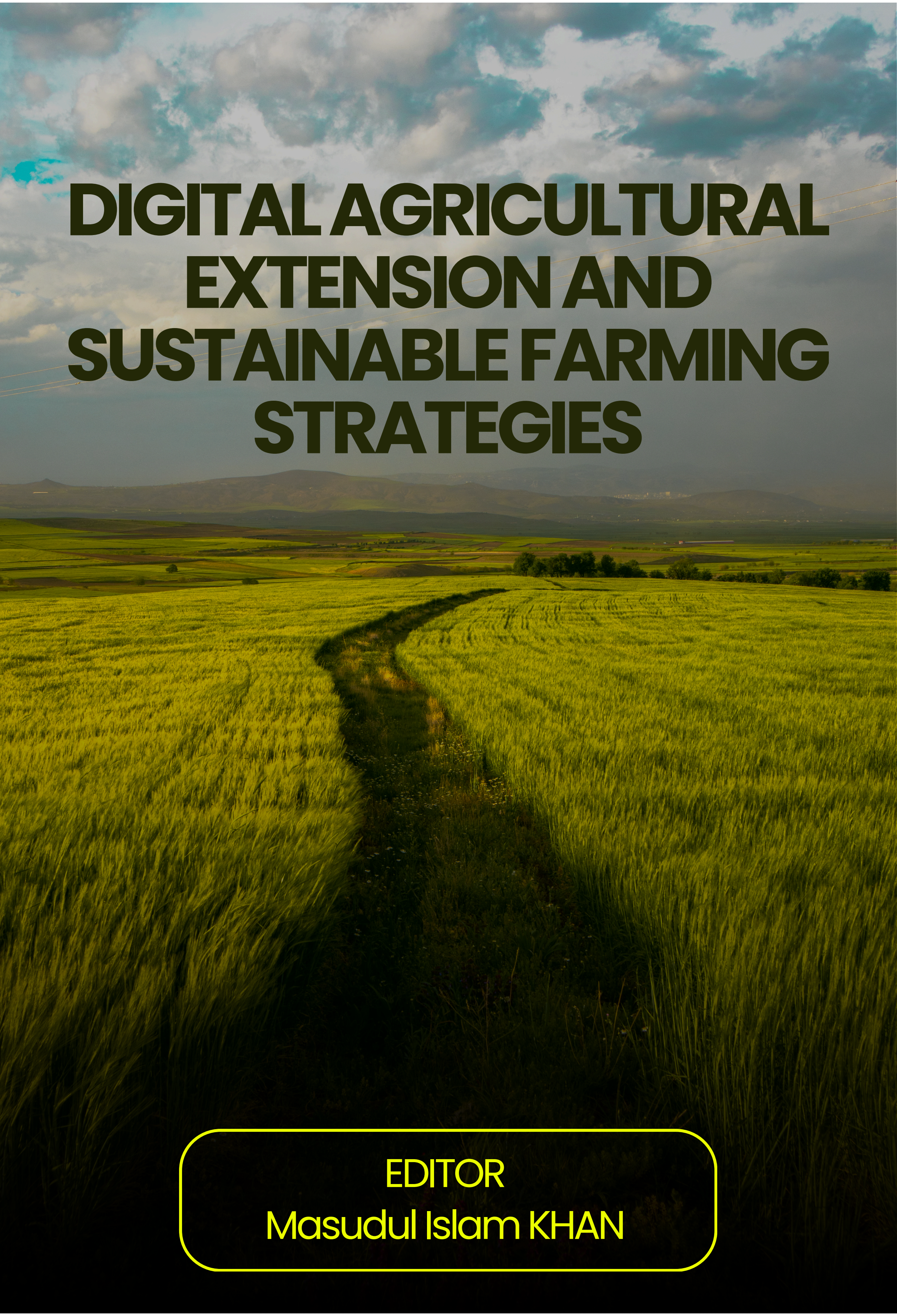

DIGITAL AGRICULTURAL EXTENSION AND SUSTAINABLE FARMING STRATEGIES

EDITOR
Masudul Islam KHAN

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PREFACE

This volume brings together multidisciplinary perspectives that address critical challenges and transformations within contemporary agricultural and food systems. By integrating economic analysis, technological innovation, plant pathology, and digital extension, the book reflects the growing need for holistic approaches to sustainability, productivity, and resilience in a globalized context.

The chapter on the global sesame market provides a comparative examination of growth dynamics and risk structures across leading producing nations, offering valuable insights into trade patterns and market vulnerabilities. Complementing this economic perspective, the discussion on membrane distillation highlights an emerging technological solution for the sustainable treatment and reuse of dairy wastewater, emphasizing resource efficiency and environmental protection.

Plant health and crop sustainability are addressed through an in-depth review of Fusarium wilt of tomato, focusing on pathogen biology and integrated management strategies. This contribution underscores the importance of disease control in safeguarding yields and ensuring food security under increasing biotic and climatic pressures.

Finally, the analysis of digital agricultural extension in Nigeria explores the opportunities and constraints of technology-driven advisory systems in developing contexts. Together, the chapters in this book contribute evidence-based knowledge and practical pathways to support innovation, informed policymaking, and sustainable agricultural development.

Editorial Team
January 29, 2026
Türkiye

CHAPTER 1
THE ANATOMY OF SESAME BOOM IN A GLOBALIZED MARKET: A COMPARATIVE DECOMPOSITION OF GROWTH AND RISK IN SIX LEADING NATIONS

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INTRODUCTION

Background of the Study

Sesame (Sesamum indicum L.), one of the oldest oilseed crops known to humanity, continues to hold significant economic and nutritional importance in the 21st century. Globally, it is prized for its high-quality oil (approximately 50-60%), rich protein content (25%), and abundance of antioxidants, vitamins, and minerals such as calcium and iron (Langyan et al., 2025). Beyond its direct consumption, sesame is a crucial cash crop for millions of smallholder farmers in tropical and subtropical regions of Africa and Asia, providing a vital source of income and contributing to rural livelihoods and food security (Waseem et al., 20017). The global market for sesame has been expanding steadily, driven by rising health consciousness and the growing demand for natural and organic foods in developed economies (Haque et al., 2025).

The production landscape of sesame is characterized by its dominance in developing countries. According to the Food and Agriculture Organization (FAO) of the United Nations, the major producers and exporters include Sudan, Myanmar, India, Tanzania, and Nigeria, among others. However, production trends are not static; they are influenced by a complex interplay of factors including climate variability, market prices, government policies, technological adoption, and socio-economic conditions at the farm level (Kassie et al., 2023). Understanding the dynamics of how and why production changes over time in these key countries is essential for predicting global supply, informing trade policies, and directing agricultural development efforts.

A critical analytical approach to understanding agricultural production changes involves decomposing total output growth into its constituent parts: changes in the area harvested (extensification) and changes in yield per unit area (intensification). Furthermore, analyzing the stability of production—measured through variance is equally important, as high volatility can lead to unpredictable supplies, price spikes, and increased income insecurity for farmers (Antle, 1987). While numerous studies have examined sesame production in individual countries, there is a comparative gap in the literature that systematically analyses and contrasts the sources of production growth and instability across the world's leading exporting nations over an extended period.

Problem Statement

Despite the economic significance of sesame, its production systems in major exporting countries face persistent challenges and exhibit divergent developmental pathways. Anecdotal evidence and aggregate national data often mask the underlying drivers and risks associated with production growth. For instance, a country may show impressive growth in total output, but this could be primarily due to the expansion of cultivated area into ecologically fragile zones, leading to environmental degradation and unsustainable practices (Dias et al., 2016). Conversely, another country might achieve growth through yield intensification, which could be hampered by yield plateaus, high input costs, or increased vulnerability to pests and diseases.

The core problem is the lack of a nuanced, comparative understanding of the components of production change and the associated shifts in production stability among the key players in the global sesame market. Policymakers and stakeholders often operate with incomplete information: they know that production has increased or decreased, but they do not fully comprehend whether this change is due to farmers planting more area, achieving higher yields, or a combination of both, and how these changes have affected the year-to-year reliability of supply. Moreover, the relationship between area and yield whether they move in tandem (positive covariance) or in opposite directions (negative covariance) can reveal important insights into farmers' decision-making and resource allocation efficiency, yet this is rarely examined in a comparative context (Oyedepo & Evbuomwan, 2024).

Therefore, a clear problem exists in deconstructing the aggregate production figures to answer critical questions: Are the major sesame exporters growing through extensification or intensification? What is the relative contribution of area, yield, and their interaction to observed production growth? How has the stability of production changed over time, and what are the sources of increased volatility or enhanced stability? Without answers to these questions, formulating effective national and international policies to ensure a stable, sustainable, and equitable global sesame supply chain remains a formidable challenge.

Justification of the Study

The justification for this research is multi-faceted, spanning academic, practical, and policy domains.

- Academic Justification: This study contributes to the field of agricultural economics and development studies by applying a robust decomposition methodology to a high-value global commodity. It moves beyond descriptive trend analysis to provide a mechanistic understanding of production changes. By focusing on a comparative framework across continents (South America, Africa, Asia), the research can identify universal patterns and context-specific peculiarities in agricultural growth, thereby enriching the theoretical discourse on agricultural transformation and the growth-stability trade-off (Garrett et al., 2013; Antle, 1987).
- Practical and Policy Justification: The findings of this study have direct practical implications. For national governments and ministries of agriculture in the studied countries, the results can serve as a diagnostic tool. For example, if a country like Brazil finds its growth is entirely area-driven and highly volatile, it may need to reorient its policies towards yield enhancement and sustainable land use. Conversely, for a yield-driven but slow-growing country like India, the analysis underscores the urgent need for research and development to break the yield barrier. For international development agencies and value chain investors, understanding which countries have stable and synergistic growth (like Tanzania or Nigeria) can guide where to channel investments for maximum impact and risk mitigation.
- Global Food Security and Trade Justification: As a nutritious crop and a key source of foreign exchange for several developing nations, a stable and growing sesame sector contributes to both global food security and economic resilience (Sadıq & Sıngh, 2020). This research provides valuable insights for international traders and policymakers seeking to predict long-term supply trends and manage risks associated with dependency on volatile sources. By highlighting the countries that have successfully combined growth with stability, the study offers models for others to emulate.

In conclusion, by dissecting the anatomy of sesame production growth and instability in the world's leading exporting nations, this study provides critical evidence-based insights that can inform smarter, more targeted, and more sustainable strategies for one of the world's most important smallholder oilseed crops.

Research Objectives

This study aims to conduct a detailed comparative analysis of sesame production trends in the world's top six exporting countries from 1994 to 2023. The specific objectives are:

- To quantify and compare the changes in mean area harvested, mean yield, and mean production of sesame between two periods, 1994-2008 (Period I) and 2009-2023 (Period II), in Brazil, Ethiopia, India, Nigeria, Pakistan, and Tanzania.
- To decompose the total change in average production for each country into four components: (a) the contribution of change in mean yield, (b) the contribution of change in mean area, (c) the interaction effect between changes in mean area and yield, and (d) the effect of change in the covariance between area and yield.
- To analyze the change in the variance of production for each country and identify the key components (e.g., changes in variance of area, variance of yield, and their covariance) driving production stability or instability.
- To provide a comparative assessment of the production growth pathways and stability profiles between and within the selected countries, drawing implications for agricultural policy, research, and development.

1. LITERATURE REVIEW

Theoretical Framework

This study is grounded in a synthesis of established economic and agricultural development theories that provide the conceptual lenses through which the changes in sesame production are analyzed. The framework integrates principles from production economics, risk analysis, and the induced innovation theory to deconstruct and interpret the dynamics observed in the data.

Production Function Decomposition and Growth Accounting

At its core, agricultural production can be modeled as a function of key inputs. The fundamental relationship is expressed as P=A×YP=A×Y, where Production (P) is the product of Area harvested (A) and Yield (Y). Yield itself is a function of a multitude of factors, including technology, input use, soil quality, and climate. To understand the sources of growth, this analysis employs a growth accounting framework, a well-established method in agricultural economics for decomposing output growth into input expansion and productivity gains (Ruttan, 1971).

The decomposition methodology used in the provided tables extends this basic principle. The change in mean production is not only attributed to changes in mean area and mean yield but also to their interaction and the change in their covariance. This approach is conceptually aligned with the Just-Pope Production Function, which allows for the separation of the effects of inputs on both the mean (output) and the variance (risk) of production (Just & Pope, 1978). The "Change in yield and area covariance" component directly addresses this relationship. A positive covariance suggests that inputs (area) are being used in a risk-increasing manner (e.g., expanding area in good years), while a negative covariance might indicate risk-management behavior. This framework allows us to move beyond simply how much production changed to how and why it changed, distinguishing between extensification, intensification, and efficiency gains in resource allocation.

The Induced Innovation Theory and Pathways of Agricultural Development

The divergent growth pathways observed across the six countries can be interpreted through the lens of the Induced Innovation Theory (Ruttan, 1971). This theory posits that technological and institutional innovations in agriculture are induced by the relative scarcities and prices of factors of production, particularly land and labor.

- Land-scarce, labor-abundant economies (the intensification pathway): In a country like India, where arable land is a limiting factor, the theory predicts that the path of development will be biased towards yield-enhancing, land-saving technological change.

This is evidenced by our findings, where 98.48% of production growth came from yield increases with negligible area expansion. This reflects an economic environment that induces innovations such as high-yielding varieties (HYVs) and precision irrigation to substitute for scarce land (Angamuthu et a., 2025).

- Land-abundant, labor-scarce economies (the extensification pathway): Conversely, in countries like Brazil, Tanzania, and Ethiopia, where land was relatively more abundant, especially in the initial period, the theory predicts a bias towards labor-saving and land-augmenting mechanical technologies that facilitate area expansion. The data strongly supports this, showing area expansion as the dominant contributor to growth. This pathway is often driven by the opening of new frontiers, a process extensively documented in the context of Brazilian agriculture (Dias et al., 2016).
- The synergistic pathway: The case of Nigeria, with its powerful interaction effect, suggests a more complex scenario where both land and yield-enhancing technologies are being adopted simultaneously. This can be seen as a response to both market opportunities and a gradual reduction in the land-to-labor ratio, inducing a dual approach. This aligns with contemporary studies on African agricultural transformation, which highlight the role of market access and commercial orientation in driving concurrent investments in both expansion and intensification (Oyedepom& Evbuomwan, 2024).

Risk and Stability in Agricultural Production

Analyzing the mean of production provides only half the picture; understanding the change in variance is crucial for assessing sustainability and farmer welfare. This study draws on the theory of production risk (Antle, 1983; Just & Pope, 1978). Yield and production risk are inherent in agriculture due to weather volatility, pest outbreaks, and market shocks.

The decomposition of production variance into its components (changes in area variance, yield variance, and their covariance) provides a diagnostic tool for identifying the sources of instability. For instance:

- High area variance, as seen in Brazil and Pakistan, often signals that planting decisions are highly sensitive to exogenous shocks like fluctuating output prices, the availability of credit, or competition from other crops (Ali & Abdulai, 2010). This makes the production system inherently volatile.
- High yield variance, as observed in Nigeria, points to agronomic and environmental vulnerabilities, such as reliance on erratic rainfall, inadequate pest control, or heterogeneous soils.
- A strong positive area-yield covariance, as in India, can be a stabilizing force, indicating that area allocation is efficient and responsive to yield-potential signals.

The trade-off between growth and stability is a central theme in agricultural development. Pushing a single input (like land in Brazil) often increases exposure to systemic risks, leading to higher variance. In contrast, a balanced approach that improves both means and manages variances, as seen in Ethiopia and Tanzania, may lead to a more resilient growth trajectory, a concept echoed in the literature on sustainable intensification (Pretty, 2018).

Conceptual Synthesis

In synthesis, this research is framed by the following interconnected theoretical propositions:

- The trajectory of agricultural production growth is path-dependent and induced by a country's specific factor endowments (Land vs. Labor), as per Ruttan (1971).
- Total production change can be mechanistically deconstructed into components attributable to area, yield, their interaction, and their covariance, providing a deeper understanding of the growth process than aggregate figures alone.
- Production stability is an equally critical dimension of performance, influenced differently by the variances and covariances of the underlying inputs, with high volatility posing risks to farmer incomes and supply chains.

By applying this integrated theoretical framework, the analysis moves beyond a descriptive account of sesame production trends.

It enables a normative assessment of the different growth models, identifying the associated risks and sustainability implications, and provides a robust foundation for deriving policy recommendations tailored to the specific economic and agricultural contexts of each country.

Conceptual Framework

The conceptual framework for this study provides a schematic model that visually and narratively outlines the key concepts, variables, and their interrelationships, guiding the analysis and interpretation of the data. It operationalizes the theoretical principles into a specific, testable structure for understanding sesame production dynamics.

The framework, as illustrated in Figure 1 below, posits that the changes in sesame production systems between two time periods (Period I: 1994-2008 and Period II: 2009-2023) can be understood by analyzing two primary dimensions: Growth in Mean Production and Change in Production Stability. These two dimensions are determined by the evolution of three core variables Area Harvested (A), Yield (Y), and their relationship which are themselves influenced by underlying contextual factors. Explanation of the Framework Components:

1.1 Foundational Elements (The Boxes - "What" is measured)

- Core Variables: The framework is built on three primary variables: Area Harvested (A), Yield (Y), and their Covariance (Cov). These are the direct, measurable components of production (P = A * Y).
- Contextual Factors: These are the exogenous forces that drive changes in the core variables between periods. They include:
- Factor Endowments: The relative scarcity of land and labor, which induces specific innovation pathways (Ruttan, 1971).
- Policies and Institutions: Government subsidies, export regulations, and research and development investments.
- Market Forces: Fluctuations in global sesame prices and demand, which influence farmer planting decisions (Oyedepo & Evbuomwan, 2024).
- Technology: Availability and adoption of improved seeds, irrigation, and mechanization.

- Climate and Environment: Rainfall patterns, droughts, and soil quality, which directly impact yield and area suitability.

