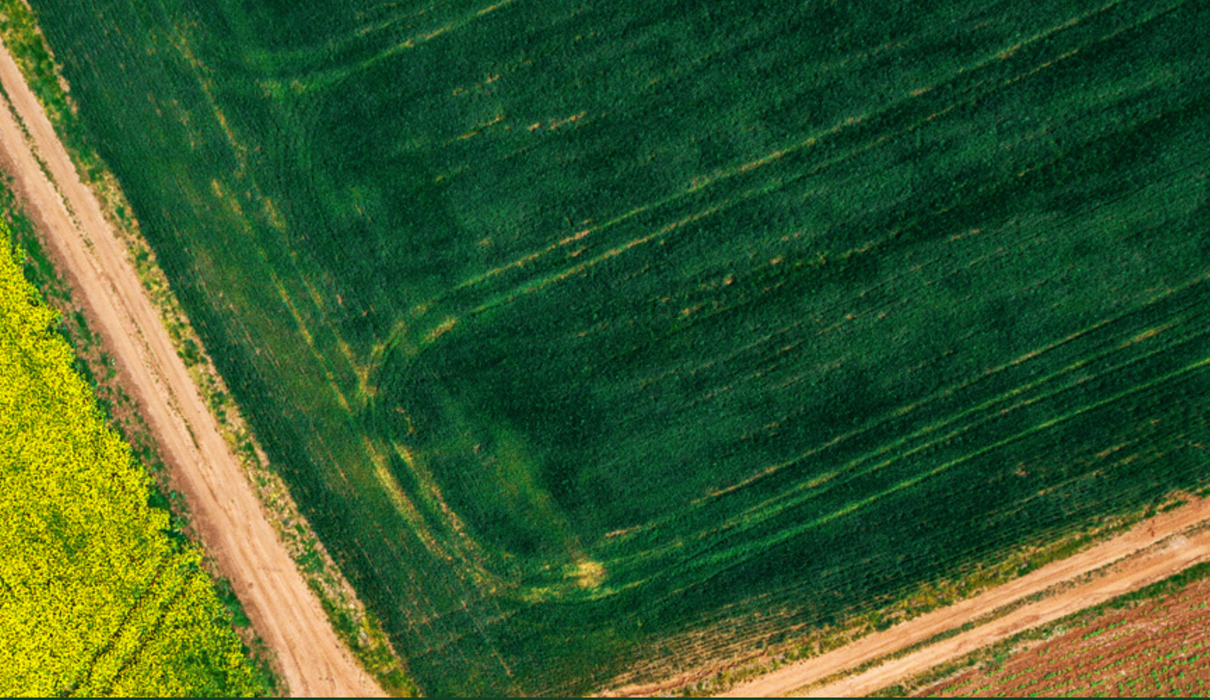

FROM TRADITION TO DIGITAL AGRICULTURE

ECONOMIC TRANSFORMATION AND POLICY CHALLENGES

EDITOR

DR. OSAMA ASANOUSİ LAMMA

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PREFACE

This volume presents three focused studies addressing contemporary challenges and innovations in agriculture across diverse contexts. Each chapter contributes to a broader understanding of how political, technological, and biological factors shape agricultural systems and development.

The first chapter analyzes the transformation of the British agricultural market in the wake of Brexit, highlighting shifts in trade policy and market structure. The second explores the role of e-extension services in Nigeria, emphasizing their potential to enhance agricultural outreach and development. The third investigates agricultural molds, offering insights into their identification, impact, and management strategies.

Together, these chapters underscore the importance of interdisciplinary approaches in addressing global agricultural issues. They offer valuable perspectives for researchers, practitioners, and policymakers engaged in advancing sustainable and resilient agricultural practices.

Editorial Team
December 9, 2025

CHAPTER 1
EVOLUTION OF BRITISH AGRICULTURAL MARKET: BEFORE AND AFTER BREXIT

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INTRODUCTION

The United Kingdom's agricultural sector has historically been shaped by the European Union's Common Agricultural Policy (CAP), which provided financial support, regulatory stability, and market access. Brexit marked a decisive break from this framework, introducing new trade rules, labor restrictions, and heightened uncertainty for producers and exporters.Several factors have recently put a strain on the British agricultural sector. The decline in the number of farmers due to the United Kingdom's withdrawal from the European Union is a significant factor in the agricultural sector in the United Kingdom.This article examines how Brexit has reshaped the UK's agricultural market, focusing on production, exports, and trade relations. Specifically, it evaluates the impact of tariff barriers, the transition from CAP to domestic support schemes such as the Environmental Land Management Scheme (ELMS) and the Sustainable Farming Incentive (SFI), and the effects of labor shortages on productivity and market stability.

This study pinpoints emerging opportunities in trade diversification beyond the EU. Drawing on official statistics, policy documents, academic literature, the study combines qualitative and quantitative analysis to assess both the disruptions caused by Brexit and the adaptive strategies that have followed. In doing so, it highlights the broader implications of policy reform and trade realignment for the resilience and future competitiveness of British agriculture.

This research is organized into three main chapters. The first chapter presents the research context by defining the study area, reviewing relevant literature, and formulating the main research questions, objectives, and hypotheses. The second chapter outlines the theoretical foundations and research methodology, including the key concepts, the analytical framework, the tools and techniques used for data collection and analysis. And, the third chapter focuses on data analysis and interpretation, starting with an overview of the United Kingdom's agricultural market before Brexit, followed by an assessment of the immediate impacts of Brexit on policies, labour, trade, and production. It concludes with an exploration of the post-Brexit adaptation strategies, such as policy reforms, technological innovation, and trade diversification with non-European Union countries.

1. DESCRIPTION OF RESEARCH SITUATION

This research is situated within the field of agricultural policy, international trade, and post-Brexit economic restructuring. It examines the implications of the UK's withdrawal from the European Union on the agricultural sector, particularly concerning policy frameworks, labour dynamics, and trade relations. The study also draws upon European studies, public policy analysis, and rural development, which reflects the multifaceted impact of Brexit on national and local agricultural systems.

1.1 Literature Review

The impact of Brexit on British agriculture has been extensively studied, with most existing research focusing on trade, subsidies, and labour. Before it departed from the European Union, the United Kingdom benefited from free access to the single market, financial support through the Common Agricultural Policy (CAP), and a steady supply of seasonal and permanent labour from EU countries.

Grant and Greer (2021) provided an in-depth analysis of the redefinition of British agricultural policy following Brexit. Their study emphasised the shift away from the European subsidy system and the development of autonomous mechanisms, such as the Environmental Land Management Scheme (ELMS). They highlighted the difficulties involved in designing a national agricultural policy that reconciles environmental goals with economic viability, especially in the absence of EU-wide support frameworks.

Berkeley Hill (2020) examined how Brexit has reshaped national agricultural policy, trade relations, and migration flows. His research underlined the economic vulnerability of British agriculture in the face of new trade barriers and the reduction in available foreign labour. He argued that the sector's exposure to international markets makes it highly sensitive to geopolitical and economic changes.

Trouvé and Bazin (2017) focused on the central role played by the CAP in supporting British agricultural income and price stability. This body of research collectively underscores how deeply intertwined the UK's farming sector is with European policy frameworks.

According to them, the withdrawal from this framework left a significant financial and structural gap, particularly for small and medium-sized farms that had relied heavily on CAP subsidies. Their work suggests that Brexit may have deepened existing inequalities within the sector.

Strong and Wells (2020) explored the media coverage of Brexit's impact on food policy and agriculture. Their research demonstrated how the British press influenced the post-Brexit political agenda by amplifying concerns over food security, supply chain disruptions, and consumer standards. They argued that media narratives played a pivotal role in shaping public expectations and government priorities.

Despite this substantial body of literature, there remains a notable gap concerning the long-term structural effects of Brexit. While most studies have concentrated on immediate disruptions and political responses, few have undertaken a comparative and forward-looking analysis that integrates economic, environmental, and technological dimensions. This research therefore aims to address that gap by assessing not only the immediate consequences of Brexit but also the sector's adaptation strategies and evolving dynamics in the post-Brexit era.

1.2 Main Research Questions

The main research question guiding this research is: How has Brexit affected the stability and evolution of the UK's agricultural market, particularly in terms of production, exports, and trade relations?

- What impact has Brexit had on UK agricultural exports to the European Union?
- How have post-Brexit agricultural policies evolved, particularly on subsidies and trade agreements?
- What has been the impact of Brexit on labour availability and agricultural production?
- Has the UK diversified its agricultural trade with non-EU countries after Brexit?

1.3 Main Research Objectives

This study aims to analyse the impact of Brexit on the United Kingdom's agricultural market, highlighting the evolution of trade relations, production processes, and agricultural policies since the country's withdrawal from the European Union.

- Evaluate the evolution of agricultural exports before and after Brexit, considering tariff barriers.
- Analyse post-Brexit reforms, particularly the transition from the CAP to a national system.
- Study the impact of labour shortages on production and market stability.
- Explore new trade directions with non-EU countries and the resulting opportunities.

1.4 Main Research Hypotheses

Brexit would be expected to lead to a decline in the stability of the United Kingdom agricultural market due to new trade barriers, the loss of EU labour, and changes in agricultural subsidies.

- It is hypothesized that new trade barriers would reduce UK agricultural exports to the European Union.
- It is expected that the lack of post-Brexit labour would weaken productivity within the agricultural sector.
- It is assumed that the United Kingdom would intensify trade relations with non-European countries, potentially increasing exports outside the European Union.

2. TERMS OF REFERENCE AND RESEARCH METHODOLOGY

The evolution of the British agricultural market can be analysed through several theoretical frameworks derived from agricultural economics and international trade. Among these, David Ricardo's theory of comparative advantage (1817) is relevant. It posits that a country should specialise in sectors where it holds a comparative advantage to stimulate international trade and optimise productivity.

Before Brexit, the UK benefited from the Common Agricultural Policy (CAP), which facilitated the free movement of agricultural products within the single market. Economic integration, according to Balassa (1961), demonstrates how such unions reduce trade barriers and stabilize the market. With Brexit, these mechanisms were altered. Restrictions on labour and new trade rules signal a return to protectionist strategies, as described by Friedrich List (1841/1909), where the state protects its industries until they achieve autonomy in the face of global competition. These theories guide the analysis of how Brexit reshaped UK competitiveness, labour, and trade.

2.1 Writings in Support of the Terms of Reference

Several studies have examined the impact of Brexit on the British agricultural market. Matthews (2018) highlights the UK agricultural sector's reliance on European labour, particularly for seasonal work. He points out that post-Brexit restrictions on free movement could lead to reduced productivity and higher costs. Fusacchia, Salvatici, and Winters (2020) showed how customs checks and tariffs have impacted agricultural exports to the EU. Ritson et al. (2024) explore how Brexit has reshaped UK food and agricultural policy. They note that the move away from EU standards and toward freer trade, exposes British agriculture to regulatory uncertainty, increased competition from imports, and potential declines in food security. These works support the chosen framework and clarify the economic and structural consequences of Brexit on British agriculture.

2.2 Important Concepts of the Chosen Model

The key concepts in this analysis are: market evolution, which refers to the changes in trade, labour, and agricultural rules since Brexit; economic impact, which highlights the rise of tariffs, disrupted trade, and labour shortages; agricultural policy shifts, which concern the move from EU policies to a national support system; and finally, economic modelling, which uses supply and demand to explain market reactions. Such changes may require farmers to adapt rapidly to new regulatory and market environments. Moreover, the long-term success of these adjustments will depend on the government's ability to design policies that mitigate risk and sustain agricultural productivity.

2.3 Methodology: Types of Information Retained and Data Analysis Methods

This research relies on secondary data from books, scientific articles, government reports, and journals. Quantitative data include production levels, trade statistics, employment rates, and price fluctuations, while qualitative data encompasses farmers' perspectives, government policies, and expert analyses. Secondary data are collected through various reliable tools, including academic databases (e.g., Routledge), official reports (e.g., DEFRA, the UK Parliament, and the UK Government), newspapers (e.g., The Guardian), as well as books and journals.

Quantitative data are analysed through statistical and trend analysis. For qualitative data, thematic and content analysis will be applied. This combined approach will provide a comprehensive understanding of the transformations in the British agricultural market since Brexit.

3. DATA ANALYSIS AND INTERPRETATION

The Common Agricultural Policy (CAP), established in 1962, has been a central element of the EU's agricultural framework. Before Brexit, it played a fundamental role in supporting British farmers. The CAP accounted for approximately 40% of the EU's total budget and aimed to guarantee a steady income for farmers while fostering competitiveness and sustainable practices across the agricultural sector. CAP support was structured around two main pillars. The first pillar (direct payments), financed by the European Agricultural Guarantee Fund (EAGF); and the second pillar (rural development), funded by the European Agricultural Fund for Rural Development (EAFRD). In 2018, direct payments represented around 80% of the UK's agricultural funding from the EU. They were primarily linked to land area and required compliance with environmental regulations known as "greening". England implemented this policy through the Basic Payment Scheme (BPS), while Scotland, Wales, and Northern Ireland managed their own equivalent systems. The second pillar, which accounted for 20% of the CAP budget allocated to the UK, supported environmental initiatives such as the conservation of natural areas and water management. It also aimed to improve agricultural productivity, for example by reducing the use of chemical fertilisers.

