***
Hybride seed use	0.1010***
Growing period	0.00001
Sex of household head	-0.0027
Age of household head	0.0004
Household size	0.0115**
No formal education	-0.0486
Received agri training	0.0360
Labor hours (total)	-7.19e-06*
Manual technical prep	-0.2444
Distance to market (m)	2.01e-07
Distance to road	3.78e-07***
Solar radiation	-0.0614***
Weekly water spending (CDF)	-1.14e-07
Rainfall Nov-Jan (mm)	0.0015***
Soil type code	0.1371***
Province	0.2362***
Cons	6.8048***
N of obs	1944
R Square	0.42

Note: *** 1% significance; ** 5% significance; * 10% significance

Table 3. OLS regression results for determinants of synthetic maize yield

4.5 Discussion

The findings not only quantify the impact of various inputs and climatic variables but also provide a foundation for evidence-based policy interventions aimed at fostering sustainable agricultural intensification.

The significant positive effect of fertiliser on maize yield, with a 0.06% increase for each additional kilogram per hectare, aligns with established agronomic principles. This elasticity, while seemingly modest, is substantial in the context of the DRC's low-input farming systems. It underscores the critical role of nutrient management in closing the yield gap. However, the reliance on synthetic fertilisers alone is a double-edged sword. As highlighted by Kalukuta

Mahina et al. (2025), this approach can lead to nutrient mining and soil degradation in the long term. Therefore, the discussion should not be limited to the quantity of fertiliser applied but should also encompass the quality of application and the integration of organic matter to enhance soil health (Cai et al., 2019). This study's results, in this context, serve as a call to action for promoting integrated soil fertility management practices, which combine the use of mineral fertilisers with organic resources environmental sustainability (Jabbar et al., 2022).

The substantial yield increases associated with insecticide (24.5%) and herbicide (44.6%) use highlight the severe constraints posed by pests and weeds in the region. These findings are particularly relevant for smallholder farmers who often lack access to effective and affordable pest management solutions. The results strongly advocate for the inclusion of pest and weed control in any strategy aimed at boosting maize productivity. However, the discussion must also address the potential negative externalities of chemical pesticide use. The high efficacy of these inputs should not overshadow the importance of integrated pest management (IPM) strategies that prioritize ecological balance. This study, therefore, provides a strong argument for promoting IPM approaches that combine biological control, cultural practices, and the judicious use of chemical pesticides to minimize environmental risks while maximizing crop protection (Owen et al., 2015).

The negative correlation between solar radiation and maize yield (a 2.9% decrease for every unit increase) suggests that heat stress is a significant limiting factor in the region. This finding is particularly pertinent in the face of climate change, which is projected to increase the frequency and intensity of heatwaves. The results of this study can be used to advocate for the development and dissemination of heat-tolerant maize varieties. Furthermore, they underscore the importance of agronomic practices that mitigate heat stress, such as mulching and conservation agriculture. This aspect of the study provides valuable data for climate change adaptation strategies and highlights the need for further research into the physiological responses of maize to heat stress in tropical environments (Tesfaye et al., 2015).

The positive impact of rainfall during the early growing season (a 0.06% increase for every additional millimeter) confirms the vulnerability of rainfed maize systems to climate variability. This finding is not novel in itself, but its quantification within the specific context of the DRC provides a powerful tool for policymakers. It can be used to justify investments in water management infrastructure, such as rainwater harvesting and small-scale irrigation. Moreover, it reinforces the need for climate information services that can help farmers make informed decisions about planting dates and other management practices (Tesfaye et al., 2015).

The comparative analysis of the Village Agricole Program in Haut-Katanga and the situation in Lualaba offers valuable insights into the role of institutional support. The program, despite its challenges, serves as a model for how targeted interventions can improve smallholder access to inputs, services, and markets. The disparities between the two provinces underscore the fact that technology adoption and productivity gains are not solely dependent on biophysical factors but are also shaped by the policy and institutional environment. This study's findings can be used to advocate for the scaling up of successful elements of the Village Agricole Program and for the development of similar initiatives in other parts of the DRC (Otchia, 2014).