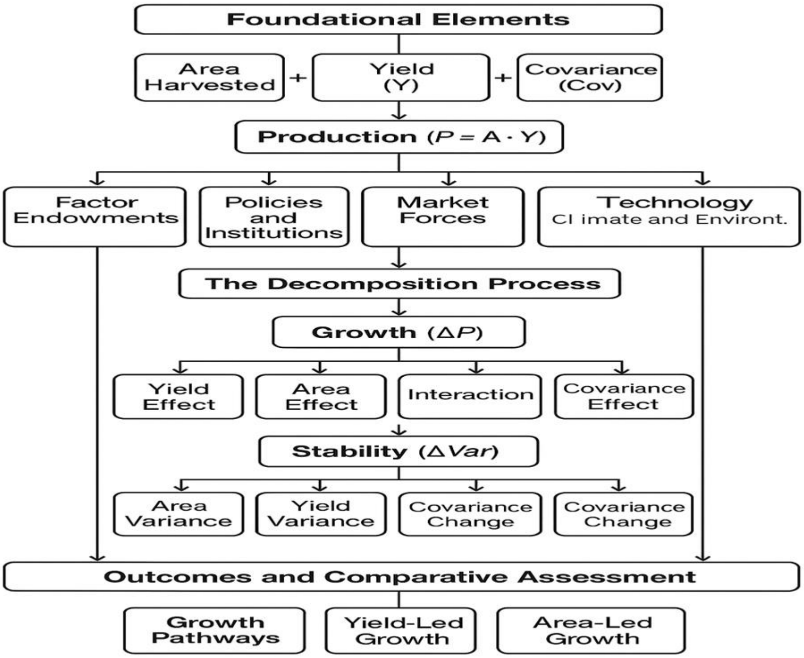

Figure 1. Conceptual framework for analyzing sesame production changes
Source: Python software, 2025

1.2 The Decomposition Process (The Arrows - "How" it is analyzed)

The framework shows that the change from Period I to Period II is not viewed as a black box. Instead, it is meticulously decomposed:

- For Growth (ΔP): The total change in average production is broken down into four additive components (as shown in the data's Table 'b' for each country). This allows us to quantify whether growth came from farmers getting better at producing on the same land (Yield Effect), from planting more land (Area Effect), from a synergistic combination of both (Interaction), or from a more efficient alignment of area with yield-potential (Covariance Effect).

- For Stability (ΔVar): The change in production variance, a measure of risk and stability, is decomposed into ten components (as in the data's Table 'c'). This complex decomposition helps pinpoint whether instability originates from volatile planting decisions (Area Variance), unpredictable yields (Yield Variance), or a changing relationship between the two (Covariance Change).

1.3 Outcomes and Comparative Assessment (The Bottom - "What it means")

The results of the decomposition feed into a typology of pathways and outcomes, enabling a systematic cross-country comparison.

- Growth Pathways: Based on the dominant components from the decomposition, countries are categorized into distinct growth models. For instance, a country where component (b) is dominant follows an Area-Led Growth pathway, while one where (a) is dominant follows a Yield-Led Growth pathway. A country with a large (c) component is experiencing Synergistic Growth.
- Stability Outcomes: Similarly, the analysis of ΔVar leads to a classification of countries based on whether their production system became more stable, less stable, or exhibited a mixed trend. This directly addresses the risk implications of each growth pathway (Just & Pope, 1978).

In essence, this conceptual framework guides the entire investigation. It posits that by starting with the contextual setting, measuring the core variables in two periods, and then deconstructing the differences, we can logically arrive at a robust classification of countries into specific, evidence-based production pathway categories. This structured approach ensures that the analysis moves from raw data to a meaningful comparative narrative about the drivers and consequences of sesame production changes in the global south.

Empirical Review

This section synthesizes existing empirical studies on sesame production in the six focus countries, situating the findings of the present analysis within the broader context of scholarly work.

The review is structured to reflect the comparative pathways identified area-led growth, yield-led intensification, and synergistic models and examines the documented evidence on production stability.

Empirical Evidence on Area-Led Growth Models

The data identified Brazil, Ethiopia, and Tanzania as exemplars of production growth driven predominantly by the expansion of harvested area. This pattern is strongly supported by the existing literature.

In Brazil, the findings of this study, which show a 110.59% contribution of area expansion to production growth, are a microcosm of a larger national agricultural trend. Research by Dias et al. (2016) extensively documented the patterns of land use extensification in the Brazilian Cerrado and Amazon biome, where the agricultural frontier has consistently expanded for soy and cattle ranching. Sesame, often cultivated as a rotational crop or in newly opened areas, has ridden this wave of extensification. The study's finding of massively increased production variance, driven by area variance, aligns with the high volatility associated with frontier agriculture, where land tenure, environmental compliance, and market fluctuations lead to unpredictable planting decisions (Garrett et al., 2013).

For Ethiopia, the empirical literature corroborates the dominance of area expansion. Kassie et al. (2023) identified that sesame area cultivation in Ethiopia, particularly in the lowland regions of Humera, Metema, and Pawe, expanded significantly due to both smallholder commercialization and large-scale land investments by domestic and foreign investors. They attribute this to favorable land policies and high international market prices. However, their work also notes the persistent challenge of low and variable yields, which is consistent with our finding that yield improvement, while positive, played a secondary role (2.60% contribution). The remarkable achievement of increased production alongside reduced variance, as found in our analysis, is less commonly highlighted but can be inferred from studies noting the consolidation of sesame as a major, stable export commodity in the Ethiopian economy (Gebreegziabher et al., 2024).

In Tanzania, the massive 708% production increase driven by area expansion (69.88% contribution) and a strong interaction effect is well-documented. Studies by Lukurugu et al.(2023); Mhagama & Mmasa (2022) highlighted that sesame production has been a key component of Tanzania's Southern Agricultural Growth Corridor (SAGCOT) initiative, which aims to transform agriculture through commercialization and infrastructure development. The expansion into central regions like Singida and Dodoma has been a direct result of these efforts. The synergistic interaction effect found in our data suggests that this expansion was not merely onto marginal lands but into areas with reasonable yield potential, a point supported by agronomic suitability mapping for sesame in Tanzania (Hyera & Isango, 2024).

Empirical Evidence on Yield-Led Intensification

The case of India presents a clear model of yield-led growth, which is a consistent theme in the literature on Indian agriculture, particularly for crops where area is stagnant.

Our finding that 98.48% of India's sesame production growth came from yield improvement resonates with studies on the subject. Singh et al.(2024); Tripathi (2021) explicitly note that the stagnation in sesame area in India is due to its status as a rainfed crop, often grown on marginal lands with little irrigation, and facing competition from more profitable crops like cotton and soybean. Consequently, any growth must come from enhanced productivity. However, they and other scholars like Sharma (2021) point out that the average national yield remains low compared to its genetic potential, hampered by the lack of widespread adoption of high-yielding varieties and integrated crop management practices. This underscores the significant achievement reflected in our data that even modest yield gains were sufficient to drive substantial absolute production increases on a massive existing area. The finding of drastically reduced production variance in India aligns with the stability of a mature, area-constant system where output fluctuations are primarily a function of monsoon variability rather than volatile planting decisions.

Empirical Evidence on Synergistic and Covariance-Driven Models

Nigeria's balanced and synergistic growth pattern, with significant contributions from area, yield, and their interaction, is increasingly reflected in recent empirical work. Sadiq et al.(2020a) described sesame as a "rising star" in Nigerian agriculture, with expansion driven by high market demand and its suitability for the country's agro-ecology. They note a growing interest from farmers in the North West and North Central states, which aligns with the area expansion component. Furthermore, initiatives by the government and NGOs to promote improved sesame varieties (e.g., NCRI BENISEED-1) have contributed to the observed yield growth (Oyedepo & Evbuomwan, 2024). The powerful interaction effect found in our analysis suggests that these two processes area expansion and technology adoption—are occurring concurrently among the same farmer populations, a sign of a dynamic and commercially responsive sector.

Pakistan's unique profile, where the change in area-yield covariance played a major positive role (15.74%), finds support in the literature on farmer decision-making. Ali & Abdulai (2010) have shown that Pakistani farmers are highly responsive to economic incentives and risk. A positive and increasing covariance indicates that farmers are adept at allocating more land to sesame in years when they anticipate high yields, likely due to favorable weather forecasts or price expectations. This behavioral sophistication, however, comes with a cost. The high area variance that drives instability in Pakistan, as per our results, is a classic feature of cash-crop systems subject to price volatility and inter-crop competition, a phenomenon detailed in studies on the Pakistani Punjab (Hussain et al., 2025).

Synthesis of Empirical Gaps and Contributions

While the existing literature provides substantial evidence on area expansion and yield challenges in these countries, this study makes a distinct empirical contribution by:

- Quantifying the exact contributions: Previous studies often qualitatively state that growth was due to "area expansion" or "yield improvement."

This study provides a precise, quantitative decomposition, revealing, for example, the critical role of the interaction effect in Nigeria and Tanzania, a nuance often overlooked.

- Systematically analyzing stability: Much of the empirical focus has been on production growth, with stability and risk receiving less attention. This study directly addresses this gap by decomposing production variance, providing empirical evidence for the high volatility in Brazil's and Nigeria's systems and the notable stability in India's and Ethiopia's.
- Providing a direct comparative lens: Existing research is largely country-specific. This review, in the context of our unified analysis, allows for a direct cross-continental comparison, revealing how different national policies, factor endowments, and market structures have shaped divergent outcomes for the same high-value crop.

In conclusion, the empirical trends revealed in this study's data are not isolated phenomena but are deeply consistent with and enriched by the body of scholarly work on sesame and agricultural development in these nations. This analysis consolidates these disparate empirical threads into a coherent comparative narrative, validating existing findings while adding new, granular insights into the components of growth and stability.

2. RESEARCH METHODOLOGY

This section outlines the methodological procedures employed to achieve the research objectives. It details the research design, the sources and nature of the data, the selection of countries and the study period, and the specific analytical models used to decompose production changes.

Research Design

This study employed a longitudinal comparative research design to analyze trends in sesame production over a 30-year period (1994-2023) across six major exporting countries. The design is ex-post facto in nature, as it investigates relationships and changes retrospectively from historical data without any manipulation of variables.

The core of the methodology is based on a decomposition analysis, a quantitative technique that breaks down an aggregate change (in this case, production and its variance) into its constituent contributing factors. This design is particularly effective for identifying and comparing the underlying drivers of agricultural growth and instability across different national contexts (Mishra et al., 2022; Pandey et al., 2020; Fan, 1991).

Data Sources and Collection

The data for this study were entirely sourced from secondary sources. The primary database was the FAOSTAT, the comprehensive statistical database of the Food and Agriculture Organization (FAO) of the United Nations. FAOSTAT is the most authoritative and widely used source for international agricultural data, ensuring consistency and comparability across countries (FAO, 2024).

The specific data series extracted for each of the six countries for the period 1994-2023 were:

- Area Harvested (Hectares): Total area from which sesame was gathered in a given year.
- Production (Tonnes): Total quantity of sesame seeds produced annually.
- Yield (Hg/Ha): Production per unit of area harvested, converted to tonnes per hectare for analysis.

The data were organized into a panel format, with country-year as the primary unit of observation.

Selection of Countries and Study Period

The selection of the six countries Brazil, Ethiopia, India, Nigeria, Pakistan, and Tanzania was based on the ranking of the World Integrated Trade Solution (WITS) for sesame exports, ensuring a focus on nations that are significant players in the global sesame market. This purposive sampling ensures the study's relevance to international trade and policy.

The 30-year study period (1994-2023) was chosen to capture long-term trends and to allow for a meaningful bifurcation into two 15-year epochs:

- Period I (1994-2008): Represents an earlier era of global agricultural trade, preceding the major commodity price spikes of 2007-2008.

- Period II (2009-2023): Represents a more recent period characterized by increased globalization, volatility in climate patterns, and potentially different agricultural policies and market dynamics.

This bifurcation facilitates a robust "before-and-after" comparison, allowing for the analysis of shifts in production structures over time.

Analytical Framework and Model Specification

The analytical approach involved a two-stage decomposition process, following a well-established methodology in agricultural economics (Kumar, 2024; Sadiq et al., 2020b,c&d; Sadiq, 2020; Bokusheva & Hockmann, 2006).

Decomposition of Change in Mean Production

Let $P_{it} = A_{it} * Y_{it} P_{it} = A_{it} * Y_{it}$ represent the production in country i_i in year t_t where AA is area and YY is yield. The average production for a period is $\overline{P} = \overline{A} * \overline{Y} + Cov(A,Y) \overline{P} = \overline{A} * \overline{Y} + (Cov(A,Y)$ where $\overline{A}\overline{A}$ and $\overline{Y}\overline{Y}$ are period means and Cov(A,Y) is the covariance between area and yield within the period.

The change in mean production between Period II (2) and Period I (1), , can be decomposed as follows (Sadiq, 2020):

$$\Delta\overline{P} = \overline{Y}1\Delta\overline{A} + \overline{A}1\Delta\overline{Y} + \Delta\overline{A}\Delta\overline{Y} + \Delta Cov(A,Y)\Delta\overline{P} = \overline{Y}1\Delta\overline{A} + \overline{A}1\Delta\overline{Y} + \Delta\overline{A}\Delta\overline{Y} + \Delta Cov(A,Y)$$

(1)

Where:

- $\overline{Y}1\Delta\overline{A}\overline{Y}1\Delta\overline{A}$: Contribution of the change in mean area, valued at the initial period's yield.
- $\overline{A}1\Delta\overline{Y}\overline{A}1\Delta\overline{Y}$: Contribution of the change in mean yield, valued at the initial period's area.
- $\Delta\overline{A}\Delta\overline{Y}\Delta\overline{A}\overline{Y}$: The interaction effect between changes in mean area and mean yield.

- $\Delta Cov(A,Y)\Delta Cov(A,Y)$: The contribution of the change in the covariance between area and yield.

This model corresponds directly to the components presented in Tables 1b to 6b of the data.

Decomposition of Change in Variance of Production

The change in the variance of production,

$$\Delta Var(P) = Var(P_2) - Var(P_1)\Delta Var(P) = Var(P_2) - Var(P_1)$$

is more complex and was decomposed into ten components, as per the methodology that expands the variance of a product (Sadiq et al., 2020b,c&d; Goodman, 1960). The general form of the decomposition for the variance of a product $(P = A*Y)$ is adapted for changes between two periods. The components include changes attributable to:

- The change in the mean yield.
- The change in the mean area.
- The change in the variance of yield.
- The change in the variance of area.
- The interaction between changes in mean yield and mean area.
- The change in the area-yield covariance.
- The interaction between changes in mean area and yield variance.
- The interaction between changes in mean yield and area variance.
- The interaction between changes in mean area, mean yield, and the area-yield covariance.
- A residual term accounting for higher-order interactions.

$$\Delta Var(P) = Var(P_2) - Var(P_1)\Delta Var(P) = Var(P_2) - Var(P_1)$$

This comprehensive decomposition, presented in Tables 1c to 6c, allows for the precise identification of the sources of increasing or decreasing production instability in each country.

Data Processing and Analysis

The collected data were processed and analyzed using statistical software. The steps involved were:

- Data cleaning: Checking for and rectifying any inconsistencies or missing values in the FAOSTAT data series.
- Calculation of period statistics: For each country and each period (I and II), the mean and variance for Area, Yield, and Production were calculated. The covariance between Area and Yield for each period was also computed.
- Decomposition analysis: The formulas specified in equations 1and 2 were applied to compute the numerical values for each component of change for all six countries.
- Comparative analysis: The results of the decomposition were then tabulated and analyzed comparatively to identify patterns, similarities, and differences in the growth pathways and stability profiles of the selected countries.

This rigorous methodology ensures that the study's findings on the drivers of sesame production growth and instability are derived from a transparent, replicable, and theoretically grounded analytical process.

3. RESULTS AND DISCUSSION

Sesame (Sesamum indicum L.) is a vital global oilseed crop, prized for its high-quality oil, protein-rich seeds, and resilience in semi-arid climates. Its production is a critical source of income for millions of smallholder farmers, particularly in developing nations across Africa and Asia. Understanding the dynamics of sesame production—specifically, the contributions of area expansion versus yield improvement to production growth, and the concomitant changes in production stability—is essential for formulating effective agricultural policies, ensuring food security, and fostering sustainable trade.

This analysis delves into the production trends of the world's top six sesame-exporting countries—Brazil, Ethiopia, India, Nigeria, Pakistan, and Tanzania—over a 30-year period from 1994 to 2023, bifurcated into two epochs: Period I (1994-2008) and Period II (2009-2023).

The decomposition methodology employed in the provided data allows for a nuanced dissection of the sources of change in both the mean and the variance of production. The change in mean production is attributed to: 1) Change in Mean Yield, 2) Change in Mean Area, 3) the Interaction between changes in mean area and yield, and 4) Change in the yield-area covariance. Similarly, the change in production variance is broken down into ten components, reflecting shifts in mean yields and areas, their variances, covariances, and complex interaction effects.

The primary objective of this section is to present a detailed results and discussion, weaving together the empirical findings from the tables with insights from previous scholarly work. The researchers conducted a comparative assessment, first examining the individual growth narratives and stability profiles of each country, and then synthesizing these to draw broader conclusions about the divergent agricultural development pathways in the global sesame sector.

Country-Specific Dimension

Brazil: The Paradigm of Rapid Area Expansion with Intensifying Volatility

Brazil's sesame sector underwent a dramatic transformation between the two periods. Mean production skyrocketed from approximately 13.5 million units in Period I to 64.3 million units in Period II, an astounding 378% increase (Table 1a & Figure 1). This represents the highest relative growth among the six nations.

Drivers of production growth: The decomposition in Table 1b reveals that this explosive growth was overwhelmingly driven by area expansion. The "Change in Mean Area" component contributed 110.59%, while the "Change in Mean Yield" contributed a mere 0.17%. This indicates that the four-fold increase in cultivated area (from ~21,667 to ~112,067 units) was the sole engine of growth, with average yield remaining virtually stagnant (621.39 vs. 625.35). The negative contribution of the covariance term (-11.45%) suggests a slight inverse relationship between area and yield in Period II, possibly due to the cultivation of sesame on marginal lands or a dilution of management focus as area expanded rapidly.

This pattern aligns with the agricultural extensification model observed in the Brazilian Cerrado and Amazon frontiers for crops like soybean, where land use change is a primary driver of output growth, often at the expense of environmental sustainability (Dias et al., 2016).

Production stability and variance: The story of instability is even more striking. The variance of production increased by a factor of over 3000, from 1.46E+12 to 4.43E+15 (Table 1a). The components of this change (Table 1c) show that the "Change in area variance" is the dominant factor, contributing 116.66. This implies that the massive fluctuation in the land area dedicated to sesame from year to year is the primary source of Brazil's high production volatility. The negative contribution of the change in area-yield covariance (-4.30) and its interaction with mean area changes (-14.87) further exacerbates this instability. When a country's production base is so heavily dependent on a highly variable input (area), its overall output becomes highly unpredictable. This poses significant risks for both domestic supply chains and international export commitments, a challenge noted in the context of other boom crops in South America (Garrett et al., 2013).

