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Understanding Technology Diffusion in the Agricultural Sector

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Abstract

The paper introduces the basic concepts related to adoption, diffusion and innovation in the agricultural sector. This paper introduces relevant definitions and issues, examines conceptual models of technology diffusion in agriculture, followed by a description of the process of technology discovery. The paper furthermore explores the channels and mechanisms of diffusion, the factors influencing adoption, the adaptation of technologies to local contexts, empirical studies illustrating innovation and diffusion patterns, the role of government policies and international organizations, and the impact of technology diffusion on agricultural productivity, sustainable development, and food security and livelihoods. The paper then discusses innovation and diffusion of agricultural biotechnologies and precision agricultural technologies by summarizing the experiences and lessons learned from insect resistant and herbicide tolerant maize, insect resistant cotton and precision agriculture technologies in a selected set of countries. The paper draws up policy lessons and recommendations that may be useful to policy and decision makers considering such technologies in their jurisdiction.

Keywords: innovation, diffusion, genetically modified crops, agriculture, Least Developed Countries

JEL:

O13 Agriculture • Natural Resources • Energy • Environment • Other Primary Products

O33 Technological Change: Choices and Consequences • Diffusion Processes

Q16 R&D • Agricultural Technology • Biofuels • Agricultural Extension Services

O31 Innovation and Invention: Processes and Incentives

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Disclaimer

The use of trademarks, name brands, company and product names must not be considered endorsement, promotion, validation or recommendation by the author. Due to many changes in the seed and pesticide industry through mergers and acquisitions, we will make use of the current company when a legacy company is mentioned in the text.

Introduction to Paper Series

This is the first paper in a two part paper series. The structure of these papers is as follows. The first paper “Understanding and Characterizing Technology Diffusion in the Agricultural Sector - The case of Bt/HT maize, Bt cotton and precision agricultural technologies” introduces the basic concepts related to adoption, diffusion and innovation in the agricultural sector. This paper discusses relevant definitions, examines the conceptual models of technology diffusion in agriculture, followed by a description of the process of technology discovery. The paper explores the channels and mechanisms of diffusion, the factors influencing adoption, the adaptation of technologies to local contexts, empirical studies illustrating diffusion patterns, the role of government policies and international organizations, and finally, the impact of technology diffusion on agricultural productivity, sustainability, and rural livelihoods.

The paper compares and contrasts the experiences between two biotechnology applications in maize and cotton, with that of precision agricultural technologies in a selected set of countries. This paper develops an international and muti-regional characterization of the diffusion, adoption and adaptation of agricultural innovation. The paper contrasts the roles of public, private and mixed public and private sectors experiences with a focus on genetically modified crops, while briefly discussing emerging genome edited crop experiences. The paper discusses who are the innovators, agricultural flows, and the enabling environment issues which determine outcomes.

The Annex of Paper 1 discusses a proposed conceptual framework that may be used to examine comprehensively the agricultural innovation process considering relevant factors identified in this background paper including the product life cycle, scaling-up, enabling environment, information & knowledge flows and political economy issues. Paper 2 presents a qualitative example of an application of the conceptual framework for the case of Maize Lethal Necrosis resistant varieties developed for East Africa through gene editing approaches, which is in the final stages before commercial release in Kenya and possibly other countries.

The second paper “Agricultural innovation adoption and diffusion in Least Developed Countries: Experiences and way forward” will build on the insights from Paper 1, by focusing on how innovation diffuses across the different segments in a few selected Least Developed Countries (LDCs). The purpose is to summarize the available literature and experiences in LDCs in contrast to that of industrialized countries. Based on the available evidence, we will discuss the role of innovation capabilities, enabling environment (legal, regulatory, IP of selected LDCs and show how diffusion takes place across their agriculture value chain. The paper describew the main challenges that the agricultural innovation systems and its stakeholders face in LDCs. The paper concludes by characterizing features from functional innovation ecosystems and suggests how these economies were able to upscale their agriculture value segments and by suggesting policy options to advance agricultural innovation in LDCs.

We hope that collectively these two papers will inform WIPO stakeholders about science, technology and innovation and the adoption and diffusion issues that may be addressed through proper landscape analysis, and the development and implementation of comprehensive policies focused on developing and enhancing the science, technology and innovation systems and the enabling environment for agricultural technologies.

Section 1. Understanding and Characterizing Technology Diffusion in the Agricultural Sector

1.1 Introduction

Global agricultural innovations have been at the forefront of helping address agricultural productivity constraints, food insecurity, and poverty issues. These efforts have yielded significant innovations that have contributed significantly to agricultural productivity and sustainability (Bailey-Serres et al., 2019; Dennis et al., 2007). Productivity has increased -including that of most factors of production- globally but this growth has been heterogenous, even having areas with negative productivity growth. In some instances, chronic -but heterogenous- R&D under investments in both developed and developing countries have been observed (Nin-Pratt, 2016).

The ability of the agricultural sector to meet the growing global demand for food is closely linked to agricultural innovations development, scaling up and widespread diffusion and utilization. The economic growth and enhanced productivity promised by agricultural innovations can only be realized when these advancements are effectively diffused and adopted across farming communities. In fact, the process by which technological improvements spread among producers, both within and across national borders, is arguably as critical as the initial stages of innovation to ensure achieving sustained long-term growth (Stokey, 2021). Understanding the dynamics of the diffusion and the adoption processes are therefore critical for researchers, policymakers, and all stakeholders aspiring to ensure global food security and promote sustainable agricultural development.

Because of this state of affairs, the need continues to identify and promote policies and approaches to ensure the continued development, scaling, adoption, diffusion and adaptation of agricultural innovation resources and tools to address specific agricultural productivity and sustainability issues (Arndt et al., 2020). To successfully leverage such resources and tools, it is essential to define a novel understanding of the food system's changing roles. This will require an enhanced understanding of the food system's ability to respond to emerging challenges such as climate change and human pandemics, comprehensively address poverty while ensuring equitable access and helping achieve the aspirational goals of securing social returns to genetic resources, innovation tools and all the products of the ag innovation system. This includes the benefits from the use of agricultural biotechnologies, including the promissory potential from agricultural gene editing (Ag GEd) technologies (Gao, 2018).

This section aims to conceptually map and empirically illustrate the complex process of agricultural technology diffusion. To accomplish this task, we need to address innovation as it moves from the initial stages of discovery to its eventual diffusion, adoption, and adaptation across various countries and regions. By synthesizing existing research and available data, this paper seeks to provide a comprehensive understanding of the factors, challenges, and mechanisms involved with a focus on the diffusion process.

1.2 The nature of technological diffusion in the agriculture sector

Context and Background

The discussion in this section -and paper series- describes the current situation where existing agricultural innovations and models used to examine them, have been characterized by fragmented and uncoordinated research applications (Faure et al., 2019). This implies that existing models examining ag innovation systems have not considered enough different and critically relevant innovation determinants. This includes the linkages and power relationships between actors, sectors, and innovation system clusters in their implementation and other aspects such as the political economy, enabling environment, product life cycle and stewardship issues.

The insufficient attention to relevant innovation determinants contributed to the development of weak synergy and complementarity policy research explorations, leading in many cases to top-to-bottom -often linear- agricultural innovation processes up to the technology scale-up (Alston et al., 2023; Kohl, 2023). Most importantly, farmers, consumers, and other relevant stakeholders were often left out of technology decision-making (Veldhuizen et al., 2020). The scaling up and diffusion processes have received much less attention than the R&D and adoption processes (Colton, 2015; Schut et al., 2020).

A critical issue relevant to this description is that agricultural innovations increasingly deal with knowledge-based products and technologies. The implication of this fact is the need to understand knowledge stocks and flows (tacit and codified), as well as actors, organizations, laws, policies, and regulations that have an impact and provide an impact pathway from R&D investments to the diffusion of ag innovations so that they are in the hands of farmers (Nin-Pratt & Stads, 2023). Exploring governance coordination between policy, regulatory, and legal processes, and actor and other governance drivers will help identify the reasons why such governance systems may or may not be conducive to an enabling environment facilitating agricultural innovation (Kohl, 2023).

An emphasis on the political economy angles of investment and development setting will help define governance and technology R&D, scaling up and deployment context. A basic task at hand is to identify and enhance desirable conditions by which the scaling-up, adoption and diffusion of valuable ag innovations occur. These conditions may be institutional, regulatory, policy, or legal. These will need to be framed within the socioeconomic and cultural context in which these technologies exist. The objective is to enhance the equitable access and expansion of the technology frontier, especially for smallholder farmers in low and middle-income countries (LMICs). The imperatives of securing equitable access and expansion of the technology frontier, while addressing multiple social and economic challenges, are a mandate of the international and national agricultural research systems.

Low and middle- countries have significant R&D trends reflecting different levels of underinvestment and gaps, although this is changing over time (Nin-Pratt & Stads, 2023). Subsequently, they also have gaps in ensuring equitable access to technologies. Resource-poor farmers and households typically do not have ready access to technologies that may help address their binding productivity constraints. It is therefore critical to define desirable conditions within the enabling environment for agricultural innovation that will help ensure equitable access. The enabling environment will then be firmly based on the farmer, household, community, and country context.

The enabling environment context in turn will be connected to the political economy and governance environment in which ag bio-innovations and other innovations operate. An important access issue is a focus on economies of scale of R&D processes and technology scaling-up efforts. This implies that technology selection, scaling up, adoption and diffusion are critical policy research issues, but also the institutional and governance environment in which technology developers operate and the type of developers and innovators. This implies re-examining the role and operational approach that the public and private sectors have in supplying ag innovations especially to smallholder farmers and households in LMICs.

The ag innovation climate in LMICs and developed countries has evolved and become more complex. So have binding constraints to ag innovations. Connections and linkages in the ag innovation system have developed and expanded between internal and external forces, including public vs private actors and ag innovation policy incentives. Because of this existing landscape, a pressing need exists to examine and consider ag innovations fit across the entire food system and how the enabling climate can empower ag innovations and innovation in general.

To understand the enabling environment for ag innovations and in particular biotechnology and Ag GEd applications, we need to examine what worked with previous ag bio-innovations and why. This will help in the process of implementing any foresight exercise that will proactively address potential gaps and hurdles to future ag bio-innovations including Ag GEd and other new plant breeding techniques. This should lead to the development and deployment of well-coordinated strategic platforms, especially international -but also national- research systems that will address the enabling environment in a comprehensive and coherent manner with a focus on delivering technologies to LMICs producers.

1.3 Technology adoption, diffusion and adaptation – definitions and foundational concepts

We start by defining key terms frequently used in agricultural research including : agricultural technology, adoption, diffusion, and adaptation. These concepts are fundamental to understanding the dynamics of innovation and change within agricultural systems.

Innovation

Agricultural innovation can be defined as the introduction and adoption of novel or significantly improved products, processes, organizational methods, or marketing approaches within the agricultural sector (Fuglie, 2016). This definition extends beyond product or technological advancements to include a broad range of developments aimed at enhancing productivity, efficiency, sustainability, and resilience across diverse agricultural systems. Innovations can be a novel crop variety, a more efficient farming technique, a new type of agricultural input, or even an improved practice developed by farmers themselves (Barrett et al., 2022).

Key innovation concepts and types are summarized in Box 1 (Fuglie, 2016; Leeuwis & Aarts, 2021a; Spielman & Birner, 2008). The most common type of innovations are product, technological and service innovations. As the innovation systems have evolved and the need to address more complex problems in more comprehensive approaches. Other innovations may be process and architectural, organization and institutional, and social and environmental.

Box 1. Key agricultural innovations types

- **Product, Technological and Service** innovations relate to the creation and deployment of new tools, machinery, crop varieties, livestock breeds, and digital technologies. Examples of the later include precision agriculture tools such as remote sensing applications, and artificial intelligence for crop management

- **Process and Architectural** innovations include improved or entirely new methods of cultivation, harvesting, processing, and distribution of agricultural products along the value chain. This can include the adoption of no-till farming practices, integrated pest management strategies, advanced irrigation techniques, and improved food safety protocols throughout the value chain.

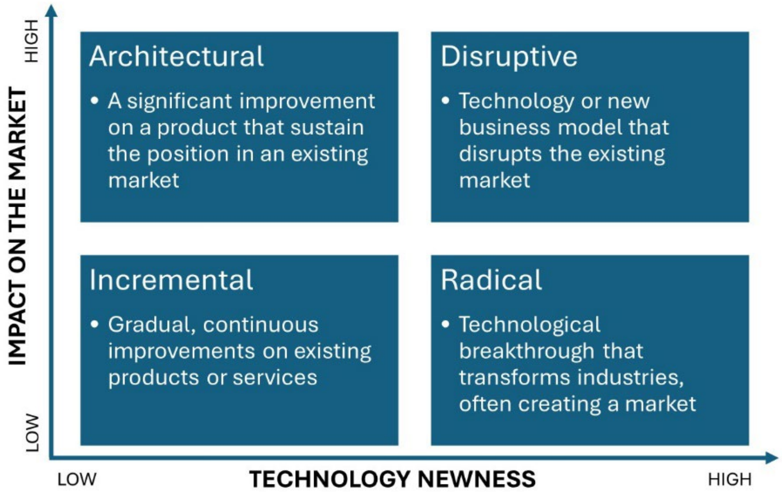
- **Organizational and Institutional** innovation may include novel ways of organizing agricultural production, value chains, and market access that go beyond products or processes. This may involve new business models for farmer organization or association types, or marketing options including contract farming models, certification schemes for sustainable products, or innovative financial instruments for agricultural investment.

- **Social and Environmental** innovations can include options to address social equity, environmental stewardship, and the challenges of climate change adaptation and mitigation. This includes innovations in sustainable resource management, biodiversity conservation, and the development of resilient farming systems capable of withstanding environmental shocks.

Source: Fuglie, 2018; Leeuwis and Aarts 2018, 2018; Spielman & Birner, 2008

Figure 1 shows that these agricultural innovation types relate to the relative impact on the market and the newness of innovation. **Architectural** innovations refer to those that are significant improvements of existing products or know-how. **Disruptive** relates to those innovations that challenge existing markets and create new ones. **Incremental** innovation sustains ongoing operations and drives gradual but continuous improvements to existing markets. **Radical** innovations enhance long-term growth and enable organizations to stay ahead of disruptive forces in the market.

Figure 1. Innovation types



Source: Dieffenbacher (2024) https://digitalleadership.com/blog/types-of-innovation/

It is important to make a distinction between **divisible** and **non-divisible** technologies, especially regarding the measurement of adoption intensity (Feder & Umali, 1993). Divisible and non-divisible innovations refer to the possibility of an innovation to be divided into smaller parts. Divisible projects can be undertaken in parts, while non-divisible projects can only be accepted or rejected wholly.

Adoption intensity of divisible technologies such as new plant varieties or the use of fertilizer innovations can be measured at the individual level over time using metrics such as the farm area share under the new technology or the quantity of input used per hectare (Feder et al., 1985a). This approach can also be applied to the aggregate level of adoption in a region. On the other hand, the extent of adoption of non-divisible agricultural technologies such as tractors and combine at the farm level at a given time is dichotomous (use or no use), and the aggregate measure becomes continuous. In the latter case, aggregate adoption of a lumpy technology can be measured by calculating the percentage of farmers using the new technology within a given area.

The effective dissemination and adoption of agricultural innovations are integrally tied to the **diffusion of knowledge and information** content that accompany them. This highlights the vital role of agricultural extension services, farmer-to-farmer learning networks, and information communication technologies in spreading knowledge and fostering widespread adoption (Spielman & Birner, 2008). Agricultural innovations are often **highly context-specific**, with their applicability and success varying significantly based on agro-ecological conditions, prevailing socio-economic factors, cultural practices, and the regulatory and policy environments in which they are implemented (Leeuwis & Aarts, 2021b).

Agricultural innovation represents a dynamic and multifaceted process that drives the continuous transformation of agricultural systems. Its primary objective is to meet evolving societal needs, addressing critical challenges related to food security, environmental sustainability, sustainable economic development, and social well-being. Agricultural innovation is characterized by a continuous cycle of discovery, development, diffusion, adaptation, and adoption, often involving complex exchanges and linkages between public and private sector actors, research institutions, and diverse farming communities.

Technology

Agricultural technology can be products, services or applications used in agriculture that improve various input and output processes. This includes a wide range of tools, techniques, and knowledge that can improve farming practices. This includes, but is not limited to, machinery and equipment, inputs, and data-driven solutions.

Adoption

Adoption refers to the decision by an individual farmer to incorporate new technology or practice into their regular farming operations (Feder et al., 1985a). Alternatively, (Rogers, 2003) defined adoption as the use of new technology by a producer at a given period. These definitions can be aggregated to other economic units such as households, communities, regions or countries.

This decision can be a one-time "use or no-use" choice for non-divisible technologies (e.g., a new tractor) or involve the intensity of use for divisible technologies (e.g., the proportion of land allocated to a new crop variety or the quantity of fertilizer applied). Adoption is not necessarily a single event but can be a dynamic process influenced by factors such as the perceived economic merits of technology, required investment, associated uncertainties, and availability. The measurement of adoption can vary, considering factors like the area covered, quality of implementation, and temporal thresholds (Hermans et al., 2021).

Feder et al., (1985) differentiated individual from aggregate adoption. Feder defined Individual adoption as the degree of use of a new technology in a long-run equilibrium when the farmer has full information about the new technology and its potential. Aggregate adoption (diffusion) was defined as the process of the spread of a technology within a region. This definition implies that aggregate adoption is measured by the aggregate level of use of a given technology within a given geographical area. Similarly, Thirtle & Ruttan, (1987) defined aggregate adoption as the spread of a new technique within a population.

The adoption decision also involves the choice of how much resource (i.e. land) to be allocated to the new and the old technologies if the technology is not divisible (e.g.

mechanization, irrigation). However, if the technology is divisible (e.g., improved seed, fertilizer and herbicide), the decision process involves area allocations as well as level of use or rate of application (Feder et al., 1985a). Thus, the process of adoption decision includes the simultaneous choice of whether to adopt a technology and the intensity of its use. Furthermore, before adoption choices are made a farmer makes several interdependent decisions (Hassan, 1996).

Diffusion

Rogers (2003) defined diffusion as the aggregated adoption process by which technology disseminates and/or is communicated through channels over time in a productive or social system. Rogers model is fundamentally a social process where subjective evaluation and communication of new ideas drive their spread. This definition recognizes the following six components: (1) the technology (2) communication channels, 3) change inducing agents (extension, technology suppliers), 4) final users or adopters (e.g., farmers), 5) the period observed, 6) A productive and/or social system.

Diffusion incorporates the spatial and temporal innovation spread, demonstrating how information about a new technology flow from change-inducing agents (e.g., extension services, technology suppliers) to the eventual users or adopters. Diffusion can occur through various means, including trade, migration, and cultural exchange, and can be influenced by factors such as the technology's profitability, required investments, and the associated degree of uncertainty to the technology. This process often follows an S-shaped curve, with initial slow uptake, followed by an acceleration, and then a leveling off.

Adaptation

Agricultural adaptation refers to the adjustments and modifications of existing technologies made by farmers, communities, or agricultural research systems to better suit local contexts and specific needs (van der Veen, 2010). Adaptation may occur in response to actual or expected environmental/ecological, social, economic, and technical changes in the user food system. These practices may help moderate harm, exploit beneficial opportunities, and ensure long-term food security and farmer livelihoods (Arunanondchai et al., 2017).

Adaptation is a dynamic, multidimensional, and iterative process that can involve incremental or more transformative technological changes. For example, incremental changes may be changing planting times to adjust to plant variety types. More transformative changes may be shifting to different farming systems or crop types while effective adaptation requires a nuanced understanding of local contexts and often involves integrating scientific knowledge with traditional practices (Ingram, 2014; Pandeya et al., 2025).

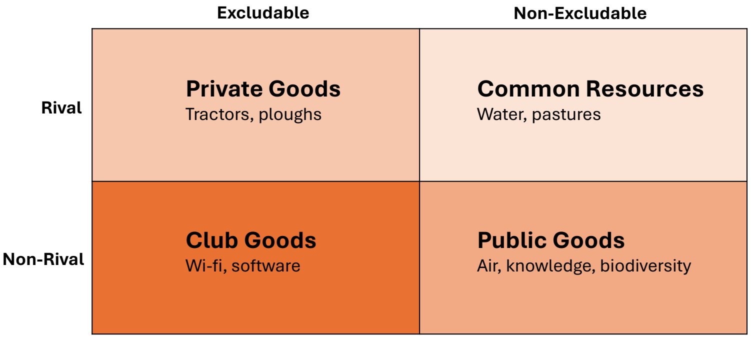
1.4 Differentiating between technology development and commercial development

In the agricultural sector, technology and commercial development is distinct but, in some cases, interconnected stages during the innovation process. The specific stages and their relative importance towards technology development will be connected to the type of goods at hand (See Box 2 for definitions).

Box 2. Types of Goods

Goods can be classified based on the combinations of rivalry and excludability. Excludability means the ability of an individual or a group of people to use a good, without excluding others from using it. For example, private goods have the legal right to the exclusive use of a good such as a tractor. Rivalry refers to the ability to utilize a good by an individual without reducing the availability or quality of the good for another person.

Classifying goods into a specific combination of rivalry and excludability can be difficult. Some goods may belong to more than one quadrant of the matrix depending upon the policy, social or a combination of both taken. Each one of the quadrants in the figure below will have their own set of policy choices, types of interventions and investments, and management options to help ensure social well-being.



	Excludable	Non-Excludable
Rival	**Private Goods** Tractors, ploughs	**Common Resources** Water, pastures
Non-Rival	**Club Goods** Wi-fi, software	**Public Goods** Air, knowledge, biodiversity

Sources: Fuglie, 2018; Leeuwis and Aarts 2018, 2018; Spielman & Birner, 2008

Technology development encompasses the stages from basic research and discovery to applied research, technology generation, testing, and adaptation. These stages primarily focus on creating functional and effective technology or practice. This involves multiple actors such as scientists, researchers, and engineers in universities, research institutions, and private companies. The goal is to develop a solution that addresses a specific agricultural challenge or improves existing practices.

Commercial development, on the other hand, typically focuses on taking on developed technology and making it available to farmers and other end-users through the market. This phase involves activities such as scaling up production, marketing, distribution, and building a viable business around the technology. The private sector, including agribusinesses and input suppliers, typically plays a leading role in commercial development (Fuglie, 2016).

While technology development focuses on the technical aspects and efficacy of innovation, commercial development is typically concerned with its market viability, accessibility, and profitability of social impacts for both the supplier and the farmer. Sometimes, technologies developed in the public sector may require private sector involvement for successful commercialization and widespread diffusion (King et al., 2012).

1.5 Conceptual Models of Technology Transfer and Diffusion in Agriculture

Foundational and conceptual models of innovation

Addressing the multi-dimensional nature of poverty and the rapidly changing landscape of productivity constraints, including climate change, biodiversity loss, and urbanization, necessitates multi-dimensional and solution-focused interventions. Understanding the theoretical and practical models that have historically underpinned science, technology, and innovation policy frameworks is crucial for developing effective contemporary approaches.

The modern concept of innovation has evolved from several foundational economic perspectives and models. The perspectives of the Neo-classical and Endogenous Growth Models, all rooted in the work of Hayami & Ruttan, (1985) , Romer, and Griliches, (1957) amongst others. Griliches posits that technical and institutional change, along with social returns to research, drive endogenous growth. Early applications of agricultural innovations, such as those during the Green Revolution, were largely based on an engineering and production economics approach, characterized by Input-Output and linear R&D models. While this engineering approach was necessary for its time, it proved insufficient to address the myriad real-world complications and challenges that emerged, particularly those related to market imperfections and broader societal impacts.

The industrial organization literature builds upon the work of Chamberlin, Mason, and Bain (Bain, 1968; Chamberlin, 1962; Robinson, 1933; Weiss, 1979), this approach applied the Structure-Conduct-Performance paradigm. It expanded on the neo-classical model by introducing concepts like limited information, transaction costs, price distortions, government policies, and barriers to entry for new firms, which are associated with imperfect competition.[1] The inclusion of these elements opened the door to recognizing market imperfections introduced by policy and regulatory frameworks.

The New Institutional Economics (NIE), pioneered by Ronald Coase, extended economic analysis by focusing on the social and legal norms and rules that underpin economic activity (Coase, 1937, 1960). It distinguishes between "institutions" as the "rules of the game" (formal legal rules and informal social norms) and "organizations" as groups of people and their governance arrangements. This perspective highlights how institutional frameworks shape individual behavior and social interactions, which is critical for understanding innovation.

The evolutionary economics and Schumpeterian creative destruction process are concerned with the transformation of ideas or social/technical knowledge, which determines socio-economic systems and dominant economic issues. Joseph Schumpeter's concept of "creative destruction" (Schumpeter, 1942) identified innovation as the critical dimension of economic change, revolving around entrepreneurial activities and market power dynamics. He argued that technological innovation often creates temporary monopolies, allowing abnormal profits that, while eventually competing, could provide better results than the "invisible hand" and pure price competition.

Emergence of Systems Thinking

The limitations of purely engineering-based or static economic models, coupled with a growing understanding of human decision-making paradigms (e.g., *Homo economicus* vs. *Homo sociologicus* vs. *Homo reciprocans*[1]), led to the development of systems thinking in innovation studies. This shift acknowledges that innovation adoption is not solely driven by rational economic calculus, but also by social norms, trust, and reciprocity. Therefore, effective frameworks must account for these non-economic drivers among farmers, policymakers, and other stakeholders.

The Innovation Systems approach based on the works of Lundvall, Freeman, Edquist, and Nelson (Freeman, 1995; Lundvall, 1985; Lundvall et al., 2002) emphasizes that innovation and technology development are the result of a complex set of relationships among actors in a system. It considers three key components: 1) Actors (public and private sector developers, adapters, investors, regulators, users), 2) Institutions (formal and informal constraints that shape human interactions), and 3)

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[1] *Homo economicus*: defines humans as agents who are consistently rational and narrowly self-interested, and who pursue their subjectively defined ends optimally by maximizing their utility, considering all outcomes. *Homo sociologicus* defines humans as agents who are bounded by society, subjected to norms values and expectations. *Homo reciprocans* defines humans as cooperative agents motivated by improving their context through positive reciprocity by rewarding other individuals, or through negative reciprocity by punishing other individuals. This may occur even in situations where no possible benefit may accrue to them.

Technological factors (elements making up the system, often linked through technology platforms).[1] This approach highlights the need to re-connect R&D with technology delivery, identifying the necessary elements for bringing final products to users, such as Public Private Partnerships and flexible human resources.

The Product Life Cycle approach integrates and improves production processes from the basic stage of science through product development and delivery to eventual disposal or termination (Levitt, 1965). It emphasizes the importance of economic, environmental, and social sustainability throughout the production process, identifying key issues, strategies, and decision points at each stage.

The evolution of economic thought towards systems thinking recognizes that agricultural innovation increasingly faces multi-dimensional challenges, including climate change, urbanization, food price volatilities, and governance issues. These require broader solutions that move beyond fragmented research applications. A critical implication of this reality is the growing importance of addressing complexity and the knowledge-based products and technologies in agricultural bio-innovation. This necessitates a deep understanding of knowledge stocks and flows (both tacit and codified), as well as the roles of actors, organizations, laws, policies, and regulations that impact the pathway from R&D investments to agricultural bio-innovations reaching farmers.

Exploring governance coordination across policy, regulatory, and legal processes, and identifying the reasons why such systems may not be conducive to an enabling environment, is essential (Kohl, 2023). An emphasis on the political economy of investment and development work helps define the broader context for technology R&D, scaling up, and deployment. The ultimate objective is to identify and enhance desirable institutional, regulatory, policy, or legal conditions that facilitate the transfer, diffusion, and uptake of valuable agricultural bio-innovations, framed within the specific socioeconomic and cultural context of their existence.

1.6 Technology Transfer vs Technology Diffusion

Technology transfer as related to the innovation diffusion framework is the process by which technologies spread within a population (Rogers, 2003; Rogers & Shoemaker, 1971) . The technology diffusion process may be seen in some cases as passive or following an endogenous set of technology adoption determinants. Although this term and definition is often used interchangeably by researchers to that of technology transfer. Technology transfer is typically viewed and defined as a more proactive process involving interventions with a goal in mind and stakeholder buy-in, collaboration and coordination (Autio & Laamanen, 1995; Hameri, 1996).

Technology transfer types follow the innovation types described in Box 1. Technology transfer may be of product and services, process and architectural, organization and institutional, social and environmental technologies and processes. In other words, technology transfer may vary from products, knowledge (know-how and know-why) and ability to address specific needs in agriculture (Hayami & Ruttan, 1985; Mansfield et al., 1971). These authors further distinguish between vertical and horizontal technology transfer. Vertical transfer refers to the technology transfer across all stages from discovery, basic and applied research to use. In turn, horizontal transfer refers to technologies originating from an individual, firm, setting to another individual, firm or setting. We will continue expanding on this concept and approach in this and other papers in this series. Souder, (1987) and Amesse & Cohendet, (2001) further expand the definition of vertical technology transfer to include the possibility of transferring technologies at any stage of the product life cycle process. This is important as agricultural innovations can and have followed this type of approaches in the past.

Key innovation and technology transfer models

The diffusion of agricultural innovations has been a subject of study across various disciplines, leading to the development of several conceptual models that attempt to explain this complex process. The seminal models of technology diffusion in agriculture were rooted in linear models. The technology transfer model, for instance, depicted a one-way flow where breakthroughs developed by researchers were transferred to extension services for delivery to users, often following a progressive farmer approach (Chambers, 1983). This and similar models aim to describe the sequential movement of technology from R&D to technology use. These early models, however, were often criticized for their top-down approach and limited consideration of farmers' needs and context (Dunchev & Beluhova-Uzunova, 2023; Montes de Oca Munguia et al., 2021).

Over time, the focus shifted towards more system-oriented views that recognized the complexity of agricultural innovation. The farming system approach built upon earlier models by emphasizing the role of technology in improving farmers' welfare, acknowledging the farm manager as an active participant in the innovation process. An example of this evolving nature of farming system approaches is the Agricultural Knowledge and Information Systems (AKIS) approach (OECD, 2012) further evolved this perspective by focusing on local capacities for adoption, empowering farmers, and integrating different types of knowledge for sustainable development. This approach represented a shift towards a bottom-up innovation flow, emphasizing joint learning and interaction among various stakeholders. The OECD (2012) report defines AKIS as:

> "… a set of organisations and/or people, including the links and interactions between them, that are active in the creation, transformation, transmission, storage, retrieval, integration, dissemination and use of knowledge and information, with the aim of working synergistically to support decision-making, problem-solving and innovation in agriculture"

The agricultural innovations system (AIS) approach (OECD, 2010, 2013) is a comprehensive system-oriented model, incorporating the political and the institutional environment. The approach highlights the importance of multi-directional knowledge flows and collaboration among diverse actors (Dunchev & Beluhova-Uzunova, 2023). The agricultural innovation systems consider farmers and public and private institutions to help enhance innovation in the agricultural sector by developing R&D processes.

Implementation of AIS approaches has been limited due to several factors including local and contextual factors influencing innovation, types and qualities of stakeholder interactions, and the enabling environment fostering agricultural innovations (Gutiérrez Cano et al., 2023; Klerkx et al., 2012; Minh, 2019). In spite of its limited application, it is important to consider approaches such as AIS, to address comprehensively a wide variety of factors and actors involved, and promoting innovative solutions to address the complex challenges of the agricultural sector.

Qualitative models of technology transfer include the seminal work by (Bar-Zakay, 1970) and applied models by (Behrman & Wallender, 1976; Dahlman & Westphal, 1981). These models attempt to describe the technology transfer process as related to the product life cycle. Quantitative models include (Klein & Lim, 1997; Raz et al., 1983; Sharif & Haq, 1980). These models used concepts such as the technological distance between donor and recipient, technology gaps, and catch-up to examine technology transfer issues as related to information flows, and negotiations. Results from these models have shown the need for firms interested in technology transfer issues to consider issues of competitiveness, security, facilitating uptake and adaption of transferred technologies and linking such activities to internal R&D capabilities and processes.