4.6 Conclusion

This study provides a robust, data-driven assessment of the primary factors constraining maize productivity in the Haut-Katanga and Lualaba provinces of the DRC. The findings demonstrate that while the increased application of mineral fertilisers and agrochemicals can significantly boost yields, a sustainable intensification pathway necessitates a more systemic, holistic approach aligned with circular economy principles. The significant negative yield impacts of heat stress and the absolute dependence on rainfall underscore the urgent need for climate-resilient practices. Furthermore, the analysis reveals that the success of interventions like the Village Agricole Program is intrinsically linked to institutional support, highlighting its critical role in any agricultural transformation.

The central conclusion of this research is that there are no singular solutions. Instead, enhancing productivity and setting the path toward a circular agricultural system requires a multi-pronged strategy. This strategy must integrate context-specific, improved agronomic practices—including concrete circular practices such as organic farming techniques and the systematic usage of cattle manure to close nutrient loops—with supportive policies explicitly designed to incentivize resource efficiency. This study provides the empirical evidence necessary to design such a strategy.

For policymakers, the transition to a circular agricultural system demands a tiered action agenda. In the short term, priorities must include an identification phase with data collection and pilot projects to identify the appropriate circular practice (e.g.: composting and manure recycling) and demonstrate its efficacy. Medium-term actions should focus on strengthening farmer cooperatives for knowledge dissemination and cocreating enabling policies with them: developing input subsidy programs that favor organic fertilizers, implementing land tenure reforms to encourage long-term soil investment, and building infrastructure for local waste-to-resource markets. The long-term vision requires integrated national policies that formally mainstream circularity into agricultural planning, large-scale investment in climate-resilient infrastructure, and the establishment of a robust monitoring framework using a comprehensive circularity metric to track progress towards sustainability targets.

The insights from this research offer a clear, evidence-based pathway for enhancing agricultural output. Future research must therefore focus on co-developing and disseminating circular practices tailored to the local context, the agronomic and economic viability of these concrete practices, quantifying their impact on soil health, yield stability, and farm-level resilience. Furthermore, operationalizing the concept of a circular agricultural system requires the development of a comprehensive, quantifiable metric to evaluate circularity. This metric would be an essential tool for monitoring progress, benchmarking interventions, and guiding the multi-scale policy agenda, encompassing factors such as organic matter recycling rates, nutrient use efficiency, and renewable energy integration. Ultimately, this study serves as a foundational roadmap for unlocking the agricultural potential of Haut-Katanga and Lualaba, transforming current challenges into opportunities for sustainable growth, and ensuring a food-secure future through the principles of a circular economy.

5 General conclusion

This doctoral thesis examined how the principles of the circular agriculture can be integrated into maize and date palm farming systems to enhance productivity and resilience in Africa, with a particular focus on resource-constrained smallholder systems. A contribution of this work lies in the collection and analysis of original empirical data from the provinces of Haut-Katanga and Lualaba in the Democratic Republic of Congo (DRC) and from the Figuig region in Morocco, where access to reliable agricultural data is extremely limited. Data were collected directly by the author, together with trained local research teams, under highly challenging field conditions characterised by poor rural infrastructure, limited housing facilities, and exposure to mosquito-borne diseases such as malaria. Beyond producing a unique, high-quality dataset, this work also aimed to strengthen local research capacities and establish replicable data collection protocols in regions where information scarcity represents a significant barrier to agricultural development and evidence-based policymaking.