In addition, it funded rural development programmes like the Countryside Stewardship Scheme.On average, UK farmers received about £3.5 billion (or €4 billion) annually from the CAP. Prior to Brexit, the United Kingdom was deeply integrated into the European Single Market and Customs Union which allowed agricultural goods to flow freely between the UK and EU member states, with no tariffs or border controls, simplifying trade operations for British exporters. This integration facilitated efficient exports and imports, reduced administrative burdens, and ensured the smooth movement of food products.

The UK’s agricultural sector heavily depended on foreign labour, particularly from Eastern Europe. Before Brexit, around 75,000 seasonal workers, mostly from Romania and Bulgaria, were recruited annually without visa restrictions due to EU free movement rights. Migrant workers made up nearly 20% of the workforce, especially in labour-intensive industries such as fruit harvesting and meat processing. For example, 63% of employees in the British Meat Processors Association were migrants, a figure that reflects the sector’s structural reliance on flexible, low-cost labour . This dependence was not only economic but also logistical: local workers were often unwilling to take on physically demanding roles with limited wages and unpredictable hours. Migrant labour thus filled critical gaps, ensuring timely harvesting, reducing food waste, and maintaining stable production across key sectors .

3.1 Market Stability and Trade Relations Before Brexit

Before Brexit, the British agricultural market was strongly tied to the EU through the Single Market. According to DEFRA (2019), between 2015 and 2019, around 60% of the UK's total agricultural exports were sent to the EU, while 70% of agricultural imports came from the European Union. In 2019, exports rose to £14.155 billion, up from £12.736 billion in 2016, while imports grew from £31.515 billion in 2016 to £33.673 billion in 2019. These exchanges led to a trade deficit in the agricultural sector, reaching over £19 billion in 2019. Thus, trade was smooth, interconnected and stable, supported by harmonised standards and zero tariffs. The European Union had established a stringent regulatory framework to ensure the safety and quality of food products traded within the bloc.

Key regulations included rules on food safety and traceability, hygiene standards in production and distribution, use of food additives after evaluation by EFSA, limiting the levels of contaminants in food such as pesticides and heavy metals, genetically modified organisms (GMOs), clear and detailed food labelling. This regulatory harmonisation facilitated the UK's reliance on EU food products and enabled highly integrated supply chains between the UK and the EU.

3.2 Post-Brexit Agricultural Market

The decision to leave the European Union (EU) had immediate consequences for agricultural policy. One of the most significant changes was the replacement of the Common Agricultural Policy (CAP) with a national framework established by the Agriculture Act 2020 . Unlike the CAP, which primarily supported land ownership through direct payments, the new system introduced by the UK government emphasises the provision of "public goods" such as biodiversity, clean air, and improved soil health. This transition led to the creation of new schemes like the Environmental Land Management Scheme (ELMS), which includes the Sustainable Farming Incentive (SFI), Countryside Stewardship, and Landscape Recovery. The Basic Payment Scheme (BPS) is gradually being phased out between 2024 and 2027, shifting towards payments decoupled from land area . This reform, although ambitious, reflects a broader goal of building a greener, more resilient agricultural sector.

Brexit gave the UK control over its food safety rules. The Food Standards Agency (FSA) (2023), adopted a more risk-based inspection model, focusing on high-risk products and simplifying processes for compliant producers. While these reforms give the UK more flexibility on pesticides, additives, and GMOs, they also raise questions about food import standards under new trade agreements with countries outside the EU (Anthony, C., & Lydgate, E., 2019). The UK remains committed to environmental goals, promoting organic farming and sustainability, but producers now face more administrative burdens and regulatory uncertainty.

These challenges are especially significant for smaller producers, who may struggle to adjust to shifting compliance requirements.

3.3 Labour Market Challenges

The end of free movement had a profound impact on British agriculture, particularly regarding its reliance on seasonal workers from Eastern Europe. The introduction of the Seasonal Worker Visa Scheme by UK Government led to a number of restrictions, such as limiting the stay to six months, the inability to bring their families, and restricted access to public assistance, among other restrictions, with quotas initially insufficient. Although the quota was increased from 45,000 to 55,000 in 2019, many farmers continued to report labour shortages, especially during harvest seasons .

The labour shortage affected both productivity and the broader food supply chain. Euronews (2021) reported that without enough seasonal workers, farmers faced difficulty collecting perishable goods on time, leading to food waste and financial strain. This drop in output, combined with rising labour costs, affected domestic food supply and exports. Supermarket shortages of fruits, vegetables, and dairy, caused price increases and more reliance on imports, adding costs during global supply chain disruptions. As highlighted in the government's qualitative assessment of the visa programme, while some improvements were noted, but the scheme has not fully resolved the labour crisis .

The Trade and Cooperation Agreement (TCA) signed between the United Kingdom and European Union preserved tariff-free trade for goods that meet rules of origin requirements. However, the requirement for additional documentation, such as sanitary and phytosanitary (SPS) certificates and customs declarations, has introduced significant delays and complexity. Post-Brexit trade frictions including customs delays and regulatory burdens continue to hinder UK exporters, particularly small and medium-sized entreprises (SMEs), leading to renewed calls for government intervention .

According to articles reported by Simpson (2024a) in The Guardian, transport delays of up to 20 hours were recorded at border crossings, causing the spoilage of perishable items and reducing their shelf life by nearly 20%. In a separate article, Simpson (2024b) reported that the UK food exports to the EU have fallen by nearly £3 billion a year due to new sanitary and administrative barriers, creating significant uncertainty for producers, especially in the meat and dairy sectors.

These logistical challenges weakened the competitiveness of British agricultural exports, as many European buyers turned to more stable suppliers. In 2023, 49% of UK agricultural exports and 67% of its imports were linked to the EU, highlighting the vulnerability of these trade flows (DEFRA, 2023).

3.4 Post-Brexit Adaptation and Market Trends

After the Brexit transition ended in 2020, the UK agricultural sector faced an urgent need to adapt. One of the key strategies was the acceleration of technological innovation to mitigate labour shortages and enhance productivity. The Agriculture Bill (2018–2020) created new opportunities for investment in automation, robotics, and artificial intelligence, particularly in areas such as crop monitoring and harvesting (DEFRA, 2018). The UK had fallen behind other European countries in adopting advanced agricultural technologies but sought to catch up post-Brexit. The UK Industrial Strategy (2017) highlighted the importance of Artificial Intelligence (AI) to boost productivity, while noting that countries such as the Netherlands and Germany had already integrated these technologies. The Agri-Tech Strategy supported the use of drones, harvest robots, and AI to improve efficiency, with funding to encourage the rapid adoption of these innovations . Programmes such as the Farming Innovation Fund and UK Research and Innovation (UKRI) initiatives provided financial support for on-farm trials and high-tech research. Private companies have also contributed significantly. RootWave developed chemical-free electric weed control systems, while Outfield Technologies and the Small Robot Company leveraged AI and automation for tasks such as crop monitoring, harvesting, and targeted weeding. Despite this progress, many farmers continue to face challenges in adopting new technologies, particularly due to high costs, lack of training, or inadequate infrastructure in rural areas.

3.5 Shift in Trade Relations: UK's New Trade Agreements

After Brexit, the United Kingdom signed several trade agreements to partially compensate for the loss of benefits from access to the EU's Single Market. While the UK-EU Trade and Cooperation Agreement (TCA) enabled tariff-free trade without quotas with the European Union, it also introduced complications and shortcomings.

These issues were particularly evident in relation to sanitary and phytosanitary standards and the fluidity of agricultural exchanges. In response, the UK sought new partners and signed agreements with Australia, New Zealand, Japan, and Canada. The United Kingdom also joined the Comprehensive and Progressive Agreement for Trans-Pacific Partnership (CPTPP), which includes 11 Asia-Pacific countries. Additionally, the free trade agreement with Norway, Iceland, and Liechtenstein also includes provisions on agricultural trade .

This shift towards non-European markets reflects the UK's strategy to diversify its trade relationships, reducing dependence on the EU and positioning itself as a global player. However, challenges remain, particularly with new regulatory standards and logistical issues with the EU. Many non-EU countries operate under different regulatory frameworks, particularly regarding pesticide residues, GMOs, and animal welfare standards. The UK, having inherited the EU's high food standards, now finds itself navigating agreements with partners whose rules may be less stringent, creating tensions both domestically and internationally. It is crucial that such agreements do not compromise the UK's established standards on food safety, animal welfare, and environmental protection. Additionally, geopolitical instability, such as the imposition of tariffs by previous US administrations, has further complicated market access and increased the urgency of securing more reliable trade routes (The Guardian, 2025).

3.6 Sustainable and Environmental Changes

The UK's post-Brexit agricultural strategy is firmly rooted in environmental transition. The Agricultural Transition Plan (2021–2028) replaced the Common Agricultural Policy's area-based subsidies with payments tied to environmental performance and sustainability objectives . At the heart of this plan is the Environmental Land Management Scheme (ELMS), which promotes responsible land stewardship. Three core programs structure this system. The Sustainable Farming Incentive (SFI) supports practices that improve soil health, reduce chemical inputs, and protect biodiversity, while Local Nature Recovery encourages ecosystem restoration, including hedgerows, wetlands, and pollinator habitats.

Landscape Recovery focuses on large-scale environmental projects such as reforestation and wildlife protection.This shift is also guided by the "public money for public goods" principle, ensuring that financial support is linked to tangible contributions to environmental and social goals. In addition, the UK has introduced the Farming Investment Fund to further support innovation and resilience across the sector, while the introduction of the Seasonal Worker Visa Scheme created by the government aims to secure the necessary labour for production, although its effectiveness remains subject to debate. Overall, these changes mark a policy shift aligning British agriculture with sustainability and food security goals.

CONCLUSION

Brexit marked a major turning point for British agriculture, challenging the foundations on which the sector had relied for decades. Before the UK's withdrawal from the European Union, the domestic agricultural industry benefited from a stable environment, supported by the Common Agricultural Policy (CAP), free access to the European single market, and an abundant, low-cost workforce primarily from Eastern Europe. These factors ensured a degree of economic stability, strong trade integration with EU countries, and a smooth functioning of supply chains. However, leaving the EU brought about a series of structural disruptions. Politically, the end of CAP subsidies forced the UK government to redefine its agricultural policy through the Agriculture Act 2020 and the introduction of initiatives such as the Environmental Land Management Scheme (ELMS). This transition aims to replace direct payments with support linked to the delivery of "public goods," such as biodiversity and environmental sustainability. While these reforms represent a step towards more ecological farming, their implementation raises significant challenges regarding profitability and farmers' capacity to adapt. Economically, post-Brexit trade barriers including customs checks and regulatory requirements have disrupted trade with the European Union, the UK's main trading partner. Agricultural exports to the EU have declined, logistical costs have risen, and many small producers are struggling to adjust to these new constraints. Meanwhile, although diversification towards non-European markets is being promoted, it remains limited due to regulatory differences and geopolitical uncertainties.

The agricultural labour market has also been deeply affected. The end of free movement for EU workers has led to labour shortages, particularly for seasonal tasks. Despite the introduction of the Seasonal Worker Visa Scheme, quotas remain insufficient and the conditions are restrictive. This has had a direct impact on productivity, leading to unharvested crops, economic losses, and pressure on food supply chains.The British agricultural sector has begun adapting through innovation. Investment in agri-tech including harvesting robots, drones, and artificial intelligence offers a promising solution to labour shortages and aims to boost productivity. Both public and private initiatives have emerged to support this technological shift, although access remains uneven due to high costs and regional disparities.Finally, Brexit has accelerated a strategic reorientation of British agriculture towards sustainability and food security objectives. The adoption of new environmental standards and the revision of agricultural priorities reflect a political will to profoundly transform the agricultural model.Nevertheless, this transition remains fragile and requires strengthened support, especially for small farms, which are the most vulnerable.

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CHAPTER 2
E-EXTENSION APPROACH IN AGRICULTURAL EXTENSION SERVICES: IMPLICATIONS FOR AGRICULTURAL DEVELOPMENT IN NIGERIA

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INTRODUCTION

Agriculture is the backbone of Nigeria's economy, employing over 70% of the rural population and contributing approximately 24% to the gross domestic product (GDP) in 2023 (Federal Ministry of Agriculture and Rural Development [FMARD], 2023). Smallholder farmers, operating on less than 2 hectares and relying on rain-fed systems, produce 90% of agricultural output but face persistent challenges: low yields (e.g., maize at 2 tons/ha vs. a potential 8 tons/ha), post-harvest losses costing ₦3.5 trillion annually, and vulnerability to climate shocks, pest outbreaks, and conflicts (ActionAid Nigeria, 2023; IITA, 2023). Traditional extension services, rooted in colonial-era models and later the Training and Visit (T&V) system, are overstretched, with agents serving 5,000–10,000 farmers each, resulting in infrequent and ineffective interactions—only 20% of farmers receive regular advisory services (Banful et al., 2010; Davis et al., 2019). E-extension, leveraging ICT tools such as mobile apps, SMS, radio, interactive voice response (IVR), and digital platforms, offers a scalable solution to deliver real-time, localized information on weather forecasts, pest management, market prices, and best practices (Aker, 2011). Globally, e-extension has revolutionized farming: India's mKisan platform reached 5 million farmers, increasing yields by 20–30% through SMS advisories (Deichmann et al., 2016), while Kenya's iCow app boosted incomes by 40% through optimized livestock management (Qiang et al., 2012). In Nigeria, where 80% of farmers are smallholders, e-extension can democratize knowledge access, addressing productivity gaps amid a population projected to reach 400 million by 2050, doubling food demand (United Nations, 2022).