1.7 Key models of technology diffusion

Rogers, (2003) Diffusion of Innovations model stands out as a foundational framework. As described in Montes de Oca Munguia et al., (2021), this model describes the process through which individuals adopt an innovation as a five-stage process: 1) knowledge: becoming aware of the innovation, 2) persuasion – developing an attitude and/or perception, 3) decision: choosing to adopt, reject or delay in order to get more information, 4) implementation: innovation use, and 5) confirmation: securing confirmation to the appropriateness of the decision.

Further, Rogers (2003) categorizes adopters into five groups based on their innovativeness: 1) innovators, 2) early adopters, 3) early majority,4) late majority, and 5) laggards. The rate of adoption is influenced by several factors, including the perceived attributes of the innovation (relative advantage, compatibility, complexity, trialability, observability), communication channels, and the nature of the social system.

The Bass Diffusion Model identifies two primary sources of adoption (McRoberts & Franke, 2008). First, external factors from the farming unit or community such as knowledge shared by extension agents and mass media advertising leading to adoption by "innovators,". Second are internal factors for individual farmers or communities including interpersonal communications among farmers resulting in adoption by "imitators". According to Mahajan et al., (1990, 1991) the Bass Model considers several assumptions which may not reflect real life decisions and context. For example, the Bass Model and similar models assumes that innovation processes do not change over time, independence between new innovations and other innovations, market potential of innovations does not change over time, and the diffusion process is not driven by changes in information sharing and price strategies.

Most importantly the Bass Model assumes major simplification of the decision making and diffusion process. Most farmers do not rely only on knowledge and information received from internal or external sources. External or internal factors may influence the diffusion of agricultural innovations but are not sufficient on their own. In fact, diffusion of agricultural innovations are typically slower than was predicted or expected by developers or extension agents (Röling, 1988). This may be due to farmer heterogeneity, changes in socio-cultural context, distortions in the message and the messaging process, or benefits from innovation change over time may help explain innovations failing to diffuse to different population segments. Furthermore, Röling, (1988) critique of extension services failing to pay sufficient attention to socio-cultural context, links and networks within the farming community and the psychological aspects of decision making has improved over time but still need to improve. A potential issue is the possibility of innovation bias where innovations are viewed as inherently positive in all situations. Furthermore, the early adopters or innovators may be paid significant attention, while most of the remaining farmers viewed as laggards or even backwards may be ignored. Early adopters tend to be larger, richer and have access to information and productive inputs. This top-down, linear perspective is increasingly viewed as insufficient for a world where innovation is a complex, non-linear, and multi-actor process.

Nevertheless, empirical models derived from Roger (2003) and Bass Models have been proposed and used in empirical work. For example, the ADOPT Model specifically focuses on relative advantage of an innovation (Kuehne et al., 2017). Adoption may be driven by relative advantage (economic, environmental, risk) and the learning of this advantage, in addition to, cause-effect relationships between variables. The ADOPT model thus measures the degree to which an innovation is perceived as better than existing innovations, becoming a key driver of adoption and diffusion in agriculture. The model provides a detailed framework for predicting adoption and diffusion outcomes in agriculture, considering both adopter and technology characteristics, but does not explicitly consider information flows between innovation and value chain stages.

Montes de Oca Munguia et al., (2021) described the Profit Advantage Model by Griliches (1957), which emphasizes profit as the main motivator for adoption. This model emphasizes the critical role of economic benefits in farmers' decisions to adopt new technologies, particularly relevant in market-oriented agricultural systems. Highlights the importance of economic incentives in technology adoption but may oversimplify the decision-making process by focusing solely on profit.

In summary, models such as the Bass and even the Rogers (2003) model rely on rational decision making, are based on economic, net benefits and innovation efficiency (see Table 1). In contrast other aspects related to decision making such as socio-cultural, psychological, political economy and institutional factors are slowly being incorporated into rational models. It is important to note that despite the multitude of models, there is no globally accepted methodology for studying agricultural innovation adoption and diffusion, reflecting the diversity in research approaches and the complexity of the process itself.

Table 1: Summary comparison of core conceptual models of technology adoption and diffusion in agriculture

Model Name	**Key Proponents**	**Core Principles**	**Strengths**	**Weaknesses**	**Relevance to Agricultural Sector**
Technology Transfer Models	Chambers (1983)	Linear, one-way flow from researchers to extension to users.	Simple, straightforward representation of technology flow.	Overly simplistic, neglects farmer input and contextual factors.	Historically common, especially in top-down agricultural development programs.
Innovations Diffusion Theory	Rogers (2003)	Innovation communicated through channels over time within a social system; stages of adoption and adopter categories; influence of perceived attributes.	Comprehensive framework for understanding individual adoption and the overall diffusion process; identifies key factors influencing adoption rate.	Can be criticized for pro-innovation bias and not fully accounting for structural inequalities.	Widely applied in agricultural extension and development to understand how new practices and technologies spread within farming communities.
Bass Diffusion Model	Bass (1969)	Adoption driven by external factors (innovators) and internal factors (imitators); models adoption rate over time.	Recognizes the role of both external outreach and social networks in driving adoption.	Assumes constant market potential and no influence of marketing strategies; distinction between internal/external factors may be too simplistic.	Useful for understanding the dynamics of adoption at the population level in agricultural communities, particularly for forecasting adoption rates.
Agricultural Innovations System (AIS)	Klerkx et al.	Multi-directional flow of knowledge and innovation involving various stakeholders and the institutional environment;	Comprehensive approach that considers the broader system of actors and influences agricultural innovation;	Can be complex to analyze and implement in practice due to the multitude of actors and factors involved.	Provides a comprehensive framework for understanding and fostering agricultural innovation by considering the interconnectedness of

		emphasize capacity building and institutional change.	acknowledges the dynamic and interactive nature of the process.		research, extension, farmers, private sector, and policy.

1.8 Adaptation and Modification of Agricultural Technologies

The effective diffusion of agricultural technologies often requires more than just the transfer of ready-made solutions. Effective diffusion necessitates context-specific adaptation to ensure the technology fits the unique agro-ecological and socio-economic conditions of a particular region. The contextual localization process involves tailoring technologies to align with local norms, practices, infrastructure, and even languages, thereby enhancing their relevance and usability for farmers.

A key aspect of successful adaptation is farmer-led experimentation, where farmers actively participate in testing and modifying technologies on their own farms to suit their specific needs and environments.(https://www.cgiar.org/news-events/news/563074-autosave-v1/). This approach recognizes the valuable local knowledge and expertise that farmers possess and empowers them to take ownership of the innovation process. The integration of indigenous knowledge, which has been developed and refined over generations, can also play a crucial role in technology adaptation (Bawack et al., 2025). Traditional farming practices often hold valuable insights into sustainable resource management and resilience to local environmental challenges, and combining this knowledge with modern technologies can lead to more appropriate and sustainable solutions (UNDP, 2024).

It is important to consider social equity to ensure that the benefits of technology adoption are shared by all farmers, including marginalized groups, and the need to focus on long-term sustainability to avoid unintended negative consequences. Successful adaptation often involves a collaborative effort among researchers, extension agents, farmers, and other stakeholders, ensuring that the technologies are not only technically effective but also socially acceptable and environmentally sound in their local context.

1.9 Contrasting High-Income vs Low- and Middle-Income Countries experiences

High-income and low- and middle-income countries have experienced differences in terms of the adoption and diffusion of agricultural innovation include (Abdulai, 2023a; Ruzzante et al., 2021a). In regard to policies, innovation and technology stock and flows, High-income countries often have more developed agricultural policies and technologies frameworks and capacities which tends to support innovation and agricultural productivity (Alston et al., 2023; Nin-Pratt, 2016). Low-income countries face challenges due to limited resources and other barriers human and knowledge capital constraints. This has resulted in a concentration of innovation in High-income countries. Groundbreaking agricultural innovations are typically concentrated in a few high-income countries and among a small number of firms, limiting the diffusion of innovations to low-income countries.

High-income countries often have more developed agricultural innovation capacities. This has led to systems in LMICs with limited capabilities for developing innovations that can be locally contextualized and thus may be adopted readily. Low-income countries face challenges due to limited resources and other barriers. An example is that of improved varieties. In low-income countries, even though the adoption of improved and high-yielding crop varieties can significantly enhance livelihoods, the limited availability and lack of adaptation to the local context limits their use. Whereas in high-income countries, these innovations are already widely used and integrated into farming practices. Low-income countries can benefit from participatory and institutional approaches that enhance trust and thus promote the adoption of new technologies. This processes are essential for overcoming constraints, resource and infrastructure limitation and challenges tends to reduce (Chen et al., 2024). For example, information flows such as branding and labels can improve adoption of improved varieties (Derwisch et al., 2016). Another example is the potential that ICTs and South-South collaborations have in support of LMICs agriculture and innovation in general. (Kaplinsky & Kraemer-Mbula, 2022). Both examples effectiveness may be limited by the LMICs context in which they may be implemented.

1.10 Mapping the channels and mechanisms of agricultural innovations Diffusion along the value chain

Production (Input to Farm gate) levels

Once technology is discovered and developed, its widespread adoption hinges on the effectiveness of various channels and mechanisms of diffusion. The overall process of technology transfer encompasses a range of approaches, evolving from traditional linear models to more modern, participatory, and systemic approaches. These mechanisms include consultancies, education and training programs, farmer field days, demonstration plots, licensing agreements, and increasingly, the strategic use of social networks and digital tools to accelerate the spread of agricultural innovations. Technology diffusion in the agricultural sector occurs through various interconnected channels along the value and supply chain. These channels facilitate the flow of knowledge, information, and the technologies themselves from their point of origin to the end-users, which are primarily farmers, but also include other actors in the chain.

The process often begins with research institutions (universities, government agencies, international organizations) where new technologies are developed. The initial diffusion often involves technology transfer to intermediaries such as agricultural extension services, which then disseminate information and provide training to farmers. Increasingly, digital platforms and ICTs are transforming diffusion by providing real-time information, connecting farmers to markets, and facilitating access to expert advice. Farmer networks and peer-to-peer learning are also vital, as farmers often trust and adopt technologies based on the experiences of their peers. The rise of digital platforms and Information and Communication Technologies (ICTs) has introduced new and transformative channels for disseminating agricultural information. These platforms, including the internet, mobile apps, radio, and television, can provide farmers with access to weather forecasts, market prices, best practices, and other crucial information in real time, potentially overcoming geographical barriers and reaching many farmers efficiently.

Formal Channels and the Role of Public and Private Extension

Traditionally, public agricultural extension services have served as the primary formal channel for diffusing new technologies and practices to farmers (FAO, 2003; Hussain et al., 1994; Tiraieyari et al., 2010) . These services are meant to bridge the gap between research institutions and farming communities, aiming to improve farmers' knowledge, attitudes, and skills (Hussain et al., 1994). However, the effectiveness of public extension has been a subject of debate. In many regions, they are plagued by declining human and financial resources, and models like the "Training and Visit" (T&V) system have been widely criticized as ineffective (Hussain et al., 1994).

The limitations of public services have paved the way for the emergence of a widely diverse extension landscape. Private sector companies, often tied to input sales (e.g., seeds, fertilizers) or specific commodities, now provide specialized extension services to farmers (FAO, 2003). Similarly, non-governmental organizations (NGOs) and community-based organizations play a crucial role, especially in developing countries, in providing tailored support and information (FAO, 2003) .

The existence of these multiple providers, each with different motivations and capacities, highlights a shift away from a single, centralized system towards a more fragmented, but potentially more responsive, ecosystem of support. Agribusiness companies, input suppliers, and other private sector actors are involved in the production, marketing, and distribution of new technologies, often driven by market incentives. Their extensive networks and commercial reach can facilitate the rapid spread of certain technologies, particularly those with clear profitability for both the supplier and the farmer.

The flow of technology can also be influenced by government policies and international organizations through funding, regulations, and support programs (Fiocco et al., 2023; Pandeya et al., 2025). Finally, non-governmental organizations (NGOs) often act as facilitators, bridging the gap between technology developers and farmers, especially in remote or underserved communities. Agricultural cooperatives represent another important mechanism for technology transfer and diffusion.(CGIAR AEC 2016). By pooling resources and knowledge among their members, cooperatives can facilitate access to information, improved inputs, credit, and technical assistance, making it easier for smallholder farmers to adopt new technologies.(CGIAR AEC 201657 The collective nature of cooperatives can help overcome some of the individual-level barriers to adoption, such as risk aversion and lack of capital.

Informal Channels and Social Networks

Beyond formal institutions, informal channels play a critical role in the diffusion of agricultural innovations. Peer-to-peer learning, where farmers observe and learn from neighbors, friends, and relatives, is a powerful mechanism for information exchange (Conley & Udry, 2010; Wu & Zhang, 2013). Research indicates that farmers rarely make decisions in isolation; they actively collect information from multiple sources and update their knowledge based on the experiences of others (Conley & Udry, 2010).

The structure of social networks significantly influences this process. Studies show that farmers who occupy more "central" positions within their networks—meaning they have a greater number of connections—are more likely to adopt new technologies (Takahashi, Muraoka, et al., 2019). The impact is even more pronounced for those who are not just recipients of information but are also active sharers of knowledge (Takahashi, Mano, et al., 2019). Being a source of knowledge is a more decisive factor in an individual's adoption behavior than simply receiving information. This finding underscores the importance of fostering active information-sharing networks among farmers to accelerate the diffusion of innovations.

Mechanisms of adoption: socio-economic and contextual factors

The decision to adopt an innovation at the farm gate is a complex process driven by a combination of socio-economic, technological, and institutional factors. At its core, the choice is influenced by the perceived benefits of innovation. These include its economic viability, such as a clear path to profitability through cost reduction or increased yield, and its ability to mitigate risks from weather, pests, or market volatility. Policy support, in the form of government subsidies, grants, or favorable regulations, can also critically lower the financial burden and risk associated with new technologies, making them more accessible to farmers (Jaruzelski et al., 2017).

Farmer characteristics also play a significant role. Factors such as farm size, education level, age, and access to financial resources are widely studied determinants of adoption (Pierpaoli et al., 2013). The literature presents a nuanced picture, with some studies showing that larger farms are more likely to adopt new technologies due to scale economies and a greater capacity to bear risk (Diederen et al., 2003), while others find that the influence of factors like education and gender can be context-specific and sometimes statistically insignificant.

The effectiveness of diffusion strategies hinges on a profound understanding of these mechanisms. The most successful approaches often employ a hybrid model that synthesizes formal expertise with informal social learning. For example, a case study on the diffusion of a flood-tolerant rice variety in India found that "farmer field days" were a highly effective intervention . These events combine the formal, structured explanation of a new technology with the credible, informal testimony of peer farmers. This design leverages the power of social learning to build trust and diminish uncertainty, resulting in a significant increase in adoption rates (Emerick & Dar, 2021). This demonstrates that successful diffusion is not just about the channel but about designing an intervention that activates the most effective mechanisms of social influence.

From Production to Value Addition

Innovations do not cease at the farm gate. They continue to diffuse through the midstream stages of the value chain. Post-harvest processing technologies are crucial for transforming raw agricultural products into value-added goods, enhancing shelf life, improving quality, and increasing market value. These technologies range from basic cleaning, grading, and milling equipment to more advanced techniques like non-thermal processing and intelligent packaging. The adoption of these innovations is a multifaceted process influenced by economic benefits, reduced waste, and improved food safety standards.

Digital and supply chain Innovations

The midstream and downstream of the AVC are increasingly shaped by the diffusion of digital and supply chain innovations. Technologies such as blockchain, Internet of Things (IoT), and artificial intelligence (AI) are redefining how agricultural products are moved, monitored, and marketed. Blockchain technology, for example, offers unparalleled transparency and traceability, allowing for a product to be tracked from the "farm to fork". Internet attuned devices and integrated into cold chain logistics, provide real-time monitoring of product temperature and location, significantly reducing spoilage and ensuring the integrity of perishable goods.

The diffusion of these technologies challenges the traditional linear model. A traceability system implemented at the retail level creates a powerful mandate for data collection and technological adoption that pulls upstream, forcing processors and farmers to adopt compatible systems. This dynamic, where the end of the chain influences the beginning, represents a reverse diffusion flow that is a critical feature of the modern agricultural innovation ecosystem. This demonstrates that technology is not simply pushed onto the chain but is also pulled through it by market forces.

Processors, traders and retailers

Processors, traders, and retailers act as crucial gatekeepers and promoters for innovation diffusion. Their role extends beyond simple transactions; they set quality standards, enforce compliance, and influence technology adoption among their suppliers. For example, the increasing consumer preference for products with specific certifications or sustainability attributes can compel these midstream actors to require their partner farmers to adopt corresponding agricultural technologies and practices (Gamage et al., 2024). Ultimately, retailers are driven by the benefits new technologies can offer to their customers, and their demands are transmitted down the value chain, creating a powerful feedback loop that connects consumer preferences to on-farm practices (Sundkvist et al., 2005).

Macro-Level and Cross-Cutting Mechanisms of Diffusion

The enabling institutional and policy environment

The broader institutional and policy environment is a critical determinant of innovation diffusion throughout the AVC. Government policies and regulatory frameworks can either accelerate or impede the adoption of new technologies (WIPO, 2017). Financial incentives, such as subsidies and grants, are powerful tools for making technologies more affordable, thereby mitigating the financial risk for farmers and businesses.

Governments also play a vital role in funding agricultural research and development (R&D) and in facilitating technology transfer from research institutions to industry partners (USDA, 2024). The US Department of Agriculture's Office of Technology Transfer, for instance, actively facilitates collaborative research and licenses patented technologies for commercialization (USDA, 2024).

Public-Private Partnerships (PPPs)

In an era of constrained public sector budgets, public-private partnerships (PPPs) emerged as a new paradigm for fostering agricultural innovation (WIPO, 2017; World Bank, 2025). These partnerships are designed to pool resources, leverage complementary strengths, and mitigate the risks associated with R&D and technology transfer (WIPO, 2017). PPPs are increasingly a mechanism for developing entire value chains, jointly funding research, and building market infrastructure (World Bank, 2025; WIPO, 2017). The Consultative Group on International Agricultural Research (CGIAR), which brings together public and private sector members to address global agricultural challenges, is a significant example of this collaborative model (CGIAR, 2024).

The rise of PPPs signifies a fundamental shift away from a clear, linear division of labor—where public institutions conduct research and the private sector handles commercialization—to a more collaborative, systemic effort. The private sector is now a major investor in agricultural R&D, and its spending has grown robustly in high-income countries, sometimes surpassing public investment (WIPO, 2017). PPPs are the institutional manifestation of this trend, blending the strengths of government, research, and private enterprise to create more dynamic and efficient innovation systems (WIPO, 2017; World Bank, 2025).

The role and power of final consumers

The end consumer is not merely the final recipient of a product but a powerful agent of innovation diffusion. Evolving consumer preferences for attributes such as sustainability, traceability, and specific quality standards create a significant "demand-pull" mechanism that drives innovation up the value chain (Sunding & Zilberman, 2001). Retailers, in a competitive market, must respond to these demands, and they, in turn, transfer these requirements to processors and producers. This consumer-driven dynamic influences everything from the adoption of organic farming practices to the implementation of complex blockchain-based traceability systems. This demonstrates a crucial feedback loop that connects the last stage of the value chain to the first, proving that diffusion is an inherently multi-directional and interconnected process.

1.11 Factors Influencing the Adoption and Diffusion of Agricultural Technologies

Several factors can either enable or obstruct the diffusion of agricultural technologies (Lee, Strong, et al., 2024; Montes de Oca Munguia et al., 2021). Based on the work by Feder et al.,(1985) and (Dissayanake et al., 2022), the decision by a farmer to adopt a new agricultural technology is influenced by a complex interplay of various factors that can be broadly categorized as 1) User related issues, 2) Economic and technology related 3) Governance and institutional, 4) Information and knowledge flow, 4) Agro-ecological and environmental factors.

There is growing recognition that factors beyond economic and technology/innovation which have been significantly emphasized in the literature are also important (Addorisio et al., 2025). For example in an examination of the adoption and diffusion literature in Africa, factors such as finances are underrepresented (Fadeyi et al., 2022). Factor impacts are heterogeneous and a single factor is rarely identified as a broad predictor of adoption (Ruzzante et al., 2021a). The review findings reveal that adoption is a collective and interactive effect of some or all factors. Thus, identification of priority factors and a holistic approach need to be considered to ensure greater adoption. We now proceed to discuss these factors in more detail.

User related issues

This includes the socio-cultural, demographic and psychological factors at the farmer, household and community levels. Feder et al., (1985) and Rizzo et al., (2024) consider factors related to the user, such as farm size, income, prior experience, gender, education level, and age; 2) risk and innovation exposure and aversion, 3) human capital, 4) labor availability, 5) Psychological, sociocultural-demographic, innovation control. These factors play a vital role in the adoption process.

Factors such as the farmer's level of education, age, farming experience, and their degree of risk aversion (Fen et al., 2025; Yeo & Keske, 2024) can all influence their willingness and ability to adopt new technologies. For instance, more educated and younger farmers might be more open to trying new innovations, while risk-averse farmers might prefer to wait and see the outcomes of adoption by others.

Socio-cultural and demographic factors are also significant determinants of technology adoption. The PRISM Sustainability Directory(https://prism.sustainability-directory.com/term/agricultural-adaptation-strategies/) lists community norms and values, traditional beliefs about farming, the influence of social networks, gender dynamics within the household and community, and the level of community ownership over the innovation can all shape a farmer's attitude towards adopting a new technology. Social and cultural barriers often play a significant role in slowing down technology adoption (Addorisio et al., 2025). Technologies that align with existing social structures and are supported by influential community members are more likely to be accepted.

Farmers may be resistant to changing traditional farming practices they are familiar with, especially if they lack trust in the new technologies or perceive them as risky. Issues related to land tenure security can also act as a barrier, as farmers may be unwilling to invest in long-term technologies if their rights to the land are uncertain (Fox & Signé, 2022). Social networks information dissemination and extension services, trust and collaboration are important but responses and interventions to such limiting factors have to be contextualized (Park et al., 2025; Wang et al., 2020). Participation in producer organizations is also important (Ramirez, 2013) as well as access to information from social and institutional networks (Abdulai et al., 2021).

These issues are important as innovation is being affected by information flows especially coming from pressure and special interest groups(Magesa et al., 2024) , which in some cases may raise the issue of technology hesitancy and misinformation and disinformation in the context of technology diffusion (Chowdhury et al., 2023; Jiang & Fang, 2019) . Ruzzante et al.,(2021) in a systematic literature review concludes that large farms are most likely to adopt new varieties, while land tenure tends to ensure adoption of sustainable land management practices. Extension tends to substitute for formal education when examining new varieties adoption, while both are complementary in the case of natural resource management.

Economic and technology related factors

This includes the perceived benefits from the technology, initial costs and affordability, size of the farm operation, and the farmer's access to credit (Massresha et al., 2021; Pandeya et al., 2025; Yeo & Keske, 2024) play a crucial role in the adoption decision. Farmers often conduct a cost-benefit analysis, weighing the potential economic returns against the investment required and the perceived risks (Yeo & Keske, 2024). Economic barriers such as the high upfront costs of many new technologies and limited access to affordable finance, particularly for smallholder farmers, remain significant obstacles (Fox & Signé, 2022) Farmers, especially those with limited resources, may be hesitant to invest in new technologies without clear evidence of a guaranteed and timely return on their investment.

Innovation and product life cycle

Innovation capabilities and technological barriers can also impede diffusion. Some modern agricultural technologies can be complex to understand, operate, and maintain, requiring specialized knowledge and skills that farmers may lack (Lee, Orton, et al., 2024) . Furthermore, the lack of adequate infrastructure in many rural areas, such as reliable internet connectivity and electricity, can limit the feasibility and effectiveness of adopting certain digital or advanced technologies (Vasavi et al., 2025).

The technology characteristics and attributes themselves, as described by Rogers' Diffusion of Innovations Theory, influence adoption rates. Technology availability compatibility, complexity, trialability and observability. Technologies that offer a clear relative advantage over existing practices, are compatible with farmers' values and needs, are not overly complex to understand and use, can be easily tried on a small scale, and whose benefits are observable to others are more likely to be adopted. Disruptive innovations may not be adopted by farmers especially in LMICs (Curry et al., 2021)

Information and knowledge flows

Access to knowledge, information and awareness about new technologies are fundamental factors helping explain ag technology adoption (Bell & Engelbert, 2025; Shoaib, 2025) Farmers need to be informed about the existence of new technologies, understand their potential benefits and drawbacks, and know how to use them effectively. Access to reliable information through extension services, farmer networks, digital platforms, and other sources plays a crucial role in reducing uncertainty and facilitating informed decision-making regarding technology adoption. For example access to internet has been shown to be critical in the diffusion of precision livestock and agricultural technologies (Greig et al., 2023)

Information and knowledge flow, gaps and asymmetries remain a major challenge (Abdulai, 2023b). Many farmers, especially those in remote areas, may lack awareness about new technologies, have limited access to reliable information about their benefits and use, and may not trust the sources of information they do receive. Overcoming these diverse barriers requires a multifaceted approach that addresses economic constraints, technological challenges, social and cultural factors, policy and institutional weaknesses, and information gaps. Information and Communication technologies can help address these challenges, but they need to be adapted to local conditions and contextualized (Mulungu et al., 2025)

Governance and institutional

Institutional issues such as policy, legal and regulatory barriers can also hinder technology diffusion including credit constraints, land and asset tenure, access to commodity markets, extension services, inputs, markets and credit facilities (de Boon et al., 2022). Inconsistent government policies, regulatory uncertainty, and a lack of adequate institutional support for technology transfer can create an unfavorable environment for adoption (Orr, 2018).

The relative importance of these factors can vary across individuals, households or communities. In a UK study by (Feliciano, 2022) on the adoption of sustainable practices, significant factors influencing adoption were economic, regulatory, and market demand concerns. Environmental and social awareness also influenced adoption. In turn, participation in knowledge networks or climate change and impact perceptions and information had little influence on the adoption of sustainable agricultural practices.

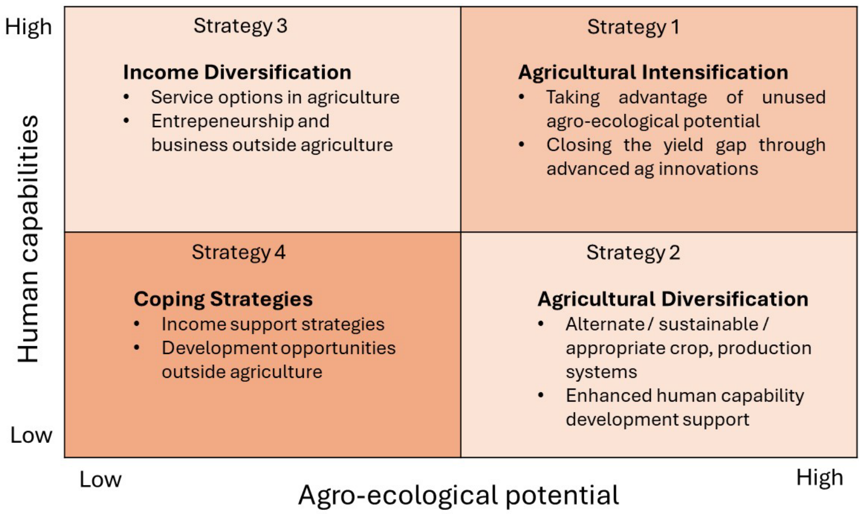
In contrast, in a systematic review across 15 countries examining the adoption of sustainable practices (Rizzo et al., 2024) identified that organic farmers have a stronger environmental view and are more likely to take less into account economics factors. Innovation complexity and aversion, as well low perceived control over the innovation were significant barriers to adoption.

Agro-ecological and environmental factors

Such as the impacts of climate change, the availability of natural resources like water, and farmers' concerns about sustainability (Dong et al., 2022; Pandeya et al., 2025) can also drive the adoption of specific agricultural technologies that help mitigate environmental risks or promote more sustainable farming practices.

One relevant aspect is the nexus between agro-ecological potential and human capital capabilities. As shown in Figure 2. Gatzweiler & von Braun, (2016) proposed a matrix of four quadrants mapping combinations of agroecological potential and human capital capabilities. Depending on the specific low or high capacity combinations, it leads to four alternative policies and intervention guiding approaches. For example, areas with high human capital and agroecological capabilities as in top right quadrant, a sensible strategy or policy is agricultural intensification taking advantage of advanced technologies and unused potential. In contrast to areas with low human capital and agroecological capabilities, it would be sensible to pursue income diversification which in some cases may imply investments to develop opportunities outside agriculture. This is an example of policy and strategy formulation processes that consider relevant factors. One can think of approaches that build upon this model to expand factor choice and combinations. Another interesting angle would be examining the situation where technologies may be used to enhance agroecological capabilities to reduce the impact of binding constraints. Similar rationale behind those technologies that may address climate change by increasing resiliency.

Figure 2. Policy strategy mapping based on human capabilities and agro-ecological potential



Strategy 3

Income Diversification
- Service options in agriculture
- Entrepeneurship and business outside agriculture

Strategy 1

Agricultural Intensification
- Taking advantage of unused agro-ecological potential
- Closing the yield gap through advanced ag innovations

Strategy 4

Coping Strategies
- Income support strategies
- Development opportunities outside agriculture

Strategy 2

Agricultural Diversification
- Alternate / sustainable / appropriate crop, production systems
- Enhanced human capability development support

Source: Gatzweiler, F. W. and J. von Braun. 2016. Innovation for Marginalized Smallholder Farmers and Development: An Overview and Implications for Policy and Research, In *Technological and Institutional Innovations for Marginalized Smallholders in Agricultural Development*, F.W. Gatzweiler, J. von Braun (eds.). DOI 10.1007/978-3-319-25718-1_11

1.12 Factors That Enable and/or Provide Obstacles in the Diffusion of Technology

Innovation and economic factors

Technologies that offer a clear relative advantage, are compatible with existing systems, are easy to understand and use, can be tried on a small scale, and have observable benefits that are more likely to be adopted (Lee, Strong, et al., 2024; Ruzzante et al., 2021b). Economic factors such as profitability, affordability, access to credit, farm size, and market access can facilitate adoption (Pandeya et al., 2025). Technologies that are too complex, do not offer clear benefits, are incompatible with local conditions, or differ to producer mindset and beliefs, may face resistance to adoption (Rizzo et al., 2024).

Economic constraints including higher additional costs of technology adoption, limited access to credit, uncertain returns on investment, and small farm sizes can hinder diffusion (Fox and Signé 2022).

Governance and Institutional Factors

Supportive government policies (subsidies, incentives, regulations), strong extension services, effective intellectual property rights, and well-functioning markets can enable diffusion (Bakali et al., 2023). The role of extension services, agricultural cooperatives and other institutions in providing access to resources and information is also crucial (Wang and Xu 2025). Institutional barriers such as inconsistent or unfavorable government policies, weak extension services, lack of infrastructure (e.g., internet, electricity), and insecure land tenure can impede adoption and diffusion (Fox & Signé, 2022).

Social and Cultural Factors

Social networks, peer influence, community norms, trust in information sources, and the level of community participation can facilitate the adoption and diffusion of technology (Park et al., 2025; Pratt et al., 2021). Other factors such as resistance to change, lack of trust in new technologies or information sources, community norms that discourage adoption, and social inequalities can act as barriers to technology adoption and diffusion (Fox & Signé, 2022).

1.13 Recent Trends That May Speed or Slow Diffusion

Several recent trends are influencing the speed of agricultural technology diffusion. Trends that may speed diffusion include:

- **Digital Agriculture, ICTs and Precision Agriculture:** The increasing availability and affordability of mobile phones, internet access, and digital platforms are accelerating information dissemination and access to new technologies. Technologies like GPS-guided equipment, sensors, drones, and data analytics are enabling more efficient and targeted use of resources, potentially leading to higher adoption rates as farmers see clear economic and environmental benefits (United States Government Accountability Office, 2024). See Box 3 for additional examples.
- **Advances in robotics and autonomous machinery** are reducing labor needs and improving efficiency, which can drive adoption, especially in regions facing labor shortages (Arockia Doss et al., 2024; Reddy, 2022).
- **Sustainability Focus:** Growing consumer demand for sustainably produced food and increasing environmental concerns are driving the adoption of technologies and practices that promote environmental sustainability (FAO 2021).
- **Public-Private Partnerships:** Increased collaboration between public and private sectors can accelerate the development and dissemination of agricultural innovations (Moreddu, 2016).