Table 1a. Changes between period I (1994-2008) versus period II (2009-2023) for Brazil

	Period	**Area**	**Yield**	**AY**
Mean	I	21666.67	621.3933	13487135
	II	112066.7	625.3467	64281966
Change		90400	3.953333	50794831
Variance	I	1516565	418.2996	1.46E+12
	II	1.34E+10	2859.607	4.43E+15
Change		1.34E+10	2441.308	4.43E+15
Covar	I	15556.6		
	II	-5798550		
Change	-5814107			

Table 1b. Components of change in average production for Brazil

SN	Source of Change	Components of Change	Percent
1	Change in mean yield	85655.56	0.16863
2	Change in mean area	56173957	110.5899
3	Interaction between changes in mean area and mean yield	357381.3	0.703578
4	Change in yield and area covariance	-5814107	-11.4463
	Total change in mean production	50794831	100

Table 1c. Components of change in variance of production for Brazil

SN	**Source of change**	**Components of change**
1	Change in mean yield	0.00963
2	Change in mean area	0.153695
3	Change in yield variance	0.025885
4	Change in area variance	116.6593
5	Interaction between changes in mean yield and mean area	0.000251
6	Change in area yield covariance	-4.29546
7	Interaction between changes in mean area and yield variance	0.666617
8	Interaction between changes in mean yield and area variance	1.489105
9	Interaction between changes in mean area and yield and change in area-yield covariance	-14.8698
10	Change in residual	0.160795
	Total change in variance of production	4.43E+15

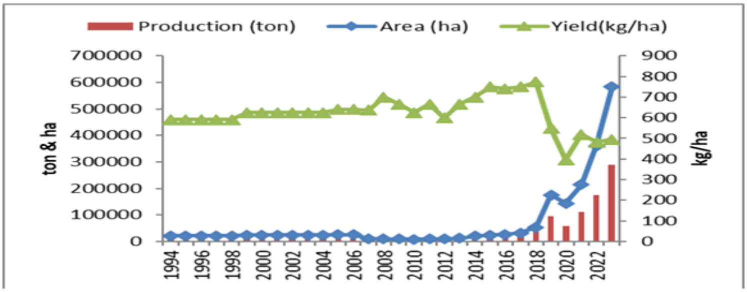

Figure 2. Production trend of sesame in Brazil

Ethiopia: The African Powerhouse with Robust, Area-Led Growth

Ethiopia solidified its position as a global sesame leader, with mean production soaring from 57 million to 238 million units, a 317% increase (Table 2a & Figure 2). This absolute increase of 181 million units is the largest among all countries studied.

Drivers of production growth: Similar to Brazil, Ethiopia's growth was predominantly fueled by area expansion, which accounted for 89.86% of the total change (Table 2b). The mean harvested area quadrupled from ~83,635 to ~323,896 units. However, unlike Brazil, Ethiopia also registered a meaningful improvement in yield (from 676.17 to 732.39), which contributed 2.60% to the production growth. Furthermore, the positive interaction term (7.47%) indicates that the expansion of area and the improvement in yield had a synergistic effect. This suggests that some of the new lands brought under sesame cultivation were potentially more productive or that better practices were adopted concurrently with expansion.

Studies on Ethiopian sesame have highlighted the role of commercial large-scale farming investments and market incentives in driving area expansion, particularly in the lowland regions of Humera, which are highly suitable for sesame (Kassie et al., 2023). The modest yield gain could be attributed to the partial adoption of improved varieties, though the gap between potential and actual yield remains wide. Production stability and variance: Interestingly, despite the massive increase in production, the overall variance of production decreased by over 50%, from 1.18E+15 to 6.24E+14 (Table 2a). The components analysis (Table 2c) is complex, but the key positive contributors are the "Change in area variance" (172.93) and the "Change in residual" (6.35). The large positive "area variance" component is offset by substantial negative components from changes in mean yield (-41.17) and mean area (-20.36), and their interactions. This indicates that while the year-to-year fluctuation in area planted increased, the significant rise in the average level of both area and yield had a stabilizing effect on total production. In essence, having a much larger and more productive base has made Ethiopia's total output less susceptible to proportional shocks. This is a sign of a maturing and more resilient production system compared to Brazil's volatile boom.

Table 2a. Changes between period I (1994-2008) versus period II (2009-2023) for Ethiopia

Item	Period	Area	Yield	AY
Mean	I	83635	676.1733	57035662
	II	323896.2	732.3867	2.38E+08
Change		240261.2	56.21333	1.81E+08
Variance	I	2.46E+09	108.2614	1.18E+15
	II	3.39E+08	1254.483	6.24E+14
Change		-2.1E+09	1146.222	-5.6E+14
Covar	I	318808.2		
	II	611785.1		
Change	292976.9			

Table 2b. Components of change in average production for Ethiopia

SN	Source of Change	Components of Change	Percent
1	Change in mean yield	4701402	2.600428
2	Change in mean area	1.62E+08	89.8585
3	Interaction between changes in mean area and mean yield	13505883	7.470341
4	Change in yield and area covariance	292976.9	0.162051
	Total change in mean production	1.81E+08	100

Table 2c. Components of change in variance of production for Ethiopia

SN	Source of change	Components of change
1	Change in mean yield	-41.1687
2	Change in mean area	-20.3576
3	Change in yield variance	-1.42941
4	Change in area variance	172.9301
5	Interaction between changes in mean yield and mean	-1.5353
6	Change in area yield covariance	-5.85913
7	Interaction between changes in mean area and yield	-20.009
8	Interaction between changes in mean yield and area	29.94809
9	Interaction between changes in mean area and yield	-18.8734
10	Change in residual	6.354304
	Total change in variance of production	-5.6E+14

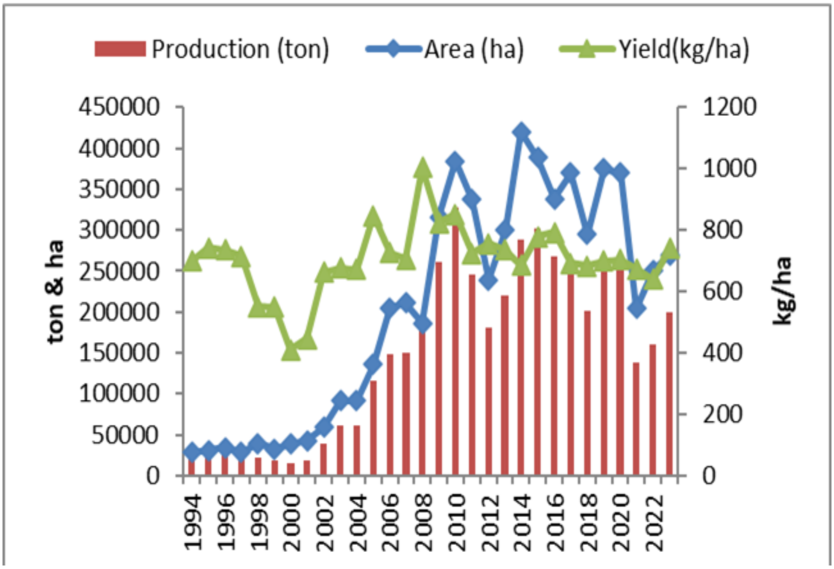

Figure 3. Production trend of sesame in Ethopia

India: The Established Producer Sustained by Yield Enhancement

India, a traditional giant in sesame production, exhibited a different growth model. Production increased from 605 million to 760 million units, a 25.6% increase (Table 3a & Figure 3). While significant in absolute terms (155 million units), this is the lowest relative growth rate in the group.

Drivers of production growth: India's story is one of intensification rather than extensification. The "Change in Mean Yield" is the overwhelming driver, contributing 98.48% of the production increase (Table 3b). The mean yield increased from 350.71 to 438.94, a 25% improvement. In stark contrast, the mean harvested area remained almost unchanged, with a negligible expansion contributing only 1.79%. This reflects a scenario of a land-scarce agriculture system where frontier expansion is limited, and gains must be squeezed from existing lands. The negative contribution of the covariance term (-1.27%) hints at a persistent challenge where yield improvements might be harder to achieve on the marginal lands where sesame is often grown as a rainfed crop.

Research confirms that Indian sesame production has long been constrained by stagnant area and low yields, with growth primarily coming from yield improvements through the adoption of high-yielding varieties and better crop management practices in focused regions, though national averages remain low due to its status as a secondary crop on poor soils (Tripathi, 2021).

Production stability and variance: India's production variance decreased dramatically, from 1.18E+15 to 5.34E+13 (Table 3a). This represents a 95% reduction in volatility, making India's output the most stable among the six countries. The components of change (Table 3c) are mixed, but the large positive contributions come from "Change in mean yield" (142.44) and, notably, "Change in area yield covariance" (213.92). A strong positive covariance indicates that in a given year, larger areas are associated with higher yields, and vice-versa, which stabilizes production. This could be due to favorable weather conditions benefiting both parameters simultaneously or concentrated efforts in high-potential regions. The reduction in variance, despite an increase in yield variance itself, underscores that systemic factors (means and covariance) have a stronger influence on overall stability than the inherent variability of yield.

Table 3a. Changes between period I (1994-2008) versus period II (2009-2023) for India

<table>
<tr><th>Item</th><th>Period</th><th>Area</th><th>Yield</th><th>AY</th></tr>
<tr><td rowspan="2">Mean</td><td>I</td><td>1731720</td><td>350.7133</td><td>6.05E+08</td></tr>
<tr><td>II</td><td>1739641</td><td>438.94</td><td>7.6E+08</td></tr>
<tr><td>Change</td><td></td><td>7920.933</td><td>88.22667</td><td>1.55E+08</td></tr>
<tr><td rowspan="2">Variance</td><td>I</td><td>5.78E+09</td><td>1237.6</td><td>1.18E+15</td></tr>
<tr><td>II</td><td>1.36E+10</td><td>1099.866</td><td>5.34E+13</td></tr>
<tr><td>Change</td><td></td><td>7.82E+09</td><td>-137.733</td><td>-1.1E+15</td></tr>
<tr><td rowspan="2">Covar</td><td>I</td><td colspan="2">-1651626</td><td></td></tr>
<tr><td>II</td><td colspan="2">-3625799</td><td></td></tr>
<tr><td>Change</td><td colspan="3">-1974173</td><td></td></tr>
</table>

Table 3b. Components of change in average production for India

SN	Source of Change	Components of Change	Percent
1	Change in mean yield	1.53E+08	98.48013
2	Change in mean Area	2777977	1.790605
3	Interaction between changes in mean area and mean yield	698837.5	0.450451
4	Change in yield and area covariance	-1974173	-1.2725
	Total change in mean production	1.55E+08	100

Table 3c. Components of change in variance of production for India

SN	Source of change	Components of change
1	Change in mean yield	142.4433
2	Change in mean area	-2.20756
3	Change in yield variance	36.68803
4	Change in area variance	-85.4554
5	Interaction between changes in mean yield and mean area	0.205045
6	Change in area yield covariance	213.9235
7	Interaction between changes in mean area and yield variance	0.336392
8	Interaction between changes in mean yield and area variance	-48.4029
9	Interaction between changes in mean area and yield and change in area-yield covariance	54.80187
10	Change in residual	-212.332
	Total change in variance of production	-1.1E+15

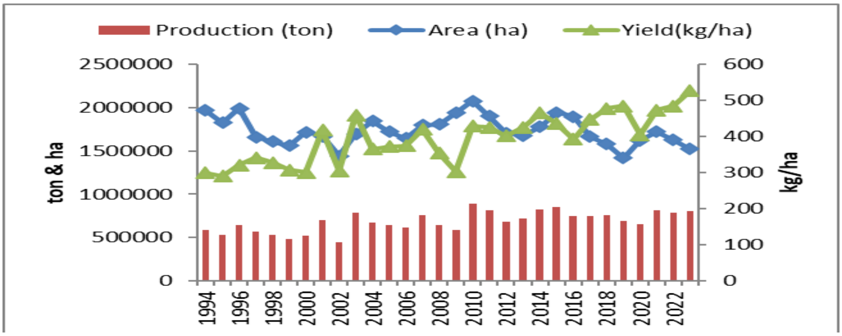

Figure 4. Production trend of sesame in India

Nigeria: The Balanced Growth Story with Soaring Volatility

Nigeria experienced explosive growth, with mean production increasing from 81.4 million to 462 million units, a 468% increase—the highest relative jump in the cohort (Table 4a & Figure 4).

Drivers of production growth: Nigeria's growth is a more balanced combination of area expansion and yield improvement. The "Change in Mean Area" contributed 43.84%, and the "Change in Mean Yield" contributed 18.25% (Table 4b). Notably, the "Interaction between Changes" is extremely large at 37.58%. This signifies that the expansion of area and the improvement in yield (from 460.88 to 855.94, an 86% increase) were powerfully synergistic. New lands brought under cultivation were likely of good quality, or more likely, the area expansion was accompanied by a significant uptake of improved agricultural practices.

This pattern is consistent with reports of sesame becoming a high-value cash crop in Nigeria's Middle Belt regions, attracting investment and leading to the adoption of better seeds and inputs by farmers (Oyedepo & Evbuomwan, 2024; Sadiq et al., 2020a; Sadiq et al., 2016a&b). The positive covariance term (0.37%) further supports this positive linkage.

Production stability and variance: Mirroring its rapid growth, Nigeria's production variance increased enormously, from 1.94E+14 to 3.29E+15 (Table 4a). The components analysis (Table 4c) shows no single overwhelming negative factor but a combination of positive contributions from nearly all sources, particularly the interaction between changes in mean area and yield variance (20.61) and the interaction between mean area, yield, and covariance (34.79). This indicates that the very drivers of its growth increased mean area and yield, and their interaction—have also introduced new dimensions of variability. The high yield variance in Period II (2770.31 vs. 303.27 in Period I) suggests that yields, while higher on average, have become much more unpredictable, possibly due to variable input use, pest outbreaks, or inconsistent rainfall patterns in a rain-fed dominant system.

Table 4a. Changes between period I (1994-2008) versus period II (2009-2023) for Nigeria

Item	Period	Area	Yield	AY
Mean	I	175784	460.88	81400530
	II	537774.5	855.94	4.62E+08
Change		361990.5	395.06	3.81E+08
Variance	I	5.57E+08	303.2719	1.94E+14
	II	1.15E+09	2770.309	3.29E+15
Change		5.91E+08	2467.037	3.09E+15
Covar	I	253779.1		
	II	1671980		
Change	1418201			

Table 4b. Components of change in average production for Nigeria

SN	Source of Change	Components of Change	Percent
1	Change in mean yield	69445227	18.24749
2	Change in mean area	1.67E+08	43.8375
3	Interaction between changes in mean area	1.43E+08	37.5769
4	Change in yield and area covariance	1418201	0.372648
	Total change in mean production	3.81E+08	100

Table 4c. Components of change in variance of production for Nigeria

SN	Source of change	Components of change
1	Change in mean yield	10.69498
2	Change in mean area	5.271718
3	Change in yield variance	2.465261
4	Change in area variance	4.062834
5	Interaction between changes in mean yield	2.347331
6	Change in area yield covariance	7.342954
7	Interaction between changes in mean area and	20.60776
8	Interaction between changes in mean yield	9.950454
9	Interaction between changes in mean area	34.79081
10	Change in residual	2.4659
	Total change in variance of production	3.09E+15

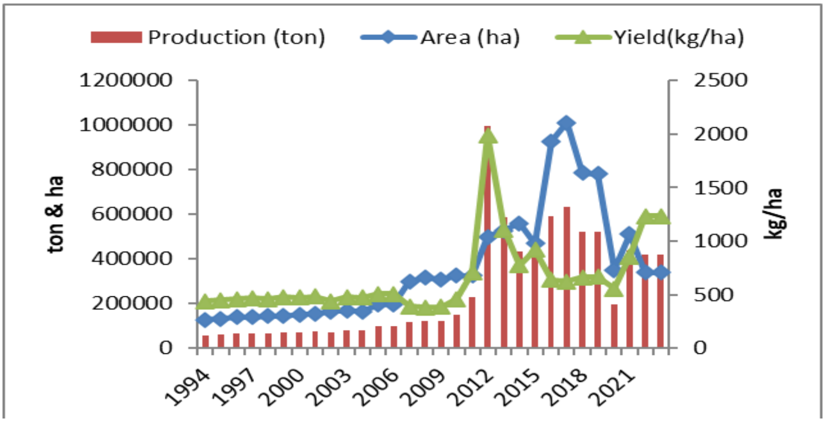

Figure 5. Production trend of sesame in Nigeria

Pakistan: Growth Fueled by Area and Covariance, Marred by Instability

Pakistan's sesame production grew substantially from 37.4 million to 67.1 million units, a 79% increase (Table 5a & Figure 5). Drivers of production growth: The growth was primarily led by area expansion (67.05% contribution), with a modest improvement in mean yield (11.29% contribution) (Table 5b). The most distinctive feature of Pakistan's growth decomposition is the significant role played by the "Change in yield and area covariance", which contributed 15.74%. This is the highest share among all countries. A positive and increasing covariance suggests that farmers are successfully allocating more land to sesame in years when conditions are favorable for high yields, indicating a responsive and market-savvy farming community. This could be a rational response to price signals or improved access to weather information.

Production stability and variance: Pakistan's production system became drastically more volatile, with variance increasing from 1.65E+13 to 1.67E+15 (Table 5a), a 100-fold increase. The components (Table 5c) point to the "Change in area variance" (46.09) and the "Change in area yield covariance" (19.71) as the biggest contributors to this instability.

This reveals a double-edged sword: while a responsive covariance fueled growth, the high variability in the area planted each year (area variance) became a major source of overall output fluctuation. This is typical of cash crops where annual planting decisions are highly sensitive to fluctuating prices, competing crops, and water availability a well-documented challenge in Pakistan's agrarian economy (Ali & Abdulai, 2010).