The thesis is structured around three interlinked chapters, each addressing a distinct but complementary stage in the progressive implementation of circular agricultural practices. Chapter 1 provided the conceptual and theoretical foundations by defining circular agriculture as “a set of agricultural practices aimed at limiting the use of inorganic fertilizers and pesticides in order to stimulate productivity, restore the soil’s original properties, maximise economic and social benefits, and minimise global emissions.” It further identifies some of the core components of circular systems, including the use of non-chemical inputs and the reuse of crop residues. This chapter situates CA within broader sustainability debates and demonstrates its potential to transform linear farming models into resilient systems capable of simultaneously addressing food security, environmental degradation, and climate change challenges in Africa.

Building on this conceptual framework, Chapter 2 provided an empirical validation through an in-depth case study of the Figuig composting station in Morocco, which illustrates how waste-to-wealth models can improve soil fertility, reduce dependence on chemical fertilizers, and generate measurable economic benefits. The cost-benefit analysis shows that composting offers both environmental and economic advantages, helping to close nutrient cycles and improve long-term soil productivity. However, the chapter also highlights significant challenges to scaling up this model, including high initial investment costs, limited infrastructure, and inadequate technical training among farmers. Moving from a pilot project, such as the Figuig production station, to a regional or national strategy would therefore require strong institutional commitment, targeted financial incentives, and knowledge transfer mechanisms to support wider adoption which are often supported by international organisation rather than national governments.

Chapter 3 represents the identification of circular opportunity into local farming systems. Using a data-driven approach, this chapter quantified the impact of fertilizer use, soil management practices, climatic conditions, and socio-economic factors on maize productivity in the DRC. In the absence of direct field-level yield measurements, a synthetic yield model was developed by combining agronomic, climatic, and socio-economic variables, enabling a more accurate and consistent measure of productivity. The analysis demonstrated that there is a high dependence on chemical inputs and opportunities to transition to a circular system whether it is through the introduction of organic amendement or natural pest control methods. The transformation of agricultural production through circular practices in smallholder systems is critically dependent on ensuring that these practices do not compromise productivity, a primary concern for farmers. The fieldwork conducted for this study, enabled by the operational agreement between Enabel and University of Lubumbashi which provided the framework for these surveys, was the baseline the development of a subsidy program by Enabel. This program was designed to support farmers who had been identified during the field surveys. This outcome underscores the critical importance of rigorous initial diagnostic in designing effective agricultural interventions.

Despite these contributions, this research acknowledges several limitations that must inform future work. The absence of longitudinal data prevents the study from capturing the long-term impacts of circular practices on soil health and yields across multiple seasons. While the application of a synthetic yield model enhances the analytical robustness compared to reliance on self-reported yield data, this methodological approach remains an imperfect proxy for direct field measurements and may introduce inherent estimation biases. An additional constraint stems from the predominant anglophone orientation of the circular agriculture literature, which presents a significant barrier to comparative analysis and constrains effective knowledge transfer to francophone African contexts. These methodological and contextual limitations collectively underscore the necessity of establishing long-term, longitudinal monitoring programs and fostering cross-institutional and multi-disciplinary research collaborations. Such partnerships, as exemplified by the collaborative frameworks underpinning the empirical work in Chapters 2 and 3, are essential for enhancing data quality, strengthening methodological rigor, and ultimately increasing the policy relevance of research findings. This is particularly critical given the frequent omission of socio-economic approaches to agronomic problems in the existing literature, an oversight that could hinder the sustainable implementation of new agricultural technologies and practices. Integrating socio-economic analysis can offer an effective and expedient pathway to bridge this gap, ensuring that interventions are not only agronomically sound but also economically viable, socially acceptable, and thus more likely to be adopted and sustained by farming communities.

In light of these findings, this thesis also emphasises the need for a progressive and economically grounded approach to the transition towards circular agriculture. The Moroccan case study has demonstrated that waste-to-wealth initiatives such as composting stations can generate substantial agronomic and economic benefits. However, the direct replication of this model in the DRC is neither feasible nor advisable at this stage, given the absence of prior field trials and the significant contextual differences between the two countries. Instead, the

Moroccan experience should serve as an inspiration and a source of methodological lessons rather than a ready-made model.