In turn trends that may slow diffusion include:

- **High costs and economic uncertainty:** Fluctuating commodity prices, rising input costs, and the high upfront investment required for some technologies can make farmers hesitant to adopt (Fiocco et al., 2023).
- **Data concerns and lack of interoperability:** Issues related to farm data ownership, security, and the lack of uniform standards for data sharing and equipment interoperability can slow the adoption of data-driven technologies(United States Government Accountability Office, 2024).
- **Socio-demographic considerations including an aging farmer population:** In some regions, an aging farmer population may be less inclined to adopt new technologies compared to younger generations (Pandeya et al., 2025).
- **Stagnation in innovation pipeline:** The are indications that the rate of transformative agricultural innovations has slowed down thus reducing the portfolio of potential technologies. This could limit the opportunities for rapid diffusion (Arndt et al., 2020; Nin-Pratt, 2016; Nin-Pratt & Stads, 2023).
- **Agro-ecological specificity and mismatch:** Technologies developed in one region may not be suitable for the agro-ecological conditions of other regions, hindering their diffusion (Moscona & Sastry, 2025, 2023). Here it is important to point out efforts designed to secure wide adaptability of agricultural innovations. An example of this was the CIMMYT's shuttle breeding efforts in wheat and maize designed to secure wide cultivar adaptability across agroecological zones or mega environments (Ortiz et al., 2007)

Box 3. Emerging Trends in Ag Tech

Artificial Intelligence and Machine Learning:

- AI-powered decision support systems that predict optimal planting and harvesting times based on detailed weather and soil data.
- Machine learning algorithms that improve over time, enhancing predictive accuracy.

Integration of Blockchain:

- Blockchain technology is being tested for supply chain transparency, ensuring the traceability of produce from farm to fork.
- This technology could also bolster data security, addressing privacy concerns associated with big data applications.

5G and IoT Expansion:

- The rollout of 5G networks will further enhance connectivity, making it possible to deploy more IoT devices reliably.
- This expansion will accelerate the adoption of real-time monitoring and precision technologies.

Automation and Robotics:

- Continued development in robotics for planting, harvesting, and warehouse management promises to reshape supply chains and reduce human dependency.
- Autonomous technology is likely to result in safer and more productive working environments.

Source: https://www.numberanalytics.com/blog/ag-diffusion-real-modern-tech-use-now

1.14 Implications for Policy and Practice

Based on the literature review and experiences with enabling environment frameworks and their application, several concrete policy recommendations emerge. We will further explore these in this paper and in papers 2 in this series.

- **Developing and enhancing the enabling environment through comprehensive approaches**: As shown in this paper, the governance, political economy and policy context matter significantly to explain adoption, scaling-up and diffusion of agricultural innovations. We have also seen that the agricultural and social context coupled with more and complex objectives including sustainable intensification, biodiversity protection and addressing climate change issues, will require integrated approaches to address such challenges. To help ensure that agricultural innovations in this context will respond positively to society’s new and upcoming challenges, the need exists to develop and enhance the enabling environment in which agricultural innovations are deployed.

- **Legal and regulatory efficiency:** Prioritizing science- and evidence-based biosafety regulations that are protective, transparent, and cost- and time-efficient is crucial. LDCs potential regulatory pathways for gene-edited products, which may avoid a full GM review, sets a positive precedent. However, the analysis in this paper highlights that it would be counterproductive to successfully navigate biosafety regulatory scrutiny only to encounter significant delivery complications due to an underdeveloped seed market. This implies that policy support for bio-innovations must be holistic and concurrent, pursuing regulatory pathways, market development strategies, and business model innovations in parallel from the early stages of product development. This calls for integrated planning and multi-disciplinary teams.
- **IPR and Licensing:** Policies need to explore feasibility of promoting flexible IP management options including, for example, humanitarian licensing models that consider royalty-free approaches. Such approaches can help ensure equitable access to agricultural innovations including gene-edited technologies, especially for smallholder farmers. These policies must incentivize such models while also adequately protecting the investments of technology developers.
- **Market Development and Business Models:** Devising innovative business models for agricultural innovation scaling up, technology transfer and product stewardship especially regarding the seed sector is essential. These models must engage both large and small seed companies, addressing persistent challenges in seed distribution, marketing, and farmer access to information and credit. Exploring the value proposition of the seed industry and other agricultural technologies in LDCs, particularly for smallholders, is key to fostering a vibrant and inclusive agricultural innovation sector.
- **Regional harmonization:** Addressing asynchronous regulatory approvals and other organizational and innovative capacities across LDCs is vital to prevent trade disruptions and facilitate seamless regional technology diffusion. Coordinated efforts towards regulatory harmonization can unlock broader market potential.
  - **Multi-stakeholder engagement:** Proactive engagement with non-governmental organizations (NGOs), civil society, and other pressure groups in decision-making processes is necessary to build social license and manage potential opposition. This moves beyond simply acknowledging their role to suggesting constructive engagement strategies to achieve desired outcomes.
  - **Evolving Roles of IARCs and NARS:** The CGIAR and other international and national research centers (IARCs and NARS) require a coordinated and strategic approach to effectively contribute to agricultural bio-innovation in LMICs. This

approach should ideally consider:

- An **enabling platform** that addresses critical policy, governance, freedom to operate, and social license issues.
- A set of **product-based and focused operational services** that ensure proper connection with the enabling platform, the product life cycle, and the technology selection and transfer, adoption, and use decision-making processes.
- The IARCs and NARS may consider efforts to continue developing **"Centers of Excellence" in** research and capacity building, particularly those which have more advanced technical capabilities, supplementing ongoing research, providing finished technologies to countries with weak research systems, and intermediate technologies to more advanced NARS.

1.15 Future Research Directions

The literature review and experiences described in this paper lay the groundwork for a robust future research agenda. The next crucial step involves operationalizing the enabling environment enhancing framework such as the one discussed in this report. This may be operationalized through quantitative modeling and conducting broader comparative analyses. Future research will involve applying the framework and quantitative model to other gene-edited products (e.g., disease-resistant cassava, drought-tolerant crops) or other agricultural bio-innovations beyond gene editing. This will provide new insights into the generalizability and context-specificity of the framework.

Furthermore, conducting inter-country assessments, like those performed by Furman, Porter, and Stern (2002), will be valuable. This will involve comparing how different policy situations across African countries influence innovation outcomes. This comparative analysis will allow for the identification of best practices and the development of context-specific policy recommendations. The following table provides a critical contextualization for future comparative research, allowing for disaggregating LMICs based on their existing biotechnology capacity and market size.

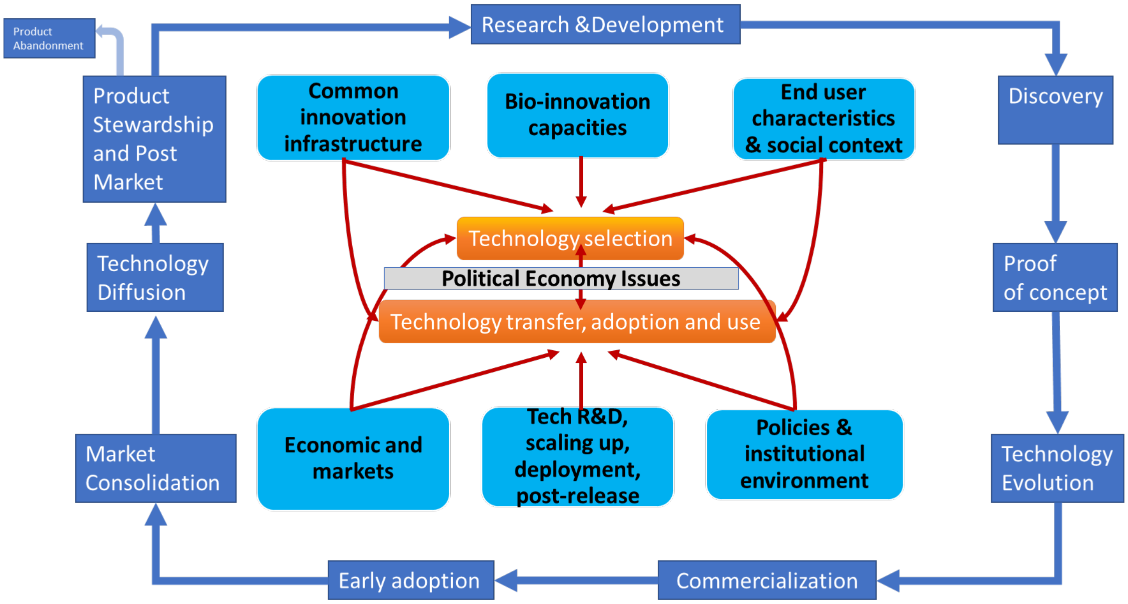
Annex 1. A proposed integrated conceptual framework to examine agricultural innovations

Building upon the theoretical foundations discussed, we propose here an integrated conceptual framework for agricultural innovations. This framework synthesizes elements from (Biagini et al., 2014) and (Furman et al., 2002a), augmented with explicit considerations for political economy and comprehensive information and knowledge flows. The application of the model in this Annex focuses on bio innovations but can be easily adapted to other types of agricultural innovations.

Core Structure

The framework, as depicted in Figure A.1, interlinks three primary components: the **Product Life Cycle** (represented by a dark blue concentric loop), the **Innovation System** (represented by light blue rectangles, defining the enabling environment), and **Decision-Making Processes** (orange squares). Crucially, **Knowledge and Information Flows** (red arrows) are highlighted as linkages that connect and influence all components of the system. This framework is designed to be sufficiently general to apply across various agricultural innovations, not limited to one bio innovation.

Figure A.1 *A stylized conceptual framework for an enabling environment for agricultural bio-innovations*



Source: Authors, based on Biagini et al (2014) and Furman Porter and Stern (2002).

Product Life Cycle stream

The Product Life Cycle component outlines the distinct stages of an innovation journey from inception to widespread use and eventual stewardship. These stages include: R&D (which encompasses blue sky research/discovery, basic, and applied research), development of proof of concept, technology evolution, early adoption, market consolidation, technology diffusion, and product stewardship. Each of these stages represents a potential decision-making point for the product developer, were choices regarding continuation, modification, or even abandonment or repurposing of the product may occur.

It is important to note that these stages are not construed as a linear process with consecutive steps. Instead, they are dynamic, often overlapping, and may include loopbacks if technology does not perform as expected or if new information or accumulated knowledge necessitates a return to an earlier stage. In this sense, it is useful to think of innovation as a stock and flow system in a dynamic context. This non-linear perspective is a significant departure from traditional linear innovation models, reflecting the iterative and adaptive nature of real-world innovation, particularly in complex biological systems and dynamic socio-political contexts. For research and policy, this implies that interventions cannot be purely sequential; they must be flexible, allow for feedback loops, and anticipate the need to revisit earlier stages, underscoring the importance of adaptive governance and continuous learning within the innovation system.

Innovation Systems and the Enabling Environment

The Innovation System represents the enabling environment that influences technology selection, transfer, adoption, and diffusion. This environment contemplates both the stocks of knowledge and resources, and the flows and linkages between various actors and innovation clusters. Key categories defining the enabling environment include:

- **Ag-Biotech R&D/Innovation:** This encompasses aspects such as research capacity, intellectual property (IP) regimes, and the formation of strategic alliances.
- **Crop/Animal Improvement:** This focuses on the availability and management of germplasm stock and the methodologies employed in breeding programs.
- **End-User Characteristics & Social Context:** This considers the specific needs and characteristics of farmers, their adoption patterns, and the broader socio-cultural factors influencing technology acceptance.
- **Economics & Markets:** This examines market size, the functionality of seed systems, and trade-related issues that can either facilitate or hinder innovation diffusion.

- **System Policies & Issues:** This critical category includes biosafety and regulatory frameworks, the overarching political economy, and various governance indicators.

It is crucial to understand that these elements do not form a rigid checklist but rather constitute a dynamic system where each component interacts with and influences the others. Political economy issues, for instance, can explicitly affect the ag-biotech R&D/Innovation component, but also broadly influence the entire product life cycle and innovation system

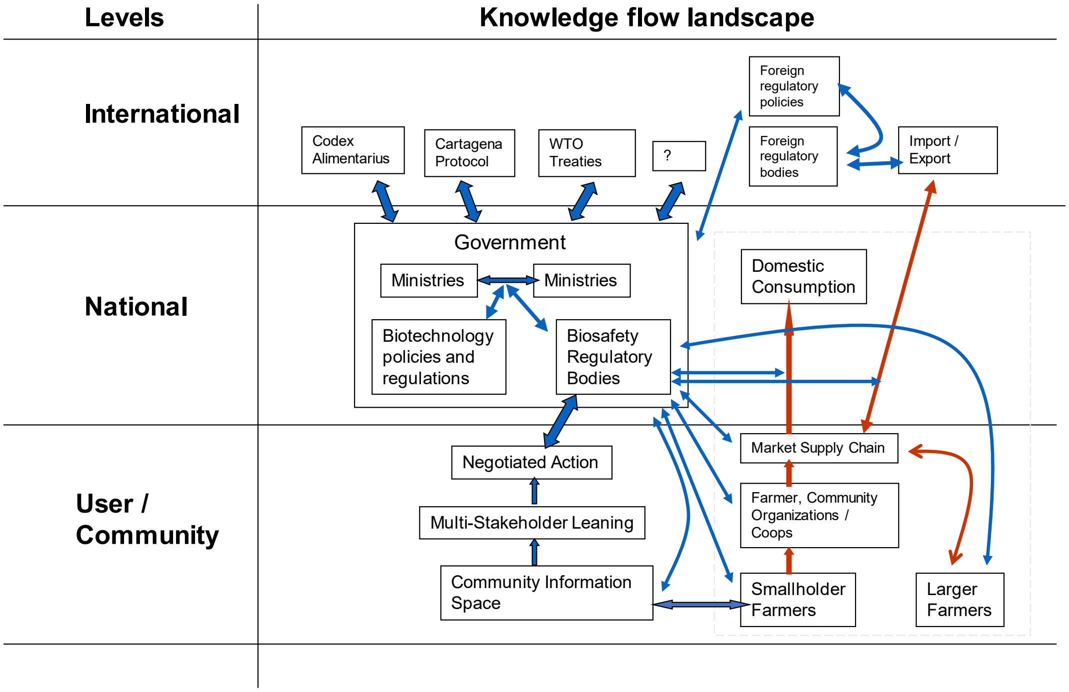
Decision-Making Processes

"Technology Selection" and "Technology Transfer, Adoption, and Diffusion" are identified as central decision-making categories within the framework. These decisions are directly or indirectly shaped by stakeholders and other actors within the system. Their outcomes are influenced and determined by the various categories that define the enabling environment.

Knowledge and Information Flows

Knowledge and information flows are critical linkages highlighted by red arrows in the framework in Figure A.2. They are essential for shaping supply and demand, informing R&D priorities, guiding regulatory decisions, and impacting market dynamics. As illustrated in Figure A.2, these flows occur at distinct levels (local, national, international) and between different actors (e.g., smallholder vs. large holders). They also interact with multiple international treaties and nationally mandated policies, laws, and regulations. These flows can be unilateral, bilateral, or multilateral, and can manifest as tacit or codified, formal or informal knowledge. The quality and efficiency of these linkages between actors, sectors, and processes largely determine whether adoptable products effectively respond to final consumer demand needs.

***Figure A.2** Knowledge and information flows in biotechnology, biosafety, and market systems*



Source: Author's own, based on Falck Zepeda, Maru, and Komen (2004). Red arrows are real resource flows, whereas blue arrows are information/knowledge flows. The weight of blue arrows qualitatively measures the degree of power strength between actor and organization interactions.

Underlying Issues and Linkages

The framework identifies four important underlying issues that influence the innovation process:

- **Political Economy:** This is a key determinant, heavily influencing technology selection, transfer, adoption, and use. Producer decisions are impacted by coercive, market, and resource drivers and actors. Coercive drivers, often influenced by social actors such as special interest groups and eNGOs, can be more powerful than market and resource drivers in shaping decisions. This highlights that even if technology is economically viable and resource-efficient, it can be derailed by non-market, often politically motivated, pressures, explaining why scientifically sound innovations may fail to reach farmers. For the framework to be truly operational, it must explicitly incorporate strategies for managing and engaging with these powerful non-economic drivers, moving beyond a purely technocratic view of innovation.
- **Supply-Demand Connection:** There is an increasing need to connect the innovation system, the supply of technologies, the users, and the final demand. This ensures that innovations are not only developed but also meet genuine needs.

- **Sustainable Development:** The framework stresses the imperative of linking bio-innovations to the three defining pillars of sustainable development: economic, social, and environmental.

- **Mapping Knowledge Flows:** Understanding and mapping knowledge and information flows at local, national, and international levels is critical for shaping supply and demand dynamics.

Policy and decision-makers must carefully balance environmental and food/feed safety protection with the promotion of innovation and the overarching goals of achieving food and nutritional security, resilience, and environmental protection.

Section 2. Characterizing the diffusion of agricultural technology across different innovation capabilities - *The case of IR/HT maize, IR cotton and precision agricultural technologies*

2.1 Introduction

Ongoing global population growth requires a permanent search for enhanced agricultural innovations that can improve productivity, enhance climate resiliency, and other sustainable development goals and objectives, to help ensure global food security. Genetically modified (GM) and other advanced agricultural biotechnology applications have emerged as significant alternatives supporting modern agriculture. GM and other biotechnologies offer potential alternatives to help to enhance yields through damage reductions, improved nutritional content, abiotic and biotic stress resistance and other valuable traits.

Among these technologies, insect resistant cotton and insect-resistant and herbicide-tolerant (IR/HT) maize, stand out as widely adopted examples. These technologies, engineered to provide protection against specific insect pests in cotton and maize and in the case of maize also tolerance to specific herbicides, have been adopted in various developed and developing nations due to their potential to provide producers with tangible benefits. A contrasting innovation alternative is Precision Agricultural Technologies (PATs). These are a portfolio of information, communication, robotics and automation, sensors, data management and now artificial intelligence which support production management and decision making.

This paper provides a comprehensive characterization of the diffusion, adoption, and adaptation of these technologies in selected countries. The selected countries represent a diverse range of agricultural systems, governance (IP, legal and regulatory) environments, and socio-economic contexts. This approach can provide valuable insights into the complex nature of agricultural innovation scaling up, adoption and diffusion.

By examining the adoption and diffusion timeline of these technologies, we will identify key innovators involved, describing the diffusion pathways across their respective agricultural value chains, and highlighting the commonalities and relevant institutional issues encountered. This report seeks to contribute to a deeper understanding of the factors that shape the trajectory of agricultural biotechnology adoption, scaling up and diffusion in a global context.

This section is organized as follows. First, we will examine the international adoption and diffusion of IR/HT maize in the USA, Brazil, Philippines and South Africa. Second, we will examine the adoption and diffusion of insect resistant (IR) cotton in the United States of America, India, China, Mexico, South Africa, and Kenya. These countries were chosen to represent a diverse range of geographical locations, economic statuses, and levels of innovation capabilities in agriculture. Next, we will conduct a comparative analysis of the diffusion of precision agricultural technologies (PATs) across seven countries including Argentina, Australia, Brazil, Canada, South Africa, and the USA. Finally, we provide a summary of lessons learned and policy recommendations.

Definitions

An important aspect is term definitions. We provide definitions used in this paper in Box 1. For the purposes of this paper, we will use the terms “Transgenic” and “Gene Editing” referring to the 1st and 2nd generation advanced genetic engineering techniques. These terms seem to be better understood in literature and by the public.

The term “Living Modified Organisms or LMOs” was introduced as a legal term by the Cartagena Protocol on Biosafety, which has triggered the development of many national regulatory frameworks. We will abstain from using LMOs as it causes some confusion. Nevertheless, we recognize that in many jurisdictions defining a genetically engineered product as an LMO” triggers regulatory scrutiny and decision making. We will use the term “Genetically Engineered” as a broad term reflecting all biotechnology-based crop improvement techniques.

Box 1. Definitions

Genome Editing: Specific modification of the DNA of an organism to create mutations or introduce new alleles or new genes.

Genetic Modified Crops: Refers to an organism whose genotype has been altered and includes alteration by genetic engineering and nongenetic engineering methods.

Transgenic crops: A crop that has had genes that contain sequences from another species or synthetic sequences introduced into its genome by genetic engineering.

Genetic Engineering: The introduction or change of DNA, RNA, or proteins by human manipulation to effect a change in an organism's genome or epigenome.

Living Modified Organisms (LMOs): A Living Modified Organism (LMO) is defined in the Cartagena Protocol on Biosafety as any living organism that possesses a novel combination of genetic material obtained using modern biotechnology.

New Breeding Techniques: New Breeding Techniques (NBT), also named New Engineering Techniques, are a portfolio of methods that have the potential of increasing and/or accelerating the development of new traits in plant, animal and other organisms breeding. These new techniques using biotechnology based approachs' objective are to introduce traits of interest into plants and other organisms.

Source: Falck-Zepeda, Zambrano, and Chambers (2025), (Lusser et al., 2011; National Academies of Sciences, Engineering, and Medicine, 2016; Secretariat of the Convention on Biological Diversity, 2000)

2.2 The International Diffusion and Adoption of IR/HT Maize: A Multi-Regional Characterization

Agriculture's global landscape has been significantly transformed by the advent and increasing adoption of genetically engineered (GE) crops. Over the past decades, a growing number of countries have recognized the potential of these technologies to enhance agricultural productivity, improve crop resilience, and contribute to food security. As of October 2024, more than 30 countries have granted cultivation approvals for GE crops, marking a notable increase from the 29 countries that planted such crops in 2019 to 32 in 2024, with Africa contributing three additional adopting nations.

The global area dedicated to biotech crops reached 209.8 million hectares in 2024 (AgBioInvestor, 2025). The observed adoption and diffusion pathways of GE crops globally likely represents the perceived and actual value GE crop technologies in agriculture. Value based on GE crop's ability to help address increasing demands for food, feed, and fiber and their associated challenges. The expansion of GE crops' cultivation into new regions, especially in low and middle income countries(LMICs), who face even more significant agricultural challenges, highlights the technology's potential to help contribute to global food security and sustainable agricultural practices.

Among the various GE technologies, transgenic insect-resistant and herbicide-tolerant (IR/HT) maize and insect resistant (IR) cotton, stand out as significant agricultural innovations. The specific type of IR maize released originally is genetically engineered to produce proteins from the soil bacterium *Bacillus thuringiensis*, which are toxic to specific insect pests, providing systemic protection against damaging target insect infestations. Herbicide-tolerant (HT) maize, on the other hand, is engineered to withstand the application of specific herbicides, such as glufosinate or glyphosate, offering farmers a more flexible and potentially more effective approach to weed management. GE cotton focused on insect resistance, uses specific proteins also derived *from Bacillus thuringiesis* to control target insects. IR cotton expressing the Bt protein, was used to manage the bollworm (*Helicoverpa zea*), budworm *(Spodoptera spp*) and the pink bollworm (*Pectinophora gossypiella*).

Recognizing the combined benefits of both insect resistance and herbicide tolerance (IR/HT) for the improvement of maize and cotton varieties, the inclusion of two or more traits has gained prominence. Combining (or stacking) IR and HT traits provide farmers with a comprehensive tool for managing both insect pests and weeds in a single crop technology. It is possible to stack more and different traits in a single crop. These technological advancements have been developed to directly address major constraints in areas where maize and cotton face specific yet binding production constraints. Targeted traits hereby offer the potential to address productivity constraints such as those for yields damage reductions , reduced input costs, and/or simplified farming practices, as compared to conventional maize and cotton varieties. These features and traits make them attractive options for producers across different agricultural systems.

United States of America

Adoption and diffusion timeline

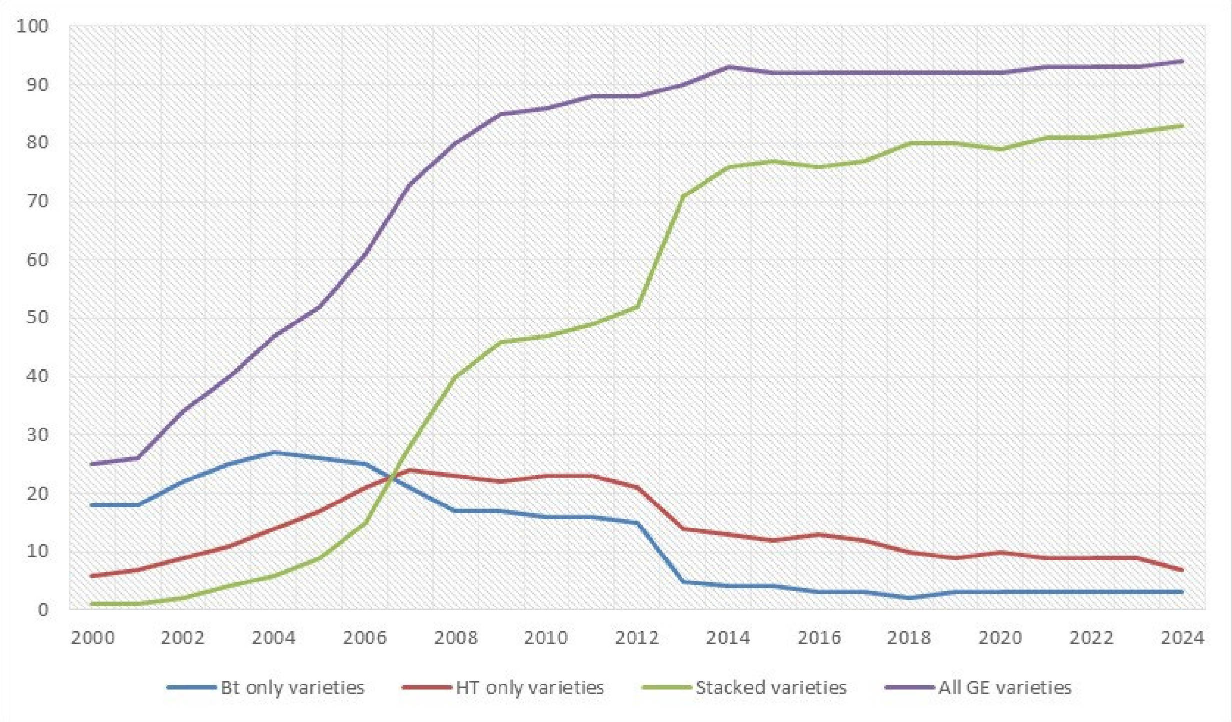
The first genetically engineered (GE) crops was used commercially where transgenic IR (insect-resistant) and HT (herbicide-tolerant) maize in 1996 in the United States of America (USA) (Fernandez-Cornejo & Caswell, 2015; Fernandez-Cornejo & Wechsler, 2012). Since their initial availability to farmers, the adoption rates for both traits have shown a consistently upward trend (Fernandez-Cornejo & Caswell, 2015). The acceptance of herbicide-tolerant (HT) maize was notoriously rapid, reflecting the benefits farmers perceived by getting access to superior weed management approaches. By 2010, HT maize had expanded to cover 70% of the total corn acreage in the U.S., and this figure further increased to 91% by 2023 (USDA Economic Research Service, 2011) .

The adoption of IR maize also experienced substantial growth, rising from approximately 1% of corn acreage in 1996 to 63% in 2010 and reaching 85% by 2023

(USDA Economic Research Service, 2011). Farmers' recognition of the advantages of combining both HT and IR traits, induced an accelerated rate of adoption, constituting 82% of the corn acres planted in the U.S. by 2023. By 2024, transgenic varieties of maize been adopted in the majority of area planted to maize in USA's agriculture, occupying over 90% of the total corn acreage, with stacked trait varieties accounting for a significant 83% of this area (USDA Economic Research Service, 2024, 2025).

As seen in Figure 1. the relatively rapid and sustained adoption in the U.S. suggests that farmers realized the significant value offered by IR/HT maize. This realization likely arises from farmers validation of a more effective target insect pests and weed control (National Academies of Sciences, Engineering, and Medicine, 2016). These outcomes contributed to enhanced yields and reduced use of pesticides compared to alternative control options. The case of herbicide tolerance is different in that the level of herbicide use increased, but the existing herbicide control system was replaced with what has been recognized as a less toxic herbicide (Kniss, 2017). The increasing preference for stacked traits further underscores a farmer-driven demand for comprehensive trait solutions embedded in elite germplasm capable of addressing multiple agricultural challenges simultaneously.

Figure 1: Timeline of transgenic maize adoption in the USA, (2000-2024)



Source: USDA, Economic Research Service using data from USDA, National Agricultural Statistics Service (NASS), June Agricultural Survey as published in the NASS report Acreage (various years), available on the NASS website.

While the adoption of transgenic corn has been widespread across the United States, there are notable variations in rates among different states. In 2023, North Dakota, Illinois, Iowa, Kansas, and Wisconsin emerged as leaders in the adoption of transgenic corn, with 95% of their respective corn acreages planted with these varieties. In contrast, Indiana reported the lowest adoption rate among the surveyed states, at 87%. (see https://www.michiganfarmnews.com/michigan-adoption-of-gmo-corn-soybean-seed-technology-mirrors-national-trends) and (USDA Economic Research Service, 2025)

Geographically, the USA Corn Belt, a region including 13 states in the Midwest, stands out as the area with the highest concentration of IR corn production (Ziwei et al., 2025) . This region's favorable climate and soil conditions have historically made it the center of maize cultivation in the country. Furthermore, the adoption of drought-tolerant corn varieties, which are often stacked with IR/HT traits, shows a distinct geographical pattern, with higher concentrations observed in the drought-prone regions of the western Corn Belt, including states such as Nebraska, Kansas, Texas, Colorado, and South Dakota (McFadden et al., 2019) .

The geographical adoption rate variation suggests a combination of explanatory factors involved with this outcome. These include differences in the prevalence and pressure of target insect pests and weed pressures across regions, the specific soil types and climatic conditions in different areas, and the prevailing local and regional agricultural practices. The high concentration of IR/HT corn in the Corn Belt is directly correlated with the region's status as the dominant maize-producing area in the USA, where the economic impact of target pest damage may be most significant.

Key innovators and innovative capacities

The innovation landscape for IR/HT maize in the USA has been primarily shaped by a combination of large multinational agribusiness corporations and public sector research initiatives. Among the key firms that pioneered and commercialized IR and HT maize technologies, Monsanto (now a part of Bayer) stands out as a major early innovator while other significant players in the transgenic seed market include Syngenta, DowDuPont (now Corteva Agriscience), and BASF (Spherical Insights, 2024). The company Pioneer Hi-Bred, also now under Corteva Agriscience, has also played a crucial role in the development and dissemination of these technologies.

In addition to the multinational corporations, universities and other research institutions across the USA have contributed to the ongoing development and rigorous testing of GE crops, providing valuable scientific insights and advancements (Anderson et al., 2019a). Furthermore, government agencies such as the USA Department of Agriculture's Economic Research Service (ERS) U.S. Department of Agriculture Agricultural Marketing System (AMS) and the USA Animal and Plant Health Inspections Services (APHIS) play an essential role by tracking and reporting on the adoption rates and trends of GE crops, risk assessments for regulatory compliance, inspection and monitoring and other services, thus providing crucial data for analysis and policy- and decision-making.

The United States of America as a pioneer and a global leader in agricultural biotechnology, is characterized by a robust innovation ecosystem and high adoption rates of GM crops. The USA agriculture biotechnology market is substantial, projected to reach USD 50.1 billion in 2024, reflecting a mature and dynamic sector (Spherical Insights, 2024). The collaborative ecosystem and network, incorporating a core innovative and cluster specific capacities (Furman et al., 2002b) involving substantial private sector investment driven by the potential for market leadership and intellectual property protection, alongside public sector contributions focused on research and oversight, has been instrumental in the development and widespread adoption of IR/HT maize in the USA.

The USA leadership is underpinned by the long-established Coordinated Framework for the Regulation of Biotechnology (Pew Charitable Trust, n.d.; USA Department of Agriculture, 2025) . Initiated in 1986, the regulatory framework for GE crops in the USA is a multi-agency effort involving the USA Department of Agriculture (USDA), the Environmental Protection Agency (EPA), and the Food and Drug Administration (FDA) (Bickel, 2021; USA Department of Agriculture, 2025) .