Table 5a. Changes between period I (1994-2008) versus period II (2009-2023) for Pakistan

Item	Period	Area	Yield	AY
Mean	I	85286.8	437.5133	37412767
	II	130838.1	476.8467	67134203
Change		45551.27	39.33333	29721435
Variance	I	31702668	349.3032	1.65E+13
	II	4.02E+09	6364.778	1.67E+15
Change		3.99E+09	6015.475	1.66E+15
Covar	I	64996.44		
	II	4744507		
Change	4679510			

Table 5b. Components of change in average production for Pakistan

SN	Source of Change	Components of Change	Percent
1	Change in mean yield	3354614	11.28685
2	Change in mean area	19929287	67.05358
3	Interaction between changes in mean area and mean yield	1791683	6.028252
4	Change in yield and area covariance	4679510	15.74456
	Total change in mean production	29721435	100

Table 5c. Components of change in variance of production for Pakistan

S N	Source of change	Components of change
1	Change in mean yield	0.361338
2	Change in mean area	0.363673
3	Change in yield variance	2.639158
4	Change in area variance	46.09308
5	Interaction between changes in mean yield and mean area	0.014048
6	Change in area yield covariance	19.70626
7	Interaction between changes in mean area and yield variance	3.571963
8	Interaction between changes in mean yield and area variance	8.660263
9	Interaction between changes in mean area and yield and change in area-yield covariance	14.15511
10	Change in residual	4.435108
	Total change in variance of production	1.66E+15

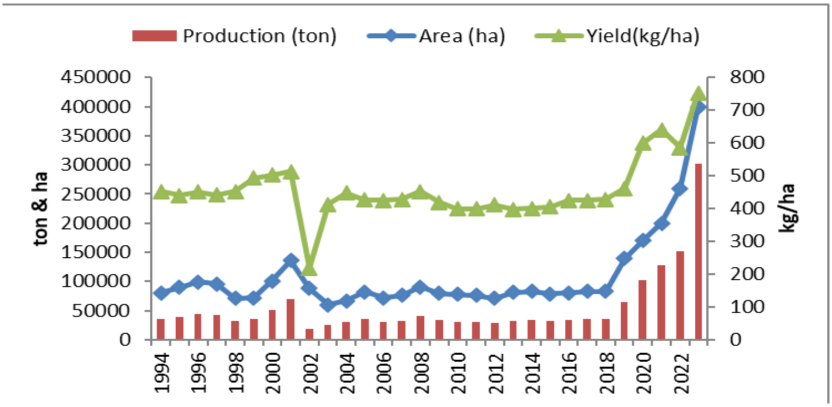

Figure 6. Production trend of sesame in Pakistan

Tanzania: Synergistic Boom with Improved Stability

Tanzania mirrored the explosive growth of its African counterparts, with production leaping from 51.3 million to 414 million units, a 708% increase the highest in the group (Table 6a & Figure 6). Drivers of production growth: The growth was led by a massive area expansion (69.88% contribution), with a six-fold increase in mean area (Table 6a, 6b).

Yield improvement contributed a modest 5.05%. The most remarkable feature is the enormous interaction effect (25.56%), second only to Nigeria. This indicates a powerful synergy where the new area brought under sesame cultivation was highly productive, likely due to the crop's shift into prime agricultural lands in regions like Singida and Manyara. The negative covariance term (-0.37%) is negligible, indicating no strong adverse relationship.

Production stability and variance: Contrary to the pattern of Brazil, Nigeria, and Pakistan, Tanzania managed its phenomenal growth alongside a significant reduction in production variance, which fell from 2.53E+14 to 5.55E+13 (Table 6a). The components (Table 6c) are a complex mix of large positive and negative values. The massive negative contributions from changes in mean area (-1204.04) and the interaction between mean yield and mean area (-72.62) were the key stabilizing forces. This suggests that establishing a much larger and more stable production base (high mean area) effectively dampened the relative impact of year-to-year fluctuations.

Table 6a. Changes between period I (1994-2008) versus period II (2009-2023) for Tanzania

Item	Period	Area	Yield	AY
Mean	I	100047.3	500.7133	51271097
	II	606681	683.8333	4.14E+08
Change		506633.7	183.12	3.63E+08
Variance	I	2.83E+08	5559.286	2.53E+14
	II	3.34E+08	1079.252	5.55E+13
Change		50997593	-4480.03	-2E+14
Covar	I	774817.9		
	II	-562927		
Change	-1337745			

Table 6b. Components of change in average production for Tanzania

SN	Source of Change	Components of Change	Percent
1	Change in mean yield	18320668	5.046534
2	Change in mean Area	2.54E+08	69.87714
3	Interaction between changes in mean area and mean yield	92774757	25.55534
4	Change in yield and area covariance	-1337745	-0.36849
	Total change in mean production	3.63E+08	100

Table 6c. Components of change in variance of production for Tanzania

SN	Source of change	Components of change
1	Change in mean yield	-70.2293
2	Change in mean area	-1204.04
3	Change in yield variance	22.65148
4	Change in area variance	-6.45851
5	Interaction between changes in mean yield and mean area	-72.6213
6	Change in area yield covariance	67.55896
7	Interaction between changes in mean area and yield variance	810.2745
8	Interaction between changes in mean yield and area variance	-5.58781
9	Interaction between changes in mean area and yield and change in area-yield covariance	492.9821
10	Change in residual	65.47319
	Total change in variance of production	-2E+14

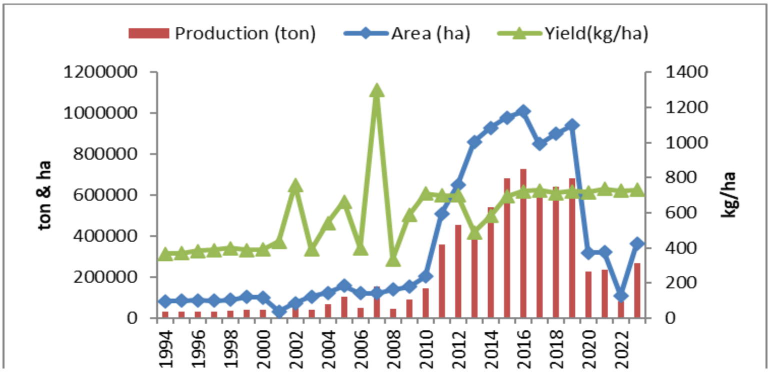

Figure 7. Production trend of sesame in Tanzania

This achievement highlights a more managed and sustainable expansion pathway compared to other high-growth countries.

Comparative Synthesis and Cross-Country Analysis

Divergent Pathways to Production Growth

The six countries clearly cluster into distinct groups based on their primary growth drivers:

- Area-driven growth model (Brazil, Ethiopia, Tanzania): These countries achieved growth primarily by bringing new land under cultivation. Brazil represents a pure, volatile extensification. Ethiopia and Tanzania, while also area-driven, benefited from positive interactions with yield and managed to significantly reduce production volatility, suggesting more sustainable and stable expansion processes.
- Yield-driven intensification model (India): As a land-constrained country, India's growth was almost entirely dependent on improving productivity per unit area. This is a classic intensification pathway seen in many Asian economies.
- Balanced/synergistic growth model (Nigeria): Nigeria stands out for its powerful combination of area expansion and yield improvement, with a massive interaction effect. This represents an ideal but volatile scenario where expansion and intensification go hand-in-hand.
- Covariance-responsive model (Pakistan): Pakistan's unique feature is the significant role of an improving area-yield covariance, indicating a highly responsive production system attuned to annual variations in growing conditions and/or economic incentives.

The Growth-Stability Trade-Off

A critical finding of this analysis is the apparent trade-off between rapid growth and production stability.

- High Growth, High Volatility: Brazil and Nigeria exemplify this group. Their rapid expansion, while impressive, has led to extreme increases in production variance, making their export supplies unpredictable.
- High Growth, Improved Stability: Ethiopia and Tanzania present a more successful model.

- They achieved phenomenal growth while simultaneously enhancing the stability of their output, which is crucial for long-term market development and food security.
- Moderate Growth, High Stability: India's model, based on yield intensification, resulted in modest but very stable growth, making it a reliable supplier.
- Moderate Growth, High Volatility: Pakistan experienced significant instability despite a more moderate growth rate, primarily due to high area variance.

This trade-off is consistent with the agricultural economic theory which posits that systems pushing a single input (like land) to its limits often face diminishing returns and increased risk (Antle, 1987).

Policy and Research Implications

The divergent pathways have clear implications:

- For Area-Driven Countries (Brazil, Ethiopia, Tanzania), the policy focus should be on sustainable land management to prevent environmental degradation and on improving yield on newly cultivated lands to sustain growth. Land tenure security and infrastructure development are key.
- For Yield-Driven India, the future lies in closing the yield gap through accelerated research on high-yielding, stress-tolerant varieties and the promotion of precision farming techniques. The challenge is to make sesame competitive for farmers against other more lucrative crops.
- For Nigeria, the priority should be to understand and mitigate the sources of high yield variance. This involves promoting drought-resilient varieties, improving pest and disease management, and ensuring reliable access to inputs.
- For Pakistan, policies aimed at stabilizing area allocation such as contract farming, price stabilization mechanisms, and efficient water management could reduce volatility without stifling the positive, responsive covariance that drives growth.

Succinctly, this detailed analysis of sesame production in six major exporting countries from 1994 to 2023 reveals a landscape of dynamic change and divergent strategies.

The world's leading sesame producers have pursued distinct pathways: from the volatile, land-intensive boom in Brazil to the stable, yield-led intensification in India, and the synergistic, high-growth models of Nigeria and Tanzania. Ethiopia and Tanzania demonstrate that it is possible to achieve massive production increases while also enhancing stability, a commendable feat. The decomposition analysis proves powerful, moving beyond simple production totals to uncover the underlying mechanics of growth (area vs. yield vs. interaction) and the root causes of instability (primarily area variance). The evidence suggests that future growth in the global sesame sector will be most sustainable and reliable if it emulates the Ethiopian and Tanzanian model of managed area expansion coupled with yield gains, rather than the volatile, pure extensification seen in Brazil. As global demand for sesame continues to rise, the lessons from these comparative national experiences are invaluable for policymakers, investors, and researchers aiming to foster a resilient and productive global sesame economy.

CONCLUSION

This study has provided a granular, comparative decomposition of sesame production trends in six major exporting countries from 1994 to 2023. The analysis conclusively demonstrates that the impressive aggregate growth in global sesame supply masks fundamentally divergent national pathways, each with distinct drivers, synergies, and associated risks. The core findings reveal a clear typology of production models: the volatile area-led extensification of Brazil; the stable yield-led intensification of India; the high-growth, high-volatility synergistic model of Nigeria; the covariance-responsive but unstable model of Pakistan; and the high-growth with improving stability models of Ethiopia and Tanzania.

A central theme emerging from this comparative assessment is the palpable trade-off between the pace of growth and production stability. Countries that pursued growth through rapid, often unmanaged area expansion (Brazil, Nigeria) achieved spectacular production increases but at the cost of extreme volatility, making their supplies unpredictable for global markets and their farmers vulnerable to income shocks.

In contrast, countries that grew through intensification (India) or managed their expansion effectively (Ethiopia, Tanzania) demonstrated that it is possible to achieve substantial growth while simultaneously enhancing the resilience of the production system. The decomposition analysis proves to be a powerful diagnostic tool, moving beyond simplistic narratives of "more production" to reveal the underlying mechanics of how that production was achieved and how stable it is likely to be. The journey of sesame from a traditional, smallholder crop to a global commodity is unfolding along different trajectories shaped by national factor endowments, policy environments, and market structures. The findings underscore that there is no one-size-fits-all model for success. The sustainability and long-term viability of a country's sesame sector depend critically on understanding and managing the specific components be it area variance, yield volatility, or their covariance—that underpin its production narrative.

Recommendations

Based on the distinct pathways identified, targeted recommendations are proposed for each country cluster.

For Area-Led Growth Countries (Brazil, Ethiopia, Tanzania)

- Shift towards sustainable land management: Policies must transition from promoting sheer area expansion to ensuring the sustainability of newly cultivated lands. This includes implementing zoning regulations to prevent deforestation (particularly in Brazil), promoting soil conservation practices, and developing irrigation infrastructure to reduce yield volatility.
- Focus on yield enhancement on new lands: Agricultural extension services should be intensified in newly expanded areas to promote the adoption of improved seeds, optimal planting densities, and integrated pest management to harness positive interaction effects, as seen in Tanzania, and move beyond pure extensification.

For the Yield-Led Growth Country (India)

- Accelerate research and development: There is an urgent need to invest in the breeding and dissemination of next-generation, high-yielding, climate-resilient sesame varieties to break the current yield plateau.
- Promote resource-use efficiency: Policies should encourage the adoption of precision farming techniques, including efficient water management (drip irrigation) and balanced fertilizer use, to increase productivity per unit of input on India's largely stagnant sesame area.

For the Synergistic Growth Country (Nigeria)

- Address sources of yield variance: The primary focus should be on stabilizing the high yield variance. This can be achieved through large-scale campaigns for drought-tolerant and pest-resistant varieties, improved access to affordable agro-inputs, and strengthening farmer capacity on climate-smart agricultural practices.

For the Covariance-Responsive Country (Pakistan)

Stabilize area allocation decisions: To mitigate the high instability from area variance, mechanisms such as contract farming, forward pricing agreements, and crop insurance schemes should be promoted. These can reduce the year-to-year fluctuation in planted area by providing farmers with more predictable income.

Policy Implications

The findings of this study carry significant implications for policymakers at national and international levels.

- National agricultural policies must be pathway-specific: The evidence clearly shows that a generic policy for sesame promotion will be ineffective. National agricultural strategies must be tailored to the specific growth model of the country:
- Brazil requires policies focused on land-use governance and environmental compliance to curb excessive volatility.
- India's policy should be centered on agricultural R&D and technology diffusion.

- Ethiopia and Tanzania should focus on consolidating their gains by investing in the sustainability of their expanded areas.
- Nigeria needs policies that de-risk production to protect its synergistic growth.
- Pakistan should prioritize market institutions that stabilize farmer expectations.,
- Prioritizing stability alongside growth: Governments and development partners should explicitly incorporate production stability as a key metric of agricultural success, alongside production volume. Incentives and support programs should be designed not only to boost output but also to reduce variance, for instance, by supporting irrigation, crop insurance, and diversified farming systems.,
- Implications for global value chains and food security: For international buyers and investors, this analysis provides a risk profile of sourcing destinations. Reliable, long-term sourcing may be better secured from stable producers like India and Ethiopia, while engagements with high-growth, high-volatility countries like Brazil and Nigeria require robust risk management strategies, such as diversified sourcing and buffer stocks. Furthermore, for food security planning in producing countries, understanding these components of change helps predict domestic availability more accurately and design better safety nets for smallholder farmers whose livelihoods depend on this crop.

In conclusion, the future of the global sesame economy hinges on the ability of its key players to navigate the complex interplay between area, yield, and risk. By leveraging the insights from this decomposition analysis, stakeholders can make more informed decisions that promote not just greater production, but a more productive, sustainable, and resilient sesame sector for the future.

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CHAPTER 2
MEMBRANE DISTILLATION AS AN EMERGING TECHNOLOGY FOR HIGH-VALUE TREATMENT AND REUSE OF DAIRY WASTEWATER

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INTRODUCTION

The global expansion of dairy production has resulted in a continuous increase in wastewater volumes generated across all stages of industrial processing. Large quantities of water are required for washing storage tanks, pipelines and heat exchangers, for pasteurization and cooling systems, as well as during cheese manufacturing and whey handling operations. Each of these steps produces wastewater streams with different compositions, often containing residual milk, detergents, disinfectants, microorganisms and process chemicals. As a result, dairy effluents typically exhibit extremely high chemical oxygen demand (COD) and biological oxygen demand (BOD) values, reflecting the presence of easily degradable organic matter such as fats, proteins and lactose. When discharged untreated, these components rapidly consume dissolved oxygen in receiving water bodies, leading to serious ecological disturbances and potential public health risks. This strong pollution potential clearly demonstrates the necessity for advanced and reliable treatment strategies capable not only of meeting discharge limits, but also of addressing long-term environmental sustainability (Al-Tayawi et al., 2023).

At the same time, regulatory frameworks in many countries are becoming increasingly stringent, and industries face expectations to minimize environmental footprints, reduce freshwater withdrawals and improve overall process efficiency. Growing awareness of climate change, coupled with recurrent episodes of water scarcity, places additional pressure on the dairy sector to rethink wastewater not as a waste stream, but as a potential source of recoverable resources. Consequently, treatment technologies are now evaluated not only on the basis of pollutant removal, but also on their ability to enable reuse, recycling and valorization within industrial systems.

Within this evolving context, membrane technologies have gained particular relevance. Their inherent selectivity allows targeted separation of suspended solids, colloids, macromolecules and dissolved salts, enabling stepwise purification and significant reduction of wastewater volume. Moreover, the production of high-quality permeate creates new opportunities for internal water reuse, thereby lowering dependence on freshwater supplies. Concentrated streams can simultaneously be directed toward processes such as anaerobic digestion or nutrient recovery, enhancing overall resource efficiency.

In this way, membrane processes actively support the transition from the traditional linear "treat-and-dispose" approach toward a circular model, in which water, nutrients and energy are continuously recovered and reintegrated into production cycles, improving both environmental and economic performance (Reig et al., 2021).

1. MEMBRANE TECHNOLOGIES APPLIED TO DAIRY WASTEWATER

Membrane processes differ fundamentally in pore size, molecular weight cut-off (MWCO) and operating pressure, parameters that jointly govern selectivity, flux behavior and energy demand. In dairy wastewater systems, microfiltration (MF) is generally used as the primary clarification stage because it efficiently removes suspended solids, fat globules and microorganisms while maintaining soluble constituents in solution. Its application reduces microbial load and hydraulic stress on downstream units, thereby preventing premature fouling and improving overall process stability (Al-Tayawi et al., 2023).

Ultrafiltration (UF) typically follows MF and enables the selective retention of proteins, colloids and macromolecular aggregates while allowing lactose and dissolved salts to permeate. This selective fractionation improves effluent quality and simultaneously opens opportunities for valorization of concentrated protein streams, which may be reused as feed or incorporated into functional ingredients (Hamdan et al., 2024).

Nanofiltration (NF) further narrows the separation boundary by partially removing multivalent ions, organic matter and residual lactose, while maintaining moderate energy requirements. NF is particularly advantageous when salinity control and COD reduction are needed without complete desalination, making it an efficient polishing step for dairy streams destined for reuse (Hosseini et al., 2023).

Reverse osmosis (RO) represents the tightest pressure-driven membrane barrier. Because RO membranes are practically impermeable to most solutes, the permeate approaches demineralized water quality and is suitable for cleaning operations, utilities and partial process recirculation.