The first step for Haut-Katanga and Lualaba is to establish a robust economic framework that identifies the key determinants of maize production and productivity. This diagnostic stage is indispensable to ensure that subsequent agronomic trials and circular innovations are anchored in the local economic realities of smallholder farmers. Such an approach ensures that the transition towards circularity is not only scientifically sound but also economically viable and socially acceptable.

From this basis, the thesis advocates a phased identification of circular opportunities directly linked to productivity determinants. In practice, this implies first identifying the by-products capable of enhancing soil fertility (e.g., organic amendments), then those that can serve as natural protectants for crops (e.g., biological pest management), and finally developing agronomic research to test and adapt these circular solutions to local conditions. This sequential logic—from economic diagnosis to agronomic experimentation—ensures that circularity targets the most pressing productivity constraints, thereby maximising the likelihood of adoption by farmers.

Ultimately, this pragmatic and scientifically rigorous pathway positions circular agriculture not as a theoretical ideal but as a practical strategy for improving yields, reducing dependency on chemical inputs, and enhancing the resilience of smallholder farming systems in the DRC. It further highlights that building a solid economic model is the necessary foundation upon which agronomic innovation can be meaningfully deployed.

The thesis also underscores the structural and institutional barriers that constrain the transition toward circular agriculture in Africa. The lack of rural infrastructure—including roads, storage facilities, irrigation systems, and composting stations—remains a critical obstacle. Policy frameworks are often delayed in integrating sustainability objectives, and there is a persistent disconnect between global agricultural ambitions and local realities. International standards frequently overlook the socio-economic constraints faced by smallholder farmers, for whom income security and immediate livelihood concerns often take precedence over adopting sustainable practices. These findings reveal a fundamental tension between policy aspirations and local priorities, highlighting the importance of developing context-specific strategies that reconcile environmental goals with economic realities.

In addition to its empirical and conceptual contributions, this thesis proposes a comprehensive policy framework to support the transition towards circular agriculture. The findings underscore the need for a multi-level governance approach operating simultaneously at international, national, provincial, and local scales to address the paradox between promoting circular practices and the limited resources available to local populations for their implementation. At the international level, funding mechanisms must be aligned with sustainability objectives to ensure coherent support for circular practices. At the national level, circularity principles should be embedded within long-term agricultural development strategies and integrated into regulatory frameworks to secure policy continuity. At the provincial and local levels, effective implementation depends on capacity-building programs, the promotion of farmer cooperatives, and tailored extension services designed to facilitate the adoption of circular practices by smallholders.

This governance framework must also be translated into a phased policy agenda, integrating short-, medium-, and long-term priorities. Accelerating the short-term adoption of circular practices hinges on three key interventions: deploying targeted training on organic amendment utilisation (including manure management) and biological pest management practices, enhancing transparency through open agricultural data, and providing financial incentives for composting and bio-input technologies. In the medium term, circularity principles should be integrated within provincial agricultural plans, supported by cooperative models that enable resource pooling and greater economies of scale. Critical investments must also target rural infrastructure to overcome structural barriers. This includes developing irrigation systems, enhancing rural transportation networks to improve market accessibility, and establishing waste management programs that facilitate household and farmers waste sorting and organic waste sanitation. Over the long term, establishing a dedicated national regulatory framework for agricultural circularity is essential to ensure consistency across policy cycles. Such a framework could, for instance, define clear national standards for fertilisers and pesticides and their modes of utilisation, establish regulatory mechanisms for the safe collection and valorisation of agricultural residues, and even provide for the creation of a state-owned company responsible for the organised collection and treatment of waste. Furthermore, enacting a law on the recycling and reuse of agricultural and food waste, similar to waste management legislation in several Western countries, would create the legal certainty and enforcement capacity needed to stimulate private investment, build local markets for bio-inputs, and accelerate the transition from a linear to a circular agricultural economy.