The US innovation landscape benefits from strong engagement from both the private and public sectors, with public (land grant) universities and research centers playing a leading role in advanced research and development (National Academies of Sciences et al., 2020). A collaborative environment, combining fundamental scientific advancements with market-driven applications, drives the continuous stream of innovations in agricultural biotechnology.

Diffusion pathways across the agricultural value chain

The diffusion of IR/HT maize technology across the agricultural value chain in the United States primarily begins with seed companies, which are responsible for the development, production, and marketing of these specialized seeds to farmers through well-established distribution networks (Zilberman et al., 2022). Farmers, seeking to enhance their crop yields and farming practices, adopt transgenic seeds, including IR/HT maize, for their perceived and actual benefits in managing insect pests and weeds. Adoption often leads to significant changes in the use of traditional agricultural inputs, such as a reduction in the field application of conventional insecticides and a shift towards the use of specific herbicides such as glyphosate, on HT maize (Fernandez-Cornejo & Li, 2005).

The widespread adoption of IR/HT maize has had a profound impact on the overall maize production and supply chain in the USA, influencing commodity markets, both domestically and internationally, and significantly affecting related industries such as livestock feed production, where maize is a primary ingredient, and the ethanol production sector, which may utilize a significant portion of the USA maize production (approximately 38% in 2023, see USA Department of Energy https://afdc.energy.gov/data)

Once harvested, maize, with the vast majority in the USA being transgenic varieties , is handled by a network of grain handlers, processors, and exporters who facilitate its movement from farms to various end-use markets. This complex value chain reflects the deep integration of IR/HT and other biotechnology based traits maize into USA agriculture.

Relevant institutional Issues

The adoption and diffusion of IR/HT maize in the USA have been significantly shaped by several key institutional factors. The Coordinated framework ensures that GE crops undergo rigorous evaluation for safety and environmental impact before commercialization. Intellectual property rights, particularly utility patents and Plant Variety Protection certificates have provided strong incentives for private sector investment in the development of GE maize seeds but also have implications for market concentration and the cost of seeds for farmers (Fuglie & McDonald, 2023; MacDonald et al., 2023) .

Farmer advocacy groups and public perception also play a crucial role in shaping the landscape of IR/HT maize adoption. Organizations such as the American Farm Bureau Federation, American Seed Trade Association, CropLife America, farmer associations and other famer interest groups generally support agricultural biotechnology, viewing it as essential for maintaining competitiveness and productivity (Edmisten, 2015). Conversely, groups such as Greenpeace, Union of Concerned Science, Non-GMO Project and others, tend to advocate against GMOs, raising concerns about their potential environmental and health impacts and promoting non-GMO alternatives (Genetic Literacy Project, 2017).

Consumer acceptance of GM foods, including maize-derived products, has been a subject of ongoing discussion and has evolved over time, influenced by factors such as labeling and information availability (Lucht, 2015). These institutional factors collectively create a complex environment that influences the trajectory of IR/HT maize adoption in the USA.

Brazil

Adoption and diffusion timeline

The adoption of transgenic corn in Brazil started after the first authorization for cultivation granted in 2007 by the National Biosafety Technical Commission (CTNBio).

Farmer adoption began in the 2008/2009 planting season. The adoption rate of transgenic corn in Brazil increased rapidly, reaching over 80% of the planted area by 2013 and currently standing close to 90% (Schuster et al., 2022).

By 2015, the adoption of biotech maize in Brazil had reached 84.6% of the total planted area. This trend continued, with the adoption rate climbing to 88.9% in 2017, where stacked traits combining insect resistance (IR) and herbicide tolerance (HT) became the dominant choice among farmers (ISAAA, 2017). In 2018, the adoption of biotech maize further increased to 89%. By 2022, the adoption rate had reached 95%.

The accelerated and broad adoption of IR/HT maize in Brazil, is like the USA pathways. As with the USA, this fact shows a validation of the technology by Brazilian farmers who also deemed the technology to be an effective target pest and weed management tool, as well as for its potential for enhanced yields as compared to conventional varieties protected with conventional means. The preference for stacked traits in Brazil is like that of the USA experience, highlighting the value of a comprehensive approaches to tackling multiple agricultural challenges as allowed by the possibility of stacking multiple traits into one seed.

Maize cultivation is a widespread agricultural activity across Brazil, with particularly significant production concentrated in the states of Mato Grosso, Paraná, Rio Grande do Sul, and Goiás (Gultig, 2025) . Among these, Mato Grosso stands out as the largest corn-producing state in the country. The adoption of GM maize has been extensive and has occurred in the major maize-producing regions in Brazil (Aparecido Alves et al., 2020).

Key innovators and innovation capacities

The landscape of agricultural biotechnology innovation in Brazil is characterized by the involvement of both major multinational agribusiness corporations and strong national research institutions. Prominent among the multinational firms are companies such as Bayer, Syngenta, DowDuPont, Corteva, BASF, and Dabei Nong, all of which have played significant roles in introducing and commercializing IR/HT maize and other biotechnologies in the Brazilian market (USDA Foreign Agricultural Service, 2023a).

In addition to the multi-national companies, a critical innovator in Brazil is the Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA), a federal government institution dedicated to agricultural research with many associated research centers and strategic alliances with universities and institutions (Figueiredo et al., 2019; Gultig, 2025). EMBRAPA has been instrumental in developing and securing approval for various biotech crops, including insect-resistant maize, specifically tailored to the agro-ecological conditions and agricultural needs of Brazil (Schuster et al., 2022).

EMBRAPA has developed networks and alliances with such institutions as Universidade de Brasilia, Fundação de Amparo à Pesquisa do Estado de São Paulo

(FAPESP) and UFRGS). The Brazilian collaborative environment, where global technological advancements are complemented by local research and development efforts, underscores Brazil's approach to agricultural biotechnology (Aparecido Alves et al., 2020) .

The significant growth is supported by a functional regulatory framework led by the National Biosafety Technical Commission (CTNBio), which approved the first transgenic corn cultivation in 2007. Since then, CTNBio has approved a substantial number of plant events, reaching 131 by 2024 (USDA Foreign Agricultural Service, 2024b). CTNBio's role is pivotal in ensuring the safety and efficacy of biotech products in Brazil, contributing to the country's capacity to evaluate and adopt new agricultural technologies. In addition, the National Biosafety Council (CNBS) provides an additional layer of oversight and has the authority to review CTNBio's decisions based on socio-economic considerations.

Diffusion pathways across the agricultural value chain

The primary pathway for the diffusion of IR/HT maize technology in Brazil involves seed companies that commercialized transgenic seeds, often through licensing agreements with the technology developers. Brazilian farmers, seeking to enhance their crop protection and management practices, readily adopt these seeds for their demonstrated benefits, such as improved control over target pests and more effective weed management (Anderson et al., 2019b). While the adoption of IR maize has been associated with a reduction in insecticide use in some instances, the use of HT varieties has, in some cases and as observed in other countries, led to an overall increase in herbicide application (Seixas et al., 2022).

Given Brazil's prominent position as a major agricultural exporter, the high rate of adoption of transgenic maize has significantly impacted its standing in the global maize market, enhancing its production capacity and export potential (Schuster et al., 2022). The maize value chain in Brazil includes various stages, from on-farm production to processing for animal feed, which constitutes a significant portion of domestic consumption, as well as for biofuel production and food products for human consumption (de Oliveira & Alvim, 2017). The economic advantages for farmers, coupled with the national emphasis on agricultural exports, serve as key drivers for the continued diffusion of IR/HT maize throughout Brazil's agricultural sector.

Relevant institutional Issues

Institutional factors have played a crucial role in shaping the adoption and diffusion of IR/HT maize in Brazil. The regulatory framework is primarily governed by the National Biosafety Technical Commission (CTNBio), which is responsible for the biosafety assessment and approval of genetically modified organisms (USDA Foreign Agricultural Service, 2023a).

In terms of intellectual property rights, while Brazilian law places restrictions on the patenting of plants and seeds (Campello Alonso, n.d.) . Brazilian law does allow for the patenting of transgenic microorganisms and the processes involved in developing GM plants. Plant variety protection is also available through the Brazilian Plant Variety Protection Law (Campello Alonso, n.d.) .

Farmer advocacy and public perception are also important aspects of the institutional landscape. Farmer organizations, such as the Association of Soybean and Corn Producers of the Mato Grosso region (Aprosoja-MT), represent the interests of producers. Simultaneously, civil society groups actively raise concerns regarding the potential environmental and health impacts of GMOs (Fontoura et al., 2022) . Consumer acceptance of GM foods in Brazil is generally considered to be relatively high, particularly considering the existing labeling requirements for products containing GMOs (Guivant & Macnaghten, 2015; Hakim et al., 2020; Oda & Soares, 2000). These institutional factors collectively shape the environment for the continued adoption and use of IR/HT maize in Brazil.

Philippines

Adoption and diffusion timeline

The Philippines has been a pioneer in the adoption of agricultural biotechnology in Southeast Asia, being the first in the region to establish a regulatory framework for transgenic crops. IR maize was first planted in the country in 2003, marking an early commitment to modern agricultural technologies((Yorobe Jr. & Smale, 2012)). Subsequently, herbicide-tolerant and stacked IR/HT corn varieties were introduced, with stacked traits accounting for 85% of the total biotech area by 2012 (See Figure 2.). By February 2024, the area planted with GE corn reached 709,000 hectares, estimated at around 85% of the total corn area (AgBioInvestor, 2025).

Figure 2. Transgenic corn adoption in the Philippines (in 1,000 hectares)

Source: (USDA Foreign Agricultural Service, 2021) based on Philippines Department of Agriculture - Biotechnology Program Office (DA-BPO).

Resource-poor farmers in the Philippines have experienced significant benefits from adopting IR maize, including enhanced yield protection and income (Mutuc et al., 2012; Yorobe Jr. & Smale, 2012) . However, the adoption and diffusion of biotech crops in the Philippines may have also been influenced by regulatory challenges and policy changes, such as the revocation of biosafety permits for Golden Rice and IR eggplant brough by the Philippines Supreme Court decisions, which have created some uncertainty in the sector (Nunez et al., 2019; Richmond, 2006).

In the Philippines, the adoption pattern has shifted from initial reliance on single-trait IR corn to a strong preference for HT and stacked IR/HT corn varieties. By 2012, stacked traits constituted most of the biotech maize area in the country, indicating the value that Filipino farmers place on the combined benefits of insect and herbicide resistance. Beyond IR/HT maize, there are ongoing research and development initiatives focused on other biotech crops relevant to the Philippines, such as Golden Rice, biofortified with pro-vitamin A, and IR eggplant, engineered for insect resistance, demonstrating a broader commitment to using biotechnology to address agricultural and nutritional needs. The emergence of new pests, like the fall armyworm, has also prompted the exploration and application of existing IR technology to manage these new threats, highlighting the adaptability of the technology to evolving pest landscapes (USDA Foreign Agricultural Service, 2021).

Key innovators and innovation capacities

The Philippines Department of Science and Technology (DOST) is the primary science and technology policymaking body in the Philippines. The DOST supports and funds various biotech research and development initiatives, often through its attached agencies including the Philippine Nuclear Research Institute (PNRI) which conducts mutation breeding to develop new and improved crop varieties.

The Department of Agriculture (DA) of the Philippines leads and funds associated agencies focused on commodity-specific biotechnology research. These includes the Philippine Rice Research Institute (PhilRice): PhilRice is the main institute for developing genetically engineered rice varieties, including the biofortified Golden Rice. Other agencies include DA's National Crop Biotechnology Center, and the Philippine Fiber Industry Development Authority (PhilFIDA) has collaborated with the University of the Philippines on research to develop virus-resistant abaca.

Local research institutions, such as the Philippine Rice Research Institute (PhilRice) and the University of the Philippines Los Baños (UPLB) and its Institute of Plant Biotechnology (IPB) and the National Institute of Molecular Biology and Biotechnology (BIOTECH), play a crucial role in developing and adapting biotech crops to local needs, exemplified by PhilRice's co-development of Golden Rice and UPLB's development of IR eggplant. Visayas State University has collaborated with UPLB's Institute of Plant Breeding to develop crops, including a virus-resistant sweet potato.

Other relevant Philippines institutions include the Department of Agriculture (DA) Crop Biotechnology Center (DA-CBC) and the University of the Philippines Diliman National Institute of Molecular Biology and Biotechnology (UPD-NIMBB). The DA-CBC is a center that conducts R&D in crop biotechnology, while UPD-NIMBB conducts research in industrial biotechnology. Other institutes in the University of the Philippines-Visayas, De La Salle University and Rizal Technological University conduct research on biotechnology approaches to marine and biodiversity conservation, crop improvement and bioprocessing.

Although not a Philippines funded institution, the International Rice Research Institute (IRRI) but located in the Philippines, IRRI is a global leader in rice research and often collaborates with national institutions on advanced breeding techniques and genetic engineering for rice. This includes the development of the pro-vitamin A enhanced rice (Golden Rice).

Diffusion pathways across the agricultural value chain

The diffusion of GM corn in the Philippines has been facilitated by various factors, including multinational seed companies activities, early farmer adopters, and knowledge dissemination and communication efforts such as demonstration farms and seminars (Torres et al., 2014). Adoption in the Philippines is punctuated by the geographical nature of the multitude of islands in the country. Adoption occurred in the northern part of Luzon, Mindanao and Visayas islands.

The process has been characterized by early adoption in many communities resulting from commercial seed companies' dissemination efforts. Companies disseminating IR/HT seeds included Bayer, Syngenta and Corteva. This approach pursued the strategy of ensuing adoption by early farmer adopters who share information about the biotech crop with related farmers (Navarro & Panopio, 2011). This is an important consideration as farmers with a low propensity to adopting in the Philippines tend to be smaller, with no access to irrigation, located in remote areas with poorer access to information and seed supplies (Mutuc et al., 2012)

Relevant institutional issues

Regulatory and governance

The regulatory framework in the Philippines, including the revised Joint Department Circular (JDC1), continues to evolve to ensure the safe and responsible use of biotechnology, with ongoing efforts to develop policies for GE animals (USDA Foreign Agricultural Service, 2024a). The National Committee on Biosafety of the Philippines (NCBP) is an integral part of the regulatory process. The NCBP enforces the country's biosafety system, ensuring that biotech products are safe and regulated under strict science-based standards (see biotech.buplant.da.gov.ph.) The Bureau of Plant Industry (BPI) issues biosafety permits for the use of biotech products, with the goal of fostering economic benefit and acceptance of these technologies.

IP

IR/HT corn planted in the Philippines are yellow maize hybrids. These are protected by IP laws. When farmers purchase seeds from formal sources, they sign a contract that is attached to the seed packet or bag. The contract signature compels farmers to save, reuse or replant seeds. Furthermore, as varieties planted are hybrids, farmers face hybrid vigor loss in the case they decide to reuse seed. This limits the potential of seed reuse and replanting. IP laws are considered under the Plant Variety Protection Law of the Philippines Act. Number 9168, which governs use of IP protected seed. Farmers get access to IP protected seed, which is more expensive than conventional hybrids, but which has consistently delivered higher yields and lower pesticide costs compared to conventional hybrids (Mutuc et al., 2012; Torres et al., 2014; Yorobe Jr. & Smale, 2012).

Stakeholders

Special interest groups have opposed GM crops in the Philippines. These include the Nisard Foundation, Philippine Reef and Rainforest Conservation Foundation, Magsasaka at Siyentipiko para sa Pag-unlad ng Agrikultura (MASIPAG), the Confederation of Indigenous Peoples Organizations in Southern Negros and other special interest groups. These organizations tend to oppose GM crops based on concerns on biodiversity and local varieties protection, food safety and food sovereignty.

In turn, the Department of Science and Technology (DOST) and the Philippine Council for Agriculture, Aquatic and Natural Resources Research and Development (PCAARRD) are actively involved in biotechnology research and development, including GM crops. These and other Philippines government departments have supported the development of transgenic crops int eh country.

Business and industry groups such as the Biotechnology Coalition of the Philippines, American Chamber of Commerce of the Philippines Inc., Makati Business Club and Management Association of the Philippines, Foundation for Economic Freedom, and the Japanese Chamber of Commerce and Industry of the Philippines Inc., have provided support for the deployment of GM crops including IR/HT maize and others.

South Africa

Adoption and diffusion timeline

South Africa has uniquely adapted IR maize for use as a staple food crop, with the development and adoption of IR white maize in addition to the IR yellow maize used primarily for animal feed (Gouse, 2012). This adaptation underscores the potential of biotechnology to enhance the productivity of staple food crops in the region.

Furthermore, efforts are underway to develop drought-tolerant maize varieties and maize with stacked traits combining IR and HT characteristics, recognizing the challenges posed by water scarcity and the need for comprehensive pest and weed management in South African agriculture. There are also specific initiatives aimed at developing maize varieties, including improved open-pollinated varieties (OPVs), that are better suited to the conditions and farming practices of smallholder farmers, with the goal of making the benefits of advanced maize genetics more accessible to this crucial sector (Gouse, Pray, et al., 2005).

In South Africa, the adoption of IR/HT maize shows a clear divergence between commercial and smallholder farmers (Gouse, 2013; Gouse, Pray, et al., 2005). By the 2009/10 season, approximately 69% of the total maize area was planted with GM maize, with IR maize alone covering 43%. However, the adoption rate among smallholder farmers has remained minimal compared to the total number of small-scale farmers in the country.

Government programs and private sector initiatives, such as those implemented by Bayer, have aimed to introduce IR maize to smallholders through workshops and the provision of free seeds. Nevertheless, smallholders face several challenges in adopting IR/HT maize, including the higher cost of seeds, limited access to seed supply, and the fact that commercial IR varieties may not always be best suited to their diverse farming systems and agro-ecological conditions.

Key innovators and innovation capacities

South Africa was the first country in Africa to commercialize GM crops, starting with IR cotton in 1997/98, followed by IR maize in 1998/99. This early adoption was supported by a robust regulatory system established through the Genetically Modified Organism ("GMO") Act of 1997. South Africa has since become one of the top 10 largest producers of GE crops globally.

Research institutions like the Agricultural Research Council (ARC) and universities, such as the Forestry and Agricultural Biotechnology Institute (FABI) at the University of Pretoria, are actively involved in biotechnology research and development, including efforts to develop maize varieties suited for smallholder conditions. South Africa also has a Bio-economy Strategy aimed at strengthening agricultural biosciences innovation to ensure food security and promote sustainable agricultural production. Government departments include the Agricultural Research Council (ARC) Biotechnology Platform (ARC-BTP), the Forestry and Agricultural Biotechnology Institute (FABI) and the DST-NRF Centre of Excellence in Plant Health Biotechnology (CTHB) have supported biotechnology research in the country.

Multinational companies' innovators include Bayer, Corteva AgriSciences, Dow Agrosciences, and Syngenta. Pannar Seed company, is a South African seed company based in Kwazulu Natal which distributed transgenic white and yellow maize hybrids in the country.

Diffusion pathways across the agricultural value chain

In South Africa, distribution channels serve as a pathway for the diffusion of IR/HT and other maize varieties. Studies conducted in South Africa tend to show that farmer organization participation, access to extension services and knowledge, irrigation and farm size are critical determinants of farm adoption on the country (Assefa & Van der Berg, 2010; Mailula et al., 2024; Ngcinela et al., 2019).

Relevant institutional issues

There are a number of institutional issues that limit transgenic maize adoption in South Africa (Escasura, 2025) . These are not exclusive to transgenic or GE maize and crops, rather they are a structural problem common to other countries in Africa and LMICs. South Africa's GMO regulatory system is based on the GMO Act of 1997. The 1997 Act delineated the regulatory requirement for risk assessment, environmental monitoring, and public comment.

Although the regulatory framework in South Africa was deemed as functional, in recent years there have been report of approval delays and overlapping mandates between departments involved in the regulatory framework. This has created delays in bringing new GM maize varieties to market, discouraging both public and private sector research investments.

The nexus between seed access, intellectual property and costs. GM maize hybrids are IP protected technologies can affect adoption (Mailula et al., 2024). The outcome of this is higher seed prices compared to conventional hybrids. This limits access to smallholder farmers, as the cash outlay for seed purchases may be limited by credit access. Typically, smallholder farmers face limited access to extension and knowledge transfer services. This may be compounded by the fact of limited extension officers training in biotechnology issues pertaining to production. This has led to some studies in the literature finding a negative correlation between extension services and GM maize adoption, in part due to outdated, incomplete or inaccurate advice. The outcome of this is poor or low awareness within smallholder farming households and communities. This limits farmer capacity for decision making.

Poor access to finance and market institutions, services and resources. Farmers face credit constraints, which in the case of smallholders, the higher cost of transgenic maize hybrids may be a deterrent for adoption. This coupled with weakly and perhaps poorly organized farmer groups and associations, may restrict the ability to negotiate seed access and grain marketing.

An important issue related to rural infrastructural and supply chains in South Africa. These include poor roads, limited access to irrigation, and insufficient storage facilities post- harvest. These issues tend to increase costs and increase post-harvest losses. A second issues are input distribution bottlenecks which include prompt delivery. Seed delivery delays can shorten planting windows, reducing flexibility and yield enhancement potential.

Socio-political and socio-cultural and special interest groups can influence transgenic crop adoption in South Africa. This may be results of incomplete or inaccurate information, public skepticism and questions, or gender and traditional seed system issues. Women in South Africa can and do have limited access to productive input, credit, and knowledge yet may express a preference for transgenic maize as it reduces labor drudgery (Gouse et al., 2016). Furthermore, households and communities may express preferences for saving seed or maintaining older varieties.

The issue of special interest groups opposing or support transgenic is important in South Africa as it may have had an influence on policy and decision making. There are several groups that oppose transgenic maize and other biotechnology develop crops (Scoones, 2008). These include includes African Centre for Biodiversity, World Council for Health South Africa, and the South African Freeze Alliance on Genetic Engineering (SAFeAGE). Other groups include worker unions, organic, consumer and rights based organizations and religious groups participating in campaigns and legal challenges to South Africa's regulatory frameworks. Groups that support transgenic and GE crops include AfricaBio, Grain SA, Biosafety South Africa, producer and grain associations

Cross-Country commonalities and institutional issues

Comparative Analysis of Adoption Timelines and Rates

A comparison of the adoption timelines reveals that the United States and South Africa were early adopters of IR/HT maize, with commercial introduction occurring in the late 1990s. Brazil and the Philippines followed later, with commercialization taking off in the late 2000s and early 2000s, respectively. However, despite these differences in the timing of initial introduction, all four countries have achieved significant and widespread adoption of IR/HT maize, indicating a general recognition of the technology's value in enhancing agricultural productivity.

Adoption rates have generally increased to high levels in all four nations, with GE maize now occupying a substantial majority of the total maize area in each country. This suggests a strong farmer-perceived benefit from utilizing these traits. Furthermore, a notable commonality is the increasing preference for stacked traits, combining both insect resistance and herbicide tolerance, which has become the dominant form of adoption in the US, Brazil, and the Philippines, and is also significantly prevalent in South Africa. This trend underscores a shared need among farmers across these diverse agricultural systems for comprehensive solutions that can effectively address both major biotic stresses – insect pests and weeds – in maize production.

Identification of common innovation stakeholders

Across the four selected countries, multinational agribusiness corporations emerge as key innovators in the development and commercialization of IR/HT maize technology. Companies such as Bayer, Syngenta, Corteva, and BASF have a significant presence in the seed markets of the USA, Brazil, Philippines, and South Africa, driving the introduction and dissemination of these GM technologies.

However, the role of public sector research institutions and universities is also crucial, particularly in Brazil and the Philippines, where entities like EMBRAPA and University of the Philippines Los Banos (UPLB) and the Institute of Plant Biotechnology (IPB) have actively engaged in adapting and developing these technologies to suit local agricultural conditions and needs. This includes the role that the international agricultural research centers such as the International Rice Research Institute (IRRI) have played in the Philippines and South Asia.

In all four countries, government agencies play an indispensable role in establishing and enforcing regulatory frameworks for the safe development and commercialization of GMOs, as well as in monitoring adoption trends and gathering crucial data on their impact. This collaborative ecosystem, involving global corporations, national research bodies, and governmental oversight, highlights a common model for agricultural biotechnology innovation and adoption.

Table 1. Total approvals for maize by country and developer

Country	Company	Count
China		
	Bayer	1
	Beijing Dabeinong Biotechnology	7
	Beijing Origin Seed	1
	China Forestry Seed Group	2
	China National Seed Group	18
	Chinese Academy of Agricultural Sciences	1
	Corteva	1
	Dow	1
	Dow & Pioneer	1
	Hangzhou Ruifeng Biotechnology	8
	Longping	1
	Longping Agricultural High-tech	1
	Monsanto	8
	Pioneer	2
	Syngenta	1
	Zhejiang Xin'an Chemical Group	1
Brazil		**139**
	Bayer	4
	Corteva	13
	Dow	12
	Dow & EMBRAPA	2
	EMBRAPA	1
	Helix Sementes e Mudas Ltda	2
	Monsanto	42
	Pioneer	20
	Syngenta	43
South Africa		**101**
	Bayer	8
	Corteva	5
	Dow	6

	Dow & Monsanto	1
	Dow & Pioneer	7
	Monsanto	32
	Pioneer	12
	Syngenta	30
Philippines		**47**
	Bayer	2
	Corteva	1
	Dow	1
	Dow & Monsanto	1
	Dow & Pioneer	1
	Monsanto	23
	Pioneer	3
	Syngenta	15
	Bayer	2
	Corteva	1
USA		**116**
	AgrEvo	6
	Agrivida	1
	Bayer	9
	Beijing Dabeinong Biotechnology	2
	Ciba-Geigy	2
	Corteva	3
	DeKalb	3
	Dow	8
	Dow & Pioneer	3
	Genective	2
	Greenlab	1
	Helix Sementes e Mudas Ltda.	1
	Monsanto	35
	Northrup King	1
	Pioneer	20
	Plant Genetic Systems	1
	Stine Seed Farms Inc.	2
	Syngenta	16

Notes: 1) Source: AgBioInvestor ”AgBioInvestor GM Monitor All Data 2025 V8” database https://gm.agbioinvestor.com/downloads , 2) Total approvals include those for cultivation, food/feed, and other types.

Analysis of similarities in diffusion mechanisms

The primary mechanism for the diffusion of IR/HT maize technology in all four countries is the commercial seed market, with well-established distribution networks facilitating the access of farmers to these specialized seeds (Gouse, Pray, et al., 2005). Farmers' decisions to adopt are consistently influenced by a set of common factors, including the perceived pressure from insect pests and weeds in their specific agricultural environments, the potential for increased crop yields and more stable production, and the possibility of achieving cost savings through reduced insecticide applications or more efficient weed management practices(Fernandez-Cornejo & Li, 2005).

Furthermore, the integration of IR/HT maize into the existing agricultural value chains, particularly its role as a key input for the animal feed industry, is a significant feature in all four countries, driving demand and contributing to its widespread adoption(De La Parra, 2024). This market-driven approach, where seed companies play a central role in making the technology available and farmers adopt based on their economic and practical needs, represents a shared pattern in the diffusion of IR/HT maize across these diverse regions.

Examination of Shared Institutional Challenges and Enabling Factors

Despite their distinct contexts, the USA, Brazil, Philippines, and South Africa share several common institutional challenges and enabling factors that have influenced the adoption of IR/HT maize.

Structural and enabling factors and environment for IR/HT Maize

Several factors play a crucial role in enabling the adoption of IR/HT maize across the selected countries. Structural factors such as farm size can influence adoption decisions differently in various regions. For example, in South Africa, larger farm size and the use of productive inputs (fertilizer, seeds, pesticides) have been shown to positively impact maize production (Mdoda et al., 2025; Obi & Ayodeji, 2020). The scale of farming operations can affect access to capital, risk tolerance, and the perceived benefits of adopting new technologies.

Adequate infrastructure, including transportation networks, storage facilities, and access to markets, is also essential for the efficient diffusion and utilization of agricultural technologies. Improved infrastructure in Brazil, for example, has been linked to greater agricultural production and the growth of the biotechnology industry (de Oliveira & Alvim, 2017) . Furthermore, market access, driven by factors like market demand, commodity prices, and export opportunities, provides a significant incentive for farmers to adopt yield-enhancing technologies such as IR/HT maize. Higher prices and strong market demand in Brazil and the Philippines have been associated with increased adoption of biotech crops.

Institutional factors also significantly shape the adoption landscape of IR/HT maize. Government policies, including financial support through subsidies and credit, and strategic policy frameworks, play a vital role in promoting the adoption of agricultural biotechnology. Regulatory frameworks governing the approval and commercialization of biotech crops vary across countries and may significantly impact adoption timelines and levels (Ngongolo & Mmbando, 2025; Sadikiel Mmbando, 2024).

All four countries have established regulatory frameworks for genetically modified organisms (GMOs), although the specific structures, processes, and levels of stringency may vary between them. The presence of these frameworks, however, provides a degree of oversight and assurance regarding the safety and environmental impact of these technologies. The USA operates under its Coordinated Framework and its agencies, Brazil under Law No. 11.105 of 2005 and CTNBio, the Philippines operates currently under the revised Joint Departmental Circular 1 (JDC1) of 2021, and South Africa has the Genetically Modified Organisms Act 15 of 1997. The regulatory framework helps to facilitate the risk assessment process when appropriate and when the regulatory system is functional. Intellectual property rights, particularly patents and seed ownership, influence the cost and availability of IR/HT maize technology.

Stronger legal protection can incentivize research and development but may also affect the affordability for smaller farmers, as seen in South Africa (Mailula et al., 2024). Finally, the presence and effectiveness of agricultural extension services and information dissemination networks are crucial for educating farmers about new technologies and supporting their adoption, especially among smallholder farmers (Gouse, Pray, et al., 2005). Extension officers in South Africa and information exchange among farmers in the Philippines is likely to have played a role in the diffusion of IR maize as part of technology packages.

Intellectual property protection for GM seeds, in various forms such as patents and plant variety protection rights, exists in all four countries. These may play a crucial role in incentivizing innovation and shaping the dynamics of the seed market, including pricing and competition.

Furthermore, the adoption of IR/HT maize in each country has been accompanied by active farmer advocacy, special interest groups and public discourse. Organizations representing farmers, environmental groups, and consumers have engaged in debates surrounding the benefits and potential risks of GM crops, influencing public perception and, at times, policy decisions. These shared institutional elements highlight the complex interplay of regulation, economic incentives, and societal values in the adoption and diffusion of agricultural biotechnology across different nations.

Adaptation and technological improvement of IR/HT maize

The technological trajectory of IR/HT maize has been marked by continuous adaptation and improvement in response to evolving agricultural challenges and regional needs. In the United States, the initial IR traits have been enhanced to target a broader spectrum of pests, including the economically significant corn rootworm and corn earworm, through the introduction of new IR protein genes (Anderson et al., 2019b).

Furthermore, there has been a significant trend towards the development and adoption of stacked traits, combining herbicide tolerance with multiple IR genes, offering farmers more comprehensive yield protection and greater convenience in managing their crops. To address the growing issue of herbicide resistance, particularly to glyphosate, the agricultural biotechnology industry has focused on developing new HT traits that confer tolerance to a wider range of herbicides and the use of herbicide rotations.

Similarly, in Brazil, the approval and widespread adoption of stacked trait maize, combining multiple IR genes for insect resistance with herbicide tolerance, have been prominent. Moreover, there has been a concerted effort to develop local IR maize varieties that are specifically adapted to the diverse agro-ecological conditions prevalent across Brazil, ensuring that farmers have access to biotech maize that performs optimally in their specific environments.

Summary and conclusions

Table 2 introduces a summary of the structural, institutional and innovation issues related to the adoption, diffusion and adaptation of IR/HT maize. The diffusion and adoption of IR/HT maize across the United States, Brazil, the Philippines, and South Africa reveal a complex interplay of factors, resulting in diverse patterns and outcomes. The United States and Brazil demonstrate high adoption rates, driven by well-established innovation ecosystems, supportive policies, and perceived economic advantages, particularly in large-scale commercial agriculture.