Nevertheless, the high pressures involved increase the susceptibility to fouling and concentration polarization, requiring optimized hydrodynamics, periodic cleaning and close operational control (Hosseini et al., 2023). When MF, UF, NF and RO are arranged in sequence, they progressively polish dairy effluents while concentrating recoverable components such as proteins and lactose. Such treatment trains support a circular approach by coupling pollutant removal with resource recovery. However, fouling remains a persistent limitation caused by deposition of colloids, denatured proteins, fats and microorganisms on the membrane surface and inside pores, leading to permeability decline and increased pressure demand. For this reason, pretreatment, optimized hydrodynamics and appropriate cleaning strategies are considered essential design elements for sustainable membrane operation (Al-Tayawi et al., 2023).

The operating ranges and separation characteristics of membrane processes used in dairy systems are illustrated in this table:

Table 1. Comparison of Membrane Separation Processes (MWCO, Pore Size, and Operating Pressure)

Process	Typical MWCO	Pore size	Operating pressure
Microfiltration (MF)	> 100,000 Da	0.1–10 µm	0.1–2 bar
Ultrafilration (UF)	1,000–100,000 Da	0.01–0.001 µm	2–10 bar
Nanofiltration (NF)	100–1,000 Da	0.001–0.0001 µm	5–40 bar
Reverse Osmosis (RO)	1–100 Da	< 0.0001 µm	30–100 bar

Table 2. Main Applications and Benefits of Membrane Processes

Proce	Main application	Added benefit
MF	Removal of bacteria, spores and fat	Improves hygiene and prevents fouling
UF	Protein concentration and standardization	Produces whey protein concentrates
NF	Partial whey demineralization	Improves nutritional/functional properties
RO	Concentration and water recovery	Enables internal water reuse

2. MEMBRANE DISTILLATION AS AN EMERGING PROCESS

Among recent advances, membrane distillation (MD) has emerged as an increasingly attractive technology for dairy wastewater treatment because it combines high separation efficiency with the possibility of resource recovery. Unlike pressure-driven membrane processes, MD is primarily governed by thermal gradients. The process relies on a hydrophobic microporous membrane that prevents liquid water from entering the pores while allowing only water vapor to pass through. When a temperature difference is applied between the hot feed and the cooler permeate side, a corresponding vapor pressure gradient is generated. This gradient becomes the driving force for mass transfer, enabling water molecules to evaporate at the feed–membrane interface, diffuse through the membrane pores in vapor form and subsequently condense on the permeate side. Meanwhile, salts, proteins, fats and other non-volatile compounds remain retained in the feed, leading to progressive concentration of the dairy effluent (Hamdan et al., 2024).

Compared with conventional thermally based processes such as evaporation or distillation, MD presents several advantages. Because it can operate at moderate temperatures, often below the boiling point of water, thermal damage to heat-sensitive components is minimized and energy requirements can be significantly lower, especially when waste heat or low-grade thermal sources are available. Laboratory and pilot-scale investigations consistently report that MD is capable of achieving very high solute rejection, typically in the range of 90–99 %, while simultaneously producing permeate of excellent quality suitable for potential reuse in cleaning or utility applications. Nevertheless, MD performance is not independent of operating conditions. It is strongly influenced by feed temperature, feed composition, membrane characteristics and hydrodynamic conditions. At elevated temperatures, protein denaturation and aggregation may occur, promoting deposition on the membrane surface and pore narrowing. Furthermore, loss of hydrophobicity may lead to pore wetting, which compromises selectivity and causes contaminants to pass into the permeate, ultimately degrading system performance (Hamdan et al., 2024).

Because temperature is the principal driving parameter in MD, understanding its effect on transport behavior is essential for process design and optimization.

For this reason, the relationship between operating temperature and permeate flux is commonly examined in the literature and is illustrated in the following curve.

The effect of temperature on permeate flux in membrane distillation is illustrated in the following curve.

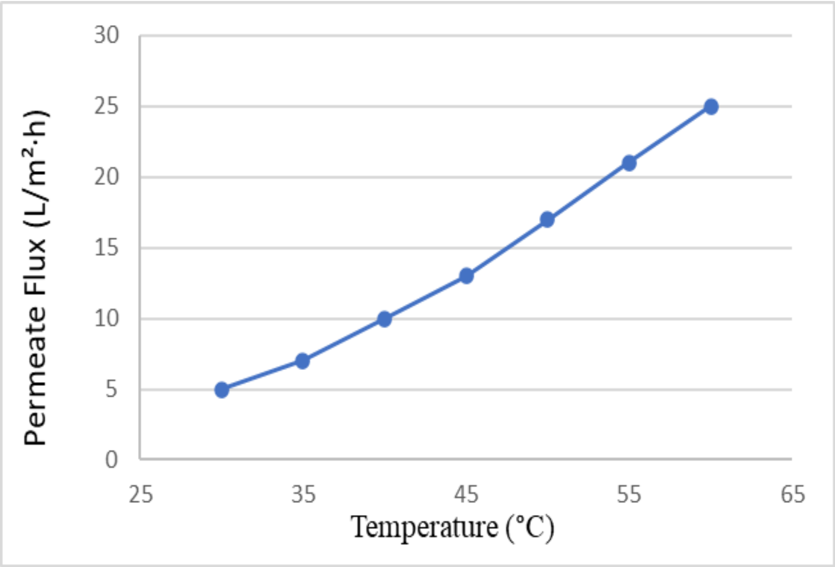

Figure 1. Conceptual representation adapted from studies on MD performance in dairy wastewater (Hamdan et al., 2024).

As shown, permeate flux increases progressively with temperature due to the rise in vapor pressure and enhancement of the driving force for mass transfer. This trend is widely reported in MD research applied to dairy effluents.

Similarly, the evolution of contaminant rejection as a function of temperature is illustrated in the next figure.

Rejection generally remains high and may slightly increase with temperature, although the risk of fouling, denaturation and membrane wetting becomes more significant at elevated operating conditions.

Therefore, optimal operating windows must be established to balance flux enhancement and membrane stability.

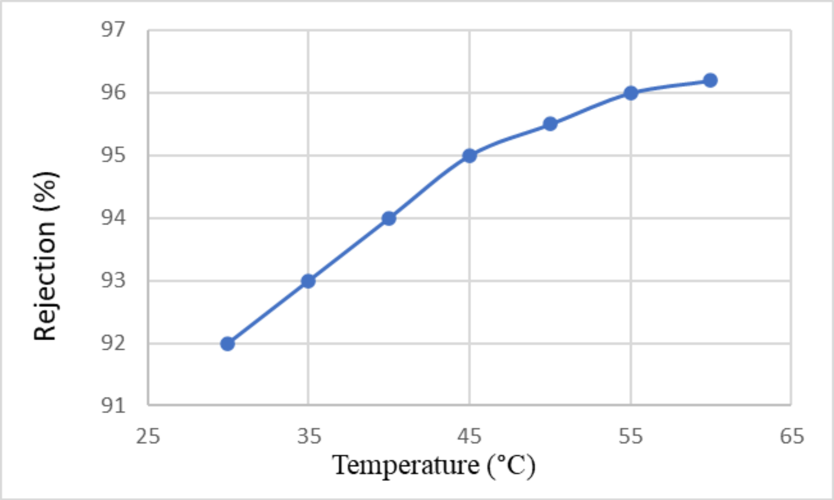

Figure 2. Conceptual representation adapted from membrane distillation studies in food and dairy systems (Hamdan et al., 2024).

Overall, membrane distillation represents a promising emerging technology capable of producing high-quality water while concentrating valuable organic components. Nevertheless, careful control of operating conditions, robust membrane materials and effective fouling mitigation strategies remain essential for long-term reliability.

3. CONFIGURATIONS AND OPERATING MODES OF MEMBRANE DISTILLATION

Membrane distillation (MD) is not a single technology, but rather a family of processes that share the same fundamental driving force: a vapor pressure gradient generated by a temperature difference across a hydrophobic membrane. Although the underlying principle is identical, the engineering design and hydrodynamic organization of the modules differ considerably, resulting in distinct performances in terms of permeate flux, energy demand, fouling behavior and system complexity.

Understanding these configurations is essential for selecting the most appropriate design for dairy wastewater treatment, where both concentration capabilities and energy efficiency are critical.

3.1 Direct Contact Membrane Distillation (DCMD)

Direct Contact Membrane Distillation (DCMD) represents the simplest and most widely studied configuration. In this system, the hot feed solution flows along one side of the membrane, while the cold permeate flows directly on the opposite side. Vapor generated at the feed–membrane interface diffuses through the membrane pores and condenses directly within the permeate stream.

Because of its simplicity, DCMD is relatively easy to construct, operate and scale up. It generally exhibits higher permeate fluxes than other MD configurations because the absence of intermediate barriers reduces mass transfer resistance. However, this advantage comes at the expense of greater conductive heat losses through the membrane structure. Over long operating periods, these losses significantly affect thermal efficiency, especially when high temperature gradients are maintained. For this reason, DCMD is often preferred in applications where heat is readily available, but optimization of module geometry and membrane thickness remains essential to minimize unnecessary energy dissipation (Francis et al., 2022).

3.2 Air Gap Membrane Distillation (AGMD)

Air Gap Membrane Distillation (AGMD) attempts to address the limitations of DCMD by inserting a thin layer of stagnant air between the membrane and the condensation surface. In this configuration, vapor travels through both the membrane pores and the air layer before condensing on a cooled wall.

The introduction of the air gap markedly reduces conductive heat transfer, thereby enhancing thermal efficiency. Consequently, AGMD is particularly attractive when energy recovery or the use of low-grade heat sources is a design priority. However, the added resistance of the air layer limits vapor transport, resulting in lower permeate fluxes compared with DCMD.

AGMD modules therefore represent a compromise between flux and energy savings, making them suitable for situations where operational stability and energy optimization outweigh maximum throughput requirements (Aytaç & Khayet, 2023).

3.3 Vacuum Membrane Distillation (VMD)

In Vacuum Membrane Distillation (VMD), a controlled vacuum is applied on the permeate side. Instead of condensing directly adjacent to the membrane, the generated vapor is transported to an external condenser. The vacuum significantly lowers the partial pressure of vapor on the permeate side, improving the driving force for mass transfer and allowing operation at lower feed temperatures while maintaining relatively high fluxes.

Despite these advantages, VMD involves more sophisticated equipment and is particularly sensitive to membrane wetting. Any loss of hydrophobicity allows liquid penetration into pores, leading to rapid contamination of the permeate. Careful control of vacuum intensity, membrane integrity and feed composition is therefore critical. Nevertheless, VMD is particularly promising for applications requiring high concentration factors and efficient dehydration of difficult effluents.

3.4 Sweeping Gas Membrane Distillation (SGMD)

Sweeping Gas Membrane Distillation (SGMD) uses an inert carrier gas to transport vapor from the membrane surface to a condenser placed downstream. The sweeping gas reduces temperature polarization near the membrane surface and may help mitigate deposition of foulants under certain operating conditions.

However, SGMD requires additional gas handling and condensation systems, increasing design complexity. From an industrial perspective, its adoption depends largely on the availability of inexpensive carrier gases and feasible integration into existing process lines. Nonetheless, its ability to stabilize temperature gradients makes it an interesting alternative in specific niche applications. The choice of MD configuration in dairy wastewater treatment is strongly context dependent.

DCMD offers simplicity and high fluxes, AGMD enhances energy efficiency, VMD provides strong driving forces at lower temperatures, and SGMD improves vapor transport stability. Ultimately, configuration selection must be aligned with process objectives such as reuse water quality, concentration level, fouling resistance and access to thermal resources.

Overall, these configurations illustrate the versatility of membrane distillation as a platform technology that can be tailored to industrial constraints and sustainability targets in the dairy sector (Francis et al., 2022; Aytaç & Khayet, 2023).

4. FOULING AND WETTING PHENOMENA IN MEMBRANE DISTILLATION

When applied to dairy effluents, membrane distillation has demonstrated strong potential in terms of pollutant removal, water purification and concentration of residual streams. A key advantage of MD compared with pressure-driven processes is that it is driven by vapor-pressure difference rather than hydraulic pressure. As a consequence, increasing the concentration of solutes does not generate osmotic pressure limitations, allowing the treatment of highly concentrated whey streams and high-strength industrial effluents that would rapidly foul or fail in conventional reverse osmosis systems.

Numerous experimental studies report rejection rates typically higher than 95–99 % for salts, macromolecules, lipids, microorganisms and suspended solids. The produced permeate frequently approaches distilled-water quality, characterized by very low conductivity, low turbidity and minimal organic content. In several applications, such water has been evaluated as suitable for non-potable reuse, including cleaning, utilities and even partial recirculation in processing operations. At the same time, MD progressively concentrates proteins, lactose, minerals and other dissolved solids in the retentate, creating opportunities for subsequent valorization.

4.1 Nature and Origins of Fouling in MD

Despite its advantages, MD performance is not immune to deterioration. One of the most critical challenges is fouling, a process by which unwanted material accumulates on the membrane surface or within its pores.

In dairy wastewater systems, fouling is inherently complex because the feed matrix contains organic, inorganic and biological components that interact with one another and with the membrane.

From a mechanistic perspective, four main categories of fouling are generally distinguished:

- Organic fouling, largely associated with proteins, fats and polysaccharides. Proteins may denature at elevated temperatures, unfold, and form cohesive layers that block vapor-transport pathways. Fat globules may adhere to hydrophobic membrane surfaces and form deposits that enhance wetting tendency.
- Inorganic or scaling fouling, resulting from precipitation of salts such as calcium carbonate, calcium phosphate or magnesium salts. Concentration polarization near the membrane surface increases local supersaturation, promoting crystal nucleation and deposition.
- Colloidal fouling, associated with fine suspended particles that aggregate and form compact cakes.
- Biofouling, caused by adsorption and growth of microorganisms, often accompanied by production of extracellular polymeric substances that create viscoelastic layers.

Each fouling type modifies the effective membrane resistance and heat transfer characteristics, leading to progressive flux decline and increased energy demand. In severe cases, fouling can irreversibly damage the membrane surface, shortening operational lifetime.

4.2 Wetting Phenomena and Loss of Selectivity

In addition to fouling, membrane wetting represents another major limitation. MD relies on the presence of air-filled pores within a hydrophobic membrane to prevent liquid penetration. When fouling, surfactants or high temperatures reduce surface hydrophobicity, liquid can partially or fully penetrate into membrane pores.

Three stages of wetting are commonly distinguished:

- Partial wetting, where some pores are filled with liquid but vapor transport still occurs.

- Pore intrusion, where liquid penetrates deeper, causing contaminant leakage into the permeate.
- Complete wetting, where the membrane loses its vapor barrier function and separation collapses.

Dairy effluents contain surface-active molecules such as proteins and fats that significantly lower surface tension, increasing the likelihood of wetting. Once wetting occurs, permeate quality deteriorates, and cleaning or membrane replacement becomes necessary.

4.3 Interplay Between Temperature, Fouling and Performance

Although higher feed temperatures enhance vapor pressure and thus permeate flux, they also accelerate fouling mechanisms. Protein denaturation, scaling kinetics and hydrophobicity loss are all temperature-dependent phenomena. Consequently, membrane distillation systems must be operated within optimized thermal windows that balance flux improvement with long-term stability.

This observation highlights that MD design should prioritize operational optimization over simple maximization of temperature or flux.

4.4 Mitigation and Control Strategies

Several engineering strategies have been proposed to minimize fouling and wetting:

- Pretreatment of feed, including microfiltration, ultrafiltration, or coagulation-flocculation to remove suspended solids and colloids.
- Optimization of hydrodynamics, such as increased cross-flow velocity, turbulence promoters or spacer design to reduce concentration polarization.
- Temperature management, maintaining moderate but stable gradients to avoid excessive thermal stress.
- Surface modification and advanced membrane materials, incorporating hydrophobic or superhydrophobic coatings, composite layers and nanostructures to delay wetting.

- Periodic cleaning protocols, combining physical rinsing, backwashing where applicable, and mild chemical treatments compatible with membrane materials.

When applied in combination, these measures extend membrane lifetime and improve process reliability.

4.5 Overall Implications

Taken together, research findings indicate that membrane distillation is capable of simultaneously producing high-quality permeate and concentrated retentates suitable for valorization. However, sustainable implementation requires systematic attention to fouling and wetting control. Rather than viewing these issues as unavoidable drawbacks, they must be integrated into design, operation and material selection strategies to ensure stable performance throughout long-term operation.

5. STRATEGIES TO IMPROVE MD PERFORMANCE

Improving the performance of membrane distillation (MD) requires more than simply adjusting operating temperature or membrane area. Instead, it involves a coordinated combination of membrane material engineering, process optimization, pretreatment design, and system-level integration. When these elements are treated holistically, MD becomes significantly more efficient, stable and economically viable, particularly for demanding industrial applications such as dairy wastewater treatment.

5.1 Membrane Material Innovations

From a materials perspective, a primary objective is to develop membranes capable of maintaining hydrophobicity and structural integrity under prolonged thermal and chemical exposure. Traditional polymeric membranes often exhibit gradual surface deterioration, loss of hydrophobicity and susceptibility to wetting. To address these weaknesses, several research directions have emerged. Composite and layered membranes combine different materials to exploit complementary properties. Hydrophobic polymer layers are frequently supported by mechanically strong substrates, reducing the risk of pore deformation or rupture under thermal cycling.

Nanostructured coatings, including fluorinated compounds and nanoparticle-based surface treatments, are applied to further increase water repellence and create micro-roughness that hinders liquid penetration.

Another strategy consists of reducing thermal conductivity within the membrane structure. Lower thermal conductivity limits heat conduction across the membrane, thereby improving energy efficiency and maintaining a more favorable temperature gradient. Hybrid ceramic–polymer membranes have also received significant interest because ceramics provide rigidity, chemical stability and resistance to cleaning agents, while polymeric layers ensure selectivity and flexibility.

Collectively, these innovations aim to delay wetting, mitigate fouling adhesion and extend operational lifetime, which are essential prerequisites for stable MD implementation in real industrial environments (Francis et al., 2022).

5.2 Optimization of Hydrodynamics and Operating Conditions

Even with advanced materials, membrane distillation performance remains highly dependent on hydrodynamic conditions. Temperature polarization caused by heat transfer limitations near the membrane surface reduces the effective vapor pressure gradient and consequently lowers flux. Increasing cross-flow velocity enhances mixing, disrupts stagnant boundary layers and promotes more uniform temperature distribution along the membrane surface. As a result, both mass and heat transfer are improved.