This chapter provides a comprehensive examination of e-extension's implications for Nigeria's agricultural development. It explores the rationale for its adoption, contrasts Nigeria's extension-to-farmer ratio with global and regional benchmarks, and analyzes benefits, challenges, and practical solutions. Empirical evidence from 2020–2025 across Nigeria, SSA, and global contexts informs the discussion, emphasizing collaboration among government, research institutions, farmer organizations, and private actors. These insights highlight the urgent need to modernize extension systems in order to enhance productivity and resilience across farming communities.

The chapter aligns with Nigeria's National Agricultural Technology and Innovation Policy (2022–2027), which prioritizes digital innovation, and regional frameworks like CAADP, offering actionable insights for stakeholders to enhance food security, economic resilience, and rural prosperity.

1. RATIONALE AND CONTEXTUAL IMPERATIVE FOR E-EXTENSION IN NIGERIA

Nigeria's agricultural sector is characterized by smallholder dominance, with 80% of farmers operating on small plots, relying on rain-fed systems and traditional methods that limit productivity (FMARD, 2023). For instance, rice yields average 2.5 tons/ha against a global benchmark of 5 tons/ha, and maize yields stagnate at 2 tons/ha compared to a potential 8 tons/ha (IITA, 2023). Climate variability, including floods in the south and droughts in the north, reduced output by 5–10% in 2022, while pest outbreaks, such as fall armyworm, caused 30% losses in maize (FMARD, 2023; FAO, 2023). Market inefficiencies exacerbate challenges, with farmers losing 40% of perishables like tomatoes, yam, and vegetables due to poor storage and limited market access, costing ₦3.5 trillion annually (ActionAid Nigeria, 2023).

Traditional extension services, constrained by logistics and underfunding, fail to deliver timely advice. Agents often visit farmers once every few months, covering only 20% of needs, particularly in remote areas like Borno, Taraba, and Zamfara, where conflict disrupts access (Davis et al., 2019). E-extension addresses these gaps by enabling scalable, interactive delivery of information tailored to local conditions, such as soil types in the Guinea Savanna or pest risks in the Niger Delta (NAERLS, 2021). For example, platforms like the National Farmers Helpline (NFHL) and FarmRadio reached 500,000 farmers with storage and market advice, reducing losses by 15–20% in pilot regions like Kano and Oyo (Sydani Group, 2023). The COVID-19 pandemic underscored the urgency, as lockdowns disrupted physical extension, yet digital platforms like Sasakawa's e-extension maintained outreach to 500,000 farmers, promoting climate-smart practices such as drought-resistant seeds and conservation tillage (SAA, 2021). Nigeria's food security crisis, with 25 million people facing acute hunger in 2023, amplifies the need for e-extension (FAO, 2023).

Post-harvest losses drain economic potential, particularly for high-value crops like yam, which lose 40% due to inadequate storage (ActionAid Nigeria, 2023). E-extension mitigates these losses by providing real-time storage techniques and market linkages. In Oyo State, AgroTech's SMS advisories reduced yam spoilage by 25%, saving farmers ₦200,000 per hectare, while in Enugu, radio advisories increased adoption of improved storage by 20% (Etuk et al., 2023; NAERLS, 2023). Scaling such interventions could avert significant economic losses, aligning with Nigeria's goal of achieving food self-sufficiency by 2030 under the Agricultural Transformation Agenda.

2. SOCIOECONOMIC AND TECHNOLOGICAL DRIVERS

Nigeria's high mobile penetration—over 200 million subscriptions by 2024, with 60% of rural households owning at least one mobile phone—creates a fertile ground for e-extension Nigeria Communication Commission (NCC, 2024). With 60% of the population under 30 and increasingly tech-savvy, digital tools resonate, particularly among youth farmers, who are 40% more likely to adopt ICT than older counterparts (UNESCO, 2023). Women farmers, constituting 50% of the workforce, benefit from mobile platforms, though access gaps persist, with only 15% owning smartphones compared to 45% of men (FAO, 2023). Globally, ICT adoption correlates with 15–25% productivity gains, as seen in Ethiopia's 8028 Farmer Hotline, which reached 4 million farmers with planting and pest advice, increasing yields by 15% (World Bank, 2021).

In Nigeria, initiatives like the Akilimo app in Ogun State increased cassava yields by 22% through soil-specific recommendations, while the Youth AgripreneurshipProgramme in Anambra trained 5,000 youths, boosting incomes by 15% through value-added processing of yam and cassava into flour and chips (Karubanga et al., 2019; NAERLS, 2021). The economic case is compelling: a 2023 Sydani Group study estimated that scaling e-extension could avert ₦3.5 trillion in losses annually by optimizing value chains, from input access to market sales (Sydani Group, 2023). For women farmers, apps like Hello Tractor facilitated equipment sharing, increasing earnings by 25% and enabling cultivation of additional hectares, critical for the 40% of women-led households in rural Nigeria (FAO, 2023).

These socioeconomic benefits highlight e-extension's potential to drive inclusive growth, particularly for marginalized groups like women and youth.

3. POLICY AND REGIONAL ALIGNMENT

E-extension aligns with Nigeria's National Agricultural Technology and Innovation Policy (2022–2027), which prioritizes digital innovation to achieve 6% annual agricultural growth (FMARD, 2023). It supports CAADP's regional goals of 10% agricultural budget allocation and SDG 2 (Zero Hunger), emphasizing ICT to enhance resilience (AU, 2022). The African Union's Digital Agriculture Strategy (2020–2030) advocates digital tools to reach 80% of smallholders by 2030, a model Nigeria can emulate through platforms like NFHL, AgroTech, and FarmRadio (AU, 2022). Without e-extension, Nigeria risks lagging behind peers like Ghana, where digital tools supplemented extension, reducing effective ratios to 1:800 in pilot areas and increasing technology adoption by 25% (FAO, 2021).

Nigeria's demographic and environmental pressures further underscore the urgency. With a population growth rate of 2.5% annually, food demand is projected to double by 2050, requiring a 70% increase in production (United Nations, 2022). Climate change exacerbates risks, with 30% of arable land affected by desertification in northern Nigeria and flooding impacting 20% of southern farmlands in 2022 (FMARD, 2023). E-extension's ability to deliver climate-smart advisories, such as drought-resistant seed recommendations or flood preparedness tips, positions it as a critical tool for sustainable development. In Adamawa, SMS alerts increased sorghum yields by 15% during 2022 dry spells, while in Delta State, radio advisories saved 20% of crops during floods (NAERLS, 2023; Sydani Group, 2023).

4. GLOBAL AND REGIONAL SUCCESS STORIES

Globally, e-extension has proven transformative. In India, the mKisan platform's SMS and IVR services reached 5 million farmers, boosting yields by 20–30% for crops like wheat and rice through timely planting and pest advice (Deichmann et al., 2016). In SSA, Kenya's iCow app increased milk yields by 20% and incomes by 15% for 1 million livestock farmers by providing breeding and feeding tips (Qiang et al., 2012).

Rwanda's Smart Nkunganire program subsidized smartphones, reaching 70% of farmers and increasing adoption of improved inputs by 40% (FAO, 2021). In Nigeria, the Sasakawa e-extension platform reached 500,000 farmers during the COVID-19 pandemic, promoting climate-smart practices and reducing losses by 15% in pilot areas like Kano and Benue (SAA, 2021). These models offer lessons for Nigeria, particularly in leveraging low-cost SMS and radio for low-literacy farmers and scaling through public-private partnerships (PPPs).

4.1 Current Extension-to-Farmer Ratio in Nigeria Compared to Global Standards: Nigeria's Extension Landscape

The extension-to-farmer ratio is a criticalindicator of advisory service efficacy. The Food and Agriculture Organization (FAO) recommends a ratio of 1:1,000 to ensure personalized support, enabling agents to address specific farmer needs like pest management or soil fertility (FAO, 2021). In Nigeria, however, the ratio ranges from 1:5,000 to 1:10,000, among the highest in SSA, reflecting a severe shortage of agents (Davis et al., 2019; Farmonaut, 2025). With only 7,000 extension agents nationwide, each serves vast areas, often covering multiple local government areas with limited transport (IFPRI, 2020). In Kaduna State, a 2021 survey reported a 1:3,000 ratio, leaving 40% of farmers without advisory access, particularly in remote areas (Kagbu& Issa, 2021).

This gap stems from chronic underfunding. Nigeria's extension budget, at 0.5% of agricultural GDP, is far below CAADP's 10% recommendation, with funding dropping 20% since the 2015 oil price crash (IFPRI, 2020). The decline in agent recruitment and training has exacerbated the issue, with 60% of agents nearing retirement age by 2023 (NAERLS, 2023). In contrast, states like Abia, with donor-supported programs, achieved ratios closer to 1:2,000, but these remain exceptions (Onah et al., 2021). In Borno State, conflict has reduced the ratio to 1:8,000, limiting access to 15% of farmers (NAERLS, 2023).

5. GLOBAL AND REGIONAL BENCHMARKS

Globally, optimal ratios drive productivity. The Netherlands achieves a 1:500 ratio, supporting precision agriculture with 50% higher yields than SSA averages (World Bank, 2022).

In SSA, Kenya's 1:1,100 ratio, bolstered by digital platforms like iCow and M-Farm, correlates with 20% income gains for connected farmers (Sennuga&Fadiji, 2020). Ghana's 1:1,300 ratio, enhanced by apps like Esoko, reaches 70% more farmers than traditional methods (FAO, 2021). The Table below compares key benchmarks.

Table 1. Comparison of extension agents-farmer ratio

Region/country	Extension agents-farmer ratio	Source
Global Standard	(1:1000)	FAO (2021)
Netherlands	(1:500)	World Bank (2022)
Sub-Saharan Africa Average	(1:2500)	Davis et al., (2019)
Kenya	(1:1,100)	Sennuga & Fadiji (2020)
Ghana	(1:1,300)	FAO (2021)
Nigeria	(1:5,000-10, 000)	Davis et al. (2019)

6. IMPLICATIONS OF NIGERIA'S EXTENSION-FARMER RATIO GAP

Nigeria's high ratio results in significant yield gaps. Maize yields remain at 2 tons/ha against a potential 8 tons/ha, and rice at 2.5 tons/ha vs. 5 tons/ha globally (IITA, 2023). Globally, optimal ratios yield 13–500% returns on extension investments, as seen in Japan's 1:600 ratio, which supports 90% technology adoption (Naswem&Ejembi, 2017). In Nigeria, overstretched agents prioritize accessible farmers, marginalizing remote and female farmers, who constitute 50% of the workforce (FAO, 2023). In Borno State, only 15% of farmers received extension visits in 2022, correlating with 30% lower adoption of improved seeds (NAERLS, 2023).

The ratio gap exacerbates post-harvest losses, as farmers lack timely storage advice. In Benue State, 40% of yam harvests were lost due to inadequate extension coverage, costing ₦300,000 per hectare (ActionAid Nigeria, 2023). In Taraba, only 10% of farmers accessed extension services in 2022, limiting adoption of modern storage techniques (NAERLS, 2023). E-extension can bridge this by virtualizing outreach, as demonstrated in Ghana, where apps reduced effective ratios to 1:800 in pilot areas, increasing technology adoption by 25% (FAO, 2021).

E-Extension As A Solution

Digital platforms can simulate lower ratios by reaching thousands simultaneously. Nigeria's NFHL reached 1 million farmers in 2023, effectively lowering the ratio to 1:1,000 in covered areas (NAERLS, 2023). In SSA, Ethiopia's 8028 Farmer Hotline reduced effective ratios to 1:500 for connected farmers, boosting yields by 15% (World Bank, 2021). In Nigeria, scaling platforms like AgroTech or FarmRadio could cover 70% of farmers by 2030, aligning ratios closer to global standards. For example, in Oyo State, AgroTech's SMS advisories reached 100,000 farmers, effectively reducing the ratio to 1:1,500 and increasing maize yields by 20% (Etuk et al., 2023).