Achieving these objectives requires strong coordination among international organisations, national authorities, and local stakeholders, but also demands the creation of independent operational units equipped with ring-fenced budgets and granted sufficient autonomy to manage circular agriculture programmes effectively, regardless of political transitions. Such institutional mechanisms are vital to guaranteeing the continuity, scalability, and long-term sustainability of circular agriculture initiatives.

There are several promising avenues for future research that can be developed based on this thesis. There is a need to develop advanced indicators of circularity that measure the effectiveness of circular practices more precisely, including nutrient recycling rates, soil organic carbon dynamics, and farm-level emissions. Longitudinal studies tracking farmers over multiple seasons would provide critical insights into the cumulative effects of circular practices on productivity. Integrating circular agriculture with emerging digital technologies, such as remote sensing, DSSAT crop modelling, and machine learning, offers further potential to optimise resource use and improve yield predictions in smallholder farming systems.

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7 Appendix

Appendix A

Farm Survey questionnaire

1. Interviewer Name
2. Farmer's Information
   - Full Name: ______
   - Contact Number: ______
   - Age: ______
   - Place of Birth: ______
   - Current Residence: ______
   - Ksar of Residence: ______
3. Education Level (Select one)
   - ☐ No formal education
   - ☐ Primary
   - ☐ Secondary
   - ☐ Higher education
4. Professional Information
   - Primary Occupation: ______
   - Years of Farming Experience: ______
5. Main Activity Sector (Select one)
   - ☐ Production
   - ☐ Local distribution
   - ☐ Processing
6. Cooperative Membership
   - Member of a cooperative? (Y/N)
   - If yes:
     - Date of cooperative establishment: ______
     - Number of members: ______
     - Cooperative location: ______
     - Main activities: ______
7. Farm Characteristics
   - GPS Coordinates: ______
   - Palm Grove Name: ______
   - Farm Area (m^2): ______
8. Workforce
   - Seasonal Workers: ______

- Permanent Workers: ______
- Female Workers: ______
- Workers aged 16–35: ______
- Worker Origins: ______

9. Farm Details
   - Number of Date Palms: ______
   - Bayoud-infected Palms: ______
   - Other Crops: ______
   - Crop Type: ______
   - Average Daily Work Hours: ______
10. Financial Information (in MAD)
    - Annual Investment: ______
    - Cost Structure: ______
    - Annual Profit: ______
    - Income Value: ______
    - Does income meet needs? (Y/N)
    - If no, other income sources: ______
11. Soil Amendment Selection Criteria (Select all that apply)
    - ☐ Availability
    - ☐ NPK Content
    - ☐ Environmental Impact
    - ☐ Soil Health
    - ☐ Organic Matter Proportion
    - ☐ Vendor Trustworthiness
    - ☐ Price
    - ☐ Proximity of Purchase Point
12. Soil Analysis
    - Conduct soil tests? (Y/N)
    - If yes:
      - Test Type: ______
      - Frequency: ______
    - Soil Quality Assessment: (Select one)
      - ☐ Depleted
      - ☐ Poor
      - ☐ Average
      - ☐ Good
      - ☐ Excellent

13. Fertiliser Use
    - Type: ______
    - Quantity: ______
    - Application Frequency (per year): ______
    - Source: ______
14. Date Palm Management
    - Pruning Frequency: ______
    - By-product Storage Method: ______
    - By-product Utilisation: ______
    - By-product Disposal Method: ______
15. Compost Knowledge and Use
    - Familiar with compost? (Y/N)
    - Use compost? (Y/N)
    - If yes:
        - Quantity: ______
        - Source: ______
    - Know SEMO experimental compost station? (Y/N)
    - Willing to:
        - Purchase SEMO compost? (Y/N)
        - Price willing to pay (MAD/kg): ______
        - Sell by-products to SEMO? (Y/N)
        - Expected price: ______
        - Exchange by-products for compost? (Y/N)

Additional Comments: ______