Additionally, staged or stepwise heating strategies help maintain optimal vapor pressure without exposing the feed to unnecessary thermal stress. This is particularly important for dairy effluents, where excessive temperature may induce protein denaturation, viscosity increase and accelerated fouling.

Control of feed concentration and circulation patterns further contributes to system stability. Continuous recirculation, rather than single-pass operation, maintains adequate turbulence while preventing localized supersaturation that could otherwise lead to scaling and wetting.

Thus, process optimization targets not only higher flux, but more importantly long-term operational stability and reproducibility (Francis et al., 2022).

5.3 Pretreatment As a Protective Barrier

Pretreatment acts as the first line of defense against fouling and wetting. In dairy wastewater systems, microfiltration and ultrafiltration are particularly relevant because they efficiently remove suspended solids, fat globules, microbial cells and colloids before they reach the MD unit.

By decreasing the organic load and reducing particle deposition, pretreatment results in slower fouling kinetics, lower cleaning frequency and extended membrane life. Pretreated feeds also show more predictable rheological behavior, facilitating temperature control and hydraulic management.

In addition, pretreatment helps minimize scaling potential by removing particulate matter that may act as nucleation sites for crystal growth. Consequently, MD becomes less affected by abrupt performance fluctuations, ensuring continuous and reliable operation.

5.4 System Integration and Functional Role of MD

Rather than functioning as an isolated process, membrane distillation performs best when embedded within broader treatment trains. In hybrid process architectures, MD is strategically positioned as a polishing or concentration step, typically downstream of pressure-driven membranes such as nanofiltration or reverse osmosis.

Upstream processes reduce the overall volume and remove bulk contaminants, while MD handles the remaining high-salinity or high-organic residual streams that conventional systems cannot effectively treat. This configuration maximizes water recovery, reduces brine discharge and contributes to near-zero-liquid-discharge scenarios.

Integration also allows energy synergies. Waste heat from industrial operations or thermal streams from other unit processes can supply the thermal gradient needed for MD operation, further enhancing economic feasibility and environmental performance.

Overall, these integrated approaches demonstrate that membrane distillation is most effective when it is deliberately positioned within a coordinated, resource-efficient treatment strategy rather than operated alone (Reig et al., 2021; Francis et al., 2022).

6. ENERGY ASPECTS AND PROCESS INTEGRATION

Energy consumption remains one of the most decisive factors governing the technical and economic feasibility of membrane distillation (MD). Although MD generally operates at significantly lower temperatures than conventional thermal distillation, it nevertheless requires continuous thermal input to sustain a temperature gradient between the feed and the permeate side. This gradient is the true driving force of the process, meaning that insufficient or unstable heat supply inevitably results in a loss of permeate flux and reduced system performance.

From an energy perspective, MD is often described as a thermally assisted separation technology, rather than an energy-intensive evaporation system. A substantial share of its efficiency stems from the fact that phase change takes place at moderate temperatures, often between 40 and 80 °C, which avoids the high energetic cost associated with boiling water. Moreover, MD systems can tolerate variable heat conditions, allowing more flexible operation compared with strictly temperature-controlled evaporators.

A key strategic advantage of membrane distillation lies in its ability to utilize low-grade or residual heat streams. Waste heat produced by pasteurization, sterilization, cleaning processes, refrigeration units and other industrial operations can be recovered and redirected to MD modules. Similarly, renewable thermal sources such as solar collectors and geothermal heat may be used to sustain operation without increasing fossil-fuel demand. When properly integrated, these heat-recovery strategies significantly reduce operating costs and improve the overall energy footprint of wastewater treatment facilities (Altieri et al., 2022).

Comparative studies repeatedly indicate that MD typically requires more thermal energy than pressure-driven systems such as reverse osmosis (RO). However, this apparent disadvantage must be interpreted within the broader functional context of the process. Whereas RO is limited by osmotic pressure and cannot effectively treat highly saline or concentrated organic effluents, MD maintains stable performance even at very high solute concentrations. As a result, MD is capable of achieving higher concentration factors and is particularly well adapted to brine minimization, retentate concentration and near-zero-liquid-discharge scenarios.

In hybrid configurations, MD is therefore strategically placed downstream of RO or nanofiltration to process residual streams that would otherwise remain untreated.

The concept of process integration becomes fundamental in maximizing energetic sustainability. Instead of installing MD as an isolated treatment unit, it is incorporated into integrated treatment trains where heat, water and material flows are optimized simultaneously. Heat exchangers, energy-recovery loops and thermal storage systems can be designed to maintain stable gradients while minimizing losses. This systemic view transforms MD from a laboratory technology into a potentially competitive industrial solution, capable of valorizing waste heat while enhancing water recovery.

Ultimately, the feasibility of membrane distillation is determined not solely by its intrinsic thermal demand, but by the availability, accessibility and intelligent recovery of thermal resources within the industrial environment. When coupling MD with heat-recovery networks, renewable heat inputs and complementary membrane processes, energy consumption becomes manageable and overall sustainability is markedly improved. Integrated design thus represents a critical step toward the large-scale deployment of MD in modern wastewater treatment infrastructures (Altieri et al., 2022; Hosseini et al., 2023).

7. ROLE OF MD IN CIRCULAR ECONOMY STRATEGIES

Membrane distillation occupies a particularly strategic position within circular-economy frameworks because it simultaneously addresses pollution control, water reuse and resource recovery. Rather than treating wastewater as an end-of-pipe residue destined for disposal, MD enables its transformation into a source of reusable water and concentrated by-products that can serve as inputs for other processes. In this sense, MD contributes directly to closing the loops of water, nutrients and energy that characterize sustainable production systems. One of the principal contributions of MD to circularity lies in its ability to generate permeate of very high quality.

The physical vapor-transport mechanism allows efficient removal of dissolved salts, organic macromolecules, microorganisms and most contaminants, resulting in water that is suitable for internal reuse in cleaning operations, utilities or partial process recirculation. Each reuse cycle reduces dependence on external freshwater resources, alleviates pressure on local water bodies and contributes to long-term water-security goals. At the same time, the reduction in discharged volumes decreases treatment loads downstream and lowers the environmental burden associated with conventional disposal pathways.

In parallel, MD produces a progressively concentrated retentate that contains the majority of the nutrients and organic matter originally present in the effluent. Instead of being perceived as waste, this fraction may be directed toward complementary valorization routes, including nutrient recovery, anaerobic digestion or the extraction of bio-based compounds. Such valorization not only mitigates environmental risks but also creates economic value by generating products such as fertilizers, biogas or functional ingredients. The dual role of MD as both a purification and concentration technology is therefore central to its contribution to circular-economy strategies.

Another important advantage is the modular and incremental nature of MD systems. They can be integrated into existing treatment infrastructures without requiring complete redesign of the plant. This allows industries to progressively adopt circular-economy practices by first implementing water-reuse units, followed by nutrient-recovery or energy-production modules as operational needs evolve. When MD is combined with renewable or recovered heat sources, its environmental footprint is further reduced, strengthening its alignment with low-carbon development objectives.

Overall, membrane distillation exemplifies how advanced separation technologies can reshape industrial wastewater management from a linear “use-and-dispose” logic to a regenerative model based on reuse, recycling and valorization. Through water recovery, concentration of reusable components and compatibility with integrated treatment systems, MD plays a pivotal role in advancing circular-economy strategies within the dairy sector and beyond (Reig et al., 2021).

CONCLUSION

The treatment and valorization of dairy wastewater through membrane-based technologies represent a decisive evolution in the transition toward sustainable industrial water management. While conventional biological and physico-chemical processes have historically formed the backbone of wastewater treatment, their limitations are increasingly evident. Excess sludge production, significant energy requirements, sensitivity to operational fluctuations and limited capacity for safe water reuse constrain their contribution to long-term sustainability. In contrast, membrane technologies introduce a fundamentally different paradigm based on selective separation, modularity and the possibility of coupling treatment with recovery of useful products.

Within this technological landscape, membrane distillation has emerged as a particularly attractive option. By exploiting the driving force generated by thermal gradients across a hydrophobic membrane, MD is capable of processing highly concentrated and compositionally complex effluents that challenge conventional systems. The process achieves very high contaminant rejection while simultaneously concentrating organic and nutrient-rich fractions, thereby creating streams that can be further valorized. Its compatibility with low-grade and waste-heat sources is especially important in industrial environments, where the possibility of energy integration reduces operating costs and improves environmental performance.

Despite its advantages, membrane distillation is not exempt from operational and technical barriers. Fouling and wetting phenomena, progressive membrane degradation, non-optimal hydrodynamics and questions related to long-term reliability still hinder full-scale adoption. Addressing these challenges requires a combination of robust pretreatment, advanced membrane materials with enhanced resistance to fouling, optimized module design and intelligent process control strategies. In parallel, techno-economic assessments and life-cycle analyses remain essential to guide decision-making and ensure that technological gains translate into measurable sustainability outcomes. Taken together, membrane distillation and complementary membrane processes extend the role of wastewater treatment beyond pollution removal.

They enable water reuse, support nutrient and organic-matter recovery, and contribute to energy-optimization strategies, thereby fitting naturally within circular-economy frameworks. With continued research, progressive industrial implementation and supportive regulatory environments, membrane-based systems are expected to move from promising alternatives to central pillars in transforming dairy wastewater from a disposal problem into a valuable and strategically managed resource.

Abbreviation

COD	Chemical Oxygen Demand
BOD	Biological Oxygen Demand
MWCO	Molecular Weight Cut-Off
MF	Microfiltration
UF	Ultrafiltration
NF	Nanofiltration
RO	Reverse Osmosis
MD	Membrane Distillation
DCMD	Direct Contact Membrane Distillation
AGMD	Air Gap Membrane Distillation
VMD	Vacuum Membrane Distillation
SGMD	Sweeping Gas Membrane Distillation

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CHAPTER 3
FUSARIUM WILT OF TOMATO (*Fusarium oxysporum* f. sp. *lycopersici*) AND ITS MANAGEMENT STRATEGIES

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INTRODUCTION

Global food security, biodiversity, and primary productivity are all seriously threatened by the rising frequency and intensity of plant disease outbreaks, particularly in susceptible areas (Nauman, 2023; Naqvi, 2024). These outbreaks cause significant yield and ecological losses. Regional economies, food security, and other interrelated socioeconomic issues are all directly impacted by this (Azeem, 2020; Ali, 2020; Anwaar, 2022, Rehman, 2023, Iftikhar, 2024). Agriculture is the backbone of any country's economy, ensuring food security, and providing raw materials to the industrial sector. However, development measures are required due to the recent drop in agricultural growth. As a major force behind future agricultural advancement, the horticulture industry is given priority. This project seeks to promote sustainable practices, increased food security, and economic growth (Ahmad, 2020). With a market value of more than USD 150 billion, the global horticulture industry has enormous economic potential (Baiphethi and Jacobs, 2009). Most nations throughout the world aim to take advantage of this by becoming significant participants in the market for high-value agricultural products. The demand for high-value perishable items like fruits and vegetables is driven by the world's growing middle class and population (Chandio, 2016). As the second most extensively grown vegetable crop worldwide, tomatoes (Solanum lycopersicum L.) are economically significant (Ma, 2023). Despite being one of the most important and extensively cultivated crops, the yield of tomatoes has varied depending on the agroe-ecological zone (Bhutani and Kallo, 1983). In horticulture, tomatoes have become increasingly important on a global scale due to their use, adaptability, freshness, nutritional value, and culinary potential. Its use in scientific studies concerning the principles of plant growth and development, as well as its integration as an essential component of many processed foods (Babalola, 2010). Tomato is often used as the main vegetable in prepared meals and as a savory addition to salads and condiments. Tomato contains a high concentration of vitamin C (31 mg per 100g), as well as vitamin A, calcium, iron, and other essential elements. Lycopene, a common antioxidant, is naturally found in tomatoes and has been shown to have anti-carcinogenic properties, thereby slowing the advancement of several cancer types (Adenuga, 2013).

The global production of tomatoes has increased dramatically. However, the crop's yield potential has not been reached. According to a study conducted by Mari (2007), the Lycopersicon genus has an excellent ability to withstand a variety of environmental and nutritional conditions. Several species have undergone hybridization techniques to produce a diverse range of varieties with the specific goal of cultivating a single harvest field crop or, when grown under protective conditions, yielding a continuous supply of fruit for the fresh market over an extended period of time. Plant breeders and agricultural engineers have worked together to make mechanized field tomato harvesting a feasible option. This technical advancement makes it possible to produce and process large amounts of tomatoes in an economical way (Fritsch, 2017). Numerous canned, frozen, preserved, or dried food items use the products.

Fusarium wilt is a common and extremely deadly disease that significantly reduces tomato yield (Srinivas, 2019; Haque, 2023). Fusarium oxysporum f.sp. lycopersici (FOL), a soil-borne fungus, invades the vascular system of the tomato plant, causing wilting and ultimately death (Michielse, 2009; Srinivas, 2019). FOL is very difficult to control since it may live in the soil for long periods of time and exists in a variety of pathogenic races (SG, 2024).

Distribution of Tomato

Tomato is generally acknowledged to have originated in Colombia, Ecuador, Peru, Bolivia, and Chile. All of the tomato's wild relatives are native to this particular area (Rick, 1973). The tomato is considered to have originated on South America's western seaboard, where typical air temperatures are assumed to be moderated by the presence of cool ocean currents, even in areas close to the equator. The countries of Ecuador and Peru exhibit a notable abundance of a variety of species scattered across the coastal plain and expanding into the Andean foothills. The genus is found from central Ecuador to northern Chile, a distance of more than 2000 kilometers. On average, nevertheless, the distance from the coast is about 200 kilometers. Historical research suggests that the native tomato species may have originated in South America. It is thought that tomato seeds eventually made their way to Mexico after dispersing northward, perhaps with the help of drainage canals.

There was a significant increase in the popularity of the fruit in this region, which led to the emergence of several different words for "tomato" in the native languages. Seeds were brought to Spain in the early 16th century by European conquistadors.

Solanum. lycopersicum

Peralta . (2006) first identified the tomato as Lycopersicon esculentum. But later research by Peralta (2006) resulted in the aforementioned plant being reclassified as S. lycopersicum. With 24 chromosomes, or 2n = 2x, the tomato plant is classified as a diploid organism. An estimated 950 megabases (Mb) of genetic material make up the tomato genome. Interestingly, heterochromatin, a genomic area marked by a lack of genes, makes up more than three-quarters of this genome. The genus Solanum section Lycopersicum (previously known as the genus Lycopersicon) is thought to have originated mostly in the Andean region, which comprises Colombia, Ecuador, Peru, Bolivia, and Chile. There are two species of Lycopersicon; the Eulycopersicon species exhibits a variety of colours, including red, yellow, and brown. On the other hand, Eriopersicon species have a predominantly green colouring, often with noticeable purple stripes. Rick (1973) has identified the geographical area where the native distribution of all tomato wild cousins is restricted. Because of its natural geographic origin, the botanical specimen was known in Italy as "porno dei Mori," or "Moor's apple." The Parisians would easily change the fruit's name to "pomme d'amour" and give it aphrodisiac qualities. Another explanation for the etymology of the name "love apple" dates back to 1554. During this time, the golden fruit was frequently referred to as "pomi d'oro," "mala aurea," or "poma amoris," words that were used interchangeably until the 19th century. In this country, the aforementioned idioms were translated as "amour apple." Even while there has been a noticeable increase in the global population, which has coincided with a growth in tomato consumption, a clear causal relationship between these two factors has not been proven. The tomato is a member of the Solanaceae family, and prior efforts to categorize the different species have mostly focused on the color of the fully mature fruit (Davies ., 1981).

1. *Fusarium oxysporum*

Phytopathogenic microorganisms are one of the major global causes of crop quality and production losses. The industries that make tomato products face a significant barrier from these phytopathogens. Diseases caused by pathogens before and after harvest cost the world's economy between 30 and 40 percent of its yearly production. Despite the widespread use and profitable impact of this crop, tomatoes are threatened by a number of illnesses, especially those brought on by bacteria, fungus, viruses, and nematodes (Lahlali, 2022). About 80% of plant diseases are caused by fungi. According to Cheng. (2021), Fusarium species are the most common cause of soil and water-borne tomato disease. Furthermore, it is well known that, if uncontrolled, the spread of diseases caused by soil-borne pathogens, such as Fusarium spp., is one of the main factors limiting agricultural productivity. According to Tang. (2021), Fusarium had been causing significant losses to tomato crops prior to its scientific discovery.

Table 1. How Fusarium attack tomato plants

Stage	Description	Impact on Plant
Inoculation	The fungus Fusarium oxysporum f. sp. lycopersici infects through the roots.	Root infection starts.
Colonization	Fungal spores germinate and mycelium grows through root cortex into vascular tissue.	Disruption of water and nutrient flow.
Symptom’s development	Vascular tissue becomes clogged, leading to wilting and yellowing of leaves.	Wilting, yellowing, and stunted growth.
Spread	Fungus spreads to other parts of the plant through the xylem.	Systemic infection, leading to plant death.
Survival	Fungal spores (chlamydospores) survive in soil	Long-term soil contamination

Fusarium wilt is a fungal disease that mostly spreads through the soil medium, blocking the xylem arteries in plants that carry water (Table 1). Plants wither and, in many cases, the vegetation dies as a result of the obstruction. The fungus enters the plant through the roots and is carried by the soil (Figure 1). It stops water from moving to the upper sections of the plant by clogging and blocking the xylem vessel. Verticillium wilt and Fusarium wilt can have extremely similar symptoms. One leaf or branch, close to the top of the plant, is where fusarium wilt first appears. At night, when the temperature is lower, the plant can recuperate. The entire plant will wilt as the disease worsens, though, and it won't recover at night. Usually only one side of the lower leaves becomes yellow. The yellowing will progressively ascend the plant. The leaves that have wilted will dry out and fall off. Cutting the afflicted stems lengthwise reveals dark brown streaks. Pathogenic strains from several Fusarium species, such as F. eumartii, F. oxysporum, F. avenaceum, F. solani, F. sulphureum, and F. tabacinum, are responsible for the incidence of Fusarium wilts. When it comes to the plants they infect, these strains frequently exhibit a significant degree of specificity. But the most frequent attacker is F. oxysporum. A group of filamentous fungus categorized under the genus Fusarium are referred to as Fusarium species. The filamentous fungus genus Fusarium oxysporum Schlechtendahl is a member of the Nectriaceae family. Molds, also known as filamentous fungi, are a varied group of microorganisms distinguished by their long, thread-like structures called hyphae. While some Fusarium species are more frequently found in temperate zones, others exhibit a limited geographic range in tropical regions. Furthermore, certain species have been found to live in arctic, alpine, and desert areas, exposing themselves to harsh weather conditions (Francis and Burgess, 1975). The geographic distribution of Fusarium species was shown to differ significantly between agriculturally productive cultivated and rangeland soils and forest soils, according to Jeschke . (1990). Fusarium species are typically identified as fungi that live parasitic or saprophytic lifestyles and are mostly found in soil, often in association with plant roots (Nelson ., 1994). The organism's wide variety of species has gained significant attention due to its noteworthy role as a pathogen in plant diseases. Mycotoxins, such as fumonisins, zearalenones, and trichothecenes, can be produced by a variety of species.