Benefits of E-Extension

E-extension's transformative potential lies in its ability to deliver scalable, precise, and inclusive services, impacting productivity, livelihoods, rural development, and environmental resilience. E-extension enhances yields by providing real-time, localized information. In Nigeria's southeast, a 2021 Agricultural Development Programme (ADP) survey found that 72% of agents reported faster growth with e-tools, with SMS advisories boosting rice yields by 25% through timely pest alerts, saving farmers ₦150,000 per hectare in losses (Onah et al., 2021). The NFHL's 2023 pilot in Kano reduced post-harvest losses by 30% via storage advice, saving ₦500,000 per hectare (Etuk et al., 2023). In SSA, Freeman & Mubichi (2024) documented 15–20% maize yield gains in Mozambique using mobile apps, a model replicable in Nigeria's northern states.

Globally, India's Digital Green videos increased technology adoption by 40%, boosting yields by 20–30% for crops like wheat and rice (Gandhi et al., 2009). In Nigeria, precision tools like Nutrient Expert, piloted in northern states, optimized fertilizer use, raising maize yields by 20–30% and reducing input costs by 15% (Liverpool-Tasie et al., 2017). During the 2022 floods in Benue State, e-alerts saved 15% of crops by guiding farmers to elevated storage, averting losses worth ₦200 million (NAERLS, 2023). In Ogun State, the Akilimo app's soil-specific recommendations increased cassava yields by 22%, from 10 to 12.2 tons/ha, adding ₦300,000 per hectare in revenue (Karubanga et al., 2019).

E-extension also supports climate-smart practices. In Plateau State, SMS alerts on weather patterns increased adoption of conservation tillage by 30%, reducing soil erosion and boosting yields by 10% (SAA, 2021). In SSA, Ethiopia's digital advisories cut water use by 25% through precise irrigation schedules, enhancing resilience in drought-prone areas (World Bank, 2021). In Nigeria's Adamawa State, SMS alerts on drought-resistant varieties increased sorghum yields by 15% during 2022 dry spells, saving farmers ₦100,000 per hectare (NAERLS, 2023).

7. IMPROVED FARMERS' LIVELIHOODS

E-extension enhances incomes through market linkages and cost efficiencies. In Ogun State, Akilimo users gained 35% revenue by accessing price forecasts, enabling sales at peak prices, adding ₦100,000 per farmer annually (Karubanga et al., 2019). A 2024 IFPRI study linked extension access to 10–15% welfare gains, including improved nutrition from diversified crops like vegetables and legumes, benefiting 60% of households (Amare et al., 2024). In SSA, Kenya's M-Farm connected 50,000 farmers to buyers, cutting intermediation costs by 20% and increasing incomes by 15% (Deichmann et al., 2016).

For Nigeria's women farmers, who face barriers to extension access, apps like Hello Tractor facilitated equipment sharing, boosting earnings by 25% and enabling cultivation of additional hectares, critical for the 40% of women-led rural households (FAO, 2023). In Anambra State, the Youth AgripreneurshipProgramme used e-platforms to train 5,000 youths, increasing incomes by 15% through value-added processing of yam and cassava into flour and chips (NAERLS, 2021). In SSA, Uganda's AgriTech platform linked farmers to credit, enabling 30% higher investments in inputs like fertilizers, a model Nigeria could adopt for its 40% unbanked rural population (SAA, 2021; World Bank, 2024).

E-extension reduces economic risks. In Nigeria's southwest, SMS alerts on market trends helped farmers avoid 20% losses from oversupply, stabilizing incomes by ₦50,000 per season (Etuk et al., 2023).

In northern Nigeria, radio-based advisories reached 70% of female farmers, improving adoption of drought-resistant seeds by 20%, adding ₦50,000 per season to household incomes (NAERLS, 2023). By reducing information asymmetries, e-extension fosters financial inclusion and resilience.

8. ENHANCED RURAL DEVELOPMENT

E-extension catalyzes rural economies by fostering agro-entrepreneurship and reducing migration. In Uganda, ICT platforms spurred 10,000 youth-led agribusinesses, creating jobs and stabilizing rural communities (SAA, 2021). Nigeria's N-Power Agro, integrated with e-extension, trained 200,000 youths, strengthening farmer clubs and value chains for crops like cassava and maize, adding ₦500 million to local economies (GFRAS, 2023). In SSA, ICT adoption correlates with 15% lower rural-urban migration by making farming viable, a trend observable in Nigeria's Oyo State, where e-extension increased youth farming by 10% (World Bank, 2021; NAERLS, 2021).

E-extension promotes inclusivity, particularly for women and youth. In Nigeria's north, radio-based advisories reached 70% of female farmers, improving adoption of improved seeds by 20% and boosting community food security (NAERLS, 2023). Globally, India's Kisan Call Centre supported 10 million farmers, spurring rural enterprises like seed banks and cooperatives, increasing incomes by 12% (Deichmann et al., 2016). In Nigeria, e-extension's linkage to cooperatives in Enugu State increased collective bargaining power, raising farmer incomes by 12% through bulk sales of rice and yam (Onah et al., 2021). By connecting farmers to markets and resources, e-extension strengthens rural economies, aligning with Nigeria's rural development goals.

8.1 Environmental and Climate Resilience

E-extension supports climate-smart agriculture, critical for Nigeria's rain-fed systems. In Borno State, SMS alerts on weather patterns increased adoption of conservation tillage by 30%, reducing soil erosion and improving yields by 10% (SAA, 2021). In SSA, Ethiopia's digital advisories cut water use by 25% through precise irrigation schedules, enhancing resilience in drought-prone areas (World Bank, 2021).

Globally, Australia's e-extension reduced pesticide use by 15% via targeted pest alerts, a strategy applicable to Nigeria's pest-prone south (FAO, 2021). In Nigeria, e-extension's role in climate adaptation is evident. In Adamawa State, advisories on drought-resistant varieties increased sorghum yields by 15% during 2022 dry spells, saving ₦100,000 per hectare (NAERLS, 2023). In Delta State, radio advisories on flood preparedness saved 20% of crops, worth ₦150 million, by guiding farmers to elevated storage (Sydani Group, 2023). In Plateau State, e-extension promoted agroforestry, reducing soil degradation by 25% and increasing yields by 10% (SAA, 2021). These practices align with Nigeria's Climate Change Policy, promoting sustainability and reducing environmental degradation.

8.2 Social and Gender Inclusion

E-extension enhances inclusivity by reaching marginalized groups. In northern Nigeria, radio and SMS platforms reached 70% of female farmers, increasing adoption of improved seeds by 20% compared to 10% for traditional extension (NAERLS, 2023). In SSA, Rwanda's women-focused e-extension programs increased female farmer incomes by 30% through targeted advisories (FAO, 2021). In Nigeria's southeast, e-extension training for women in Enugu boosted vegetable production by 15%, adding ₦80,000 per season (Onah et al., 2021). Youth engagement through platforms like N-Power Agro increased agribusiness participation by 10%, creating 5,000 jobs in Anambra (NAERLS, 2021).

8.3 Challenges and Limitations

Despite its potentials, e-extension faces significant hurdles in Nigeria, rooted in structural, socioeconomic, and institutional constraints. Only 40% of rural Nigerians own smartphones, with internet access at 20% in remote areas, compared to 80% in urban centers (NCC, 2024). In northern states, literacy rates below 50% limit app usability, particularly among women (15% smartphone ownership) and older farmers (UNESCO, 2023). In SSA, digital divides exacerbate inequalities, with 60% of rural farmers excluded from ICT benefits, a trend mirrored in Nigeria's rural north (Mapfumo et al., 2023).

In Zamfara State, only 15% of farmers accessed e-extension due to device costs averaging ₦30,000, limiting reach (NAERLS, 2023).

8.4 Inadequate Infrastructure

Poor network coverage affects 60% of rural Nigeria, with 4G absent in 40% of villages, hindering real-time advisories (Sydani Group, 2023). Power outages, averaging 12 hours daily, disrupt device charging, while solar solutions cost ₦50,000 per unit (ITU, 2022). In SSA, connectivity gaps cost $100 billion annually, limiting digital agriculture's reach (World Bank, 2021). Nigeria's 2023 telecom investment of $500 million lags behind Kenya's $1.2 billion, constraining rural connectivity (NCC, 2024). In Bauchi State, 50% of e-extension users reported network failures, reducing adoption by 20% (Etuk et al., 2023).

8.5 Insufficient Funding

Nigeria's extension budget is 0.5% of agricultural GDP, far below CAADP's 10% recommendation, limiting ICT scaling (IFPRI, 2020). Developing a single e-extension app costs ₦10 million, with annual maintenance at ₦5 million, deterring investment (Etuk et al., 2023). In SSA, funding shortages reduced e-extension coverage by 30% in Malawi, a risk Nigeria faces without increased budgets (FAO, 2021). Donor-funded pilots, like Sasakawa's, reached 500,000 farmers but lack sustainability without domestic funding (SAA, 2021).

8.6 Skills and Capacity Gaps

Over 70% of Nigerian extension agents lack ICT training, limiting e-extension delivery (Sennuga&Fadiji, 2020). Farmers' digital literacy is low, with only 25% of rural farmers able to navigate apps, particularly in northern states with 40% illiteracy (NAERLS, 2023). In SSA, similar gaps reduced e-extension impact by 40% in Zambia (Mapfumo et al., 2023). Cultural resistance, especially among older farmers, slows adoption, with 30% preferring traditional methods in Abia State (Onah et al., 2021). In Kano, 60% of agents reported inadequate training, reducing e-extension efficacy by 25% (Kagbu& Issa, 2021).

8.7 Policy and Coordination Challenges

Fragmented policies hinder e-extension. Nigeria's 2023 extension policy draft lacks clear ICT integration targets, delaying implementation (GFRAS, 2023). Weak research-extension-farmer linkages, via the Research-Extension-Farmer-Input-Linkage-System (REFILS), limit content relevance, with only 20% of advisories tailored to local needs (IFPRI, 2020). In SSA, uncoordinated stakeholder efforts reduced e-extension reach by 25% in Mozambique (FAO, 2021). In Nigeria, overlapping mandates between FMARD and state ADPs cause duplication, wasting 15% of extension budgets (Sydani Group, 2023).

8.8 Gender and Social Inclusion Barriers

Women farmers, who account for 50% of Nigeria's agricultural workforce, face disproportionate barriers, with only 30% accessing e-extension due to lower smartphone ownership (15% vs. 45% for men) (FAO, 2023). In northern Nigeria, cultural norms restrict women's mobility, limiting access to ICT kiosks, with only 20% of women in Kano accessing e-extension (NAERLS, 2023). Youth, while tech-savvy, often lack land ownership, reducing e-extension's impact, as seen in Oyo State, where 40% of youth farmers reported access barriers due to land tenure issues (Sennuga&Fadiji, 2020).

9. SOLUTIONS AND RECOMMENDATIONS

Addressing these challenges requires a multi-faceted, evidence-based approach, integrating policy, infrastructure, and capacity-building strategies. Enact the National Agricultural Extension Policy (2023 draft), allocating 5% of GDP to extension and mandating ICT integration, with clear targets to reach 70% of farmers by 2030 (GFRAS, 2023). Establish PPPs to fund platforms, as in Kenya, where Safaricom's Digifarm reached 1 million farmers, increasing incomes by 20% (FAO, 2021). Align with CAADP's 10% budget commitment, offering tax incentives for ICT adopters, such as 50% tax breaks for telecoms investing in rural networks (AU, 2022). Create a National E-Extension Taskforce, including FMARD, NAERLS, farmer cooperatives, and private actors, to coordinate efforts and ensure gender-inclusive policies targeting women farmers (FAO, 2023).

Incorporate e-extension into Nigeria's Climate Change Policy, mandating advisories on climate-smart practices, as in Ethiopia, where policy integration increased adoption by 25% (World Bank, 2021). Develop a regulatory framework for data privacy in e-extension platforms, ensuring farmer trust, as in India's e-Choupal, which boosted adoption by 30% through secure data systems (Deichmann et al., 2016). Establish a ₦10 billion e-extension fund to support app development and maintenance, targeting 5 million farmers by 2030 (Sydani Group, 2023).

9.1 Investment in Infrastructure

Deploy 10,000 solar-powered ICT kiosks in rural areas, costing ₦50 billion, through PPPs with telecoms like MTN and Airtel, as piloted in Rwanda's Smart Nkunganire program, which reached 70% of farmers (FAO, 2021; NCC, 2024). Expand 4G coverage to 80% of villages by 2030, leveraging Nigeria's $500 million telecom fund, which could add ₦200 billion in agricultural value (NCC, 2024). Subsidize smartphones, reducing costs from ₦30,000 to ₦10,000, as in Ghana, where subsidies increased adoption by 40% (FAO, 2021).

Invest in renewable energy, deploying 5, Invest in renewable energy, deploying 5,000 solar charging stations at ₦100,000 each, totaling ₦500 million, to address power outages (ITU, 2022). Partner with initiatives like the World Bank's Digital Agriculture Strategies, which allocated $1 billion for SSA connectivity, to fund Nigeria's rural networks (World Bank, 2024). In Kano, a pilot solar kiosk reached 2,000 farmers, increasing e-extension adoption by 15% (Sydani Group, 2023). Expand rural broadband through satellite internet, as piloted in Kenya, reaching 80% of remote farmers (FAO,2021).