The Philippines, as an early adopter in Southeast Asia, showcases the potential of biotech maize to benefit smallholder farmers significantly, although regulatory hurdles have presented challenges. South Africa exhibits a notable disparity in adoption between the commercial sector, which has readily embraced the technology, and smallholder farmers, who face barriers related to cost, access, and suitability.

The adoption and diffusion and adaptation of IR/HT (and for individual traits) maize in the USA, Brazil, Philippines, and South Africa reveal a complex interaction between technological advancements, agricultural practices, economic drivers, and institutional frameworks. While the timelines of initial adoption varied across these countries, all four have witnessed a significant integration of this technology into their agricultural sectors. The geographical spread within each nation most likely reflects target pests and weeds prevalence, as well as the dominance of maize production in specific regions.

Key enabling factors vary in their influence across these regions. In the US and Brazil, the strong presence of multinational corporations and robust research and development capabilities have been pivotal. Government policies, including financial support and regulatory frameworks, have played a crucial role in facilitating adoption in all four countries, though the specifics and effectiveness differ. Intellectual property rights structures influence the cost and accessibility of the technology, particularly impacting smallholder farmers in developing countries like South Africa. The effectiveness of extension services and information dissemination is critical for ensuring that farmers, especially smallholders, understand and can benefit from IR/HT maize.

Table 2. Structural, institutional and innovative capacities summary

Country	**Structural Factors**	**Institutional Factors**	**Innovation Capabilities**
USA	Large average farm size; Well-developed infrastructure	Coordinated Framework for Regulation; Strong government support for agricultural R&D; Robust IP protection	• Global innovator in ag biotech • Strong public and private sector R&D • Advanced gene editing capabilities in universities, small and medium enterprises, large enterprises • High number of approved biotech events
Brazil	Large agricultural sector; Focus on export-oriented production	CTNBio regulatory body; Government subsidies and credit; Increasing focus on sustainable agriculture policies	• Second-largest producer of biotech crops • Strong domestic and multinational seed companies • Growing focus on biological agents and sustainable solutions • High number of approved biotech events

Philippines	Smaller average farm size; Developing infrastructure	Early regulatory framework (JDC1); Government support for biotech R&D (DA Biotech Program); Strong public awareness efforts	• Pioneer in biotech adoption in Southeast Asia • Local research institutions (PhilRice, UPLB) • Focus on developing biotech crops for food security and nutrition (e.g., Golden Rice) • Moderate number of approved biotech events
South Africa	Dual agricultural sector (commercial and smallholder)	GMO Act regulatory framework; Government programs to introduce biotech to smallholders; Bio-economy Strategy	• First in Africa to commercialize GM crops • Strong commercial ag sector • Research institutions (ARC, universities) involved in biotech R&D • Focus on drought tolerance and varieties for smallholders • Moderate number of approved biotech events, but regulatory approach for gene editing is cautious

Key innovators consistently include multinational agribusiness corporations, working often with local public research institutions and universities, demonstrating opportunities for partnerships focused on global technological transfer and local adaptation capabilities. The primary diffusion pathway remains the commercial seed market, with farmers making adoption decisions largely based on the perceived economic and practical benefits of improved pest and weed control, and the potential for enhanced yields and their own socio-demographic and economic context.

There are several common factors amongst these four countries that have influenced the adoption of agricultural innovation. The prominent role of multinational corporations in driving the technology and shaping the market is evident across all four nations. The establishment of functional regulatory frameworks and decision making processes, with expected variations in their specific structures and level of scrutiny, has been a crucial enabling factor for the commercialization and use of IR/HT maize.

The economic incentives for farmers, to adopt the technology resulting from expectations about the increased productivity and reduced input costs potential, consistently emerge as a primary driver of adoption in diverse agricultural contexts. Finally, the influence of farmer advocacy groups, consumer organizations and special interest groups, and the evolving public perception of GM crops underscore the importance of societal considerations in shaping the trajectory of agricultural biotechnology.

Adaptation strategies and technological improvements reflect the specific challenges and innovation capabilities of each country. The US and Brazil have focused on developing and adopting stacked traits and addressing herbicide resistance through new HT varieties. The Philippines has seen a shift towards stacked traits and continues to innovate in other biotech crops. South Africa has uniquely adapted IR maize for staple food production and is focusing on developing drought-tolerant varieties and those suited for smallholder farming systems. The level of innovative capacities within each country directly influences its ability to adapt and improve IR/HT maize technology to meet their specific agricultural needs and challenges. Countries with strong research infrastructure and supportive policies are better positioned to drive technological advancements and tailor these innovations to their unique contexts.

The findings from this comparative analysis hold significant implications for future agricultural technology development and dissemination. They highlight the need for a comprehensive approach that not only focuses on enhancing yields and productivity but also considers the sustainability of agricultural practices, ensures equitable access to technology for farmers of varying scales, and proactively addresses the societal concerns and ethical considerations associated with genetically modified crops. These lessons apply to innovators and developers in the public and private sectors.

2.3 The international adoption and diffusion of insect-resistant (IR) cotton in agriculture

Introduction

Agricultural innovation plays a pivotal role in meeting the escalating global demand for food, especially when confronted with challenges such as a growing population and increasing environmental constraints. Among the significant advancements in agricultural technology, genetically modified (GM) crops stand out as a key innovation aimed at enhancing productivity and sustainability. Insect-resistant (IR) cotton, a genetically engineered variety, exemplifies the successful adoption of biotechnology in agriculture across various regions worldwide.

By examining the trajectory of IR cotton in these countries, this paper aims to elucidate the patterns and pathways of agricultural technology diffusion, the factors enabling its adoption, and the processes of technological improvement and adaptation that have occurred in different agricultural ecosystems.

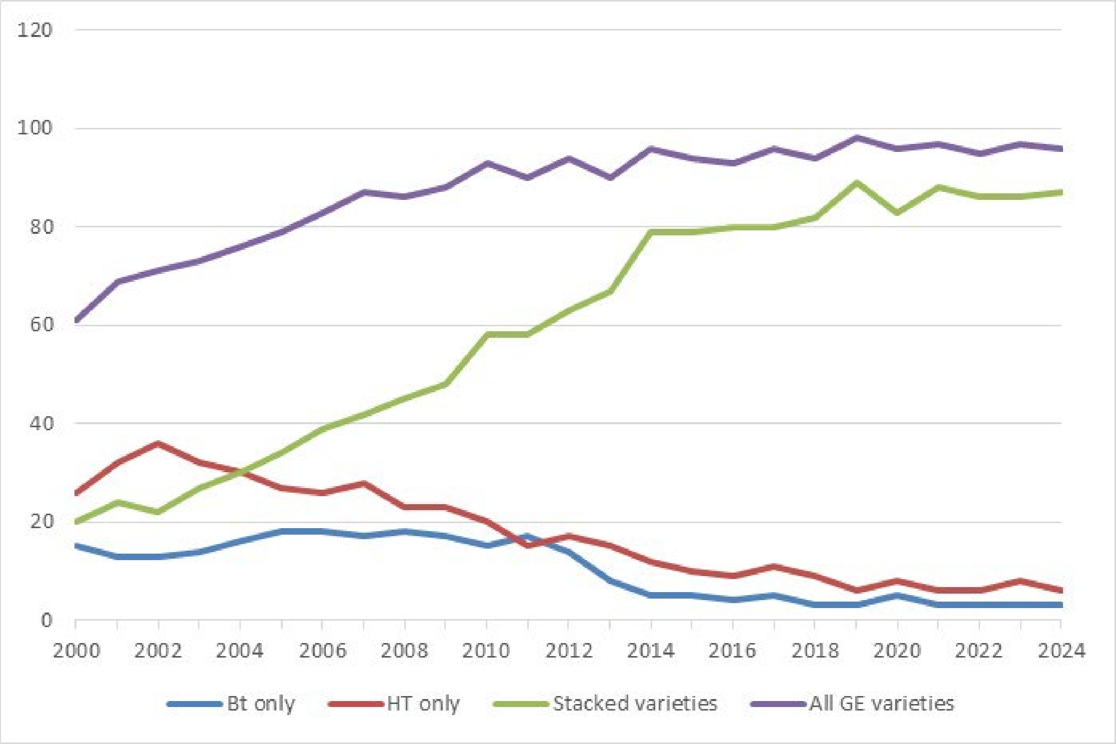
Furthermore, it will address key questions concerning the main innovators, the flow of technology across borders, the structural and institutional factors facilitating adoption, the occurrence of technological advancements in regions with varying innovation capacities, the role of institutions in this process, and the extent to which the ease of adoption is influenced by the technological relatedness of adopting regions. We will discuss the case of IR cotton adoption, diffusion and adaptation in the United States of America, China, India, Mexico and South Africa.

United States of America

Adoption and diffusion timeline

The adoption of IR cotton in the USA rapidly expanded following its commercial introduction. From the initial 730,000 hectares planted in 1996 (Edge et al., 2001), the technology gained widespread acceptance among American cotton farmers. By 2013, IR cotton was planted on approximately 75% of the total cotton acreage in the USA , and this figure rose to over 90% by 2023 (Fernandez-Cornejo et al., 2014; USDA Economic Research Service, 2024). As seen in Figure 3. Adoption has increased to 94% achieving a level of saturation that may be considered as full. Adoption rates varied across different regions of the country, influenced by the prevalence and severity of specific cotton pests.

Figure 3. USA adoption of transgenic cotton varieties (percent of all upland cotton planted)



Source: USDA, Economic Research Service using data from USDA, National Agricultural Statistics Service (NASS), June Agricultural Survey as published in the NASS report Acreage (various years), available on the NASS website.

The EPA played a crucial role in overseeing the technology, granting initial approvals and establishing guidelines for its use, including the important requirement for farmers to plant non-IR cotton refuge areas to mitigate the development of insect resistance. These refuge strategies, typically requiring 20-50% of a farmer's cotton acreage to be planted with non-IR varieties, aimed to ensure the survival of susceptible insects. An interesting ecological consequence observed in the USA and in other countries such as China and Mexico, was the increased abundance of non-target pests, such as mirid bugs, in some areas following the introduction of IR cotton. This was attributed to the reduced use of broad-spectrum insecticides that had previously controlled these secondary pests.

Key innovators

The United States emerged as the leading innovator and early adopter of IR cotton. The IR cotton technology underwent its initial development and regulatory scrutiny in the USA, setting the stage for its subsequent global diffusion. Field trials of IR cotton were first approved in the United States in 1993, followed by commercial approval in 1995 by the USA Environmental Protection Agency (EPA).

Bayer (through Monsanto Company) played a central role in this process as a gene innovator, developing the first genetically engineered cotton by inserting a Cry1Ac gene from *Bacillus thuringiensis* into the cotton genome. The gene innovator entered into strategic alliances with the lead cotton germplasm innovators, the Delta and Pineland company, to develop innovative IR cotton varieties through licensing agreements.

The IR cotton innovation was first commercialized under the trade name Bollgard^{TM} in 1996 (Nester et al., 2002). Early adoption was seen in states like Alabama, Mississippi, and Arizona in 1996, where IR cotton was primarily used to combat the bollworm and budworm complex and the pink bollworm, major pest in the southeastern and western cotton-growing regions. This initial introduction proved successful in alleviating pest issues and often led to increased yields and higher profits for farmers (Falck-Zepeda et al., 2000).

Building on this foundation, continuous innovation occurred in the USA, with Bayer and other agricultural biotechnology companies developing subsequent generations of IR cotton. Bollgard II^{TM}, introduced in 2003, incorporated two Bt genes (Cry 1Ac and Cry 2Ab), while WideStrike^{TM}, registered in 2004, expressed Cry1Ac and Cry1F, offering improved control over a broader range of caterpillar pests. Further advancements led to the development of other IR technologies such as Bollgard III^{TM}, WideStrike 3^{TM}, and TwinLink Plus^{TM} (which express the Vip3A toxin), providing enhanced control of several budworm/bollworm pests. These early efforts in the USA not only provided American farmers with an effective and novel tools for pest management but also laid the groundwork for the technology's adoption and adaptation in other cotton-producing countries facing similar challenges.

The stakeholders involved in the adoption process were diverse, ranging from farmers making planting decisions to biotechnology companies like Bayer that developed and marketed the technology, seed companies that incorporated the IR trait into their cotton lines, and government agencies like the USDA and EPA that provided oversight and support.

Relevant institutional issues

The USA has a well-established agricultural research infrastructure, including USDA-ARS facilities and land-grant universities supported by the Federal governments and its agencies. These agencies contributed significantly to the development, evaluation, and continuous improvement of IR cotton technology.

The USA Cooperative Extension System played a vital role in disseminating information and providing farmers with the knowledge needed for successful adoption and management of IR cotton. Furthermore, the biotechnology and GMO policies in the USA provided a comprehensive regulatory framework involving the USDA, EPA, and FDA to ensure the safety of genetically engineered crops for both the environment and human health.

India

Adoption and diffusion timeline

Following its introduction, IR cotton rapidly spread across India, becoming the first genetically modified crop approved for commercial cultivation in the country. By 2008-2011, it was cultivated on over 90% of the total cotton area, reaching 94% in 2018 (Blaise & Kranthi, 2019). Gujarat and Maharashtra were the early adopters of IR cotton in the country that commenced in 2002 followed by Andhra Pradesh and Karnataka (Gandhi & Jain, 2016).

A relevant feature of cotton in India, is the widespread use of cotton hybrids. India is the only country that has commercially adopted hybrid globally (Blaise & Kranthi, 2019). The initial introduction of cotton hybrids induced higher yields and production in India. This strategy however has been under some scrutiny due to cotton hybrids higher prices, observed instances of resistance to the Bt toxin, and the appearance of secondary pests (Gutierrez et al., 2023).

Key innovators

IR cotton was introduced to India in 2002 through a joint venture between Monsanto and the Maharashtra Hybrid Seeds Company (Mahyco), known as Mahyco Monsanto Biotech (MMB). IR cotton was approved by the Government of India through its Genetic Engineering Approval Committee (GEAC) for commercial cultivation in India in 2002, after the unauthorized appearance of IR Cotton in Gujarat in 2001. The GEAC as the regulatory authority of the Government of India for transgenic crops, approved the commercial cultivation of three IR cotton varieties: Bt Mech 12, Bt Mech 162 and Bt Mech 184. In response to the high cost and proprietary nature of MMB seeds, the Indian Council of Agricultural Research (ICAR) and other Indian seed companies developed their own, often cheaper, IR cotton varieties and hybrids, including varieties with reusable seeds.

Key institutions facilitating the adoption process included the Indian Council for Agricultural Research (ICAR) for research and development of local varieties, the government's Genetic Engineering Approval Committee (GEAC) for regulatory approvals, private seed companies, and the Central Institute for Cotton Research (CICR) for research and developing diagnostic tools(Peschard, 2022) .

India has a robust agricultural research infrastructure comprising ICAR institutes and State Agricultural Universities (SAUs) that supported the development and assessment of IR cotton. Agricultural extension services, including Krishi Vigyan Kendras (KVKs) and Agricultural Technology Management Agencies (ATMAs), may have played a role in disseminating knowledge and providing support to farmers in general.

The Department of Biotechnology (DBT) funded R&D in agricultural biotechnology, while the Biotechnology Industry Research Assistance Council (BIRAC) provided financial assistance to support biotechnology startups, biotech parks and other innovative approaches to innovation promotion. State Agricultural Universities (SAU) and other universities such as Delhi University and its Genetic Manipulation of Crop Plants (CGMCP) center have submitted applications for transgenic technologies. These capacities are supported by a well develop and extensive capacity in bioinformatics, biosimilars, and vaccine/pharmaceutical production capabilities.

Relevant institutional and structural issues

The adoption of IR cotton in India has been subject to various controversies, including debates about its long-term effectiveness in pest control, alleged links to farmer suicides which have been largely refuted, and the development of resistance in pests like the pink bollworm. Despite these issues, IR cotton has had significant socio-economic impacts in India, leading to increased cotton yields, a reduction in the use of chemical insecticides (especially in the initial years), and higher profits for many smallholder farmers, ultimately transforming India into the world's leading cotton exporter and the second-largest producer.

The biotechnology and GMO policies in India involved a stringent regulatory framework for the approval of IR cotton and continue to evolve in response to new developments and concerns. This is the results of a perceived weak political support for transgenic crops commercialization in the country.

China

Adoption and diffusion timeline

China approved the commercial planting of IR cotton in 1997, becoming one of the first countries to adopt this technology. The primary impetus for this adoption was the severe outbreaks of the cotton bollworm (*Helicoverpa armigera*) in the mid-1990s, which were causing significant damage to cotton crops. GE cotton is approved for cultivation in three agroecological zones including Xinjiang, Yellow River Basin, and Yangtze River Basin.

IR cotton adoption and diffusion in China was rapid, reaching over 90% of the cotton area in major producing regions like the Yellow River Valley and the Yangtze River Valley by the mid-2000s. According to GAIN report China Cotton and Products Annual 2024 (USDA Foreign Agricultural Service, 2024d), China's MY2024/25 cotton planted area is forecast at 2.9 million ha, of which 95% is estimated to be transgenic cotton. This widespread adoption and diffusion led to a significant reduction in the use of chemical insecticides, with some studies reporting a decrease of 60-80% (Pray et al., 2002) .

While yield gains were observed, they were generally modest in some areas. A notable ecological impact was the emergence of secondary pests, such as mirid bugs, which became more abundant due to the reduced application of broad-spectrum insecticides (Wang et al., 2009; Zhang et al., 2018) . Other concerns that arose over time included efficacy variability, susceptibility to premature senescence, pest resistance, and yield disadvantage compared to conventional varieties. Important noting that these issues have been addressed over time while gaining a better understanding of the IR cotton technology as related to the production system and emerging challenges (Zhang & Dong, 2024). Long-term studies in China have indicated that the benefits of IR cotton, particularly the reduction in pesticide use, have been sustained over more than a decade, and bollworms have not yet developed widespread resistance to the Bt toxin (Huang et al., 2002; Qiao et al., 2016).

Key innovators

China developed its own IR cotton varieties through the Chinese Academy of Agricultural Sciences (CAAS) and its Biotechnology Research Institute (BRI), alongside the introduction of Monsanto's Cry1Ac gene into local varieties through joint ventures. Important noting the extensive Chinese agricultural biotechnology networks included those that received funding at one point in time and through their five year plans over time.

These include those key laboratories such as the National Key Labs of Agricultural Biotechnology at China Agricultural University, National Key Labs of Crop Genetic Improvement at Central China Agricultural University, and the National Key Labs of Plant Disease and Pest Biology at Institute of Plant Protection (CAAS). Some may have been involved in the development of the Chinese IR cotton and/other cotton and crop transgenic technologies.

This significant capacity to conduct R&D in transgenic and other advanced biotechnologies is the result of extensive investments in agricultural biotechnology and other types of biotechnology by the Chinese government. The limited release of Chinese transgenic technologies for commercialization may be the results of uncertain support for commercialization by the Chinese government.

From the standpoint of multinational companies, Bayer and Syngenta, have played a role in conducting R&D and in cotton innovation in China and elsewhere. They are not alone, as several Chinese companies have developed their own IR cotton technologies and/or have entered strategic alliances to Bt gene technologies from abroad.

Relevant institutional issues

The adoption of key institutions involved in this process included the Chinese government for its early approval and continued support for biotechnology, CAAS for its research and development of domestic varieties, Bayer for its technology contribution, and various seed companies for production and distribution(Li et al., 2017).

China has a substantial agricultural research infrastructure and extension services with numerous institutes and universities contributing to advancements in agricultural technology in general. China's biotechnology and GMO policies reflect a significant government investment in this sector, with a focus on ensuring food security and environmental safety through a well-established regulatory framework (Mirae Assets, 2021)

Mexico

Adoption and diffusion timeline

Mexico was among the first countries to commercially plant IR cotton, starting in 1996.4 The adoption rates varied across the country. The Comarca Lagunera region in the northern states of Coahuila and Durango, achieved high adoptions levels, reaching 96% by the year 2000 (Traxler & Godoy Avila, 2004) . The primary motivation for adopting IR cotton in Mexico was to revitalize cotton production, which had suffered due to severe pest infestations, economic instability, and limited water availability (Rocha-Munive et al., 2018)

The IR cotton technology in Mexico was predominantly based on Monsanto's BollgardTM system, with varieties like NuCOTN 33B^{TM} and NuCOTN 35B^{TM} being widely used. The adoption of IR cotton led to a significant reduction in pesticide use, especially against the pink bollworm, and resulted in increased yields and profitability for farmers in regions with high adoption rates like Comarca Lagunera in Northcentral Mexico. The emergence of IR cotton in Mexico was the result of price and exchange rates volatility, scarcity of irrigation water, and changes in government policies (Traxler & Godoy Avila, 2004).

Key innovators

Bayer and Delta & Pineland companies where the key innovators as they provided the gene and germplasm materials to farmers in north central Mexico. The National Institute of Forest, Agriculture and Livestock Research (INIFAP in spanish) is a public research center part of the Secretariat of Agriculture and Rural Development (SAGARPA). INIFAP's North-Center center in the Comarca Lagunera was instrumental in the field evaluation, testing, monitoring, and communication dissemination of IR cotton in the region.

Mexico established a three-stage biosafety testing and approval process for transgenic crops, including IR cotton. Key institutions involved in this process included the Mexican government through the Secretariat of Agriculture and Rural Development (SAGARPA) and the National Service of Health, Safety and Agri-Food Quality (SENASICA), Monsanto and Delta & Pineland Companies, as the main technology providers, regional agricultural input distributors, producer associations, and the National Agricultural Research Institute (INIFAP).

Mexico has an established agricultural research infrastructure that supports innovation in the sector(USDA Foreign Agricultural Service, 2025) . Agricultural extension services in Mexico have evolved towards a more privatized, demand-driven model, with private contractors and producer organizations playing increasingly important roles(Uscanga & Edwards, 2016). The country's biotechnology and GMO policies reflect its early engagement with transgenic crops and a relatively well-defined biosafety framework, although recent years have seen increased uncertainty and debates, particularly concerning GMO corn (USDA Foreign Agricultural Service, 2025).

Relevant institutional issues

The political climate has changed from a precautionary to a restrictive approach. The current administration approved a ban on transgenic maize cultivation, and the herbicide glyphosate use in the country in 2025 but repealed a ban on imports of transgenic maize. The tariff and trade issues are undergoing negotiations and rearrangements which will influence a policy environment in the country with regard to transgenic crops.

IP

Bayer and other companies disseminating IR cotton in Mexico pursued an IP protection strategy that included contract-in-a-bag at purchase. The contracts mandated selling seed cotton to approved ginneries (Traxler & Godoy Avila, 2004). Furthermore, field representatives in the region conducted spot checks of cotton fields using field test kits.

Cottonseed can only be separated from cotton lint in ginneries, planting unlinted seed reduces germination significantly, implying that ginneries became a useful strategy to control cotton seed flows. Important to note, that from the 34 cotton gins in 1990, only 12 remained by the time of IR cotton release. Given the high adoption rate in the region, all cottons gins signed contract with Bayer as approved gins.

Stakeholders

Groups opposing transgenic crops in general include Asociación Nacional de Empresas Comercializadoras de Productores del Campo, Grupo Vicente Guerrero, PODER, Semillas de Vida, Via Campesina, and international environmental and food sovereignty organizations. These groups have focused their efforts on transgenic maize linking it to food sovereignty, cultural and religious considerations, and indigenous rights issues.

South Africa

Adoption and diffusion timeline

South Africa was the first country in Africa to commercially produce a genetically modified crop, introducing IR cotton in 1997/1998. The country experienced high adoption rates of IR cotton among both large-scale commercial farmers and small-scale, resource-poor farmers in regions like the Makhathini Flats and Tonga. The IR cotton technology in South Africa was primarily based on the companies Bayer and Delta & Pine Land Bollgard^{TM} system, with varieties like NuCOTN 35B^{TM} and NuCOTN 37B^{TM} being widely adopted (Ismael et al., 2002) .

The adoption of IR cotton in South Africa led to increased yields for both small and large farmers, reduced insecticide use, higher gross margins, and even a decrease in insecticide poisoning incidents among smallholders as compared to conventional cotton producers (Gouse et al., 2004) .Key institutions involved in facilitating IR cotton adoption in South Africa included the government through the Genetically Modified Organisms Act of 1997 and its Executive Council, Bayer and Delta & Pine Land as the technology providers, Vunisa Cotton for its role in supplying inputs and credit to small farmers in Makhathini, and Cotton SA as an industry body (Gouse et al., 2003).

Key innovators

South Africa has a well-established agricultural research infrastructure, including the Agricultural Research Council (ARC), which supports advancements in the sector(Department of Science and Technology South Africa, 2016). Agricultural extension services, including the South African Society for Agricultural Extension (SASAE), also played a role in disseminating information and promoting best practices.

Relevant institutional issues

South Africa's biotechnology and GMO policies have been relatively supportive of the technology, with a national biotechnology strategy and a functional regulatory framework (Department of Science and Technology South Africa, 2013). The South African government has recently seemed to take a more precautionary approach especially with regard to upcoming biotechnologies such as gene editing. Discussions are undergoing whether gene editing approaches will be considered under current GM regulations. This approach would align South Africa with the ongoing discussions in the European Union towards gene editing. If gene editing are regulated under the GMO Act of 1997, these approaches will face the same issues of potential delays, additional costs and uncertainty in South Africa.

The discussions about the regulatory and governance environment in South Africa serve to open the discussion about what Gouse and colleagues have termed “technological triumphs and institutional failures” (Gouse, Kirsten, et al., 2005). As these researchers showed in KwaZulu Natal in South Africa, the IR cotton technology worked as designed. If used properly, the technology reduced or eliminated the damage caused by the target pest. IR cotton is a technological triumph. The technology was deployed in KwaZulu Natal, adoption reached 90%, with contracts and loan support provided by a ginning company Vunisa and other partners.

A second company started operations, and a number of farmers sold their harvest to this company, inflicting heavy financial losses to the original company. Vunisa no longer offered credit and support to farmers. Issues of regulating markets with potential monopoly/monopsony conditions, while ensuring farmer access becomes an institutional issue. Here Gouse and colleagues report an institutional failure which led to significant decreases in cotton cultivation in KwaZulu Natal. Institutional and enabling environment issues are critical to the deployment of transgenic technologies. This will likely be the norm for all future agricultural innovations and technologies.

Kenya

Adoption and diffusion timeline

Kenya recently joined the list of African countries developing and adopting IR cotton. Commercial approval was granted in 2019 and the first plantings taking place in 2020 after extensive research and field trials (Kedisso et al., 2023). The primary motivations for this adoption were to revitalize Kenya's struggling cotton industry, boost overall agricultural productivity, and reduce the significant pest pressure from the African bollworm (ISAAA, 2019).

Key innovators

Key institutions involved in this process include the Kenyan government, the Kenya Agricultural and Livestock Research Organization (KALRO), Mahyco Seed (providing IR cotton seeds), National Environment Management Authority (NEMA), and the National Biosafety Authority (NBA) for regulatory oversight. The country anticipates significant positive impacts, including a potential increases in cotton yields, a reduction in production costs by an estimated 40%, and the creation of opportunities for apparel export earnings and job creation (Ministry of Industry, Trade and Cooperatives - Kenya, n.d.).

Relevant institutional issues

Initial challenges included ensuring access to seeds for farmers, disruptions due to the COVID-19 pandemic, and court challenges to the government's decision to lift a decade-long ban on GMOs (Kedisso et al., 2023) . Early reports from Kenyan farmers who adopted IR cotton have indicated satisfaction with its performance, noting high germination rates, early maturation, and effective resistance to the African bollworm

(Nanteza, 2022). There is a strong focus on benefiting smallholder farmers in Kenya's rainfed agricultural systems through this technology.

Kenya has an existing agricultural research infrastructure, with the Kenyan Agricultural, Livestock Research Organization (KALRO) playing a central role in agricultural research and innovation. Agricultural extension services are also being strengthened to support farmers in the adoption and management of IR cotton. Kenya has developed a national biotechnology policy and enacted a biosafety act yet put in place a ban on GM technologies Kenya banned GM crops in 2012.

The ministerial statement on the ban was largely informed by a 2012 scientific study that reported an association between GMOs consumption and cancer in rats. Anti-GMO activists used this study and the potential and unknown food safety impact of gene modifications and the environmental risk to the environment -such as impacts on non-target pests- as reasons for pushing for such bans. The recent lifting of the GMO ban signals a more enabling environment for the technology, although public and legal debates continue (ISAAA, 2025) .

Comparative Analysis

Patterns and pathways of diffusion across regions

The diffusion of IR cotton technology across the selected countries reveals a varied landscape influenced by timelines, pathways, and adoption factors unique to each region. The United States, as the pioneer, initiated field trials in 1993 and commercialized IR cotton by 1995. Mexico followed shortly after, with commercial planting beginning in 1996. China adopted IR cotton in 1997, while South Africa started commercial production in 1997/1998. India's adoption timeline was slightly later, with commercial approval in 2002. Kenya is the most recent entrant among these countries, commercializing IR cotton in 2019 with first plantings in 2020. Table 3 summarizes the experience from all countries.

The diffusion pathways differed significantly with respect to lead innovator. In the USA and Mexico, the private sector, particularly the companies Monsanto and Delta & Pineland, played a dominant role in the early stages, developing and commercializing the technology. In contrast, India and China saw a more substantial involvement of national research institutions like ICAR and CAAS in developing and adapting IR cotton to local conditions, often in collaboration with multinational corporations and local seed companies.

Government policies and regulatory frameworks were crucial in all countries, either facilitating adoption through timely approvals and supportive policies (e.g., South Africa's GMO Act) or creating hurdles through delays or bans (e.g., Kenya's GMOs ban). Farmer-to-farmer networks and agricultural extension services were important in facilitating the widespread adoption of IR cotton in developing countries, helping to disseminate information and build trust in the new technology (Bilal & Jaghdani, 2024; Vitale et al., 2011). Issues with information sharing can be significant to the proper use of the technology (Ahmad, 2022). See Table 3 for a summary by country.

Adoption rates and influencing factors showed both similarities and differences between the developed country (USA) and the developing countries. The USA experienced a steady and high adoption rate, driven by the technology's effectiveness against major pests and its positive impact on yields (Fernandez-Cornejo et al., 2014). In developing countries like India and China, the scale of smallholder farming and the severity of pest problems like bollworms were significant drivers of adoption.

South Africa's success was notable for its high adoption among both commercial and small-scale farmers, facilitated by a supportive regulatory environment and private sector involvement (ISAAA, 2025), but faced institutional issues which largely limited the area planted to IR cotton in the country. Kenya, as a recent adopter, is showing promising initial adoption rates among smallholders, driven by the potential for increased yields and reduced pesticide use. Factors such as access to credit, information, and extension services played a more critical role in the adoption process in developing countries compared to the USA.

Table 3. Innovation, adoption and diffusion summary of IR cotton by country

Country	Approval of Field Trials	Approval for Commercial Use	Year of Peak Adoption (Approx.)	Key Innovators/Stakeholders
USA	1993	1995	Ongoing	Bayer, Delta & Pine Land Co., USDA, EPA
India	1995	2002	2011-2014	Bayer, Mahyco, ICAR, GEAC, Private Seed Companies
China	Early 1990s	1997	2007	Chinese Academy of Agricultural Sciences (CAAS), Bayer, Biocentury Transgene Corporation Ltd.
Mexico	1988	1996	2004-2008	Bayer, Delta & Pine Land Co., SAGARPA, INIFAP
South Africa	1997	1998	2001-2002	Bayer, Delta & Pine Land Inc. South Africa, Vunisa Cotton, ARC

Kenya	2004-2010	2019	Early stages	Kenyan Government, KALRO, Mahyco Seed, National Biosafety Authority

Source: Compiled by author

The existing agricultural infrastructure and innovation ecosystems also played a crucial role in the diffusion process. Countries with established research institutions and extension networks, like India and China, demonstrated a greater capacity to adapt and further develop IR cotton technology to suit local conditions. Mexico's existing irrigated agricultural systems in regions like Comarca Lagunera facilitated the integration of IR cotton. South Africa's well-organized agricultural sector and the role of companies like Vunisa Cotton were enabling factors. Kenya is leveraging its existing agricultural research institutions and extension services to support the adoption of IR cotton.