Contamination of the plants and subsequent absorption into the ecological food chain are the results of this process. Numerous ecological components, such as wildlife, livestock, agricultural products, and human populations, are at serious risk for health and safety due to mycotoxins (Arif, 2011; Balali and Iranpoor, 2006; Wang ., 2011). Nelson. (1994) found that the remarkable capacity of Fusarium species to flourish on a wide variety of substrates, along with their very efficient systems for distributing spores, was responsible for their extensive distribution. The ability of the Fusarium species to behave as plant pathogens and cause a variety of diseases, such as scab, head blight, and crown rot, makes them economically significant. The agricultural industry and the economy as a whole are impacted by these diseases, which primarily damage grain crops. Furthermore, it is noteworthy that these specific species contribute significantly to the induction of vascular wilts in a variety of horticultural crops, such as bananas, tomatoes, and cucurbits. Due to its considerable impact on the occurrence of root rots, cankers, and various diseases including bakanae disease in rice and pokkah-boeng in sugarcane, the Fusarium genus has attracted a great deal of scientific attention (Booth, 1977).

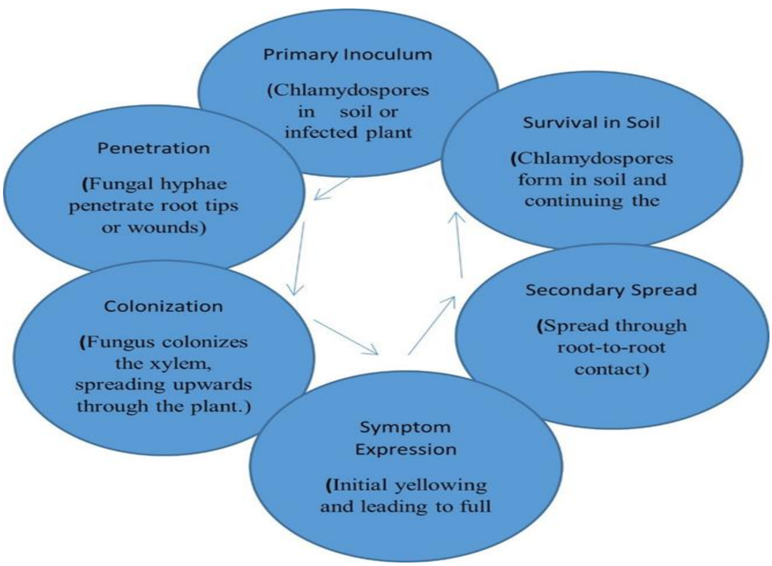

Figure 1. Disease cycle of Fusarium wilt of tomato.

1.1 Morphological and Molecular Characterization of Fusarium wilt

Based on the groundbreaking study by Mueller and Beckman (1988) and the follow-up study by Wang. (2011), it has been determined that the taxonomic taxonomy of the genus Fusarium includes a thorough collection of at least 20 distinct species. The empirical data presented by clarifies whether certain Fusarium species exhibit a teleomorphic condition. Fusarium solani, F. oxysporum, F. equisetti, and F. chlamydosporum are the species reported in the specific context in question (Chimbekujwo, 2000; Summerell, 2001). The method of classification used for Fusarium species is based on fundamental traits that include a wide variety of observable and microscopic features. The aforementioned features include the pigmentation of the colony, the size and shape of the macroconidia, the number, form, and arrangement of microconidia, and the presence or absence of chlamydospores (De Hoog, 2000).

Fusarium wilts are a collection of plant diseases brought on by the activities of different fungus species. On Sabouraud Dextrose Agar, a growth medium, a varied collection of 85 different cultures of Fusarium species were grown under carefully regulated conditions at a constant temperature of 25°C. Yogalakshmi. (2021) found a variety of colony morphologies in these cultures. The studied morphologies exhibited a range of growth patterns, including fuzzy, cottony, flat, and spreading. When viewed from a higher perspective, the colony's colors is variable, including white, cream, tan, salmon, cinnamon, yellow, red, violet, pink, and purple. According to Nelson. (1994), the underside of the object shows a wide range of colors, including tan, red, dark purple, brown, and possibly a lack of pigmentation. The fungus can generate sclerotia, a single organism known as sclerotium, under unfavorable circumstances. According to Yogalakshmi. (2021), a "sclerotium" is a group of hyphae that go through a latent phase in reaction to unfavorable environmental circumstances. The sclerotium acts as a possible reservoir of infection by initiating the germination process whenever favorable circumstances are restored. According to Nelson. (1994), Fusarium species frequently use thin phialides to produce both macroconidia and microconidia. The macroconidia are made up of two or more cells and have translucent characteristics.

The organisms have a wide range of morphologies, from sickle-shaped to fusiform. The presence of an extended apical cell and a pedicellate basal cell differentiates the morphological traits under discussion. The aforementioned structural structure is common among the majority of people. Microconidia have a variety of characteristics, including one to two cells, a translucent morphology, and pyriform, fusiform, or ovoid structures. Furthermore, the shape of microconidia might be straight or curved.

2. MANAGEMENT OF FUSARIUM WILT OF TOMATO

Numerous biotic agents, including fungi, bacteria, and viruses, are causing the tomato crop's production to decline. However, it is important to recognize that soil-borne diseases play a significant role in reducing total crop yield (Agrios, 2005). One vegetable crop with substantial economic worth is the tomato. However, because of various pathogens, pests, the high cost of agricultural inputs (fertilizer, pesticides), and the lack of contemporary technologies, it is on the verge of collapse. The main reasons for the low tomato yield are a lack of perception and water scarcity. Fusarium, Verticillium, Pythium, and Rhizoctonia are among the soil-borne fungi that mostly attack tomatoes and have an impact on their yield and quality. Tomato wilt is the most destructive disease of all, resulting in significant production loss.

2.1 Use of Pesticides

Chemicals are frequently employed to control plant diseases in many countries, yet they can have negative effects on both health and the environment. Large-scale usage of pesticides to grow tomatoes has a negative impact on the environment, beneficial bacteria and fungi, water channels, and non-target soil. According to earlier research, excessive pesticide usage damages ecosystems, produces serious illnesses in humans, and poses serious risks to groundwater quality (Arias-Estévez ., 2008; Athukorala ., 2012; Okello and Swinton, 2010). It also depletes beneficial organisms necessary for plant growth and has an impact on marine life (Brethour and Weersink, 2001; Cuyno, 2001; Skevas, 2013). Almost 75% of all imported pesticide applications on tomatoes disrupt the ecology and have a negative impact on the health of rural people.

According to Khooharo. (2008), the data show a significant increase in pesticide use, as evidenced by the substantial increase in quantities from 906 metric tonnes in 1980 to 5519 metric tonnes in 1992. Khan. (2020) give data on market share distribution among pesticide manufacturers across different provinces. Punjab constituted the majority with a considerable part of 90%, followed by Sindh with a proportion of 8%. In comparison, Baluchistan and KPK contributed only 2%. Cotton agriculture accounts for 2.4% of the total arable land accessible worldwide. Significantly, cotton cultivation plays a noteworthy role in satisfying a considerable proportion of the worldwide need for insecticides, accounting for 24%, and contributes to 11% of the global demand for pesticides. According to the World Wildlife Fund (WWF, 2003), groundwater contamination is caused by pesticide use. Pesticides are expensive and harmful to both the environment and human health. As a result, university researchers and private companies worldwide are working to provide non-chemical means of disease management. The efficiency of fungicides in providing enough protection against Fusarium wilts has yet to be determined. Furthermore, there is an increasing trend toward implementing and promoting sustainable farming methods (Lemanceau and Alabouvette, 1993). There is no doubt that adding chemicals, especially pesticides, can degrade the general quality of food items and the environment. There is an urgent need to discover alternative methods of suppressing Fusarium wilts, such as biological control.

2.2 Use of Biocontrol Agents

Soil-borne diseases can be controlled through cultural methods such as increasing the host's tolerance, introducing the other organism into the soil, utilizing fumigants, and mimicking native microflora without affecting the environment (Deacon, 1988). As a result, the goal of this study is to create new disease control strategies that are simple to implement and environmentally beneficial. Bio-control agents are natural means to manage plant diseases and reduce inoculum through another organism without completely destroying crops. They have been reported to be used in the control of Fusarium wilts for many crops including tomato, cucumber, melon, strawberry, banana and carnation (Horinouchi, 2008).

Bio-control agents such as non-pathogenic F. oxysporum (Katsube and Akasaka, 1997; Momol and Pernezny, 2003), hypovirulent binucleate Rhizoctonia (Muslim, 2003), Gliocladium virens, Trichoderma hamatum, Burkholderia cepaci, Pseudomonas fluorescens (Larkin . 1996), Bacillus subtilis, Streptomyces pulcher (Monda, 2002), Baccillus polymayxa (Hamed . 2009) and Enterobacter cloacae (Tsuda . 2001) have been reported to control Fusarium wilt disease. Use of Mycoparasites such as T. harzianum, T. viride and T. harmatum as bio-control agents in tomato field significantly controlled tomato wilt caused by F. oxysporum f. sp. lycopersici (Ojha and Chatterjee, 2012). The biocontrol applied to the soil to reduce wilt fungus must first multiply in the rhizosphere before colonizing the root to become systemic. The majority of Trichoderma species grow naturally, colonizing root surfaces or becoming endophytes (Ruano-Rosa, 2016). Pandya. (2011) provided the first recorded documentation of Trichoderma's biocontrol effectiveness. Trichoderma species are widely recognized as effective biocontrol agents against fungal phytopathogens. Microorganisms can have indirect effects through a variety of processes, including competing for necessary nutrients and physical space, influencing environmental circumstances, stimulating plant development, evoking plant defense responses, and initiating antibiosis. In addition, microorganisms can exert direct influences via mechanisms such as mycoparasitism (Papavizas, 1985; Howell, 2003).

Rapid growth, persistent conidia, and a broad spectrum of substrate usage are characteristics of Trichoderma species. Hjeljord. (2000) claim that these species are very effective at competing for food and habitat. Trichoderma species have a remarkable ability to synthesize siderophores, which efficiently sequester iron and prevent the growth of other fungal species (Benítez ., 2004). Therefore, Trichoderma's effectiveness as a biocontrol agent is influenced by the characteristics of the soil. The enhanced competitive ability of antagonistic microorganisms in nutrient competition compared to pathogens is thought to be the primary contributing factor to the various mechanisms put forth to explain the phenomenon of biocontrol (Lemanceau, 1989; Couteaudier and Alabouvette, 1990; Schuster and Schmoll, 2010). The putative mechanism of action against Fusarium oxysporum may entail the production of lytic enzymes by antagonistic microorganisms.

Mitchell and Alexander (1961) documented the utilization of bacterial strains that demonstrate lytic enzyme production to control Fusarium wilt. The idea of employing nonpathogenic Fusaria to manage Fusarium wilts emerged from the study of soils that exhibit inherent suppressive characteristics against Fusarium wilts. Fusarium. Research is ongoing to develop effective management strategies, including exploring eco-friendly methods and understanding the genetic makeup of the pathogen (Inami . 2014; SG, 2024). Suppression of Fusarium wilt using biocontrol agents has been achieved through interactions among the plant, the pathogen, the biocontrol agents, the microbial community around the plant and the physical environment (Barea . 2004). Hydrolytic enzymes of antagonistic microorganisms have been considered to play an important role in the biological control of plant pathogens. Many enzymes have been isolated from various strains of Trichoderma species (Harman . 1996), Gliocladium vixens (Di-pietro . 2003), Paenibacillus and Streptomyces species (Singh . 1999), and their activities were assayed and found effective in controlling Fusarium wilts. This is accomplished through competition; secretions of antibiotics, parasitism and induced resistance (Shishido. 2005).

CONCLUSION

Tomato yield is seriously threatened by fusarium wilt, which can reduce biomass and growth by 9 to 24%. Although chemical fungicides have always been employed for management, their effectiveness against FOL and other soilborne diseases is frequently restricted. Additionally, the search for safer, environmentally friendly substitutes is required due to growing worries about their harmful effects on the environment and human health. The non-chemical management techniques that have the ability to successfully control FOL are highlighted in this chapter. FOL management is made more difficult by the appearance of more virulent strains, the eradication of helpful soil microbes caused by fungicides, and the impossibility of long-term crop rotation. The creation of innovative substitutes is essential for sustainable tomato production given the disadvantages of chemical control. The potential of Trichoderma harzianum as a biocontrol agent is demonstrated by our research.

Applying this fungus greatly decreased the severity of wilt (9–28%) and increased biomass (15–21%) and plant growth parameters (9–28%). It is crucial to recognize that not all soil-borne diseases may be totally eliminated by using these environmentally friendly techniques. Integrated Disease Management (IDM) techniques, which combine these methods with appropriate fungicide use, provide a more comprehensive answer. This multimodal method is strongly suggested for ensuring the long-term viability of tomato production. The findings reported here offer a solid foundation for creating successful IDM methods to protect tomatoes from FOL. However, field trials are required to evaluate the efficacy of the reported Trichoderma isolates before they are widely used by farmers.

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CHAPTER 4
A REVIEW OF DIGITAL AGRICULTURAL EXTENSION IN NIGERIA: OPPORTUNITIES, CONSTRAINTS, AND FUTURE PATHWAYS

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INTRODUCTION

Agricultural extension has long been recognised as a cornerstone of agricultural development, serving as a bridge between research institutions and farming communities. Through extension systems, innovations generated by research are translated into practical knowledge and practices that farmers can apply to improve productivity, resilience, and livelihoods. In Nigeria, where agriculture employs a substantial proportion of the population and contributes significantly to national food security and rural income, the effectiveness of extension services is of strategic importance. Beyond its economic role, agriculture remains deeply embedded in Nigeria's social structure, providing employment, food, and income for millions of rural households. Historically, agricultural extension in Nigeria has been delivered primarily through public-sector institutions, most notably the Agricultural Development Programmes (ADPs) established in the late 1970s and early 1980s. These programmes were designed to promote improved technologies through the Training and Visit (T&V) system, emphasizing regular contact between extension agents and farmers. While the ADPs contributed to notable gains in technology dissemination during their early years, their effectiveness has gradually declined due to chronic underfunding, high extension agent–farmer ratios, inadequate logistics, and weak institutional coordination. As Nigeria's population has grown and farming systems have become more complex, these structural weaknesses have constrained the capacity of conventional extension to meet farmers' diverse and evolving information needs.

In this context, digital transformation has increasingly been promoted as a pathway for revitalizing agricultural extension systems. Advances in information and communication technologies (ICTs) including mobile phones, internet connectivity, satellite-based data, and digital platforms have created new possibilities for delivering advisory services at scale. Digital agricultural extension, also referred to as e-extension or ICT-enabled extension, encompasses a wide range of tools such as short message services (SMS), interactive voice response (IVR), call centers, mobile applications, social media platforms, web portals, and decision-support systems.

These tools enable the dissemination of information on crop and livestock production, soil and nutrient management, pest and disease control, weather and climate, markets, and financial services. Nigeria provides a particularly important context for examining the potential and limitations of digital agricultural extension. The country has experienced rapid growth in mobile phone penetration over the past two decades, alongside expanding internet access and increased engagement by private-sector actors, development partners, and research institutions in digital agriculture initiatives. Digital tools are increasingly used to deliver agronomic recommendations, climate advisories, market information, and financial services to farmers. These innovations are often promoted as solutions to long-standing extension challenges related to scale, cost efficiency, and timeliness of information delivery. However, emerging evidence suggests that the promise of digital agricultural extension is unevenly realized. While some farmers benefit from improved access to information and services, others remain excluded due to infrastructural deficits, socio-economic inequalities, gender disparities, and limited digital skills. Moreover, concerns have been raised regarding the sustainability of donor-driven digital initiatives, the governance of farmer data, and the extent to which digital tools genuinely complement rather than undermine face-to-face extension relationships. Without careful integration into existing extension systems, digital platforms risk becoming fragmented, short-lived interventions rather than transformative solutions.

It is against this backdrop, this chapter provides a comprehensive and critical review of digital agricultural extension in Nigeria. Submitted under the Agriculture theme of this edited volume, the chapter focuses on how digital extension systems are reshaping knowledge delivery, farmer engagement, and agricultural governance. The specific objectives are to: (i) synthesise recent empirical evidence on the opportunities associated with digital agricultural extension; (ii) examine key constraints and challenges affecting adoption, use, and impact; (iii) analyse selected Nigerian case examples; and (iv) propose future pathways, policy recommendations, and research priorities for scaling inclusive and sustainable digital extension systems in Nigeria and comparable developing-country contexts.

1. METHODOLOGY AND CONCEPTUAL FRAMING

Review Approach

This chapter adopts a narrative review methodology, which is appropriate for synthesising diverse strands of literature, integrating empirical findings with policy insights, and identifying conceptual patterns and research gaps. Peer-reviewed journal articles, programme reports, policy briefs, and institutional publications released between 2020 and 2025 were reviewed. Literature was sourced from databases and repositories such as ScienceDirect, SpringerLink, Google Scholar, CGIAR platforms, and the websites of national and international development organisations.

Search terms included combinations of digital agricultural extension, e-extension, mobile phone agricultural information, RiceAdvice Nigeria, ICTs in agriculture Nigeria, and related phrases. Priority was given to studies that provided empirical evidence on adoption determinants, impacts on productivity and decision-making, usability assessments, gender dimensions, and institutional or policy implications within the Nigerian context. Earlier foundational studies were also consulted where necessary to provide conceptual grounding.