9.2 Capacity-Building Programmes

Train 50,000 extension agents in ICT through the Sasakawa Africa Fund for Extension Education (SAFE), costing ₦20 billion over five years, as piloted in Uganda, where 80% of agents became ICT-proficient (SAA, 2021). Implement farmer literacy drives, targeting 80% digital literacy by 2030, modeled on Ghana's 70% success rate, which used radio and video for low-literacy farmers (FAO, 2021).

In Nigeria's north, radio advisories reached 70% of farmers, increasing seed adoption by 20% (NAERLS, 2023). Engage youth as digital ambassadors, training 100,000 to support community adoption, as in Ethiopia, where youth facilitators increased e-extension reach by 30% (World Bank, 2021). Develop multilingual apps in Hausa, Yoruba, Igbo, and Pidgin, as piloted by NFHL, which boosted adoption by 25% in diverse regions (NAERLS, 2023). Establish 500 e-extension training centers, costing ₦10 billion, to provide hands-on ICT skills, targeting women and youth (GFRAS, 2023). In Abia State, a pilot training center increased agent ICT proficiency by 40%, boosting e-extension delivery (Onah et al., 2021).

9.3 Strengthening Research-Extension-Farmer Linkages (REFILS)

Revive REFILS to develop localized content, linking universities, NAERLS, and farmers, as in India, where research-driven advisories increased yields by 20% (IFPRI, 2020; Deichmann et al., 2016). Pilot 50 research-driven e-extension hubs, costing ₦5 billion, to test innovations like drone-based soil mapping, as in Nigeria's Smart Farming Project, which reached 10,000 farmers (IITA, 2023). In SSA, Ethiopia's research-linked advisories increased adoption by 25%, a model Nigeria could scale (World Bank, 2021). Collaborate with institutions like IITA to develop AI-driven advisories, predicting pest outbreaks with 90% accuracy, as piloted in Kenya (FAO, 2021). Ensure content relevance by involving farmer cooperatives in content design, as in Uganda, where participatory approaches increased adoption by 15% (SAA, 2021). Establish 100 research-extension partnerships, costing ₦2 billion, to develop region-specific advisories, such as yam storage techniques in the southeast (NAERLS, 2023).

9.4 Monitoring and Evaluation

Establish KPIs, targeting 70% farmer reach by 2030, 20% yield gains, and 15% loss reductions. Use blockchain for transparent tracking, as in Ghana, where it ensured 95% accountability in extension delivery (FAO, 2021). Conduct gender-disaggregated impact assessments to ensure inclusivity, addressing the 50% female farmer base (FAO,2023).

Implement real-time feedback systems, like NFHL's SMS surveys, which achieved 80% response rates, to refine platforms (NAERLS, 2023). Allocate ₦2 billion for M&E systems, ensuring data-driven scaling.

9.5 Addressing Gender and Social Inclusion

Develop women-focused e-extension programs, providing subsidized smartphones and training, as in Rwanda, where women's adoption rose by 40% (FAO, 2021). Establish 1,000 women-led ICT hubs, costing ₦3 billion, to address cultural barriers, as piloted in Kano, where women's access increased by 20% (NAERLS, 2023). Engage youth through agribusiness incubators, as in Uganda, where 5,000 youth enterprises boosted incomes by 25% (SAA, 2021). Address land tenure barriers for youth through policy reforms, as 40% of youth farmers in Oyo State reported access issues (Sennuga&Fadiji, 2020). Pilot 50 youth-focused e-extension programs, costing ₦1 billion, to enhance agribusiness skills (GFRAS, 2023).

10. CASE STUDIES AND BEST PRACTICES

Nigeria: National Farmers Helpline (NFHL)

Launched in 2020, NFHL reached 1 million farmers by 2023, delivering SMS and voice advisories in Hausa, Yoruba, and Igbo. In Kano, it reduced post-harvest losses by 30% through storage tips, with 80% user satisfaction, saving ₦500 million (NAERLS, 2023). Challenges include network gaps, addressed through radio backups, reaching 70% of low-literacy farmers. Scaling NFHL to 5 million farmers could save ₦1 trillion annually, requiring ₦10 billion in investment (Sydani Group, 2023).

Sub-Sahara Africa: Kenya's iCow

The iCow app, serving 1 million farmers, provides SMS tips on livestock management, boosting milk yields by 20% and incomes by 15% at $0.01 per message (Qiang et al., 2012). Nigeria can replicate this with multilingual apps for crops like yam and cassava, targeting 3 million farmers by 2030. iCow's low-cost model is scalable through telecom partnerships (FAO, 2021).

Global: India's Digital Green

Digital Green's videos, viewed by 10 million farmers, increased adoption of best practices by 40%, boosting yields by 20–30% (Gandhi et al., 2009). Nigeria's youth, with 60% video literacy, can produce similar content on platforms like YouTube, reaching 30% of rural farmers (UNESCO, 2023). Piloting video-based extension in Enugu could reach 500,000 farmers, costing ₦2 billion (Sydani Group, 2023).

Nigeria: AgroTech SMS Platform

In Oyo State, AgroTech's SMS advisories reached 100,000 farmers, increasing maize yields by 20% and reducing losses by 15% through timely planting tips, saving ₦200 million (Etuk et al., 2023). Its success lies in low-cost delivery (₦5 per message) and partnerships with MTN, scalable to 2 million farmers with ₦5 billion investment (Sydani Group, 2023).

SSA: Rwanda's Smart Nkunganire

Rwanda's program subsidized smartphones, reaching 70% of farmers and increasing input adoption by 40% (FAO, 2021). Nigeria could adopt this model, subsidizing 1 million smartphones at ₦10 billion, targeting women and youth to close the digital gap (NCC, 2024).

10.1 Future Directions

Scaling e-extension requires sustained investment and innovation. Drones and AI, as piloted in Nigeria's Smart Farming Project, could enhance precision advisories, targeting 5 million farmers by 2030 with pest and soil data, costing ₦20 billion (IITA, 2023). Public-private consortia, modeled on India's e-Choupal, could integrate value chains, boosting incomes by 30% through market linkages (Deichmann et al., 2016). Satellite-based advisories, as in Australia, could predict weather with 95% accuracy, reducing crop losses by 20% (FAO, 2021).

Research should focus on long-term impacts, particularly for women and youth. Gender-disaggregated studies in Kenya revealed 25% higher benefits for women with tailored content (FAO, 2021). Nigeria could pilot 50 women-focused e-extension programs, costing ₦1 billion, to assess impacts.

Youth agribusiness incubators, like Uganda's, could train 100,000 youths, adding ₦500 billion to GDP (SAA, 2021). Blockchain-based platforms could ensure transparent input distribution, as in Ghana, increasing trust by 30% (FAO, 2021). Emerging technologies like IoT and big data analytics could revolutionize e-extension. In India, IoT sensors monitored soil moisture, increasing yields by 15% (Deichmann et al., 2016). Nigeria's IITA is piloting IoT in Kano, targeting 10,000 farmers by 2026, with potential 20% productivity gains (IITA, 2023). Machine learning models, as in Australia, could predict pest outbreaks with 90% accuracy, reducing losses by 25% (FAO, 2021). Scaling these requires ₦30 billion in R&D investment over five years.

CONCLUSION

E-extension offers a transformative pathway for Nigeria's agriculture, addressing low productivity, high losses, and ratio imbalances. Empirical evidence from 2020–2025 demonstrates 20–30% yield gains, improved livelihoods, and rural development potential through platforms like NFHL and AgroTech. Challenges, including limited technology access, infrastructure deficits, funding shortages, and gender barriers, demand urgent action. Policy reforms, infrastructure investments, capacity building, and stakeholder collaboration can scale e-extension to reach 70% of farmers by 2030, aligning with Nigeria's Agricultural Transformation Agenda and CAADP. Future research should evaluate scaled pilots, focusing on gender and youth impacts, to ensure inclusive, sustainable growth. By leveraging ICT, Nigeria can achieve food security, economic resilience, and rural prosperity, positioning itself as a leader in Africa's agricultural transformation.

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CHAPTER 3
AGRICULTURAL MOLDS: IDENTIFICATION, IMPACTS, AND MANAGEMENT STRATEGIES

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INTRODUCTION

Molds represent a diverse group of filamentous fungi that play a dual role in agricultural systems. Although filamentous fungi offer considerable benefits to industry, these molds cause the deterioration of various foodstuffs by reducing their organoleptic qualities and altering their nutritional value (Shuping and Eloff, 2017). They can grow in a wide variety of foods, including raw materials such as cereals, vegetables, fruit, meat and milk, as well as processed products (Filtenborg et al., 1996). These microscopic fungi can cause damage at different stages of food processing, such as harvesting, storage, packaging and transport of post-harvest products (Shuping and Eloff, 2017).

Fungal contamination causes serious economic losses for food manufacturers. Globally, it is estimated that over 25% of the world's crops are contaminated annually by mold-related pathogens, particularly during storage and post-harvest handling (Pitt and Hocking, 2009). Various species belonging to the genera Penicillium, Aspergillus and Fusarium cause plant diseases such as green and blue mould in citrus fruits, which are caused by the phytopathogens Penicillium italicum and P. digitatum (Moss, 2008). Fusarium head blight is associated with species of the genera Fusarium and Michrodochium. The main phytopathogenic species of the genus Fusarium is F. graminearum (Chetouhi et al., 2016). Black rot of onions is associated with Aspergillus niger (Narayana et al., 2007). These plant diseases often lead to food losses, reduced yields and impaired seed and health qualities in cereals.

The challenge lies not only in the presence of molds but also in their detection, identification, and timely control. Traditional methods such as morphological observation and culturing, though still widely used, often lack precision and are time-consuming. Recent advances in molecular biology and biotechnology have introduced faster and more accurate identification techniques, including PCR, DNA barcoding, and MALDI-TOF mass spectrometry. These tools are crucial for implementing effective monitoring and control strategies, especially in large-scale production systems.

Furthermore, the impact of molds on agriculture extends beyond physical contamination. Molds are capable of producing various dangerous secondary metabolites, including mycotoxins. Aspergillus, Penicillium and Fusarium are the main genera capable of producing these products (Pitt and Hocking 2009).

Aflatoxins, fumonisins, and deoxynivalenol (DON) are among the most studied and regulated mycotoxins worldwide due to their carcinogenic, immunosuppressive, and teratogenic properties. Contaminated crops are often rejected in export markets, leading to severe economic repercussions for farmers and national economies (Omotayo et al., 2019).

In order to inhibit or control the species responsible for fungal contamination, various strategies have been applied at different steps in the pre- and post-harvest stages. Usually, in the post-harvest stage, these strategies involve food processing, packaging and storage and rely solely or in combination on pH reduction, preservatives, limiting water activity, controlling oxygen tension, heat treatment and airtight packaging (Snyder and Worobo, 2018), as well as the use of good hygiene practices and the Hazard Analysis Critical Control Point (HACCP) system. In the pre-harvest stage, various agrochemicals have been developed and used to control phytopathogenic fungi. The introduction of various chemically synthesized products (since the 1800s) into agricultural production over the years has reduced the impact of many phytopathogenic molds and increased crop yields, resulting in financial benefits (Gianessi and Reigner, 2006).

However, fungicides have frequently been found to be toxic to non-target organisms such as earthworms, certain microorganisms and humans (genotoxicity), leading to imbalances in ecosystems (Patel et al., 2014). Most of these chemicals decompose slowly and are difficult to remove. They can also contaminate water systems and rivers (Stamatis et al., 2010).

Par conséquent, l'utilisation de produits naturels retient de plus en plus l'attention des agriculteurs dans la production d'aliments biologiques soutenu par les environnementalistes et certains consommateurs. Ces substances naturelles sont appelées des biopesticides, ils comprennent les produits chimiques qui peuvent dériver des microorganismes, des plantes ou des animaux. L'utilisation potentielle de micro-organismes dans le traitement des maladies fongiques des plantes est basée sur l'antagonisme naturel des microbes envers les pathogènes fongiques. Les résultats des études expérimentales et des essais sur le terrain de ces antagonistes contre les phytopathogènes fongiques sont prometteurs (Sharma et al., 2009).

Consequently, the use of natural products is becoming popular among farmers in organic food production, supported by environmentalists and certain consumers. These natural substances are called biopesticides and include chemicals that can be derived from microorganisms, plants or animals. The potential use of microorganisms in the treatment of fungal diseases in plants is based on the natural antagonism of microbes towards fungal pathogens. The results of experimental studies and field trials of these antagonists against fungal phytopathogens are promising (Sharma et al., 2009).

This chapter aims to provide a comprehensive overview of the main types of molds affecting agriculture, the current methods used for their identification, and their implications for food production and safety. It also discusses the economic and health-related consequences of mold contamination and explores strategies to mitigate their impact, including preventive agricultural practices, biocontrol options, and advances in early detection technologies.