Table 4 compiles the total regulatory approvals by country for cotton. This is an indicator of the innovators involved with cotton in each country. Understanding the context in which these innovators and their trajectory is important to understand the innovation process. The primary innovators in IR cotton technology were located the United States, predominantly through the efforts of the companies Bayer Company and Delta & Pine Land, and other emerging companies producing the gene and germplasm technologies. In other cases, national agricultural research systems in developing countries like the Chinese Academy of Agricultural Sciences (CAAS) in China and the Indian Council of Agricultural Research (ICAR) in India, have been supporting agricultural biotechnology innovation. Universities also contributed to the foundational research and ongoing improvements.

These innovators connected with one another through various mechanisms. Bayer pursued a strategy of international expansion by forming joint ventures with established local seed companies, such as Mahyco in India (leading to MMB) and Delta & Pine Land in China and Mexico. These collaborations facilitated the transfer of IR cotton technology and provided access to local markets and distribution networks (Peschard, 2022). Furthermore, the licensing agreements also served as a crucial channel for the flow of technology, allowing local companies to incorporate the patented IR gene into their own cotton varieties.

Table 4. Total approvals for cotton by country and developer

Country	**Crop/Company**	
China		**51**
	Bayer	11
	China National Seed Group	1
	Chinese Academy of Agricultural Sciences	3

	Cotton Research Institute	7
	Dow	2
	Hebei Shenniu Agricultural Technology	1
	Huazhong Agricultural University	12
	Hubei Jinhu Crop Research Institute	1
	Hunan Qicheng Agricultural Technology	1
	Hunan Xiangza Seed Industry	1
	Kejidalong Biotechnology	1
	Na	1
	Nongji'an Zhengzi	6
	Shandong Yinxing Seed Industry	2
	Wuhan Longfukang Agricultural	1
India		**5**
	JK Agrigenetics	1
	Metahelix Life Sciences	1
	Bayer	2
	Nath Seeds	1
South Africa		**13**
	Bayer	4
	Dow	2
	Monsanto	7
USA		**62**
	Aventis	1
	BASF	3
	Bayer	30
	Calgene	11
	Dow	7
	Pioneer	2
	Syngenta	6
	Texas A&M	2

Notes: 1) Source: Compiled by author from AgBioInvestor ”AgBioInvestor GM Monitor All Data 2025 V8” database https://gm.agbioinvestor.com/downloads , 2) Total approvals include those for cultivation, food/feed, and other types.

The flow of IR cotton technology across regions and countries initially moved from the USA, the source of the innovation, to other cotton-growing areas globally through these commercial channels and strategic collaborations. This flow involved not only the transfer of the IR gene but also the movement of cotton germplasm containing the GM gene . International collaborations between research institutions, such as the partnership between Bayer and CAAS (Pray et al., 2001), also played a role in adapting the technology.

The particularities of each region and country significantly influenced the diffusion process. In the USA, the strong agricultural research infrastructure and the presence of a well-developed seed industry facilitated rapid adoption. India's vast cotton-growing area and the significant problems caused by bollworm infestations created a strong demand for the technology, which was further enabled by proactive government support and the development of local research capacity. China's adoption was driven by severe bollworm outbreaks, coupled with strong financial government backing for agricultural biotechnology and a large base of smallholder farmers in need for alternatives to their production issues.

Mexico's needed to revive its cotton production sector, coupled with existing irrigated agriculture and government support through credit and integrated pest management programs, created a favorable environment for IR cotton adoption (Rocha-Munive et al., 2018; Traxler & Godoy Avila, 2004). South Africa's well-regulated GMO environment and the involvement of private companies like Vunisa Cotton in providing inputs and extension services to small farmers were key factors in its successful adoption(Gouse, 2013) . Kenya's recent adoption was spurred by the desire to revitalize its cotton industry and combat high pest pressure from the African bollworm, with strong government support playing a crucial role (Ministry of Industry, Trade and Cooperatives - Kenya, n.d.).

Enabling Factors for Adoption and Adaptation: Structural and Institutional Influences

The adoption and adaptation of IR cotton were influenced by a complex interplay of structural and institutional factors that varied across the selected countries. Structural factors such as farm size, irrigation infrastructure, and market access played significant roles. In India and China, the widespread adoption of IR cotton by smallholder farmers demonstrated that the technology was not limited to large-scale farms and land holders (Kathage & Qaim, 2012). The availability of irrigation infrastructure, as seen in parts of the USA, China, and Mexico, provided more stable growing conditions and supported the adoption of IR cotton. Access to well-established cotton markets and value chains was also crucial for the successful integration of IR cotton production.

Institutional factors, including government policies and regulations, extension services, and farmer organizations, were equally important. Supportive government policies and streamlined regulatory processes, such as those in South Africa and initially in China, facilitated the adoption of IR cotton(Huang et al., 2002; Li et al., 2017) . In contrast, delays or uncertainties in regulatory approvals, as experienced in Kenya and more recently in Mexico, could hinder the adoption process (USDA Foreign Agricultural Service, 2023b).

Effective agricultural extension systems in countries like China and India may have played a role in disseminating information about IR cotton and providing farmers with the necessary technical support. Additionally, farmer organizations and cooperatives played a vital role in facilitating collective learning, improving access to inputs, and advocating for the interests of farmers concerning IR cotton adoption (Traxler & Godoy Avila, 2004). The specific combination and effectiveness of these structural and institutional factors varied across the six countries, ultimately shaping the trajectory and impact of IR cotton adoption in each context.

Technological Improvement and Innovation Capabilities Across Regions

The evolution of IR cotton technology demonstrated varying levels of improvement and innovation across the selected regions, reflecting their differing innovation capabilities. The USA, as the originator of the IR cotton technology, maintained a strong focus on continuous improvement, leading to the development of stacked-gene varieties like Bollgard II^{TM} and WideStrike^{TM}, and later generations like Bollgard III^{TM}, aimed at enhancing pest control efficacy and managing insect resistance.

In contrast, India and China showcased significant capabilities in adapting and even improving upon the initial IR cotton technology. India, through ICAR and private seed companies, developed its own, often more affordable, IR cotton varieties and hybrids, with a focus on traits like reusable seeds that addressed the specific needs of Indian farmers. China, similarly, saw the Chinese Academy of Agricultural Sciences (CAAS) develop and patent its own IR gene, which was then incorporated into local cotton varieties alongside the introduction of Bayer's technology. Chinese researchers also explored dual-gene transgenic cotton to enhance pest resistance (Li et al., 2017).

Mexico and South Africa primarily adopted the IR cotton technology developed in the USA, with less evidence of independent innovation in the core IR trait itself. Mexico focused on integrating the existing technology into its regional farming systems and addressing local pest pressures. South Africa relied heavily on Bayer's IR gene, incorporated into varieties by Delta & Pine Land. Kenya, as a more recent adopter, initially utilized imported IR cotton seeds from India, with potential for local seed production in the future.

These patterns indicate that while the USA remained a key innovator in IR cotton technology, countries like India and China with stronger agricultural research and development infrastructure demonstrated a greater capacity to adapt and improve upon the technology to meet their specific needs. The level of innovation capability in a region thus influenced its ability to move beyond basic adoption towards developing more advanced or locally tailored solutions.

The innovation ecosystems and technology flows

To understand the connections between national level innovation capacities and agricultural ecosystems, it is important to map in what crop biotechnology innovation may be occurring. One indicator of innovative activity is the level of regulatory approvals by country and by crop. This is typically an indicator of the level of investment and the innovators' perceptions of the enabling environment and the possibilities of securing returns to their investments.

Table 5 introduces data on the total regulatory approvals by country and crop. The countries with the most total regulatory approvals are the USA, Canada, Brazil, Colombia and China. The crops with the highest number of approvals are not surprisingly maize, soybeans, cotton and canola. These are commercial crops with large market size potential, where developers focus their investments to secure returns on investments. The possibility of spillovers to smaller, resource-poor farmers and smallholders was an additional innovation benefit to society. What has changed over time is the fact that beyond the "big four" investments have been in other crops such as potatoes, rice, wheat, and others. Others include fruits, vegetables, forages, trees, shrubs, roots and tubers, and others.

Table 5. Total approvals all transgenic crops by country

Country	**Canola**	**Cotton**	**Maize**	**Soybean**	**Potato**	**Rice**	**Wheat**	**Other**	**Total**	***% share of total***
Argentina		20	92	41	2	1	2	9	167	*4.1%*
Australia	18	17						6	41	*1.0%*
Australia & New Zealand	14	19	38	23	21	2	2	9	128	*3.1%*
Bangladesh		2						1	3	*0.1%*
Bolivia				4				0	4	*0.1%*
Brazil		28	139	37			2	23	229	*5.6%*
Canada	47	23	159	58	47	1		29	364	*8.9%*
China	12	51	55	34		2		8	162	*4.0%*
Colombia	7	41	109	32		2	2	2	195	*4.8%*
Costa Rica		34	1	5				1	41	*1.0%*
Ethiopia		2	2					0	4	*0.1%*
EU	10	15	73	29				1	128	*3.1%*
Ghana			8	6				0	14	*0.3%*
Honduras			19			1		3	23	*0.6%*
India	1	5		6				0	12	*0.3%*
Indonesia	9	8	38	19	2		2	6	84	*2.1%*
Indonesia		2	11	3		1		0	17	*0.4%*
Japan	24	47	202	29	12			9	323	*7.9%*
Kenya		2	2					1	5	*0.1%*
Malaysia	3	6	22	16	3			0	50	*1.2%*

Mexico	10	34	86	28	8	1		4	171	*4.2%*
Nigeria		1	21	13	6		1	1	43	*1.1%*
Pakistan		2						0	2	*0.0%*
Paraguay		12	40	14			1	0	67	*1.6%*
Philippines	8	16	47	25	6	2		8	112	*2.7%*
Russia			15	10		1		1	27	*0.7%*
Singapore	7	18	61	17	3			2	108	*2.6%*
South Africa	5	13	101	29		1	1	0	150	*3.7%*
South Korea	23	41	112	34	10			6	226	*5.5%*
Switzerland	8	9	29	20				0	66	*1.6%*
Taiwan, Province of China	15	33	92	30				1	171	*4.2%*
Turkey		1	32	15				0	48	*1.2%*
UK (Excluding Northern Ireland)	9	14	227	24				1	275	*6.7%*
Uruguay		18	54	45				0	117	*2.9%*
USA	38	62	116	50	79	7	3	102	457	*11.2%*
Vietnam	3	8	25	16				4	56	*1.4%*
Grand total	**271**	**604**	**2028**	**712**	**199**	**22**	**16**	**238**	**4090**	*100.0%*
% share ot total	*6.6%*	*14.8%*	*49.6%*	*17.4%*	*4.9%*	*0.5%*	*0.4%*	*5.8%*		

Notes: 1) Source: AgBioInvestor ”AgBioInvestor GM Monitor All Data 2025 V8” database https://gm.agbioinvestor.com/downloads , 2) Total approvals include those for cultivation, food/feed, and other types.

Table 6 describes the situation for regulatory approvals for cultivation. One of the drawbacks of using total regulatory approvals is that developers may conduct earlier regulatory stage research with scientific, strategic or communications purposes in mind. Total regulatory approvals for cultivation provide a better understanding of investment decisions for commercial purposes, as getting to the cultivation regulatory approval implies cost and time for completion. Outcomes are not so different from Table 5 in that the “big four” are still individual crops with highest share of approvals. Investments in other crops beyond the big four still remain, implying private and public research in developing crops and traits of interest to countries allowing transgenic research to proceed.

Table 6. Approvals for cultivation only, by country and crop

Country	**Canola**	**Cotton**	**Maize**	**Soybean**	**Rice & Wheat**	**Other**	**Total**	**% share of total**
Argentina		10	51	22	1	8	92	**8%**
Australia	18	17				5	40	**4%**
Bangladesh		2				1	3	**0%**
Bolivia				3		0	3	**0%**
Brazil		26	79	28	1	17	151	**14%**

Canada	25		111	34		33	203	**19%**
China		34	26	11		0	71	**6%**
Colombia		9	18	1		1	29	**3%**
Costa Rica		34	1	5		1	41	**4%**
Ethiopia		2	1			0	3	**0%**
EU			1			0	1	**0%**
Honduras			9			0	9	**1%**
India		5				0	5	**0%**
Indonesia		2	5			4	11	**1%**
Kenya		1	1			0	2	**0%**
Mexico		4				0	4	**0%**
Nigeria		1	2			1	4	**0%**
Pakistan		2				0	2	**0%**
Paraguay		9	28	12	1	0	50	**5%**
Philippines		1	7		1	1	10	**1%**
South Africa		9	28	7		0	44	**4%**
Taiwan, Province of China			1			0	1	**0%**
Uruguay		15	28	23		0	66	**6%**
USA	16	31	57	28	4	108	244	**22%**
Vietnam			5			0	5	**0%**
Grand Total	**59**	**214**	**459**	**174**	**8**	**180**	**1094**	**100%**
% share of total	**5.4%**	**19.6%**	**42.0%**	**15.9%**	**0.8%**	**16.5%**		

Notes: 1) Source: Compiled from AgBioInvestor ”AgBioInvestor GM Monitor All Data 2025 V8” database https://gm.agbioinvestor.com/downloads , 2) Total approvals include those for cultivation, food/feed, and other types.

The role of institutions in facilitating or hindering technology adoption

Various institutions played critical roles in either facilitating or hindering the adoption of IR cotton across the selected countries. Government agencies were central to this process. In the USA, the EPA approved and oversaw the technology, while in India, the GEAC regulated its commercial release. South Africa's government established the GMO Act, providing a framework for responsible development and use. However, institutional factors could also create barriers. The initial ban on GMOs in Kenya and recent debates surrounding GMO corn in Mexico (Quintana, 2025) illustrate how government policies can impact adoption.

Research organizations like the USDA-ARS in the USA, ICAR in India, CAAS in China, INIFAP in Mexico, and KALRO in Kenya were instrumental in developing, testing, and adapting IR cotton technology for their respective regions. The private sector, led by companies such as Monsanto, Mahyco, and Delta & Pine Land, played a crucial role in the commercialization, marketing, and distribution of IR cotton seeds.

Non-governmental organizations (NGOs) often played an advocacy role, raising awareness about potential risks and benefits. Different organizations emphasized risk versus benefits distinctively. Farmer organizations and cooperatives were important in disseminating information, facilitating access to inputs, and representing the interests of farmers. The effectiveness and coordination of these institutions significantly influenced the pace and success of IR cotton adoption in each country.

In turn, environmental, social justice, and indigenous and local community rights organizations tended to oppose the IR cotton technology, setting up legal challenges to the regulatory system and by implementing information campaigns highlighting their positions related to the technology. Environmental and food safety concerns were often intertwined with food sovereignty issues including monopolistic control of agriculture, economic dependence, indigenous rights and beliefs, and neoliberal policies impact of smallholder poor farmers.

Influence of technological relatedness and complexity on adoption ease

The ease with which IR cotton was adopted in different regions appears to have been influenced by the technological relatedness and complexity of neighboring capabilities within the adopting regions. In the USA, where farmers were already accustomed to a long history of modern improved cotton varieties flow over time and modern farming practices, the adoption of IR cotton was relatively expedient. Similarly, in India, the existing widespread cultivation of hybrid cotton provided a familiar germplasm background into which IR technology could be readily integrated, facilitating its rapid adoption.

China's agricultural practices, including the use of improved cotton varieties and seedling transplantation in some areas, were also compatible with the introduction of IR cotton. In Mexico, the intensive, irrigated cotton production systems in regions like Comarca Lagunera in Northcentral Mexico, were conducive to the adoption of IR cotton, indicating a level of technological relatedness to the institutional context. South Africa's established commercial farming sector, coupled with a structured distribution system for IR cotton seeds, facilitated its uptake. Kenya, as a more recent adopter, is likely to see the ease of adoption influenced by its existing cotton farming practices and the effectiveness of support systems in place.

Synthesis, conclusions, and implications for agricultural innovation

The global history of IR cotton diffusion from its inception in the USA to its adoption and adaptation across diverse agricultural landscapes highlights a complex interplay of technological advancements, environmental imperatives, socio-economic factors, and institutional frameworks.

The experiences of the USA, India, China, Mexico, South Africa, and Kenya collectively underscore that while a single agricultural innovation can have broad applicability, its success and impact are profoundly shaped by the specific context of each adopting region. The diffusion pathways varied, with multinational corporations playing a significant early role, particularly in the USA and Mexico, while national research institutions in India and China demonstrated a strong capacity for adaptation and indigenous innovation.

Adoption rates were influenced by factors such as the severity of pest pressures, the economic benefits perceived by farmers, and the effectiveness of institutional support mechanisms, including government policies, regulatory environments, and agricultural extension services.

The case of IR cotton also reveals that the long-term success of agricultural innovations hinges on a continuous cycle of research, adaptation, and robust institutional support. Challenges such as the emergence of pest resistance and ecological shifts necessitate ongoing monitoring and proactive management strategies. Moreover, the ease of adopting new technologies is often linked to their compatibility with existing farming systems and the level of technological sophistication within a region.

The widespread adoption of IR cotton in countries with predominantly smallholder farming systems demonstrates the potential of agricultural biotechnology to benefit farmers across different scales of operation, provided that appropriate support and enabling policies are in place. Ultimately, the story of IR cotton serves as a valuable case study for future agricultural innovations. It underscores the importance of a comprehensive yet context-specific approaches to technology development and dissemination.

Effective agricultural technology adoption requires strong linkages between innovators, research institutions, governments, extension services, and farmers, along with policies that support innovation, address farmer needs, ensure environmental sustainability, and foster equitable access to the benefits of technological advancements. The diverse experiences of the selected countries provide valuable lessons for policymakers and researchers striving to promote responsible and impactful agricultural innovation to enhance global food security and improve livelihoods worldwide.

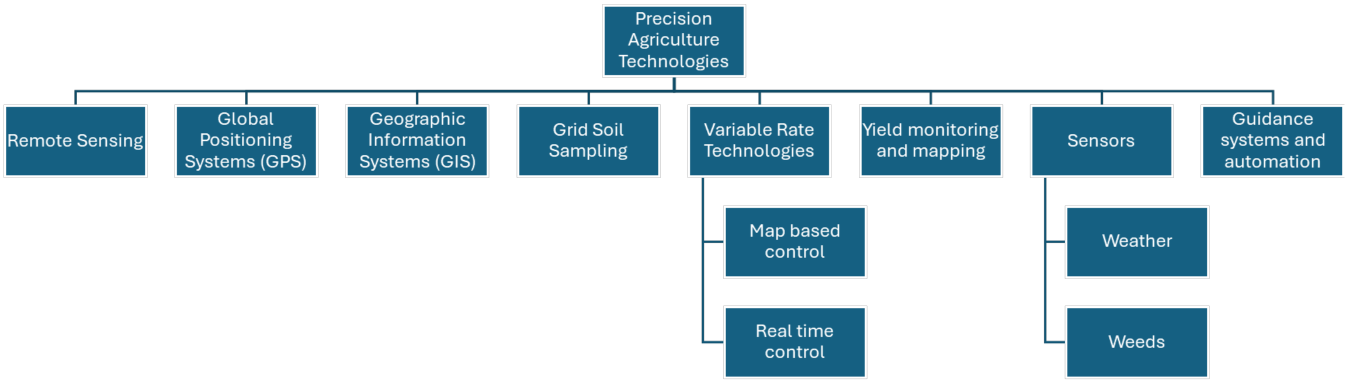
2.4 Diffusion of Precision Agricultural Technologies (PATs)

Introduction

Multiple definitions for precision agriculture technologies (PATs) exist (Roberson, 2000; Wolfert et al., 2017). These and other authors tend to define PATs as a comprehensive system to optimize agricultural production by leveraging crop information, information and communication technologies, and management practices. This approach allows the use of technologies to acquire and analyze data to support decision making. PATs can help reduce input use, improve yields and profits, increase food quality, and reduce the environmental impact of agriculture (see https://ezfloinjection.com/what-is-precision-agriculture-an-in-depth-look-at-the-future-of-farming/).

As seen in Figure 4. these technologies encompass a broad portfolio of tools and techniques. These include Global Positioning Systems (GPS), sensors, Variable Rate Technologies (VRT), data analytics, automation and now the use of artificial intelligence, big data and blockchain approaches (McFadden & Lim, 2024) There is some controversy in the literature of whether precision agriculture technologies are a significant innovation or are the sum of older and new technologies as a process innovation. Nevertheless, PATs can be a change in farm management, moving away from uniform field treatments to site-specific interventions based on data-driven insights augmented recently by artificial intelligence and Big Data.

Figure 4. “Typical” Precision Agriculture Technologies package



Source: Author’s own

PATs rely on approaches to collecting detailed data about spatial and temporal variability within fields on crops, soil and environmental conditions. This is followed by advanced data analysis, and implementing management decisions tailored to these specific conditions (US GAO, 2024).

PATs differ from the two biotechnologies described in Section 2 in that adoption may be partial or complete for the technology package. In principle, components of the PATs portfolio may work synergistically to produce benefits for producers. For example, VRT requires information generated from Global Positioning Systems (GPS) and Global

Navigation Satellite Systems (GNSS) systems, that have been processed through data analytics. Adoption rates may vary between specific components of a PATs package. In this sense, adoption is usually defined at the specific component level or alternatively for arbitrary cutoff points where adoption is considered to have occurred after a pre-determined number of components have been adopted by an individual producer.

Research has provided evidence that shows that producers adopt PATs slowly and often adopt discrete components rather than complete PATs "packages" (Miller et al., 2017, 2019). The development and deployment of PATs over time has occurred in a top-down fashion (Gardezi & Bronson, 2020; Rotz et al., 2019).

Box 2. Six key tensions in the discourse around precision agriculture technologies

1) A set of tools vs. a management philosophy
2) Sum of older innovations vs. a new innovation
3) Productivity goals vs. environmental benefits goals... both, or neither?
4) Adopted or rejected by farmers... how, when and under what conditions?
5) Evidence of farmer use
6) Technology impacts

Source: Adapted from (Duncan et al., 2021)

This paper undertakes a comparative analysis to examine the current state of PATs diffusion across a diverse set of agricultural systems in a diverse set of countries including Argentina, Australia, Brazil, Canada, South Africa, and the USA. The primary objective is to provide an understanding of the prevalent technologies and their adoption and diffusion levels in each country, explore the institutional factors that are driving diffusion, trace the historical evolution of PATs in these regions, and assess the impact of relevant government policies.

This comparative approach aims to highlight global trends in PATS adoption while also shedding light on the unique circumstances and challenges faced by each country. This approach can contribute valuable insights for stakeholders in the agricultural technology sector. The analysis done for PATs will be contrasted to the biotechnologies described in previous sub-sections in a final section of this paper.

It is important to note that the literature, data, and evidence on PATs is quite thin and scarce even for developed economies. This is a limitation to the analysis done in this paper, with the expectation that as these technologies diffuse in space and time, we will be able to gather more and better information.

Country-specific analysis of PATs adoption, diffusion and adaptation

United States of America

A range of precision agriculture technologies are currently employed in the US. These include guidance autosteering systems, yield monitors and sensors, yield and soil maps are also commonly used to provide insights into crop performance and soil characteristics. Variable rate technology (VRT) enables the precise application of inputs such as fertilizer, pesticides, and seeds based on site-specific needs. Remote sensing platforms, including drones, ground robots, and satellite imagery, are increasingly utilized for crop monitoring and data acquisition.

In-ground sensors provide near-real-time information on soil properties like moisture, temperature, and nutrient levels. Targeted spray systems and automated mechanical weeders represent emerging technologies aimed at improving input efficiency and reducing environmental impact. Additionally, fleet analytics (telematics) and precision irrigation systems are being adopted to optimize equipment management and water usage.

Adoption, diffusion and adaptation timeline

The USA has been at the forefront of precision agriculture adoption, commencing in the 1980s. Over the past several years, a consistent increase in the use of these technologies has been observed. The evolution of PATs in the US can be broadly categorized into two waves (Haneklaus et al., 2016). The first wave, spanning the 1980s and 1990s, saw the emergence of technologies such as satellite and aerial imagery, weather prediction, variable rate fertilizer application, and crop health indicators. The second wave, from the 2000s onwards, has been characterized by the aggregation of machine data for more precise planting, topographical mapping, and soil data analysis.

Early adoption was primarily focused on basic techniques such as grid sampling, mapping for fertilizers and pH corrections, and yield measurements, which by the mid-1990s witnessed an increase in the adoption of GPS and variable rate technology (Greenberg, 2021) . By the 2000s, auto-guidance systems had become almost essential for farmers seeking to maximize income from their land. Over the past two decades, the adoption rate has steadily increased, with precision agriculture becoming a near-ubiquitous approach for those aiming to derive income from their land.

The adoption of Global Navigation Satellite Systems (GNSS) guidance and associated automated technologies has been remarkably rapid, however, the adoption of VRT has progressed at a slower pace compared to guidance systems (Lowenberg-DeBoer & Erickson, 2019). As of 2023, approximately 27% of farms or ranches in the USA had adopted one or more precision agriculture technologies (US GAO, 2024) . Adoption and diffusion rates vary depending on the specific PATS technology, local conditions, and the relative cost of the technology.

The utilization of these technologies demonstrates a clear correlation with farm size (Schimmelpfennig, 2016) . For example, in 2023, guidance autosteering systems were employed by 52% of midsize farms and a substantial 70% of large-scale crop-producing farms (McFadden & Lim, 2024). In addition, yield monitors, yield maps, and soil maps were in use on 68% of large-scale crop-producing farms. In contrast, the same authors find that small family farms, defined as those with a gross cash farm income (GCFI) of less than $350,000, exhibited the lowest rates of adoption across all technology categories

Furthermore, among these smaller farms, the lowest adoption levels were observed on farms where the principal operator was retired or those with very low sales (GCFI less than $150,000). Notably, a broader estimate suggests that 15-40% of large farms in the US utilize some form of precision technology, such as variable-rate technology or guidance systems. The extent of precision agriculture technology use also varies by crop, with wheat showing the highest recorded instances of adoption.

A significant factor influencing the potential for PATS adoption is the availability of broadband internet access in rural areas(US GAO, 2024) . In 2021, nearly 20% of US farms lacked access to broadband internet, posing a considerable barrier for technologies that rely on web-based platforms and real-time data connectivity.

The considerable difference in adoption rates based on farm size suggests that the economic feasibility and accessibility of PATs are significant determinants. Larger farms likely possess the financial resources and operational scale necessary to realize greater benefits from these technologies. The limited broadband infrastructure in rural areas presents a critical obstacle to the widespread implementation of PATs in the US, particularly for those technologies that depend on seamless data transfer and cloud-based services.

Relevant institutional issues

The adoption of PATs in the US is driven by several key factors. Farmers commonly report adopting these technologies to increase yields, save labor time, reduce purchased input costs, alleviate operator fatigue, and improve soil health or reduce environmental impacts.

However, several challenges limit broader adoption (US GAO, 2024). High upfront acquisition costs for the latest technologies can be prohibitive for farmers with limited resources or access to capital. Concerns regarding farm data sharing and ownership pose obstacles to the widespread use of AI in agriculture. The absence of uniform standards can hinder interoperability between different precision agriculture technologies. Furthermore, the limited availability of analytical tools and software to translate farm data into actionable decisions, coupled with a lack of knowledge and training on these complex systems, also impedes adoption. The uneven availability of broadband access, particularly in rural areas, further restricts the use of certain web-based technologies.

The recognized benefits of PATs can be relevant , yet the significant initial investment and the complexities of data management and technology integration present considerable challenges for many farmers. The cost-benefit analysis may not be favorable for smaller farms or those with limited capital, and issues such as data security and usage can create resistance to adoption.

Federal agencies such as the USDA and the National Science Foundation (NSF) actively support the adoption of precision agriculture through various means, including financial assistance, loan programs, and funding for research and development.[2] USDA programs offer payments to farmers for implementing practices that provide a conservation benefit (Lowenberg-DeBoer & Erickson, 2019).

Recognizing the importance of connectivity, the Federal Communications Commission (FCC) established the Precision Ag Connectivity Task Force with the goal of advancing the deployment of broadband internet access on unserved agricultural lands (see https://www.fcc.gov/task-force-reviewing-connectivity-and-technology-needs-precision-agriculture-united-states).

Additionally, the U.S. government regularly funds research on precision agriculture at universities across the country. These governmental initiatives play a vital role in facilitating PATs adoption by addressing financial limitations and improving rural connectivity. Continued support from these agencies is likely to be crucial for achieving broader diffusion of these technologies across the US agricultural sector.

Canada

Precision agriculture has been progressively adopted within the Canadian agricultural sector over recent decades (Macintosh, 2022). Early adoption primarily focused on the implementation of GPS guidance systems for tractors. Between 2017 and 2019, there was an observed increase in the adoption rates of most precision agriculture technologies among agronomic service providers in Ontario (Mitchell et al., 2021) . Geographic service technologies emerged as the most adopted during this period.

However, studies have indicated a relatively limited adoption of advanced digital agriculture technologies among crop producers in Canada when compared to the widespread use of basic wireless internet and GPS technologies (Huneke et al., 2024). Furthermore, the adoption of technologies like variable rate application (VRT) has been notably slow (Mitchell et al., 2021).

Adoption and diffusion timeline

Current Adoption Rates

Canada is a leader country in adopting precision agriculture technologies. As of 2021, approximately one-quarter of grains and oilseeds farmers in Canada were utilizing variable-rate input application and geographic information system (GIS) mapping. For example, in Western Canada, the adoption of GPS guidance is widespread, with 98% of farmers using some form of it and 79% employing GPS auto-steer (Canola Council of Canada, 2025).

Automatic sectional control for spray applications is also prevalent in this region, with 73% of growers utilizing this technology. In-season satellite imagery or remote sensing technology is used by 28% of growers in Western Canada, while yield mapping has been adopted by 48%. However, adoption rates tend to be lower for smaller farms, defined as those with less than 500 acres or an annual income below $75,000 (Agriculture and Agri-food Canada, 2018).

While Canada exhibits significant adoption of foundational technologies like GPS, there is still considerable potential for the increased uptake of more advanced technologies and their application on smaller agricultural operations. The initial focus of PATs development on large-scale farming might explain the comparatively lower adoption rates among smaller farms, where cost and the complexity of implementation could pose more significant barriers.

Relevant institutional issues

The Government of Canada actively invests in the adoption of precision agriculture through various programs, such as the Agricultural Clean Technology (ACT) Program. These initiatives prioritize the adoption of clean technologies that meaningfully reduce greenhouse gas emissions and promote overall sustainable agricultural practices. The government is committed to supporting research, development, and the broader adoption of clean technologies within the agricultural sector. Canada is also recognized as a global leader in the agricultural technology industry (Preston, 2024).

Government funding and supportive programs are crucial in incentivizing the adoption of PATs in Canada, particularly those technologies that align with national environmental sustainability objectives. Financial assistance can alleviate the initial cost burden associated with PATSs’ adoption, while clear policy signals can guide the agricultural sector towards specific types of beneficial technologies.

Several factors are driving the adoption of PATs in Canada. These include the potential for increased efficiency, enhanced production, improved sustainability, reduced chemical usage, better pollination rates, targeted application of inputs, and the prospect of higher yields (Mitchell et al., 2021) . However, challenges also exist. High upfront costs associated with technology acquisition, an unclear return on investment (ROI) for some technologies, and the complexity of implementation can deter adoption (Preston, 2024).

Financial pressures on farm incomes, the cost of technologies potentially exceeding perceived benefits, a lack of confidence among producers in the agronomic recommendations derived from site-specific data, and insufficient integration between equipment dealers, agronomists, and input suppliers also contribute to these challenges.

The economic viability and ease of use are critical determinants of PATs adoption in Canada. Addressing the specific needs and limitations of smaller farming operations is also essential for achieving broader uptake. Farmers need to perceive a clear and timely return on their investment in PATs, and technologies that are intuitive and seamlessly integrate with their existing farming practices are more likely to be embraced.

Prevalent Technologies

Canadian farmers are increasingly employing a variety of precision agriculture technologies. These include GPS guidance and auto-steer systems, which enhance the accuracy and efficiency of field operations. Variable rate technology (VRT) is utilized for the precise application of inputs. Satellite-based monitoring systems and remote sensing are used for crop health assessment and management.