Conceptual Perspective

The review is informed by a systems perspective on agricultural extension, which conceptualises extension as an interactive process involving multiple actors, institutions, and feedback mechanisms. From this perspective, digital tools are not substitutes for extension systems but components that interact with existing human, organisational, and policy structures. Successful digital agricultural extension therefore depends on complementarity between digital and face-to-face approaches, inclusiveness in access and use, and robust governance arrangements. This systems lens allows for a balanced assessment of both technological potential and institutional realities.

Opportunities and Benefits of Digital Agricultural Extension in Nigeria

Digital agricultural extension offers a range of opportunities that extend beyond improved information dissemination to encompass broader transformations in agricultural systems, labour markets, and governance. In Nigeria, where conventional extension systems face persistent capacity constraints, digital tools provide avenues for enhancing efficiency, inclusiveness, and responsiveness. This section synthesises key opportunity areas, with explicit attention to youth engagement and employment within the emerging digital agriculture ecosystem.

2. IMPROVED ACCESS TO TIMELY AND SITE-SPECIFIC AGRONOMIC INFORMATION

One of the most widely cited benefits of digital agricultural extension is enhanced access to timely, accurate, and context-specific agronomic information. Digital platforms can deliver recommendations tailored to agro-ecological conditions, crop varieties, soil characteristics, and management practices. Tools such as Rice Advice generate fertilizer and crop management advice based on location-specific data, enabling farmers to optimize input use and improve productivity. Compared with traditional blanket recommendations, such personalized advice has the potential to reduce input waste, lower production costs, and mitigate environmental risks associated with over-application of fertilizers and agrochemicals. In Nigeria, empirical studies indicate that farmers who access digital advisory services are more likely to adjust agronomic practices in line with recommended standards, particularly when digital advice is reinforced through extension agents or demonstration plots. Timeliness is a critical advantage of digital tools, as information can be delivered at key decision points within the production cycle, such as planting, fertilizer application, and pest management. This responsiveness is especially valuable in smallholder systems where delayed information can lead to significant yield losses.

3. CLIMATE AND WEATHER ADVISORY SERVICES FOR RISK MANAGEMENT

Climate variability and change pose increasing risks to Nigerian agriculture, which remains predominantly rain-fed. Digital agricultural extension platforms can integrate weather forecasts and climate advisories to support climate-smart decision-making. Mobile-based alerts on rainfall onset, dry spells, flooding risks, and heat stress enable farmers to adjust planting dates, select appropriate crop varieties, and plan input application more effectively. Digital climate advisory services are particularly relevant in Nigeria's diverse agro-ecological zones, where climate risks vary spatially and temporally. By enhancing farmers' anticipatory capacity, these services contribute to risk reduction, yield stability, and livelihood resilience. When combined with agronomic advice and early warning systems for pests and diseases, digital climate services strengthen farmers' ability to cope with climate-related shocks.

Market Access, Value-Chain Integration, and Commercialization

Digital agricultural extension increasingly extends beyond production advice to encompass market and value-chain information. Platforms that disseminate real-time market prices, quality standards, and buyer contacts can reduce information asymmetries and transaction costs. Improved access to market information enhances farmers' bargaining power and supports market-oriented production decisions, thereby facilitating the transition from subsistence to commercial agriculture. In Nigeria, digital tools linking farmers to aggregators, processors, and traders have demonstrated potential for strengthening value-chain integration. Extension messages that incorporate market signals can guide farmers toward crops, varieties, and production schedules that align with market demand. Such integration is particularly important for perishable commodities, where timely market information can reduce post-harvest losses and improve incomes.

Financial Inclusion and Integrated Digital Services

The integration of digital extension services with digital financial tools represents a critical opportunity for addressing liquidity constraints faced by smallholder farmers. Mobile platforms can facilitate access to digital payments, savings, credit, and insurance products. When combined with advisory services, digital finance enables farmers to act on extension recommendations by easing constraints related to input purchase and risk management. Evidence from Nigeria suggests that farmers are more likely to adopt improved technologies when extension advice is complemented by access to credit or input financing through digital channels. Digital platforms can also support risk-sharing mechanisms such as weather-indexed insurance, thereby enhancing farmers' willingness to invest in productivity-enhancing practices. However, realizing these benefits requires careful attention to trust, transparency, and consumer protection.

Youth Engagement, Employment, and the Digital Agriculture Economy

An increasingly important opportunity associated with digital agricultural extension lies in its potential to engage Nigeria's large youth population and generate employment within the digital agriculture ecosystem. Nigeria faces a dual challenge of high youth unemployment and an ageing farming population. Digital agriculture initiatives, including extension platforms, offer entry points for youth as data collectors, platform managers, content developers, digital extension facilitators, and agri-tech entrepreneurs. Young people are often more familiar with digital technologies and may serve as intermediaries between digital platforms and farming communities. Programmes that train youth as digital extension agents or community-based service providers can simultaneously address extension capacity gaps and create employment opportunities. In addition, digital platforms can support youth-led agribusinesses by providing access to information, markets, and financial services. By reframing agriculture as a knowledge-intensive and technology-enabled sector, digital agricultural extension has the potential to improve the attractiveness of agriculture to young Nigerians.

However, realizing this potential requires deliberate strategies to integrate youth into extension systems, including targeted training, mentorship, and support for innovation and entrepreneurship.

Data-Driven Extension Planning, Learning, and Innovation Systems

Digital agricultural extension systems generate large volumes of data on farmer characteristics, practices, and outcomes. When responsibly managed, these data can support evidence-based extension planning, monitoring, and learning. Extension organizations can use digital data to identify priority needs, tailor advisory content, and track adoption patterns over time.

At the system level, digital data can strengthen linkages between research, extension, and policy by providing feedback on technology performance and farmer responses. Such feedback loops are essential for adaptive management and continuous improvement of extension services. However, the effective use of data for learning and innovation depends on institutional capacity, interoperability among platforms, and robust data governance frameworks.

4. CONSTRAINTS AND CHALLENGES FACING DIGITAL AGRICULTURAL EXTENSION

Connectivity and Rural Infrastructure Gaps

Despite improvements in mobile phone penetration, significant disparities persist in rural connectivity, electricity supply, and internet reliability across Nigeria. Poor network coverage, high data costs, and unreliable power supply limit the reach and effectiveness of internet-based digital extension services. These infrastructural constraints remain among the most significant barriers to scaling digital agricultural extension nationwide.

Digital Literacy and Human Capacity Limitations

Low digital literacy among farmers, coupled with limited digital competencies among extension personnel, constrains adoption and effective use of digital tools. Many farmers face difficulties navigating smartphone interfaces, interpreting digital content, or troubleshooting technical problems.

Extension agents themselves may lack training in digital facilitation, underscoring the need for systematic capacity building.

Affordability, Devices, and Sustainability of Use

While basic mobile phone ownership is widespread, access to smartphones and affordable data remains uneven. The cost of devices, applications, and data subscriptions poses challenges for sustained use, particularly among poorer households. These constraints raise concerns about equity and long-term sustainability.

Gender and Socio-Economic Inequalities

Gender disparities in access to digital technologies are well documented in Nigeria. Women farmers are less likely to own smartphones, possess digital skills, or control financial resources required for paid services. Socio-economic inequalities similarly shape access to and benefits from digital extension, highlighting the need for inclusive design.

Trust, Information Quality, and Relevance

Farmers' trust in digital advisory services depends on perceived accuracy, relevance, and timeliness of information. Generic or poorly contextualised recommendations can undermine confidence. Strong linkages with research institutions and feedback mechanisms are essential for maintaining credibility.

Institutional and Policy Constraints

Public extension agencies often lack clear digital strategies, adequate funding, and skilled personnel to lead digital transformation. Many private and donor-driven initiatives remain fragmented and pilot-oriented, with limited integration into national systems. Weak coordination undermines sustainability.

Data Privacy, Ethics, and Governance

Digital extension systems collect sensitive data on farmers and livelihoods. In the absence of robust governance frameworks, risks related to privacy breaches and misuse of data arise. Establishing clear standards for consent, access, and ethical use of data is essential.

5. CASE EXAMPLES FROM NIGERIA

5.1 Rice Advice and Targeted Nutrient Management: An Analytical Synthesis

Rice Advice is among the most extensively documented digital agricultural extension tools implemented in Nigeria and across several African countries. Developed under the CGIAR framework, the application provides site-specific nutrient management recommendations for rice farmers based on information on location, soil characteristics, cropping system, and farmers' management practices. Unlike conventional blanket fertilizer recommendations traditionally promoted through public extension systems, Rice Advice is designed to tailor advice to local agro-ecological conditions, thereby improving both agronomic efficiency and environmental sustainability. Empirical evidence from Nigeria indicates that Rice Advice has contributed to improved decision-making among rice farmers, particularly in relation to fertilizer application rates and timing. Studies report that farmers using Rice Advice are more likely to apply fertilizer closer to recommended levels, reducing both under-application, which constrains yields, and over-application, which increases costs and environmental risks. These outcomes directly reflect the opportunity discussed earlier regarding timely and site-specific agronomic information delivered through digital extension platforms. By translating complex agronomic models into user-friendly recommendations, Rice Advice addresses one of the longstanding weaknesses of conventional extension: limited capacity to provide personalized advice at scale.

Beyond agronomic outcomes, Rice Advice offers insights into how digital extension interacts with institutional and human factors. Evidence suggests that the effectiveness of the application depends heavily on complementary support from extension agents and development programmes.

Farmers who received training, follow-up visits, or group demonstrations alongside digital recommendations reported higher levels of trust and sustained use. This finding reinforces the systems perspective outlined earlier in the chapter, highlighting that digital tools are most effective when embedded within blended extension models rather than deployed as stand-alone solutions.

The Rice Advice case also illustrates several constraints identified in Section 4. Adoption and sustained use have been uneven, with higher uptake among farmers who possess smartphones, basic digital literacy, and access to reliable connectivity. Women farmers and poorer households are less likely to use the application independently, reflecting broader gender and socio-economic inequalities in access to digital technologies. Language barriers and the need for localization of content further affect usability, underscoring the importance of context-specific design. From a policy perspective, Rice Advice demonstrates the potential value of partnerships between international research organizations, national extension systems, and development partners. However, it also highlights challenges related to sustainability and institutional ownership. Many deployments of Rice Advice in Nigeria have been project-based, raising questions about long-term financing, integration into public extension mandates, and alignment with national digital agriculture strategies. Addressing these issues is essential for moving from pilot success to system-wide impact.

Overall, Rice Advice exemplifies both the promise and limitations of digital agricultural extension in Nigeria. It confirms that digital decision-support tools can enhance agronomic efficiency and farmer learning, while also illustrating that technology alone cannot overcome structural constraints related to infrastructure, capacity, and inequality.

5.2 Digital Climate Advisory Services in Nigeria

Nigeria's increasing exposure to climate variability has elevated climate advisory services as a critical dimension of digital agricultural extension. Digital climate advisory initiatives integrate meteorological data, agronomic knowledge, and ICT platforms to deliver weather forecasts, seasonal climate predictions, and risk advisories to farmers.

These services directly link to the opportunity areas discussed earlier on climate and weather advisory services and risk management. In Nigeria, the Nigerian Meteorological Agency (NiMet) plays a central role in generating climate and agro-meteorological information. Recent collaborations between NiMet, extension agencies, and digital service providers have enabled the dissemination of advisories through SMS, interactive voice response, mobile applications, and digitally supported radio programmes. Such multi-channel approaches are particularly important in reaching farmers with varying levels of literacy and device access. Empirical evidence from pilot initiatives suggests that farmers who receive timely digital climate advisories are better able to adjust planting dates, manage input application, and anticipate climate-related risks such as floods or dry spells. These behavioral adjustments mirror the benefits described in Section 3.2 and demonstrate how digital extension can strengthen adaptive capacity in predominantly rain-fed farming systems. Extension agents often play a mediating role by helping farmers interpret probabilistic forecasts, thereby addressing trust and comprehension challenges noted among the constraints.

The climate advisory case also highlights persistent limitations. Inaccurate or poorly localised forecasts can undermine farmer confidence, while limited connectivity and low climate literacy restrict impact. Gender disparities are evident, as women farmers often have less access to mobile phones and climate information channels. These challenges reinforce the need for inclusive design, capacity building, and institutional coordination emphasized earlier in the chapter.

Together, the Rice Advice and climate advisory cases demonstrate how digital agricultural extension in Nigeria operates at the intersection of technological innovation, institutional capacity, and socio-economic context. They provide concrete evidence that supports the chapter's broader argument: digital extension offers substantial opportunities, but its success depends on addressing structural constraints and embedding digital tools within coherent extension systems.

5.3 Smartphone-Based Advisory Initiatives

Studies documenting smartphone-based advisory services in Nigeria reveal growing awareness but uneven sustained use. Evidence suggests that blended approaches combining digital tools with demonstrations and interpersonal support are more effective than purely digital models.

5.4 Policy and Institutional Implications

Digital agricultural extension has significant implications for agricultural governance, public administration, and rural development policy in Nigeria. To move beyond fragmented pilots, digital extension must be embedded within coherent national strategies that clarify institutional roles and responsibilities. Public investment is required to strengthen extension agencies' digital capacity, while regulatory frameworks should guide public–private partnerships and data governance. Policies should promote interoperability among platforms, protect farmer data, and ensure that digital services align with public extension objectives. Integrating digital extension into broader agricultural, ICT, and rural development policies can enhance coherence and impact.

Future Pathways for Scaling Inclusive Digital Agricultural Extension

This section elaborates pathways including blended extension models, public–private partnerships, investment in rural infrastructure, capacity building, gender-responsive targeting, and robust data governance. These strategies collectively emphasize that technology must be embedded within supportive institutions and inclusive practices.

Policy and Institutional Implications for Digital Agricultural Extension in Nigeria

The empirical evidence and case studies presented in this chapter underscore the need for a coherent policy and institutional framework to guide the development and scaling of digital agricultural extension in Nigeria.

While numerous digital initiatives have demonstrated potential to improve advisory services, productivity, and resilience, their long-term impact depends on alignment with national extension policy, effective coordination among actors, and sustainable financing and governance arrangements.

Alignment with National Agricultural Extension Policy

Nigeria's National Agricultural Extension Policy emphasizes pluralism, demand-driven services, and the use of information and communication technologies to enhance extension reach and effectiveness. Digital agricultural extension initiatives such as Rice Advice and climate advisory services align closely with these policy objectives by enabling more personalized, timely, and data-driven advisory support. However, the evidence reviewed in this chapter suggests that digital tools have largely been implemented through time-bound projects rather than as integral components of the national extension system. This fragmentation limits scalability and institutional learning.

To maximize impact, digital extension platforms should be formally embedded within national and sub-national extension strategies. This requires clear policy guidance on standards for digital advisory content, data governance, interoperability among platforms, and mechanisms for quality assurance. Integrating digital tools into extension policy frameworks would also help clarify expectations regarding the complementary roles of human-mediated and technology-enabled extension services.

6. ROLES OF KEY INSTITUTIONAL ACTORS

The National Agricultural Extension and Research Liaison Services (NAERLS) occupies a strategic position in Nigeria's extension architecture, serving as a bridge between agricultural research institutions and extension delivery systems. In the context of digital extension, NAERLS can play a coordinating and standard-setting role by synthesizing research outputs into digital-ready advisory content, supporting capacity building for extension personnel, and facilitating knowledge exchange among federal, state, and non-state actors. Strengthening NAERLS' digital mandate would enhance coherence and reduce duplication across initiatives.

State-level Agricultural Development Programmes (ADPs) remain the primary interface between extension services and farmers. Evidence from digital initiatives indicates that ADPs are critical for contextualizing digital advisories, mobilizing farmer participation, and providing feedback from the field. However, many ADPs face chronic capacity constraints, including limited funding, ageing extension staff, and inadequate digital infrastructure. Policy reforms must therefore prioritize investment in ADP revitalization, including training in digital skills, provision of devices, and incentives for integrating digital tools into routine extension work.

The private sector has emerged as a key driver of innovation in digital agricultural extension, particularly through agritech startups and mobile service providers. These actors contribute technological expertise, agility, and market-oriented approaches that complement public extension systems. Nevertheless, private-sector-led digital services often target commercially viable farmer segments, raising concerns about equity and inclusion. Public–private partnerships, guided by clear policy frameworks, can help balance innovation with public-interest objectives by leveraging private capabilities while ensuring coverage of marginalized groups.

Development partners and donors have played a significant role in piloting and scaling digital extension initiatives in Nigeria. Their support has facilitated experimentation, learning, and capacity development. However, donor-driven projects sometimes operate in parallel with national systems, contributing to fragmentation. Future donor engagement should prioritize alignment with national policies, support institutional strengthening, and invest in mechanisms that promote sustainability beyond project lifecycles.

7. GOVERNANCE, COORDINATION, AND SUSTAINABILITY

Effective governance is central to the success of digital agricultural extension. The multiplicity of actors involved government agencies, research institutions, private firms, and development partners necessitates strong coordination mechanisms to avoid duplication and ensure complementarity.

Establishing inter-agency platforms or steering committees focused on digital extension could facilitate information sharing, joint planning, and harmonization of approaches.

Sustainability remains a major challenge. Many digital extension initiatives rely on external funding, raising concerns about continuity once projects end. Sustainable models may include a combination of public financing, cost-sharing arrangements, and value-added services that generate revenue without excluding resource-poor farmers. Clear policy guidance on financing models and accountability mechanisms is essential to support long-term viability.

Data governance and ethical considerations also warrant attention. Digital extension platforms collect large volumes of farmer data, creating risks related to privacy, consent, and misuse. National policies should establish clear guidelines on data ownership, protection, and responsible use to safeguard farmer interests while enabling innovation.

Overall, the policy and institutional implications discussed in this section reinforce the chapter's central argument: digital agricultural extension in Nigeria holds significant promise, but realizing its potential requires deliberate policy integration, institutional coordination, and sustainable governance arrangements. By aligning digital initiatives with national extension policy and strengthening the roles of key actors, Nigeria can move toward a more resilient, inclusive, and effective extension system.

CONCLUSION

Digital agricultural extension represents a transformative pathway for revitalising Nigeria's agricultural sector amid persistent extension capacity gaps and rural inequalities. This chapter has shown that while digital tools offer significant opportunities, their effectiveness depends on institutional integration, human capacity, and inclusive governance. By advancing evidence-informed pathways and policy recommendations, the chapter contributes to scholarship and practice aimed at building resilient, equitable, and sustainable agricultural extension systems in Nigeria and comparable contexts.

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