1. AGRICULTURAL MOLDS: IDENTIFICATION, KEY SPECIES, AND MYCOTOXINS

Molds include all microscopic fungi that are of economic or environmental interest, whether beneficial or harmful. These microorganisms are eukaryotes with elongated cells forming filaments approximately 2 to 12 µm in diameter. They are either coenocytic or septate and are generally heterotrophic, as they are unable to synthesize organic matter from atmospheric carbon dioxide. All molds are saprophytes, growing at the cost of an inert or decomposing substrate (paper, wood, food, etc.). Some can be opportunistic, and in certain cases behave as parasites, proliferating on living animal or plant organisms and even humans whose immunity are weakened (Pitt and Hocking 2009, Samson et al., 2010). The development of mold involves two phases: a vegetative phase ensuring growth and nutrition and, almost simultaneously, a reproductive phase during which a large number of spores are formed, ensuring considerable dispersal power. These spores are produced by various modes of sexual and asexual reproduction, and their germination leads to the emergence of the vegetative form (Farian et al., 2021).

In agricultural systems, five major genera : Fusarium, Aspergillus, Penicillium, Alternaria, and Cladosporium, are recurrently associated with contamination in both pre- and post-harvest phases. In general, the classification of the fungi kingdom is based on various methods and criteria: the characteristics of the filaments (lower fungi and higher fungi), cultures, sexual reproduction, vegetative propagation, fungal physiology, and molecular studies.

1.1 Phenotypic Identification of Molds

Traditional identification of fungi is based mainly on microscopic morphological criteria (observation of reproductive structures) and macroscopic criteria (appearance of the mycelium) (Pitt and Hocking, 2009). Species identification is often supplemented by molecular methods.

1.1.1 Macroscopic Identification

Macroscopic identification is based on observation of the macroscopic characteristics of colonies according to the culture medium and incubation temperature. The most commonly used media are based on malt or potato extract (Malt Agar, PDA: Potato Dextrose Agar) or specific media (Czapeck) (Samson et al., 2010). Macroscopic identification is based on the observation of several criteria, including:

- The appearance and color of the colonies: smooth, hairless, moist, shiny or matt for leviriform fungi, while the colonies of filamentous fungi may be fluffy, woolly, cottony, powdery or granular. The color of the colony and the presence of pigment in the agar are important criteria for identifying fungi (Samson et al., 2010).
- Colony size and growth rate: colonies can be small, 5-6 cm in diameter for Aspergillus sp. and Penicillium sp., for example, or invasive, with a diameter of 7-8 cm for Botrytis sp. (Pitt and Hocking, 2009; Samson et al., 2010). The growth rate of colonies can be a good indicator for identifying a mold.

1.1.2 Microscopic Identification

Microscopic identification is based on the observation of different mold structures such as the vegetative apparatus, fruiting bodies and sometimes spores. Observations of fungal structures can be made using preparations mounted in lactophenol blue under an optical microscope. The most commonly used criteria are:

- The shape and branching of the conidiophores (straight, brush-like, tree-like, etc.),
- The type of phialides (monoverticillate, biverticillate, metulate, etc.),
- The size, shape, texture and grouping of conidia (in chains, compact heads, isolated, etc.),
- The presence or absence of vesicles or sterile elements.

In some cases, molecular identification is necessary for reliable identification, particularly to differentiate between morphologically similar species.

1.2 Molecular Identification

Traditional identification requires extensive experience in fungal taxonomy and is a long process. It requires a minimum of seven days of cultivation for conidia development and must sometimes be carried out on specific culture media. Furthermore, within a single genus, there are a large number of species, which makes distinction very complicated and requires a high degree of specialization. In addition, taxonomy is constantly evolving, which can lead to the reclassification of certain species. To avoid this problem, numerous identification methods based on molecular biology, mainly polymerase chain reaction (PCR) amplification, have been developed. Several studies aimed at identifying fungi have used molecular biology (Kuzdraliński et al., 2017).

The use of PCR is a technique that has revolutionized several fields of organism research in general and microorganism research in particular. It has been the basis for the development of rapid and accurate detection techniques for toxin-producing fungi (Yoo et al., 2017).

Unique DNA sequences must be selected as primers for the detection and identification of specific mycotoxin-producing fungi. Genes involved in the mycotoxin biosynthesis pathway may provide an ideal basis for the sensitive and accurate detection of these fungi. The study by Sohrabi and Taghizadeh (2018) enabled the identification by PCR of aflatoxin-producing Aspergillus strains in animal feed samples using specific primers for the aflD, aflP and aflR genes.

In addition, a multiplex PCR method was also developed to simultaneously detect mycotoxin-producing fungi of the genera Aspergillus, Fusarium and Penicillium, in order to assess their potential for multiple contamination in food and feed. The primers designed targeted the ITS (Internal Transcribed Spacer) regions for Aspergillus and Penicillium, and the EF-1α gene for Fusarium, generating specific amplicons of 170, 750 and 490 bp, respectively (Rahman et al., 2020). A similar approach was conducted using multiplex PCR combined with RT-PCR, allowing the simultaneous detection of different molds belonging to the genera Aspergillus, Fusarium, Penicillium and Alternaria. Multiple markers based on genes essential for the biosynthesis pathway of fumonisins (fum6 and fum8), trichothecenes (tri5 and tri6), zearalenone (zea2) and alternariol (PKSJ). The results showed that this method enabled rapid, sensitive and reliable detection of mycotoxin-producing fungi in stored maize seeds (Al-Zaban et al., 2023).

Although less practical for quantitative purposes, some applications combine the PCR approach with different technologies such as restriction fragment length polymorphism (RFLP) and denaturing gradient gel electrophoresis (DGGE). PCR-RFLP is a method based on combining PCR and amplification of a conserved DNA region with digestion of the PCR products by one or more restriction endonucleases. Each species encountered will therefore have its own typical restriction profile. This technique has enabled the identification and differentiation of the F. graminearum species from other Fusarium species using the unique restriction enzyme BsaHI in the transcription elongation factor (TEF 1-α) gene (Garmendi et al., 2018). Additionally, the method is valued for its relatively low cost and straightforward laboratory workflow, making it accessible for routine diagnostic use.

In the case of the method that combines PCR and denaturing gradient gel electrophoresis (PCR-DGGE), PCR-amplified DNA fragments of the same length but with different sequences are separated on a denaturing electrophoresis gel according to their melting temperature. Using this technique, Durand et al. (2019) were able to differentiate between the two species Aspergillus ochraceus and Aspergillus westerdijkiae, which are very similar from a phylogenetic and genomic point of view.

In addition to PCR-based techniques, other molecular biology methods have been developed, such as DNA chips, metagenomic approaches and mass spectrometry (MALDI-TOF: Matrix Assisted Laser Desorption Ionisation - Time of Flight).

The DNA chip technique is based on comparative genomic hybridization. It allows the level of gene expression (transcripts) to be analyzed at a given time and in relation to a reference sample. In this case, thousands of DNA oligonucleotide points are fixed to a small solid surface (chip), each point containing picomoles of a specific sequence (probe). The probe can be designed not only from conserved or anonymous genes, but also from genes linked to host specificity and pathogenicity or to mycotoxin biosynthesis pathways (Munaut et al., 2011). The design and validation of the first Affymetrix GeneChip DNA chip based on the entire genome of F. graminearum, aimed at establishing the expression profile of fungal genes in vitro, was carried out by Güldener et al. (2006).

More recently, a Japanese team developed a signal probe chip based on the FRET (Förster Resonance Energy Transfer) principle, initially designed for bacterial genes. In this study, they demonstrated its effectiveness on phytopathogenic molds (Aspergillus niger, Candida albicans, Chaetomium globosum) via specific detection of 18S rDNA, with a complete protocol taking less than 95 minutes (Maemura et al., 2024).

Metagenomic approaches refer to the study of genetic material directly in its natural environment, bypassing the need to isolate and cultivate the fungal species to be identified (Tedersoo et al., 2022). Combined with high-throughput sequencing (HTS), the metagenomic approach has enabled researchers to rapidly identify organisms present in a complex environmental sample.

The team led by Mesquita et al. (2024) revealed a high diversity of molds (up to 289 genera per sample) by analyzing 855 samples from extreme environments, while highlighting their adaptive potential through functional analysis of stress-related genes.

The most widely used method for taxonomic analysis of fungi remains targeted ITS sequencing (Terdersoo et al., 2022). The rapid development of databases such as UNITE (Nilsson et al., 2019), FungalTraits (Polme et al., 2020) and FunGuild (Nguyen et al., 2016) is enabling continuous improvement in the accuracy of taxonomic and ecological identifications. Thus, the growing list of sequenced genomes provides new information on fungal physiology, pathogenicity, mycotoxin biosynthesis, phylogenetic relationships, gene regulation and evolution. The availability of whole genome sequence data makes it possible to predict all the genes in the genome, and in general, the genes of secondary metabolite pathways tend to be grouped into a single cluster (Umemura et al., 2013).

Mass spectrometry coupled with matrix-assisted laser desorption/ionisation time-of-flight mass spectrometry (MALDI-TOF MS), initially used for protein analysis, is now widely used for the identification of microorganisms. Studies have demonstrated the high efficiency of the MALDI-TOF MS technique for identifying species and strains belonging to the Fusarium genus (Guo et al., 2022). This technique has also been used to differentiate species belonging to the genus Aspergillus section Flavi as well as genetic populations of Penicillium roqueforti with more than 94% correct identifications (Quéro et al., 2020).

1.3 Key Fungal Genera and Their Agricultural Impact

Aspergillus sp.

The genus Aspergillus belongs to the kingdom Fungi, division Ascomycota, sub-division Pezizomycotina, class Eurotiomycetes, order Eurotiales, family Aspergillacea (Samson et al., 2010). It includes 339 species described to date (Samson et al., 2014). Many of these species are of significant industrial, medical, and agricultural importance due to their diverse metabolic capabilities. Additionally, their widespread distribution in soil, air, and decaying organic matter highlights their ecological versatility and adaptability.

Species of the genus Aspergillus, belonging to the class Ascomycetes, are cosmopolitan and are isolated from a variety of biotopes such as soil, decomposing organic matter, stored cereals, but also in extreme environments (deserts, hypersaline substrates, etc.) (Abdel-Azeem, 2019). These molds are generally cultivated at a temperature of 22 to 25°C on conventional culture media (Sabouraud, malt agar). However, there are thermophilic species such as A. fumigatus that grow at temperatures above 45°C (Witfeld et al., 2021).

The main macroscopic characteristics for identifying mold species belonging to the genus Aspergillus are growth rate and color. With the exception of certain species, the growth rate of these molds is rapid to moderately rapid. After 7 days of incubation at 25°C on Czapek agar, the colonies of most species measure between 1 and 9 cm. Aspergillus colonies have a fluffy to powdery texture. The color of the surface and underside may vary depending on the species.

The fundamental microscopic morphology is the same for all species. The thallus of Aspergillus is formed of hyaline mycelial filaments. These are characterized by a fine, regular diameter and are septate and ramified. Upright, non-septate filaments (conidiophores) arise from the vegetative filaments and terminate in a vesicle of variable shape on which the conidiogenous cells or phialides are located. The phialides may be inserted directly onto the vesicle (uniserial heads) or carried by small structures inserted onto the vesicle (biseriate heads) called metulae or sterigmata (Samson et al., 2010). The genus Aspergillus is distinguished by the aspergillate head consisting of the vesicle, metulae, phialides and conidia (Pitt and Hocking, 2009).

The pathogenicity of Aspergillus in plants generally requires injuries or lesions to enable infection and colonization of the plant host (Sexton and Howlett, 2006). The infectious process involves several stages: conidia germination, followed by hyphal penetration and colonization of plant tissues (Sexton and Howlett, 2006). Aspergillus species produce various lytic enzymes, including proteases, which act as virulence factors by facilitating colonization, nutrient uptake and dissemination in plant tissues (Ogawa et al., 1992 ; Kunert and Kopecek, 2000). Melanin, a component of the fungal cell wall, confers resistance to UV rays and contributes to fungal virulence (Nosanchuk and Casadevall, 2006).

Aspergillus causes several major crop diseases. Corn ear rot, mainly caused by A. flavus, is a significant concern due to the production of aflatoxins (Zakaria, 2024). In peanuts, A. niger causes crown and root rot, while A. flavus and A. parasiticus are responsible for yellow mold (Torres et al., 2014).

Aspergillus infects a wide range of fruits, particularly grapes, where A. niger and A. carbonarius cause bunch rot and vine canker (Latorre, 2007). Citrus fruits, tropical fruits such as mangoes and papayas, and nuts are also susceptible to Aspergillus infections (Tournas and Katsoudas, 2005 ; Kolhe et al., 2021). Onions and garlic develop a characteristic black mold caused mainly by A. niger (Varga et al., 2012).

Fusarium sp.