Recent developments include AI-driven crop management tools are gaining traction for optimized decision-making, as well as IoT sensors facilitate real-time data collection on various environmental and crop parameters (Macintosh, 2022). Drone technology is employed for aerial crop assessment and targeted spraying. Precision irrigation technologies help optimize water usage. Furthermore, autonomous field navigation systems and robotic solutions for weeding and harvesting are being explored.

Australia

Australia has consistently been at the forefront of developing precision agriculture tools and practical applications, largely due to its unique range of production conditions. Initial experimentation with varying nutrient applications occurred in the mid to late 1990s while he late 1990s also saw the initial commercial introduction and use of variable-rate controllers (Whelan, 2019). The sugar and grains industries have experienced a rapid adoption of auto-steer technology (Bramley & Tengrove, 2013). In 2002, SPAA (Precision Agriculture Australia) was established as a non-profit organization to promote the development and wider adoption of PATs across the country. The uptake of variable rate application technologies for the application of phosphorus fertilizer has been slow but steady.

Adoption and diffusion timeline

According to a farm survey by the research firm Roy Morgan (Roy Morgan, 2024) significant majority of Australian farmers, 89%, have either used or would consider using Agricultural Technology. Among these, 72% are currently utilizing precision agricultural technologies (known in Australia as AgTech) in their farming operations, with only a small fraction, 6%, having discontinued its use after initial adoption. The leading forms of PATs employed by Australian farmers include farm management software, electronic ID tags, satellite technology, precision farming techniques, drones, and remote sensors.

In the grains industry, the adoption of auto-steer technology is particularly high, potentially reaching 90% (Bramley & Tengrove, 2013) . As of 2012, approximately 20% of Australian grain growers had implemented some form of variable rate application (VRA). Projections indicate that Internet of Things (IoT) devices are expected to be integrated into around 20% of Australian farms by 2024 or shortly thereafter, while drones and Unmanned Aerial Vehicles (UAVs) are anticipated to be used by over 15% of farms by 2023 (KG2 Consulting, 2024).

Australia exhibits a strong level of interest and adoption in PATs, including precision farming, with particularly high uptake in foundational technologies like guidance systems. However, the adoption rates for other advanced technologies vary across different agricultural sectors (Jochinke et al., 2007). The large farm sizes characteristic of Australian agriculture, coupled with its export-oriented nature, likely incentivize the adoption of technologies that can enhance operational efficiency and overall productivity.

Relevant institutional issues

Several factors are propelling the adoption of PATs in Australia. These include the increasing demand for sustainable farming practices, the challenges posed by water scarcity, government support for agricultural technology initiatives, advancements in IoT and artificial intelligence, rising labor costs within the agricultural sector, and the increasing variability of the climate. Furthermore, the need for Australian farmers to improve their profitability and maintain access to international export markets also drives technology adoption.

However, several challenges impede broader adoption. High initial costs associated with purchasing and implementing PATs, a lack of readily available information and technical knowledge among farmers, poor internet connectivity in rural areas, the perceived complexity of some technologies, difficulties in integrating different technological components, and challenges in data interpretation all contribute to these barriers.

While the costs and knowledge gaps remain significant hurdles, the increasing emphasis on sustainability and the pressing need to address the impacts of climate change are strong motivators for the continued adoption of PATs across Australia. Australia's susceptibility to drought conditions and the critical importance of its agricultural exports necessitates the implementation of efficient and sustainable farming practices, making PATs an increasingly attractive and necessary solution for the sector.

Australian agriculture boasts strong sustainability credentials, with levels of chemical and fertilizer use considered to be world-best practice (ABARES Australian Government, 2025). Mandatory climate reporting for large businesses began to be phased in from January 2025, indicating a growing regulatory focus on environmental impact. Government programs are in place to finance smart agriculture initiatives, further encouraging the adoption of environmentally sound practices.

In contrast to the USA and other countries, Australia has largely transitioned away from public sector agricultural extension services, with farmer-led groups playing a crucial role in facilitating knowledge sharing and the adoption of new technologies (Lowenberg-DeBoer, 2003). The Grains Research and Development Corporation (GRDC) serves as a key source of funding for precision agriculture research and development in Australia.

Environmental concerns and evolving regulations, combined with a robust industry-driven approach to knowledge dissemination and research funding, are significantly shaping the adoption and direction of PATs within the Australian agricultural sector (Bramley & Tengrove, 2013; Jochinke et al., 2007). The need to meet increasingly stringent environmental standards, coupled with the proactive engagement of farmer groups in promoting technology adoption, creates a distinctive environment for the diffusion of PATs throughout the country (Bramley & Tengrove, 2013).

Prevalent Technologies

A variety of precision agriculture technologies are used in Australia. These include GPS and GNSS-based guidance and auto-steer systems, which improve the accuracy of field operations(Roy Morgan, 2024). Variable rate technology (VRT) is utilized for the site-specific application of inputs. Remote sensing, employing both satellite and aerial imagery, is used for crop monitoring and data acquisition.

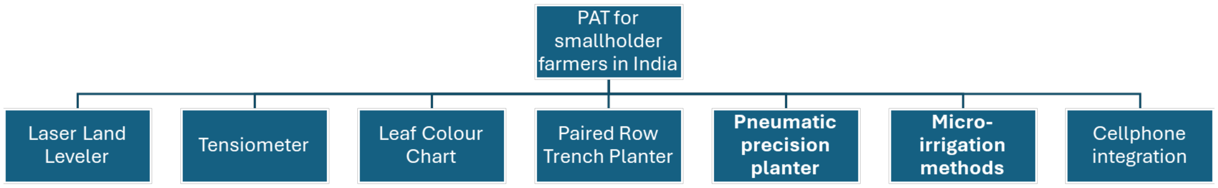
Drones and UAVs are increasingly employed for tasks such as crop monitoring, targeted spraying, and field mapping. IoT sensors are deployed to monitor soil moisture, weather Patterns, and other critical environmental parameters. Farm management software is also a widely adopted tool for Australian farmers. Precision irrigation systems are utilized to optimize water usage, particularly in water-scarce regions (Roy Morgan, 2024).

India

Precision farming has been introduced in India in recent years and is still in the early stages of its development and adoption. The application of these technologies has so far primarily focused on enhancing the efficiency of nutrient and water use in agricultural practices(Council on Energy, Environment and Water (CEEW, 2023). The CEEW report of 2023 also indicates that the Government of India has initiated various projects and programs aimed at promoting precision farming and the integration of modern technology within the agricultural sector. A significant initiative was the Tamil Nadu Precision Farming Project (TNPFF), launched in 2004-2005, which played a crucial role in spearheading the adoption of drip irrigation technologies across the state.

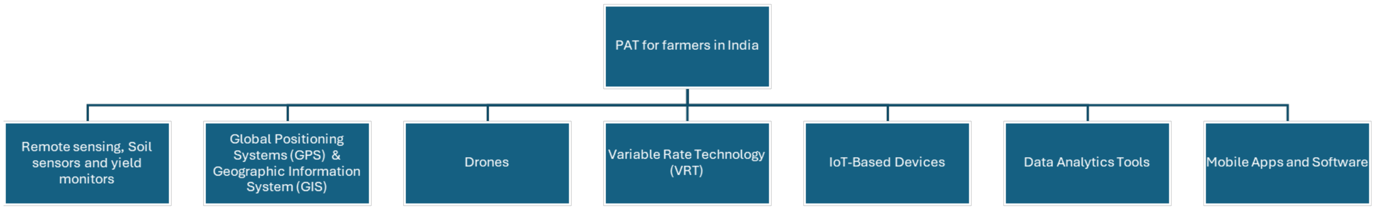
Figures 5 and 6 show two additional interpretations of PATs package in India. Figure 5 focuses on those packages that may be more suitable for smallholder farmers in the country. These tend to use lower cost technologies that may be even developed within the country for use in the country. Figure 6 is a more conventional PATs package with higher cost components and the use of more advanced technologies. These two views and versions are not mutually exclusive. They need to be evaluated and assessed based on the local context, feasibility, impact and access to the intended target clients conditions.

Figure 5. PATs for smallholder farmers – India



Source: (Mahatma Gandhi Gramodaya University, 2025)

Figure 6. PATS for farmers - India



Source: (Mahatma Gandhi Gramodaya University, 2025)

Adoption and diffusion timeline

Precision farming in India is currently in its nascent stages, with primary development focused on enhancing nutrient-use efficiency (NUE) and water-use efficiency (WUE) (Council on Energy, Environment and Water (CEEW, 2023) . The practice is largely confined to a limited number of farmers, often those operating on a single field, conducting experimental trials, or managing commercial farms that cultivate high-value crops. There are some indications of efforts to include other precisions agricultural technologies such as those pursued by ICAR (Singh, 2022).

A rough estimate suggests that around 3 million farmers in India have adopted some form of precision farming, predominantly located in irrigated agricultural regions (Council on Energy, Environment and Water (CEEW, 2023). Micro-irrigation techniques, such as drip and sprinkler irrigation, have achieved significant coverage, encompassing approximately 9.2 million hectares across about 29 states, which have notably, the implementation of precision agriculture technology has been reported to increase crop yields by up to 30% on some Indian farms that utilize satellite imagery for monitoring (Singh, 2022).

However, the prevalence of small and fragmented landholdings presents a unique challenge to the widespread adoption of large-scale PATs solutions. While PATs offers significant potential for Indian agriculture, its adoption is still in the early phases, with a primary focus on basic efficiency improvements. The dominance of smallholder farmers and the fragmented nature of land ownership pose considerable difficulties in implementing comprehensive PATs solutions.

Key innovators

The Indian government has launched several initiatives to actively promote the adoption of precision farming and modern technologies in agriculture. These include the Rashtriya Krishi Vikas Yojana (RKVY), which aims to promote overall agricultural development and enhance farm income and the Pradhan Mantri Krishi Sinchai Yojana (PMKSY) focuses on improving farm productivity through efficient utilization of water resources, aligning with precision irrigation practices (Mahatma Gandhi Gramodaya University, 2025) .

The Digital India Program seeks to transform India into a digitally empowered society, which includes promoting the use of digital technologies in agriculture. The National e-Governance Plan in Agriculture (NeGPA) specifically aims to bring the benefits of information and communication technology (ICT) to the agricultural sector. The Digital Agriculture Mission (2021-2025) signifies a focused effort by the government towards promoting digital technologies, including precision agriculture.

The Government of India has provided support for PATs through programs and projects. Examples include the Sub-Mission on Agricultural Mechanization (SMAM) aims to encourage the use of modern farm machinery, which is often integral to precision farming (see https://www.pib.gov.in/PressReleasePage.aspx?PRID=2118770&reg=3&lang=2#:~:text=The%20Sub%2DMission%20on%20Agricultural,and%20livelihood%20support%20to%20them.). Another example is the Agri-Stack Initiative suggests a move towards creating a comprehensive digital ecosystem for agriculture, likely to support precision farming platforms and services (see https://agristack.gov.in/#/).

The Government of India is also actively working on creating awareness among farmers about the benefits and practical applications of precision farming and providing necessary technical assistance. Furthermore, India is collaborating with Brazil to enhance agricultural technology, innovation, and trade between the two countries, with a focus on sharing knowledge and technologies related to precision farming (see https://www.pib.gov.in/PressReleseDetailm.aspx?PRID=2123055). These various governmental initiatives reflect a strong commitment to leveraging PATs for the modernization and advancement of India's agricultural sector and to ensure national food security.

Relevant institutional issues

The adoption of PATs in India is driven by several critical factors including the country's need to meet the food demands of a large and growing population, coupled with the challenges posed by climate change, droughts, and floods, necessitates more efficient farming practices (Singh, 2022). Precision agriculture offers the potential for higher crop yields and overall productivity, more efficient utilization of scarce resources, reduced water consumption, cost savings in the use of fertilizers and pesticides, and ultimately, better profitability for farmers (Mahatma Gandhi Gramodaya University, 2025).

However, several significant challenges hinder widespread adoption. The high initial costs associated with purchasing and implementing PATs are a major barrier, particularly for smallholder farmers (Council on Energy, Environment and Water (CEEW, 2023). There is also a limited level of awareness among many farmers regarding the possibilities and benefits of precision farming. Poor internet connectivity in rural areas further restricts the use of many digital agriculture technologies. The issue of fragmented landholdings makes it challenging to deploy large-scale precision farming machinery effectively (Gunasekar, 2020) . Furthermore, skill gaps and the need for adequate training on these new technologies also pose a significant hurdle including managing the vast amounts of data generated by PATs add further complexity.

While the potential benefits of PATs are substantial for India's agricultural sector, overcoming the significant challenges related to cost, infrastructure, and farmer education is crucial for achieving broader and more impactful adoption. The economic limitations faced by smallholder farmers and the inadequate infrastructure in many rural regions are key obstacles to the widespread uptake of advanced PATS solutions.

Prevalent Technologies

Indian farmers are beginning to utilize several precision agriculture technologies. Drip and sprinkler irrigation systems are prominent for efficient water management. Satellite imaging and remote sensing are employed for monitoring crop health across large areas. IoT sensors are being used for real-time monitoring of soil health and moisture levels. Artificial intelligence (AI)-based analysis is being explored for optimizing the use of various agricultural resources.

Drones are increasingly used for tasks such as spraying pesticides and monitoring overall soil health. GPS and GIS technologies are being adopted for field mapping and more precise resource management. Additionally, mobile applications are emerging as tools to provide farmers with access to weather forecasts, market price information, and agricultural advisory services.

Brazil

The introduction of precision agriculture techniques in Brazil occurred in the late 1990s, spearheaded by pioneering research conducted at public universities and within the Brazilian Agricultural Research Corporation (Embrapa) (Cherubin et al., 2022). The initial focus of research and development was largely on evaluating and adapting technologies that had been imported from other countries.

Between 2005 and 2010, there was a notable surge in the number of new precision agriculture service providers entering the Brazilian market, primarily focusing on soil sampling services and the application of lime and fertilizers using variable-rate technology (VRT)(Alburquerque, 2017). Initially, the marketing and operational focus of many of these service providers was on achieving cost savings for farmers. However, over time, some of these providers evolved to emphasize the potential for higher productivity gains through precision agriculture, while others have since exited the market (Bolfe et al., 2020; Borghi et al., 2016) .

Adoption and diffusion timeline

The adoption of precision agriculture principles and tools in Brazil commenced in the late 1990s, however, the initial rate of adoption was slow, with more significant uptake occurring from the mid-2000s onwards (Cherubin et al., 2022). Current estimates suggest an adoption rate of approximately 20% across Brazilian agricultural areas, although this distribution is quite diverse across different regions and crop types. Data from 2020 indicates that 84% of interviewed farmers in Brazil were using at least one form of digital technology in their production systems(Borghi et al., 2016) . There is a particularly strong demand for precision agriculture technologies within the Cereal & Grain segment of the Brazilian agricultural market (MarkNtel Advisors, 2024).

In the state of Mato Grosso, a major soybean-producing region, farmers utilizing satellite-based precision farming techniques have reported yield increases and reductions in fertilizer use (Arvor et al., 2012). While PATs adoption began relatively early in Brazil, the overall rate remains moderate, indicating a substantial potential for future growth, especially within the large-scale production of grains and oilseeds. The vast agricultural landscape of Brazil and the economic significance of commodities such as soybeans likely drive the adoption of technologies that can improve efficiency and boost yields in these critical sectors.

Key innovators

The Brazilian government has implemented Law No. 14.475, which establishes the National Policy to Promote Precision Agriculture and Livestock (United Nations Environment Programme, 2022) . This policy aims to expand the use of precision agriculture techniques across Brazil to increase efficiency in the application of resources and production inputs, reduce waste, lower production costs, and enhance both productivity and profitability, while also ensuring environmental, social, and economic sustainability.

The policy provides guidelines and instruments to support innovation, promote sustainability, foster technological development and its diffusion, expand the research and development network in the agricultural sector, encourage technical assistance, facilitate managerial training, improve access to credit for equipment, and promote the development of standards.

Additionally, the National Policy on Agroecology and Organic Production (PNAPO) emphasizes sustainable agricultural practices, including precision farming techniques.[63] The Forest Code, which mandates landowners to maintain a certain portion of their land as legal reserves, also indirectly incentivizes farmers to utilize precision techniques to maximize production within the designated areas (MarkNtel Advisors, 2024).

The Brazilian Agricultural Research Corporation (EMBRAPA) receives substantial government funding for research and development in agricultural technologies, including precision farming tools and methodologies (Cherubin et al., 2022). Furthermore, initiatives and policies posed by the Brazilian federal and state governments have provided financial support to farmers who adopt sustainable and precision farming practices (USDA Foreign Agricultural Service, 2024c). These various government policies and funding mechanisms demonstrate a clear commitment to promoting and supporting the growth and adoption of precision agriculture within Brazil to achieve a more efficient, sustainable, and productive agricultural sector.

Relevant institutional issues

Several factors are driving the adoption of PATs in Brazil. These include the enhanced ability of these technologies to address contemporary agricultural challenges such as resource scarcity, environmental concerns, and the imperative for sustainable farming practices (Bolfe et al., 2020; Cherubin et al., 2022) . Government policies, particularly Law No. 14.475, which established the National Policy to Promote Precision Agriculture and Livestock, play a significant role in incentivizing adoption.

Emerging governmental initiatives focused on environmental sustainability are also providing incentives to market growth (MarkNtel Advisors, 2024). Furthermore, the potential for achieving increased productivity and reduced operational costs through PATs adoption is a major driving force. However, significant challenges remain (Arraes Pereira et al., 2012; Puntel et al., 2022). The high cost associated with the initial investment in precision agriculture technology and the affordability barrier that limits accessibility, particularly for smaller farmers, are major impediment.

Additionally, environmental sustainability concerns, such as deforestation in regions like the Amazon, also present a complex backdrop for agricultural development and technology adoption. While the benefits of PATs are increasingly recognized, the substantial upfront financial commitment continues to be a significant hurdle, especially for smaller agricultural producers. Balancing the expansion of agricultural activities with the critical need for environmental conservation remains a key challenge in Brazil, and PATS offers promising solutions for achieving more sustainable resource management.

Prevalent technologies

Brazilian farmers are increasingly utilizing a range of precision agriculture technologies (Cherubin et al., 2022; Puntel et al., 2022). These include soil sampling and the application of lime and fertilizers using variable-rate technology (VRT). GPS guidance systems are also becoming more common. Satellite data is extensively used for crop health monitoring, irrigation management, and yield prediction. Proximal sensors are employed for monitoring both soil and crop development at close range.

Remote sensing techniques utilizing both satellite and drone imagery are also gaining popularity. LiDAR (Light Detection and Ranging) technology integrated into drone systems is being adopted for precise field mapping and monitoring. Furthermore, AI-driven analytics and sophisticated farm management software are increasingly being utilized to support decision-making and optimize agricultural operations.

Argentina

Argentina has a long and notable history as a major global agricultural producer, with its prominence dating back over a century (Plaza, 2024). Grain farming played a pivotal role in the country's economic expansion between 1860 and 1910, establishing Argentina as a leading exporter of wheat, corn, and linseed by the 1930s (World Bank, 2006).

Following a period of decline in the 1940s, Argentina's farming sector has experienced a significant resurgence, marked by the increasing application of precision agriculture techniques, widespread adoption of GPS-supported ground equipment, and the integration of drone technology (Pamplona & Silva, 2019). The 1990s marked a period of significant advancement in Argentine agriculture, with the incorporation of new technologies such as no-till farming practices and genetically modified organisms (GMOs), particularly RR soybeans, which led to a substantial increase in grain production (Qaim & Traxler, 2005; Tejeda Rodriguez et al., 2021) .

Adoption and diffusion timeline

Argentina exhibits widespread adoption of GPS-supported ground equipment and an increasing use of drones within its agricultural sector. The country is recognized as a leader in no-till farming practices, with approximately 80% of all Argentinian farmers having adopted this method (Trigo et al., 2010) . Furthermore, Argentina holds a leading position in precision agriculture within South America.

The Asociación de Cooperativas Argentinas (ACA) is a key player in the development of precision agriculture technology in the country, working with over 50,000 farmers to increase their crop yields through these advancements. In the context of extensive agricultural crops, the implementation of precision agriculture is particularly widespread (Munoz et al., 2021) .

Notably, around 10% of large-scale farmers in Argentina have access to advanced digital technologies, primarily in the areas of remote sensing and machine learning and possess the digital literacy skills necessary to effectively analyze the resulting datasets (Munoz et al., 2021). These large-scale farms, despite representing a smaller percentage of the total number of farms, occupy a significant 78% of the total agricultural land in Argentina. Argentina has established a strong foundation in precision agriculture, particularly within its large-scale farming operations (Gras & Hernandez, 2014).

The high adoption rate of no-till farming, coupled with the increasing integration of advanced technologies like GPS and drones, become indicators of the sector's innovation (Guaglianone, 2025). The country's historical role as a major agricultural producer and exporter likely fuels the adoption of technologies aimed at maintaining and enhancing its competitive position in the global market.

Relevant institutional issues

Several factors are driving the adoption of precision agriculture in Argentina. A primary driver is the need to enhance agricultural productivity and increase annual crop yields to ensure food security for the population. Optimizing the use of agricultural resources, such as water and fertilizers, is another significant motivator. Precision agriculture also offers the potential to reduce operational costs and minimize the environmental impact of farming practices, contributing to more sustainable production.

Furthermore, increased crop yields and improved quality can enhance Argentina's ability to expand its agricultural exports in the global market. However, the agricultural sector in Argentina and PATs faces several challenges (Di Mauro et al., 2025; López & Lachman, 2018). This includes a long-term struggle with political and policy instability which can create uncertainty and investment disincentives for farmers and investors (Durand-Morat, 2019; Roy, 2024).

Environmental degradation of natural resources, exacerbated by climate variability, poses a significant threat to long-term agricultural productivity (Philipp, 2023). Economic and spatial inequities in productivity also need to be addressed. In addition, in some regions, a lack of adequate waterways and irrigation networks can hinder agricultural expansion and productivity.

Despite these economic and policy-related challenges, Argentina's rich agricultural tradition and a strong emphasis on technological innovation are driving the continued adoption of PATs to achieve improved productivity, greater sustainability, and enhanced economic outcomes for the sector. The pressing need to address food security issues and adapt to the growing impacts of climate change further underscores the importance of PATs as a vital tool for the future of Argentine agriculture.

Prevalent technologies

A variety of precision agriculture technologies are currently utilized in Argentina (López & Lachman, 2018). These include GPS-guided tractors and other farm machinery, which enable precise field operations. Smart combine harvesters equipped with yield mapping capabilities allow farmers to track productivity across their fields in real-time.

Precision planting equipment ensures optimal seed depth and spacing for enhanced crop establishment. Intelligent irrigation systems, which utilize soil moisture sensors and weather data, apply water precisely where and when it is needed, conserving these valuable resources. Satellite-based crop health monitoring provides farmers with valuable insights into the condition of their crops.

AI-driven advisory systems offer real-time insights and expert crop management strategies. Drones are employed for field mapping and the precise application of pesticides. Additionally, geospatial data analysis, cloud computing, and machine learning technologies are being increasingly integrated into agricultural practices.

South Africa

Precision agriculture Technologies are overall considered to be in an early phase of adoption within South Africa, with comprehensive information on its history and current state still limited . However, there has been a noticeable increase in the adoption of UAV technology for various agricultural applications in South Africa in recent years, indicating a growing interest and investment in this specific area of precision agriculture (Echemi, 2024). For example, precision irrigation, as a key aspect of precision agriculture, is a relatively recent development in irrigation farming both worldwide and in South Africa (Dennis & Nell, 2002).

Despite the existing challenges, South Africa possesses significant opportunities to leverage precision agriculture technologies for the betterment of its agricultural sector. There is a substantial potential to improve agricultural practices and overall production for small-scale farmers through the implementation of AI-driven precision agriculture solutions (Aroba & Rudolph, 2024).

PATs offer the opportunity to optimize crop production, minimize the environmental footprint of farming, and enhance the overall efficiency of agricultural operations across different scales (Platt, 2023). Furthermore, the adoption of precision agriculture holds the promise of reducing the agricultural carbon footprint while simultaneously increasing the financial benefits for large-scale food production, contributing to a more sustainable and economically viable agricultural sector. Realizing these opportunities will likely require targeted efforts to address the specific needs and limitations of smallholder farmers, including providing accessible training, affordable technology options, and support in data management and analysis.

Adoption and diffusion timeline

In the broader agricultural sector, precision agriculture is considered to be in an early stage of adoption, with limited comprehensive data available on its overall prevalence.[47] However, South Africa currently leads the African continent in the use of UAV technology within agriculture, as the drone market in the country is experiencing rapid growth and is projected to reach $138 million by 2025 (Echemi, 2024). In the summer rainfall maize producing areas of South Africa, adoption rates for specific precision agriculture technologies were found to be 65% for guidance/auto-steer systems, 51% for section control, and 49% for variable-rate application(Baker, 2021).

Dairy farms and businesses in South Africa are increasingly adopting new technologies to gather data and insights into business performance and herd health (Food for Mzansi, 2024). Larger dairy farms, particularly those with over 500 cows, are significantly more likely to adopt labor-saving technologies such as automatic cup removers, electronic cow identification, and herd management software.

While adoption is clearly on the rise, especially in specific sectors like dairy farming and with the use of drone technology, precision agriculture is generally still in its initial phases in South Africa, particularly among the numerous small-scale farmers who constitute a significant portion of the agricultural population. The dual structure of South African agriculture, characterized by a mix of large commercial farms and a substantial number of smaller, often resource-constrained farms, likely contributes to the varying rates of PATs adoption across the country.

Relevant institutional issues

Several factors are driving the adoption of precision agriculture in South Africa. These include the significant potential to optimize crop production, reduce the environmental impact of farming practices, and enhance the overall efficiency of agricultural operations (Platt, 2023).

For large-scale food production, PATs offer opportunities to increase financial benefits and maintain competitiveness in the global agricultural market, where there is pressure to produce profitably at export parity prices. The persistent issue of water scarcity in many parts of South Africa also serves as a major driver for the adoption of precision irrigation and other water-efficient technologies.

However, several challenges hinder broader adoption of PATs and other innovations, particularly among small-scale farmers (Aroba & Rudolph, 2024; Human Sciences Research Council (HSRC), 2024; Nxumalo & Chauke, 2025) . These include the impacts of climate change, a lack of adequate access to essential infrastructure and training programs, high labor costs which make labor-saving technologies attractive for larger farms, limited access to modern agricultural technologies for small-scale farmers, and various resource constraints.

The high cost associated with the acquisition and maintenance of precision agriculture technologies, coupled with a lack of sufficient technical expertise and digital literacy among small-scale farmers, also present significant obstacles to wider adoption.

While the potential benefits of PATs are evident, particularly in addressing water scarcity and enhancing efficiency, the issues of affordability, access to knowledge, and the development of supporting infrastructure need to be addressed, especially to facilitate adoption among smallholder farmers who form a substantial part of the agricultural sector in South Africa.

Prevalent technologies

South African farmers are utilizing a range of precision agriculture technologies. GPS (Global Positioning System) technology is being adopted for various applications. Remote sensing, particularly through satellite imagery, is used for large-scale crop monitoring. Drones and UAVs are increasingly employed for tasks such as soil sampling, comprehensive field analysis, planting operations, and the precise application of pesticides.

Precision irrigation systems are being implemented to optimize water usage, especially in water-scarce regions. IoT (Internet of Things) sensors are deployed to collect real-time data on soil moisture levels, prevailing weather PATs, and other critical environmental parameters. Machine learning algorithms are being utilized for advanced data analysis to support more informed decision-making. GIS (Geographic Information System) technology is also being adopted for spatial data management and analysis.

Comparative analysis of PATS diffusion across countries

Table 7. provides a summary view of the varying stages and characteristics of PATs diffusion across the seven countries. The USA and Canada represent more mature markets with higher overall adoption rates, particularly on larger farms. Australia demonstrates a strong engagement with AgTech across various sectors. India and South Africa are in earlier phases, facing challenges related to infrastructure, farm size, and affordability. Brazil and Argentina have established a significant presence in precision agriculture, driven by their large-scale agricultural production and a focus on sustainability.

The dominant technologies vary across the countries, reflecting their specific agricultural needs and priorities. For instance, the high adoption of micro-irrigation in India is driven by water scarcity, while the strong focus on guidance systems in the USA and Australia reflects the prevalence of large-scale cropping.

Common drivers across all regions include the pursuit of increased efficiency, productivity, and sustainability. Economic benefits, such as reduced input costs and higher yields, are also strong motivators. However, the challenges faced by each country can be unique. For India and South Africa, the high cost of technology and the prevalence of smallholder farms are significant hurdles. In the USA and Canada, while adoption is higher, issues like data management and the need for better analytical tools persist. Australia grapples with connectivity issues in its vast rural landscape.

Government policies play a crucial role in shaping the diffusion of PATs. Countries like Canada and Brazil have implemented specific programs and policies to encourage adoption and support research. In the USA, federal agencies provide funding and support. Australia relies more on industry-led initiatives and research funding. India is actively promoting PATS through various national schemes. Argentina's adoption is driven more by its agricultural tradition and innovation.

Farm size significantly influences adoption patterns. Larger farms in the USA, Canada, Australia, and Argentina tend to adopt PATs at higher rates due to economies of scale and greater access to capital. In India and South Africa, where smallholder farming dominates, the challenges of affordability and suitability of technologies are more pronounced.

An important insight from this summary is that the diffusion of PATs is a complex process influenced by a multitude of interconnected factors that vary significantly across different countries. While the pursuit of efficiency and sustainability is a global trend, the specific Pathways and rates of adoption are shaped by local economic conditions, agricultural practices, technological infrastructure, and government support.

Table 7. Summary comparative analysis of target countries

Country	Overall Adoption Stage	Dominant Technologies	Key Drivers	Key Challenges	Government Role	Influence of Farm Size
USA	Mature	Guidance, Yield Monitoring, VRT, Remote Sensing, Sensors	Increased yields, labor saving, reduced input costs, environmental benefits	● High upfront costs, ● data concerns, ● lack of standards, ● limited analytical tools, broadband access	Strong support through funding, research, and broadband initiatives	Higher adoption on larger farms due to economic viability and scale
Canada	Growing	GPS Guidance, VRT, Remote Sensing, AI Tools, IoT	Increased efficiency, sustainability, potential for higher yields	● High upfront costs, ● unclear ROI, ● complex implementation, ● financial pressures, ● lack of confidence in recommendations	Investment in adoption through programs like ACT, focus on clean technology	Lower adoption on smaller farms due to cost and complexity
Australia	High Interest/Growing	GPS Guidance, VRT, Drones, Remote Sensing, Farm Software	Sustainability, water scarcity, government support, labor costs, climate	● High cost, lack of information,	Funding for research (GRDC), emphasis on industry-led	Larger farms are likely early adopters, but increasing interest across farm sizes

			variability, export market needs	● poor connectivity, ● perceived complexity and integration issues	knowledge sharing	
India	Nascent	Micro-irrigation, Satellite Imaging, IoT Sensors, AI	Need for food security, climate change adaptation, resource efficiency, potential for higher yields	● High initial costs, ● limited awareness, ● poor connectivity, ● fragmented landholdings, ● skill gaps	Active promotion through various schemes and missions, collaboration with other nations	Small and fragmented landholdings pose a significant challenge
Brazil	Moderate	Soil Sampling, VRT, GPS Guidance, Satellite Data, Drones	Addressing modern challenges, government policies, sustainability initiatives, potential for increased productivity	● High initial costs, ● affordability barrier, ● environmental sustainability concerns (deforestation)	Strong government support through policies and funding for R&D	Large-scale grain and oilseed production is likely driving adoption
Argentina	Established	GPS Guidance, Smart Harvesters, Precision Planting, Drones	Need to eliminate food insecurity, combat climate change, increase yields, optimize resource use,	● Unclear policy environment coupled with environmental concerns	Less direct government intervention, but strong agricultural heritage and	Strong adoption in large-scale farming

			potential for increased exports	● economic and spatial inequities ● lack of irrigation in some areas	innovation drive adoption	
South Africa	Early Growing	GPS, Remote Sensing, Drones, Precision Irrigation, IoT	Optimize production, reduce environmental impact, enhance efficiency, financial benefits for large scale, water scarcity	● High cost, ● lack of infrastructure and training, ● high labor costs, ● limited access for small-scale farmers, ● resource constraints ● lack of technical expertise and digital literacy among smallholders	Government support for technology adoption, but more focus is needed on smallholder farmers	Larger farms are more likely to adopt labor-saving technologies, but potential across farm sizes

Factors enabling Precision Agriculture Technologies diffusion

Economic Benefits

A primary driver for the adoption of precision agriculture technologies globally is the compelling array of economic benefits they offer to farmers. Implementing PATs can lead to significant increases in crop yields and overall farm profitability. Furthermore, these technologies enable farmers to achieve substantial reductions in input costs, including expenses related to fertilizers, pesticides, water, and fuel, by optimizing their application.

The optimized resource utilization also translates into improved resource efficiency and a reduction in waste, contributing to a more sustainable and economically sound farming operation. Ultimately, the effective implementation of PATs can result in higher returns on investment (ROI) for farmers, making the initial costs more justifiable over time. The clear economic advantages, such as the potential for cost savings and enhanced yields, serve as major catalysts for the worldwide adoption of PATs. The ability for farmers to achieve greater output with fewer resources presents a highly attractive value proposition for agricultural businesses of all sizes.

Technological Advancements

The continuous stream of technological advancements in the field of precision agriculture is a critical factor enabling its widespread diffusion. The increasing availability and affordability of Global Positioning Systems (GPS) and Global Navigation Satellite Systems (GNSS) have laid the foundation for many PATS applications.

The ongoing development of more sophisticated and cost-effective sensors, drones, and robotics is expanding the possibilities for data collection and automated field operations. Significant advances in data analytics, artificial intelligence (AI), and machine learning are providing farmers with increasingly powerful tools for interpreting complex agricultural data and making more informed decisions. Improvements in connectivity and the expansion of the Internet of Things (IoT) are enabling seamless data transfer and remote monitoring of farm operations.

Furthermore, the development of more user-friendly interfaces and intuitive software platforms is making these advanced technologies more accessible to a wider range of farmers, regardless of their technical expertise. This continuous innovation in PATs is making the technology more effective, more affordable, and easier to integrate into existing farming practices, thereby significantly driving its wider diffusion across diverse agricultural landscapes and contexts.

Environmental Concerns

The growing global awareness of agriculture's significant environmental footprint and the increasing imperative for more sustainable farming practices are substantial drivers for the adoption of precision agriculture technologies. PATs offer a suite of solutions for addressing critical environmental issues. Precision irrigation technologies help farmers significantly reduce water usage and better manage water scarcity, a growing concern in many agricultural regions. By enabling more targeted fertilizers, pesticides, and herbicides applications, PATs help minimize the overall use of chemical inputs and reduces the risk of harmful runoff into soil and waterways.

Furthermore, the efficient use of resources and optimized field operations facilitated by PATs can contribute to a reduction in greenhouse gas emissions and the overall carbon footprint of agricultural activities. PATs also support improved soil health and help prevent soil erosion through data-driven management practices. The increasing environmental consciousness within the agricultural sector and among consumers is therefore a significant factor driving the adoption of PATs, which offers practical solutions for achieving more sustainable and environmentally responsible farming practices.

Agricultural Practices

Existing trends and shifts in agricultural practices also play a crucial role in enabling the diffusion of precision agriculture technologies. In some regions, there has been a trend towards increasing farm sizes, which can make the adoption of certain PATs solutions more economically viable due to economies of scale.

The growing adoption of conservation tillage and no-till farming practices in many parts of the world creates a favorable context for PATs, as these methods often complement precision input application and soil management techniques. The ability of PATs technologies to be seamlessly integrated with existing farm machinery and established workflows is also a significant factor in their adoption.

Farmers are more likely to embrace technologies that can be incorporated into their current operations without requiring radical changes or significant additional investments in new equipment. The overarching focus on optimizing inputs and improving overall resource management in modern agriculture aligns perfectly with the core principles of precision agriculture, creating a strong impetus for its continued diffusion across various farming systems.

Key innovators and stakeholders in PATs innovation

Multinational Companies

Multinational corporations play a pivotal role in the diffusion of precision agricultural technologies (PATs) on a global scale. Key companies include those such as: Aerobotics, AgEagle Aerial Systems Inc., AgJunction, Ag Leader Technology, AGCO

Corporation, CropX Inc, ., Climate Corporation (Subsidiary of Bayer), FarmersEdge, FlyPix AI , Deere & Company Precision Planting, LLC, Raven Industries, TeeJet Technologies Topcon, and Trimble Inc. These companies are at the front of PATs supply market.

Collectively, these companies offer comprehensive suites of hardware and software solutions designed for precision farming, including GPS guidance systems, variable rate technology (VRT), a wide array of sensors, sophisticated data analytics platforms, and increasingly, autonomous agricultural equipment. These companies have invested significant resources for R&D activities aimed at continuously improving their existing PATs offerings and expanding into new areas of innovation within the agricultural technology space (US GAO, 2024).

To further enhance their capabilities and broaden their market reach, these multinational companies often engage in strategic alliances and acquisitions with other technology providers and agricultural businesses. Through their extensive research, product development, marketing efforts, and global distribution networks, these companies are instrumental in driving technological innovation in precision agriculture and making these advanced tools and techniques more accessible to farmers across the world. Their significant investments and strategic partnerships are crucial for the continued advancement and wider adoption of PATs in the agricultural sector.

Domestic Companies

An important development is the emergence of national companies such as those in Box 3 reflect growing innovative capacities to research, develop, adapt and integrate software, equipment, and AI approaches to help enhance precision agriculture.

Box 3. Examples of national (domestic) precision agriculture technologies companies

Brazil
Farmonaut, Solinftec, Fendt/AGCO, Falker

South Africa
Lynxio Tech (Plantify Tech), Smart Agri Africa Pty Ltd, Revolute Systems, Perfect Precision, Ronin Precision Agriculture, Twiga Foods, Apollo Agriculture.

Argentina
CampoGIS, Mimicking Nature, Kilimo, SIMA Monitoreo Agricola

India
AVPL, CropIn Technology Solutions

Source: Author's web review

Academic Institutions

Academic institutions serve as a cornerstone in the diffusion and advancement of precision agriculture technologies (PATs) worldwide. They conduct fundamental research that deepens our understanding of crucial agricultural factors such as soil variability, optimal crop management strategies, and the overall effectiveness of various PATs applications (US GAO, 2024). Often in collaboration with industry partners, universities and research centers play a key role in developing innovative PATs tools and techniques that address specific agricultural challenges and opportunities (USDA Agricultural Research Service, 2025).

Furthermore, these institutions are vital in educating the next generation of agricultural professionals, scientists, and researchers, equipping them with the knowledge and skills necessary to drive the future of precision agriculture (US GAO, 2024). Through their extension services and outreach programs, academic institutions provide valuable training and support to help farmers adopt and effectively implement PATs in their own operations. They also often facilitate international research collaborations, fostering the exchange of ideas and expertise that contributes to the global advancement of the field. By generating new knowledge, developing human capital, and providing unbiased information and practical support, academic institutions are indispensable for the long-term growth and widespread adoption of PATs within the agricultural community.

International Research Collaborations

Collaborative research efforts that span across international borders are increasingly important in facilitating the diffusion and progress of precision agriculture (PATs) on a global scale. These collaborations enable the crucial sharing of knowledge, valuable research data, and best practices developed in different agricultural contexts around the world. By bringing together researchers and experts from diverse regions, these collaborations facilitate the adaptation of PATs solutions to the specific needs and unique characteristics of various agricultural systems and environments.

International partnerships are also instrumental in promoting the development of innovative solutions to address pressing global challenges such as ensuring food security for a growing population and mitigating the impacts of climate change on agricultural production (Trimble, 2022).

Furthermore, these collaborations can contribute to the establishment of international standards and protocols for the development and implementation of PATs, ensuring greater interoperability and facilitating wider adoption. They also play a crucial role in the transfer of technology and knowledge between developed and developing countries, helping to bridge the technological gap and promote sustainable agricultural advancements in regions where they are most needed. By fostering a global network of researchers and practitioners, international research collaborations are essential for accelerating the progress and expanding the global reach of precision agriculture, ultimately leading to more effective and sustainable food production systems worldwide.

Influence of USA precision agriculture

The adoption of digital and precision farming practices in Argentina has been shown to improve crop resiliency and boost overall productivity, mirroring trends observed in the USA (US GAO, 2024). Precision agriculture has been identified as a fundamental strategy to enhance resilience against climate change and natural disasters, a concern shared by both the USA and Argentina as major agricultural producers facing environmental challenges. Notably, the cost of GPS differential correction in Argentina has been historically lower compared to Brazil, potentially facilitating earlier and wider adoption of GPS-based technologies, a factor that also influenced adoption patterns in the USA.

While the direct influence of USA methodologies on Argentinian precision agriculture economics research isn't explicitly detailed, the US's established history and extensive research in PATs may have indirectly shaped approaches in other major agricultural nations. Given the similarities in the scale of agricultural operations and the focus on commodity crops between the USA and Argentina, it is plausible that the transfer and adaptation of PA technologies and knowledge have occurred between these two significant players in the global agricultural landscape.

Conclusion and Recommendations

The diffusion of precision agricultural technologies across India, Brazil, Argentina, South Africa, the USA, Canada, and Australia presents a complex landscape characterized by varying levels of adoption, diverse technological preferences, and a mix of common and country-specific drivers and challenges. While the USA and Canada have demonstrated leadership in the adoption of certain PATs, Australia showcases a strong overall integration of agricultural technologies in general than include PATs.

Developing economies like India and South Africa are in earlier stages, navigating unique hurdles related to infrastructure and the prevalence of smallholder farming. Brazil and Argentina, with their significant agricultural output with a significant export sector, have established a notable presence in precision agriculture, driven by large-scale farming and a growing emphasis on sustainability.

Economic benefits, continuous technological advancements, and increasing environmental concerns are the primary forces propelling PATs diffusion across all these regions. However, significant challenges remain, including the high initial costs of technology, the need for enhanced digital literacy among farmers, and the necessity for robust infrastructure, particularly in rural areas.

Government policies and international research collaborations are playing increasingly vital roles in shaping the trajectory of PATs adoption, with targeted initiatives and knowledge-sharing efforts tailored to the specific agricultural contexts of each nation. Farm size continues to be a significant factor influencing adoption rates, with larger farms generally exhibiting higher levels of technology integration due to economies of scale and greater access to capital.

To further accelerate the beneficial diffusion of PATs and maximize its potential to enhance global agriculture, the following recommendations are offered:

- **Policymakers:** Sensible approach is to prioritize the creation of supportive regulatory environments that foster innovation and address concerns around data privacy and security. Investing in the expansion of rural broadband infrastructure is crucial for enabling the full potential of PATs in agriculture that utilize digital technologies. Offering targeted financial incentives, such as subsidies and grants, can help overcome the high initial costs associated with PATs adoption, particularly for smallholder farmers who may face greater financial constraints.
- **Technology providers:** A continued focus on developing PATs solutions that are not only technologically advanced but also affordable, user-friendly, and interoperable with existing farm equipment and systems is prudent. Tailoring technologies to the specific needs and scales of different farming operations and regions is essential for broader adoption. Continued innovation should also prioritize addressing challenges such as data management and providing

accessible analytical tools for farmers.

- **Farmers:** Prudent to actively seek out opportunities for lifelong learning and engage in training programs to develop the necessary skills to effectively utilize PATs. Considering the long-term benefits of these technologies for enhancing productivity, improving resource efficiency, and promoting environmental sustainability is crucial for making informed adoption decisions.
- **Researchers:** Ensure a continued focus on developing innovative and practical PATs solutions that address the evolving needs of the agricultural sector. Encouraging stronger collaborations with farmers, industry stakeholders, and international partners is essential for ensuring that research efforts are relevant and impactful.

Precision agriculture Technologies in developing countries may help increase productivity while reducing production costs and or enhancing input efficiency. Developing countries nevertheless face several and more specific challenges including addressing limited investments in development, especially with regard to PATs scaling up and adoption and diffusion.

Increased investments need to go hand in hand with support of enabling-environment including policies and governance issues with a focus on addressing technology diffusion. This includes developing low-cost alternatives which can provide benefits to smallholder producers and smallholder agriculture in developing countries.

By addressing these recommendations, stakeholders may be able to work collaboratively to unlock the full potential of precision agriculture, leading to a more sustainable, efficient, and productive global agricultural system. By adopting these policies, governments and stakeholders can foster an environment where technology diffuses seamlessly, leading to a resilient, productive, and sustainable agricultural sector.

2.5 Contrasting the IR/HT maize, IR cotton and PATs adoption and diffusion

Transgenic maize and cotton, and precision agriculture technologies are both innovative agricultural technologies. They have similarities but also fundamental differences in terms of innovation, institutional, governance, and public reception issues. These ultimately will define the trajectory and pathway by which they may reach farmers and the delivery of the potential benefits to society. Both transgenic and PATs innovations have significant efforts by the private and public sector during the innovation process. The relative share of private and public development will likely depend on the crop, trait, country and/or region in which they may be released.

The enabling environment has been relevant especially in the case of transgenic innovations. Transgenic crops are regulated articles under the Cartagena Protocol on Biosafety under national biosafety frameworks. These face extensive, costly and complex regulatory hurdles globally, particularly in the European Union and other countries. This has translated into reduced access, delays and trade issues. PATs are in general less regulated, although some components may face guidelines and rules. PATs may face potential regulatory purview in terms of data privacy, antitrust and labor protection issues, not the innovation's safety per se. The regulatory environment helps reduce uncertainty, providing incentives to adoption and diffusion.

Transgenic crops have been highly controversial since their release. These innovations have been met by different degrees of public skepticism and mistrust, especially in Europe. Although this has been changing over time, surveys have shown segments of society expressing concerns regarding food safety, corporate control of agriculture, and environmental risks. In turn, PATs have faced a less controversial public opinion environment. Concerns raised by some segments of society are focused on data privacy, corporate control of agriculture, impact of industrial agriculture on the environment and biodiversity, and potential impacts on small farms.

Transgenic crop adoption and diffusion have been rapid in those regions favorable to the technology. Rapid adoption has been observed largely for commercial crops including maize, cotton, soybeans and canola. In those countries with excessively precautionary regulatory hurdles, adoption and diffusion have not occurred. The adoption and diffusion process has been consistently determined by cost, expected reductions in yield damage and/or inputs, and the expectations about future pest and weed pressures. In some countries, bans or moratoriums have obstructed or slowed adoption.

For PATs, package adoption rates have varied significantly depending on the technology. Important determinants of adoption have been initial costs, available infrastructure, integration with existing production systems, and access. These have been significant barriers for small-scale farmers in developing countries.

The similarities and differences between transgenic crops and PATs provide some important lessons for future agricultural innovations, especially those advanced biotechnologies such as gene- and genome-editing, and integrative precision agriculture technologies with advanced artificial intelligence applications. Securing public trust as early as possible is critical. Even though transgenic and all biotechnology crops are technological triumphs, their benefits and merits are not sufficient to gain broad public acceptance. Future agricultural innovations will require addressing public concerns about food, environmental and biodiversity concerns, as well as ethics and societal rights.

The enabling environment will continue to be a critical step for all agricultural innovations. Even though transgenic crops are one of the few agricultural technologies currently regulated over its product life cycle, the expectation is that future agricultural technologies will face some degree of regulatory scrutiny. The additional regulatory scrutiny has increased costs, not only due to the additional resources required to comply with regulations, but also due to the time to complete regulatory review and the uncertainty associated with the process. In practice, this translates into higher costs and reduced access to farmers of technologies that may benefit them.

Finally, the need exists to clearly define and communicate what technology does in terms of final product reaching product. Transgenic approaches do change the product, as all new breeding techniques used by humanity have been doing for centuries. Explaining the process so that the public understands how it happens will be critical to reduce negative perceptions. This will imply using novel approaches to communication and outreach as early as possible in the product life cycle. PATs are a tool package used to optimize management and thus face less public perception scrutiny.

2.6 Policy lessons and action plans recommendations

To promote the responsible and beneficial adoption of agricultural biotechnology, it is prudent for policymakers to consider the following recommendations:

1. **Strengthen innovation ecosystems and national innovative capacities:** Invest in public and private research and development to foster continuous innovation in agricultural biotechnology, focusing on addressing local challenges such as pest resistance, herbicide resistance, and climate change impacts.
2. **Develop adaptive and functional regulatory frameworks as part of a supportive enabling environment:** Establish efficient, transparent, and adaptive regulatory frameworks that ensure the safety of biotech crops while facilitating their timely deployment to farmers. These frameworks should be flexible enough to accommodate new technologies and evolving scientific understanding.
3. **Support smallholder farmers:** Implement targeted policies and programs to support the adoption of beneficial agricultural technologies by smallholder farmers. This includes providing access to affordable seeds, credit, and effective extension services tailored to their specific needs and farming systems.
4. **Enhance information dissemination:** Invest in agricultural extension services and information networks to educate farmers about the benefits and proper management practices associated with biotech crops. This is crucial for ensuring effective adoption and maximizing the potential benefits. This implies purposive and comprehensive approaches to address misinformation and disinformation which

have been shaping and influencing decision and policy making in the agricultural sector.

5. **Foster international collaboration and strategic alliances:** Encourage international collaboration and knowledge sharing in agricultural biotechnology research and regulation to facilitate the transfer of best practices and technologies, particularly between developed and developing countries.

Areas for future agricultural R&D

1. **Developing climate-resilient varieties:** Focus on developing IR/HT maize varieties with enhanced tolerance to climate-related stresses such as drought, heat, and salinity.
2. **Addressing emerging pests and diseases:** Continuously monitor for and develop solutions to address emerging pest and disease threats to maize production.
3. **Improving nutritional value:** Explore opportunities to enhance the nutritional content of maize through biotechnology, such as biofortification with essential vitamins and minerals.
4. **Sustainable management practices:** Conduct research on sustainable management practices for IR/HT maize, including strategies to mitigate the development of pest and herbicide resistance and to promote soil health and biodiversity.
5. **Integration between biological and knowledge-based approaches**: PATs integrate multiple tools that enhance management. Future will become even more integrative as biological and knowledge-based innovations reach the market. This is a major challenge especially for securing their access to developing economies.

By addressing these areas, stakeholders can work towards ensuring that agricultural biotechnology, including IR/HT maize, IR cotton and precision agriculture may be able to contribute to sustainable and resilient food systems globally.

Annex 2. Qualitative Application of the conceptual framework for the case of the Maize Lethal Necrosis (MLN) Resistant GEd Hybrids Case in Kenya

This section applies the proposed conceptual framework to the case of Maize Lethal Necrosis (MLN) resistant hybrids developed using gene editing for Kenya and potentially East Africa. This qualitative application illustrates the framework's utility in diagnosing real-world challenges and identifying critical decision points within the innovation process.

Context of MLN in Kenya

Maize Lethal Necrosis (MLN) is a complex viral disease caused by a combination of Maize Chlorotic Mottle Virus (MCMV) and various Potyviruses, such as Sugarcane Mosaic Virus (Mahuku et al., 2015). Since 2011, MLN has posed a severe threat to maize production and the livelihoods of smallholder farmers across Africa, affecting countries including Kenya, Tanzania, Uganda, DR Congo, Rwanda, and Ethiopia (Jafari Jozani et al., 2019) Mwatumi et al., 2020).[1] In Kenya, where the disease was identified in 2011, estimates of damage indicated a 22% reduction in yields, leading to production losses of approximately USD180 million (Batchelor et al., 2020; Boddupalli et al., 2020; De Groote et al., 2016). The devastating impact of MLN, with yield damage reaching up to 100% in some situations (Redinbaugh & Stewart, 2018), forced many farmers to abandon maize cultivation, underscoring the urgent need for effective control measures.

Application of Innovation System and Enabling Environment Determinants Conceptual Framework

CIMMYT and its partners have adopted a multi-pronged approach to combat MLN, including the development of resistant varieties through both conventional breeding and gene editing. The gene-edited MLN-resistant maize in Kenya is currently transitioning from the technology evolution stage to early adoption, following the completion of R&D and regulatory processes, as well as seed certification. This trajectory demonstrates the framework's ability to track a specific innovation's progress through its distinct life cycle stages. The MLN case provides a rich illustration of how the various determinants within the innovation system interact to shape the deployment of a bio-innovation:

- **Technology Selection (End-user characteristics & social context):** Maize is Kenya's most important staple crop, yet the country faces chronic yearly production deficits. While improved maize varieties can boost production and curb losses, successful scaling and adoption depend not only on technical efficacy but also on addressing farmer needs, ensuring affordability, and considering socio-cultural factors influencing adoption (Almekinders et al., 2021; Rutsaert et al., 2021).

- **Crop/Animal Improvement & Ag-Biotech R&D/Innovation:** Kenyan public organizations like KALRO, private companies, and CIMMYT are collaboratively developing MLN-tolerant hybrids using gene editing to duplicate natural mutations in maize. This approach ensures that commercially accepted and demanded traits are delivered alongside MLN resistance.

Gene editing significantly reduces the development time for a resistant hybrid to approximately 3 years, compared to 4-5 years for conventional breeding, thereby lowering costs and accelerating technology provision. Furthermore, gene editing has the potential to reduce "yield drag," a common issue in traditional breeding. Humanitarian licensing agreements by CIMMYT stipulate that seed companies will not charge royalties or premiums for these MLN-resistant hybrids, aiming to ensure equitable access for smallholder farmers. Strategic alliances with funders and partners, including the Bill and Melinda Gates Foundation, Corteva Agriscience, and various CGIAR centers, are crucial for securing intellectual property (IP) access and funding for these initiatives.

- **Biosafety/Regulatory:** A significant development in Kenya is the possibility that gene-edited MLN-tolerant maize technology will not be regulated as a genetically modified (GM) crop. This differentiation, if realized, would substantially reduce the time and cost associated with developing and releasing an improved hybrid, as regulatory delays have historically been a major barrier for GM crops (Smyth et al., 2016; Wesseler et al., 2014).

Kenya possesses a functional biosafety framework, with previous approvals for GM events and confined field trials for genome-edited products, indicating growing experience and confidence within its National Biosafety Authority. The regulatory approach is expected to resemble Argentina's model, where gene-edited products without foreign DNA may not require a full biosafety review. This outcome, however, is a policy choice, not a technical inevitability, highlighting the critical role of political will and consistent capacity strengthening for the National Biosafety Authority to render and sustain such decisions.

- **Intellectual Property and Strategic Alliances:** The IP landscape for gene editing, particularly the CRISPR-CAS9 system, is becoming clearer, with PATsent holders actively facilitating licensing to downstream product developers (Bagley, 2021) . CIMMYT's agreements, such as with Corteva for royalty-free humanitarian use of key gene editing technologies, are instrumental in securing freedom to operate and promoting equitable access. These strategic alliances are vital for navigating the complex IP environment and ensuring that innovations reach those who need them most.
- **Technology R&D, scaling-up, deployment, post-release:** As the MLN-tolerant maize is still in early adoption, the discussion focuses on potential issues. Key

challenges include appropriately targeting hybrids to adapted germplasm and major agroecological zones, managing other prevalent pests like Fall Armyworm (FAW), and developing viable business models for smallholders. The existing seed system in Kenya presents several constraints that could hinder the dissemination of MLN-resistant maize. These include a lack of farmer awareness, high seed prices relative to grain, reluctance to change practices, and limited access to quality seed and credit (Langyintuo et al., 2010).

Table 1: Seed systems constraints in Kenya

Main constraint area	**Constraint**
Complex institutional structure	Government ownership of public R&D and partial ownership of a major seed company (Kenya Seed Company).
Seed production	Based on production from publicly developed OPVs and hybrids. Implemented through contracts with large & irrigated farms for seed reproduction. Reliance on the production of simpler single cross publicly developed hybrids which may have low producibility – reduces the profitability of hybrid seed production. Land to produce seed.
Seed distribution	Poor roads and infrastructure for seed delivery.
Marketing and sales	• Viable business models for smallholders are underdeveloped or non-existent. Existing experience with local community-based distribution models. • Most sales in Kenya are through agro-dealers, large retail stores, NGOs, and governments. Integration with extension services that are underinvested. • Poor seed knowledge dissemination services are being addressed through new ICT and product dissemination models (cellphones, farmer leader and model farmers, computers in community centers).

	• High seed prices are in part due to market concentration issues.

The formal seed system in Kenya is dominated by public and private institutions, with a significant informal sector accounting for approximately 30% of the market (Langyintuo et al., 2016). Despite a high adoption rate of improved varieties, a substantial portion of farmers still relies on informal channels, highlighting the need for innovative business models for small and medium enterprises (SMEs) and the public sector to effectively serve smallholders.

- **Economics and markets:** Estimated yield losses from MLN vary significantly (4-100%), underscoring the substantial potential market for resistant varieties. Spatial modeling work indicates that MLN disease can disseminate across eastern, central, and southern Africa, reinforcing the broad applicability and urgency of MLN-resistant technologies. Trade-related issues also emerge, particularly concerning asynchronous regulatory approvals across East Africa. If other countries in the region require full biosafety reviews for gene-edited products, unlike Kenya's potential approach, this could introduce trade constraints and interrupt maize flows, necessitating regional harmonization efforts.
- **Political economy, policies, and overall innovation environment:** Kenya has a complex history with bio-innovation investments. While demonstrating dedicated support for plant breeding and genetic resources, its experience with GM crops has been mixed, with past political decisions leading to production and importation bans influenced by special interest groups. These political economy developments imposed significant opportunity costs in terms of lost benefits[1] However, current food security pressures from MLN, FAW, and drought are providing strong incentives for the government to advance agricultural innovations.[1] Kenya is currently transitioning towards becoming a "biotechnology tool user," indicating a growing capacity and willingness to adopt and utilize advanced biotech tools (Chambers et al., 2016; Trigo, Falck-Zepeda, and Falconi, 2012).

Potential Economic Impact of MLN Resistant GEd Hybrids

Preliminary economic assessments underscore the significant value of MLN resistance. Simulations using IFPRI’s IMPACT model show that MLN could lead to increased maize net trade deficits (12-25 million tons), a rise in global maize prices (0.5%), and an increase in the number of persons at risk of hunger (up to 500,000+). Further estimations using the DREAMpy tool, implementing the economic surplus approach, indicate additional net benefits from the adoption of MLN-resistant maize hybrids ranging from US$1.5 to US$33 million per year in Kenya alone, and US$59 to US$106 million per year with adoption expansion into other East African countries.

These results highlight the substantial market and social value of developing resistance to MLN disease in Eastern, Central, and Southern Africa (Klümper and Qaim, 2014). Securing technologies that can prevent such damage is crucial, emphasizing the importance of facilitating an enabling environment for their deployment.

Discussion and Policy Implications

Synthesis of Key Insights

The qualitative application of the integrated conceptual framework to the MLN-resistant maize case in Kenya demonstrates that successful bio-innovation deployment is not solely dependent on scientific and technical R&D. Instead, it critically hinges on a well-functioning, integrated innovation system and enabling environment that effectively addresses complex regulatory, intellectual property, market, and political economy factors.

The qualitative application of the conceptual framework presented here for Kenya, highlights the dynamic and non-linear nature of innovation, where stages can overlap and feedback loops are common, necessitating adaptive governance and continuous learning throughout the product life cycle. A crucial finding is the significant role of non-economic drivers, such as political will, social acceptance, and stakeholder pressures, in shaping innovation outcomes. These factors can, at times, exert more influence than purely market or resource considerations, explaining why technically sound innovations may face barriers to adoption.

A critical observation from the MLN case is the potential for gene-edited technologies to avoid the extensive biosafety regulatory scrutiny often associated with genetically modified crops in Kenya and other countries (Ludlow et al., 2021; Pixley et al., 2022), which could significantly reduce development time and cost. However, this advantage is contingent on policy choices and interpretations of existing biosafety laws, rather than being an inherent technical inevitability.

This underscores that the framework's utility lies not just in describing the regulatory environment but in identifying policy levers that can unlock the full potential of gene editing. The "cost of R&D and regulatory delays" (Wesseler et al., 2014) is a substantial barrier, and the gene-edited approach offers a pathway to circumvent it, but only if the political and regulatory systems are aligned. Furthermore, the analysis reveals a fundamental tension between the efficiency of disseminating MLN-resistant hybrids through large, dominant firms and the goal of fostering equitable access and market development by supporting smaller seed companies. While a "royalty-free" approach is intended to promote widespread access, its interaction with existing market structures can lead to unintended consequences, such as reinforcing market concentration.

The differing preferences for exclusive versus non-exclusive licenses among seed companies further complicate this dynamic. This suggests that a successful enabling environment requires not just technology transfer but also strategic market shaping. Policies around IP licensing and business model development need to be designed to actively foster competition and inclusivity, rather than inadvertently exacerbating existing market power imbalances. The "enabling environment" is thus not a neutral space but one shaped by power dynamics and strategic choices with significant distributive consequences.

Concrete Policy Recommendations

Based on the framework's application, several concrete policy recommendations emerge:

- **IPR and licensing:** Policies should promote the exploration of flexible, humanitarian licensing models, such as CIMMYT’s royalty-free approach, to help ensure equitable access to gene-edited technologies, especially for smallholder farmers. These policies should provide incentives for such approaches while also adequately protecting the investments of technology developers.
- **Regulatory efficiency:** Prioritizing science- and evidence-based biosafety regulations that are protective, transparent, and cost- and time-efficient is crucial. Kenya's potential regulatory pathway for gene-edited products, which may avoid a full GM review, sets a positive precedent. However, the analysis highlights that it would be counterproductive to successfully navigate biosafety regulatory scrutiny only to encounter significant delivery complications due to an underdeveloped seed market.

  This implies that policy support for bio-innovations must be holistic and concurrent, pursuing regulatory pathways, market development strategies, and business model innovations in parallel from the early stages of product development. This calls for integrated planning and multi-disciplinary teams.
- **Market and business models development:** Devising innovative business models for gene-edited maize delivery is essential. These models must engage both large and small seed companies, addressing persistent challenges in seed distribution, marketing, and farmer access to information and credit. Exploring the value proposition of the seed industry in Kenya, particularly for smallholders, is key to fostering a vibrant and inclusive seed sector.
- **Regional harmonization:** Addressing asynchronous regulatory approvals across East African countries is vital to prevent trade disruptions and facilitate seamless regional technology diffusion. Coordinated efforts towards regulatory harmonization can unlock broader market potential and help foster an enabling environment at the national and regional levels.

- **Multi-stakeholder engagement:** Proactive engagement with non-governmental organizations (NGOs), civil society, and other pressure groups in decision-making processes is necessary to build social license and manage potential opposition. This moves beyond simply acknowledging their role to suggesting constructive engagement strategies to achieve desired outcomes.
- **Evolving roles of IARCs and NARS:** The CGIAR and other international and national research centers (IARCs and NARS) require a coordinated and strategic approach to effectively contribute to agricultural bio-innovation in LMICs. This approach should ideally consist of two distinct but highly coordinated components that include 1) An **enabling platform** that addresses critical policy, governance, freedom to operate, and social license issues and 2) a set of **product-based and focused operational services** that ensure proper connection with the enabling platform, the product life cycle, and the technology selection and transfer, adoption, and use decision-making processes. This model suggests that IARCs and NARS could continue evolving towards the development of "Centers of Excellence" in research and capacity building particularly those which have more advanced technical capabilities, supplementing ongoing research, providing finished technologies to countries with weak research systems, and intermediate technologies to more advanced NARS.

The Maputo 2003 and African Union Summit 2009 Declarations, which supported raising agricultural productivity and biotechnology, represent lofty policy goals that have not yet materialized to a satisfactory level. This highlights a critical gap between high-level political commitment and on-the-ground implementation, suggesting that policy mechanisms for translating intent into tangible outcomes are often insufficient or hindered by the very complexities the framework addresses. Future efforts must focus not just on *what* policies are declared, but *how* they are implemented, enforced, and adapted within dynamic national and regional contexts, prioritizing governance effectiveness and institutional capacity building.

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