Fusarium is a cosmopolitan genus belonging to the filamentous ascomycete fungi (Sordariomycetes/Hypocreales/Nectriaceae). This genus includes nearly 300 phylogenetically distinct species, discovered through molecular phylogenetics (Aoki et al., 2014). They are predominant in a wide range of environmental and climatic zones in different ecosystems, as they can colonize a wide variety of substrates. In addition, this genus is characteristic of soil, widely distributed and generally abundant in all soil types worldwide (Backhouse et al., 2001).

The optimum growth temperature for Fusarium is between 22 and 37°C. These molds are generally cultivated on an agar malt extract medium or PDA medium. The colonies are fluffy or cottony in appearance and vary in color (white, cream, yellow, pink, red, purple or lilac) depending on the species (Pitt and Hocking, 2009). These fungi are characterized by the presence of fusiform, septate macroconidia. The conidiophores are short and ramified. Phialides often have a single budding site (monophialide) located at the end of an elongated stipe, as is the case with F. solani. In the case of F. oxysporum, the stipe is short and stocky. In other species, such as F. proliferatum, the phialides have several budding sites (polyphialides). Phialides can produce two types of conidia: microconidia and macroconidia. Microconidia are conidia 4 to 8 µm long, uni- or bicellular, elongated, cylindrical or ovoid, isolated, solitary or grouped, arranged in whorls or, more rarely, in chains (F. verticilloides).

Fusarium species cause a wide range of plant diseases that affect all parts of plants, from roots to fruit. Cereals are particularly affected, with diseases such as Fusarium head blight caused by F. graminearum and F. avenaceum on wheat and barley (Brandfass and Karlovsky, 2006 ; Aktaruzzaman et al., 2014), and corn ear rot caused by F. verticillioides (Boutigny et al., 2011). Vascular wilting represents another major category of infections, including banana wilt (Panama disease) caused by F. oxysporum f.sp. cubense, oil palm wilt caused by F. oxysporum f.sp. elaeidis (Flood, 2007), and various specialised forms of F. oxysporum affecting potatoes (Aktaruzzaman et al., 2014), lilies (Prados-Ligero et al., 2008) and other crops. Fruit and vegetable rot is also a major economic problem, with F. solani causing rot in avocados (Wanjiku et al., 2020), and paprika (Jee et al., 2005), while F. proliferatum infects mangoes (Omar et al., 2018), pineapples (Barral et al., 2020) and chillies (Rampersad and Teelicksingh, 2011).

These pathogens demonstrate remarkable diversity in their infection strategies and host specificity. Some species, such as F. fujikuroi, cause unique diseases such as Bakanae disease in rice, characterized by abnormal elongation of the plants (Wulff et al., 2010), while others, such as F. verticillioides and F. graminearum, cause crown rot in bananas (Umaña-Rojas and Garcia, 2011). The ability of these pathogens to produce mycotoxins adds an additional dimension of concern, as infections are often accompanied by contamination with toxins such as fumonisins, deoxynivalenol (DON) or zearalenone, rendering agricultural products unfit for consumption (Ekwomadu and Mwanza, 2023). This pathological diversity, combined with its ability to survive for long periods in the soil and adapt to different environments, makes Fusarium one of the most problematic fungal genera for global agriculture, causing considerable yield losses and threatening food security.

Penicillium sp.

Penicillium is a very large and ubiquitous genus that currently contains 354 accepted species (Visagie et al., 2014) found in the natural environment and in food. Its main function in nature is the decomposition of organic matter, where species cause devastating rot as pathogens before and after the harvest of food crops.

Penicillium is one of the most common fungi found in a wide variety of habitats, including soil (Visagie et al., 2016), air, extreme environments (temperature, salinity, water deficiency and pH) (Visagie et al., 2016) and various food products (Sang et al., 2013). Penicillium colonies (other than P. marneffei) are flat, filamentous, with a velvety, woolly or cottony texture, and their color varies depending on the species, with a generally pale to yellowish underside. They grow at moderate temperatures ranging from 20 to 27°C.

Morphologically, Penicillium species are distinguished by the brush-like arrangement of their conidiophores. These conidiophores, borne by septate, hyaline mycelial filaments (the thallus), may be smooth or granular, simple or ramified, and end in a penicillium. They may be isolated, grouped in loose fascicles, or aggregated into well-defined coremia. The phialides, arranged in whorls at the ends of the conidiophores, may be inserted directly or via one or two rows of metulae. In the case of one row of metulae, the fungus is referred to as biverticillate, and in the case of two successive rows of metulae, it is referred to as triverticillate. The phialides (conidiogenous cells) give rise to conidia arranged in long chains. Conidia are unicellular spores that are globular, elliptical, cylindrical or fusiform, smooth or rough, hyaline, greyish or greenish (Pitt and Hocking, 2009).

Penicillium species are a major group of post-harvest pathogens that mainly affect stored fruit and vegetables, causing considerable economic losses in the agri-food industry. P. expansum is the most economically important pathogen, causing blue rot in apples and pears and producing patulin, a mycotoxin of concern for food safety (Luciano-Rosario et al., 2020). P. digitatum is the major source of post-harvest rot in citrus fruits worldwide, followed by P. italicum, causing green mold disease and blue rot in citrus fruits, respectively (Costa et al., 2019). These pathogens require wounds (stem removal, perforations, bruises, shoulder cracks) or natural openings (lenticels, stem ends, calyx sinuses) to penetrate and infect the tissue (Luciano-Rosario et al., 2020). Symptoms of rot initially appear as light brown to dark brown circular lesions with a defined margin between rotten and healthy tissue, with the affected tissue becoming soft and watery, and blue-green spore masses appearing on the surface of the infected areas (Costa et al., 2019).

These pathogens are characterized by their remarkable host specificity and sophisticated infection strategies. P. digitatum has a limited host range, being able to infect mainly ripe fruits belonging to the Rutaceae family, while P. expansum has a wider host range including pome fruits, stone fruits (cherries, plums, peaches), small fruits (grapes, strawberries, kiwis) and nuts (Costa et al., 2019; Luciano-Rosario et al., 2020). The mechanisms of infection involve modulating the pH of the host by secreting organic acids, producing cell wall degradation enzymes such as polygalacturonases, and avoiding oxidative burst in the host by increasing catalase production (Costa et al., 2019).

1.4 Impact of Mycotoxins on Agriculture and Human Health

Mycotoxins produced by the three dominant fungal genera: Aspergillus, Fusarium and Penicillium represent a major threat to global food security and public health, with more than 300 mycotoxins identified, only six of which are regularly detected in food (El-Sayed et al., 2022). These low molecular weight secondary metabolites (often less than 1000 Da) are ubiquitous in nature and virtually unavoidable, directly or indirectly contaminating the food chain through toxigenic fungal growth on food (El-Sayed et al., 2022). The term 'mycotoxin' was introduced in 1960 following an incident in the United Kingdom where 100,000 turkeys died after consuming feed contaminated with secondary metabolites of A. flavus (El-Sayed et al., 2022).

Aflatoxins

Aflatoxins, mainly produced by A. flavus and A. parasiticus (Kumar et al., 2017), are the most toxic and economically significant mycotoxins. Of the 20 aflatoxins discovered, AFB1, AFB2, AFG1 and AFG2 are the four most significant (Schuda, 1980), with AFB1 classified as a potential human carcinogen by the International Agency for Research on Cancer (IARC, 2012). These difuranocoumarin compounds (Schuda, 1980) cause severe hepatotoxicity, liver cancer and serious hepatitis, with outbreaks of acute aflatoxicosis leading to deaths, particularly in Kenya (Probst et al., 2007). The toxicity of aflatoxins involves their conversion by cytochrome P450 enzymes to AFB1-exo-8,9-epoxide, an active intermediate that binds to DNA and proteins (Eaton et Groopman, 2013).

Synergy with hepatitis B is particularly concerning, as combined exposure increases the relative risk of liver cancer by 60 times, compared to a relative risk of 2 for aflatoxin alone and 5 for hepatitis B virus alone (Oguz, 2017). Contamination particularly affects peanuts, nuts, figs, maize, rice, spices and dried fruit (Martinez-Miranda et al., 2019), with 37.6% of cereals tested contaminated with at least one aflatoxin (Andrade and Caldas, 2015).

Fumonisins

Fumonisins, produced mainly by F. verticillioides, F. proliferatum and related species (Rheeder et al., 2002), as well as by A. niger in certain crops (Astoreca et al., 2007), mainly contaminate maize and maize-based products (Cendoya, 2018). More than 15 fumonisin homologues have been identified (Braun et Wink, 2018), with FB1, FB2 and FB3 being the most abundant forms, FB1 being the most dangerous (Damiani et al., 2019). These toxins cause oesophageal cancer in humans (Stoev, 2017) and equine leukoencephalomalacia, porcine pulmonary oedema, hepatotoxicity and nephrotoxicity in animals (Voss et al., 1998). Fumonisin production occurs mainly during the pre-harvest period, but can also occur after harvest under unfavourable storage conditions (Chulze, 2010). The impact extends to marine species, with fumonisins affecting the hepatic expression of growth hormone receptors and insulin-like growth factor in Nile tilapia (Silva et al., 2019).

Ochratoxin A

Ochratoxin A (OTA), isolated and characterized in 1965 (Van Der Merwe et al., 1965), is produced by various species of Aspergillus (A. ochraceus, A. carbonarius, A. niger, A. westerdijkiae, A. steynii) and Penicillium (P. verrucosum, P. nordicum) (Samson et al., 2004). This mycotoxin has hepatotoxic, nephrotoxic, neurotoxic, teratogenic, embryotoxic, genotoxic, immunotoxic and carcinogenic properties (Pfhol-Leszkowicz and Manderville, 2006) and was classified as a potential human carcinogen (category 2B) by the IARC in 1993. OTA is particularly associated with endemic nephropathy in the Balkans (Maaroufi et al., 1995) and chronic interstitial nephritis in Tunisia (Maaroufi et al., 1995 ; Fuchs and Peraica, 2006).

Its persistence in the body, due to significant plasma protein binding (90%) and enterohepatic recirculation, explains its particular toxicity (Malir et al., 2016). OTA is found in more than 90 different foods of plant and animal origin, including cereals, coffee, wine and spices, with average concentrations between 0.1 and 100 ng/g (Ostry et al., 2015).

Trichothecenes and Zerealenone

Trichothecenes, a large family of structurally similar sesquiterpenoids (Abdallah et al., 2018), are produced by various species of Fusarium, Cephalosporium and Trichoderma. These toxins cause immunosuppression, cytotoxicity, skin necrosis, haemorrhages, anaemia and gastrointestinal lesions (He et al., 2010). Their production is influenced by genetic and environmental factors, with tropical and subtropical conditions favouring their development (He et al., 2010). Zearalenone, an oestrogenic mycotoxin produced by F. graminearum, F. culmorum and related species (Gadzala-Kopciuch et al., 2011) contaminates maize, sorghum, wheat, rice, barley, oats, nuts, soybeans and sesame (Abia et al., 2013). Due to its similarity to natural oestrogens, it disrupts hormonal balance (Kowalska et al., 2016), causing reproductive and fertility problems in mammals (Tralamazza et al., 2016), with bioavailability reaching up to 80% in humans and animals.

2. ECONOMIC IMPACT AND AGRICULTURAL LOSSES DUE TO MOLDS AND MYCOTOXINS

Fungal contamination of crops is one of the major causes of agricultural losses worldwide, affecting approximately 25% of annual harvests (Marin et al., 2013). Molds of the genera Aspergillus, Penicillium and Fusarium cause direct damage to crops by deteriorating grain quality, reducing seed germination and decreasing yields. In arid regions and subtropical climates, Penicillium digitatum alone accounts for 90% of post-harvest losses in citrus cultivation (Costa et al., 2019). For pome fruits, blue mould caused by P. expansum results in losses estimated at between 1 and 5% on fruits treated with fungicides, representing economic losses of $50 to $250 million per year in the United States alone (Luciano-Rosario et al., 2020).

Fusarium infections cause devastating diseases such as wheat ear blight, banana wilt (Panama disease) and corn ear rot, with considerable socio-economic impacts on major food and cash crops (Ekwomadu & Mwanza, 2023). Global citrus production, estimated at around 98.3 million tonnes including oranges, mandarins, lemons and grapefruit, suffers significant losses due to post-harvest pathogens, with nearly 50% wasted at various stages of post-harvest storage (Costa et al., 2019).

Beyond yield losses, mycotoxin contamination generates considerable economic costs for the entire agri-food sector. Although impossible to calculate exactly, it is estimated that mycotoxin contamination causes significant economic losses as well as food safety and public health problems (El-Sayed et al., 2022). Aflatoxins are a major economic concern, with estimated losses ranging from 50 to 250 million dollars annually in the United States for contamination of agricultural products alone. The decrease in the value of grains as animal feed and export products is significant, as contamination has been linked to increased mortality in farm animals (Smith and Moss, 1985). Strategies to control mold and mycotoxins also generate substantial costs for producers. The application of pre-harvest and post-harvest fungicides, although limited for some crops, represents a significant economic investment. For citrus fruits, four post-harvest fungicides are currently registered for disease management, but the emergence of resistant populations of Penicillium spp. significantly reduces their effectiveness, requiring repeated applications or the use of more expensive products (Luciano-Rosario et al., 2020). Sanitary methods in production and packing stations, including disinfecting containers, cleaning infrastructure and maintaining appropriate levels of chlorine in grading water, are critical components of an integrated management strategy but increase operational costs. Mycotoxin monitoring and analysis technics, using techniques such as high-performance liquid chromatography (HPLC), ELISA tests or mass spectrometry (LC-MS), also represent significant financial investments to ensure regulatory compliance (El-Sayed et al., 2022). In addition, producers must often invest in training personnel to correctly implement these monitoring protocols, which further raises total expenditures.

2.1 Regulatory Constraints and Global Risk Distribution

The European Union, the US Food and Drug Administration (FDA) and many other regulatory authorities have established strict maximum limits for various mycotoxins in food and animal feed. For example, the EU has set limits of 20 to 350 µg/kg for zearalenone in various processed and unprocessed cereal products (EFSA, 2014), while the limit for patulin is set at 50 µg/L for fruit juices and derived products, 25 µg/L for solid apple products, and 10 µg/L for juices and foods intended for infants and young children (El-Sayed et al., 2022). These regulations lead to frequent rejections of contaminated batches at frontiers, generating significant economic losses for exporting countries, particularly developing countries that depend on export revenues from these crops to import food produced elsewhere (Ostry et al., 2015). The loss of commercial crops due to fungal diseases destabilizes the economies of developing nations and increases the threat to food security (Ekwomadu & Mwanza, 2023).

The economic impact differs widely across geographical regions. Although robust agricultural practices and effective quality control mechanisms are expected to reduce the risk of mycotoxin exposure in industrialized countries, several developing regions are currently at high risk of severe to extreme mycotoxin prevalence (Gruber-Dorninger et al., 2019). Mycotoxins are particularly prevalent in North and Central America and South Asia, with moderate to high levels in Southeast Asia, Oceania and Europe (Gruber-Dorninger et al., 2019). Climate change is making this situation worse, with changes in traditional aflatoxin occurrence areas making Mediterranean areas more susceptible to aflatoxin contamination due to increases in average temperatures, CO_2 levels and rainfall patterns (Leslie, 2008). This geographical expansion of fungal contamination increases the vulnerability of new agricultural regions and raises the overall costs of mycotoxin management in areas that were previously less affected. Unfavorable agroclimatic conditions, particularly a lack of agricultural resources and inadequate post-harvest activities (inappropriate drying techniques, handling procedures, packaging materials and methods, storage and transport conditions) promote fungal growth and mycotoxin accumulation (Marin et al., 2013).

3. STRATEGIES FOR MANAGING AND PREVENTING MOLD AND MYCOTOXINS

3.1. Pre-Harvest Control Strategies

RNA-based fungicides offer remarkable specificity against mycotoxigenic fungi. This technology uses double-stranded interfering RNAs (dsRNAs) that target genes essential for mycotoxin production or pathogen virulence (Cai et al., 2018). Applied by spraying, these molecules enable gene silencing without modifying the host plant, thereby circumventing concerns related to GMOs (Lefebvre et al., 2019). Studies demonstrate the effectiveness of this approach against Fusarium graminearum, which causes fusarium head blight in wheat and produces DON and zearalenone (McLoughlin et al., 2018; Wang et al., 2016). The mechanisms involve either direct absorption of the RNAs by the pathogens during infection or their accumulation in plant tissues followed by transfer to fungal cells (Wang and Jin, 2017).

Biocontrol is a particularly effective natural alternative for Aspergillus and Fusarium species. Fungi of the genus Trichoderma demonstrate notable efficacy against Fusarium spp. through several complementary mechanisms: competition for nutrients and space, synthesis of antifungal substances and secondary metabolites, and induction of plant defenses (Bubici et al., 2019; Harman et al., 2004; Hermosa et al., 2013). A recent innovation combines Trichoderma harzianum with biosynthesized selenium nanoparticles, showing a significant reduction in fumonisin (FB_1) production of 63% and DON of 76%, accompanied by a decrease in the expression of mycotoxin biosynthesis genes (Hu et al., 2019). This biological-nanomaterial synergy represents a promising approach for the simultaneous control of pathogens and their toxins.

3.1.1 Natural Products and Biofumigation

Natural antifungal products are attracting growing interest for pre-harvest control of mycotoxins. Biofumigation, which involves incorporating freshly harvested cover crops into the soil, releases glucosinolate degradation products (isothiocyanates) that cleanse the soil of fungal pathogens (Calmes et al., 2015).

For the control of Fusarium graminearum on wheat, mulching treatments composed of cover crops (white mustard, Indian mustard, alfalfa) suppress infection, reduce mycotoxin load, and improve grain yield (Drakopoulos et al., 2020). Polyphenols extracted from plants also demonstrate inhibitory properties against mycotoxin production: umbelliferon and quercetin downregulate the genes involved in the biosynthetic pathway of patulin produced by Penicillium expansum (Sanzani et al., 2009), while chlorogenic and gallic acids inhibit the production of AFB_1 by Aspergillus spp. in legumes (Telles et al., 2017). These natural compounds act through their antioxidant properties, lipophilicity, structural modifications of the fungal membrane, and negative regulation of gene expression.

3.1.2 Stimulation of Defenses and Passive Approaches

Stimulating plants natural defenses offers a preventive strategy against infection by Aspergillus, Penicillium, and Fusarium. Signaling molecules such as salicylic acid and jasmonic acid induce effective systemic resistance against these pathogens (Park et al., 2007; Robert-Seilaniantz et al., 2011). Periodic low-dose UV-C treatments stimulate the production of defensive secondary metabolites and increase resistance, particularly against Botrytis but also applicable to other post-harvest pathogens (Jin et al., 2017; Scott et al., 2019).

An innovative passive approach uses (meth)acrylate polymers that block the adhesion of fungal spores to plant surfaces (Vallières et al., 2020). This anti-adhesion strategy, although mainly tested on Botrytis cinerea, could be applied to Aspergillus and Penicillium conidia. The major advantage lies in the absence of selective pressure favoring resistance, as the development of increased attachment capacity poses considerable evolutionary barriers (Cohen-Gihon et al., 2011).

3.2 Post-Harvest Control and Detoxification

Nanoparticles and magnetic materials offer environmentally friendly solutions for the adsorption and detoxification of mycotoxins. Selenium nanoparticles (SEN) biosynthesized by Trichoderma harzianum effectively reduce fumonisins (Fusarium) by 63% and DON by 76% (Hu et al., 2019).

Zinc oxide (ZON) and silver (SLN) nanoparticles inhibit the growth of ochratoxigenic and aflatoxigenic Aspergillus spp. and Fusarium spp., while reducing the production of OTA, aflatoxins, and FB_1 in model food systems (Hassan et al., 2013). The mechanism of action of ZON involves the production of reactive oxygen species that damage the membrane lipid bilayer of fungal hyphae, causing cell deformation and rupture (Pietrzak et al., 2015).

Natural adsorbents also show significant potential. Magnetic particles (Fe_3O_4) coated with chitosan effectively adsorb patulin (Penicillium) from fruit juices, while nanocellulose conjugated with retinoic acid adsorbs AFB_1 without residual toxicity (Jebali et al., 2015; Luo et al., 2017). Magnetic carbon nanocomposites synthesized from corn by-products show remarkable potential for AFB_1 detoxification, achieving up to 90% adsorption at pH 7 within 180 minutes of application (Zahoor and Ali Khan, 2016). More recently, calcium bentonite used as a food additive effectively removes OTA (Aspergillus and Penicillium) from cheeses such as Karish and Roomy, with initial concentrations of 3,399 and 4,138 µg/kg respectively, while preserving sensory attributes and food safety (Hamad et al., 2022).

3.2.1 Physical Treatments and Essential Oils

Electrolyzed water (EW) and ozonated water treatments are promising alternatives for post-harvest decontamination of products susceptible to Aspergillus and Penicillium. EW, produced on site by electrolysis of water and NaCl, generates free active chlorine and other reactive species (O_3, ClO_2, H_2O_2, hydroxyl radicals), reducing the formation of chlorinated by-products while maintaining superior efficacy to conventional NaOCl (Graça et al., 2020; Koide et al., 2009). Ozonated water, which is chlorine-free, decomposes into oxygen and water without toxic residues (Brodowska et al., 2018), although its limited stability may affect its effectiveness against certain filamentous fungi.

Essential oils (EOs) show notable antifungal activity against Aspergillus, Penicillium, and Fusarium. Curcuma oil (Curcuma longa) completely inhibits the growth of A. flavus and aflatoxin contamination in corn (Hu et al., 2017), while spearmint oil (Mentha spicata) inhibits toxin production by A. flavus in chickpeas for one year by disrupting the plasma membrane (Kedia et al., 2016).

For ochratoxin A, capsaicin inhibits production by Aspergillus section Nigri and A. carbonarius by 78.1% and 61.5%, respectively, and garlic and wild oregano essential oils completely prevent OTA production (Kollia et al., 2019; Ozcakmak et al., 2017). Regarding Fusarium, Curcuma longa oil completely suppresses the growth of F. graminearum and reduces the production of zearalenone to low levels (Naveen Kumar et al., 2016; Perczak et al., 2016).

3.3. Preservation of Stored Foods

Biopreservation using lactic acid bacteria (LAB) offers an effective strategy against deterioration caused by Aspergillus and Penicillium in stored food products. LAB of the Lactobacillus and Streptococcus genera produce organic acids, bacteriocins, and fatty acids that disrupt the fungal cell membrane, with FDA and EU approval as food preservatives (Oliveira et al., 2014; Ribes et al., 2018). These biopreservatives extend the shelf life of refrigerated dairy products by at least 3 weeks, effectively controlling yeasts and molds (Leyva Salas et al., 2018).

Nanoemulsions of clove and oregano essential oils inhibit Zygosaccharomyces bailii in salad dressings with minimum inhibitory concentrations of 1.75 mg/mL (Ribes et al., 2019), although their organoleptic impacts require careful evaluation. Flavanones extracted from citrus by-products (hesperidin, neohesperidin, naringin) achieve at least a 95% reduction in patulin (Penicillium) accumulation (Salas et al., 2012). β-cyclodextrin complexes with bioactive phenols based on the nanosponge technique show promising potential for inhibiting fungal attacks and detoxifying mycotoxins (Makhuvele et al., 2020).

CONCLUSION

Phytopathogenic molds of the genera Aspergillus, Penicillium, and Fusarium represent a major, multidimensional threat to global agriculture and food security. This chapter has highlighted the complexity of the interactions between these filamentous fungi and their plant hosts, from complex infection mechanisms to the considerable economic and health impacts they cause.

Accurate identification of these pathogens, combining traditional phenotypic approaches with advanced molecular techniques, is the foundation for effective management of the diseases they cause. The three fungal genera studied have distinct pathogenic profiles but all converge toward devastating economic consequences. Aspergillus spp., particularly A. flavus and A. parasiticus, mainly contaminate pre-harvest crops in warm regions and produce the most dangerous aflatoxins known. Penicillium spp. dominate post-harvest infections of stored fruits, with P. expansum and P. digitatum causing blue rot in apples and green mold in citrus fruits, respectively, resulting in losses of several hundred million dollars annually. Fusarium spp. affect a wide range of crops, causing devastating diseases such as fusarium ear blight, vascular wilt, and root rot, while producing various mycotoxins including fumonisins, trichothecenes, and zearalenone.

The production of mycotoxins by these fungi adds a critical toxicological dimension to the phytopathological problem. With 25% of global crops affected annually and more than 300 mycotoxins identified, mycotoxin contamination represents not only a direct economic loss due to product deterioration, but also a major health risk for human and animal populations. The carcinogenic, hepatotoxic, nephrotoxic, and immunosuppressive properties of these toxins, combined with their thermostability and persistence in the food chain, make them particularly concerning contaminants. The resulting strict international regulations create significant trade barriers, particularly affecting developing countries whose economies depend on agricultural exports.

In view of these challenges, integrated management appears to be the only way forward, combining preventive cultivation practices, rational chemical control, biocontrol, rigorous post-harvest management, and biotechnological innovations. The emergence of fungicide resistance highlights the urgent need to develop sustainable alternatives, while advances in genomics offer promising prospects for identifying resistance genes and developing tolerant varieties. Climate change, by altering the geographical distribution of these pathogens and extending the areas at risk to regions previously unaffected, adds an additional dimension of urgency to these research and development efforts.

Future prospects require a multidisciplinary approach integrating mycology, plant pathology, genomics, biotechnology, and social sciences to develop adapted solutions to local contexts. Improving monitoring systems, strengthening analytical capacities, particularly in developing countries, and transferring technologies to farmers are priorities for reducing the overall impact of these pathogens. International collaboration remains essential to harmonize regulatory standards, share knowledge, and develop effective management strategies on a global scale. Ultimately, future food security will depend on our collective ability to understand, monitor, and control these ubiquitous fungi that continue to threaten global agricultural production.

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