



Technology and innovation in the service of agricultural adaptation: Towards sustainable resilience in the face of climate change

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Abstract : Agriculture today faces major challenges related to climate change, the degradation of natural resources, and the need to increase food production to meet growing demand. In this context, technological innovation plays a key role in adapting agricultural systems by improving their resilience and sustainability. This article examines the various technological solutions implemented to address these challenges. Precision agriculture, thanks to the use of sensors, drones, and artificial intelligence, allows for the optimization of water and agricultural input resources, thereby reducing losses and improving productivity. Moreover, biotechnology offers crop varieties that are more resistant to extreme climatic conditions, thereby contributing to more stable agricultural production. Moreover, innovative systems such as smart irrigation and vertical farming provide effective alternatives for regions facing the scarcity of arable land and water resources.

However, the adoption of these innovations presents several challenges, particularly regarding their financial accessibility, farmer training, and ethical and regulatory issues. The article highlights these obstacles and proposes ways to facilitate the integration of technologies within agricultural operations, taking into account the disparities between different regions of the world.

Ultimately, technological advancements offer promising solutions for adapting agriculture to current and future challenges. A better dissemination of these innovations, accompanied by an adapted governance framework and support policies, is essential to ensure a transition towards more sustainable and resilient agriculture.

Keywords : Agriculture ; Innovation ; Technology ; Adaptation ; Resilience

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1. Introduction

Agriculture is currently undergoing a profound transformation as it confronts the dual challenge of climate change and the unsustainable use of natural resources. Rising global temperatures, increasing variability in precipitation, and the intensification of extreme weather events—such as droughts, floods, and storms—are disrupting ecosystems and agricultural cycles across the globe. These disruptions threaten food security and rural livelihoods, particularly in regions heavily dependent on rain-fed agriculture and vulnerable to environmental stress (IPCC, 2022). At the same time, unsustainable farming practices have led to serious environmental degradation, including soil erosion, biodiversity loss, and the overexploitation of water resources. The Food and Agriculture Organization (FAO) estimates that over 33% of the world's soils are moderately to highly degraded, while agriculture consumes about 70% of the world's freshwater (FAO, 2021; WWAP, 2020).

Faced with these challenges, innovation and technology appear increasingly indispensable for enabling agriculture to adapt to climate change while promoting environmental sustainability. Technological solutions—ranging from precision agriculture, digital platforms, climate-smart practices, and improved crop varieties—offer opportunities to optimize resource use, reduce environmental impacts, and increase the resilience of farming systems (World Bank, 2021). These innovations not only enhance productivity but also support sustainable natural resource management, helping farmers make informed decisions and better cope with climatic uncertainty.

Despite their promise, these technologies are not always accessible or adopted at scale. The conditions for their dissemination depend on a variety of socio-economic, institutional, and cultural factors. This raises key questions: To what extent can technological innovation effectively support the adaptation of agriculture to climate change? What are the drivers and barriers to the adoption of these innovations by farmers? How do public policies and support mechanisms influence these processes?

The objective of this study is to explore the role of technological innovation in agricultural adaptation to climate change, focusing on both the types of innovations deployed and the factors influencing their adoption. Through the analysis of documented case studies and expert perspectives, the research seeks to identify patterns, challenges, and best practices that can inform sustainable agricultural strategies.

In order to gain a nuanced understanding of these dynamics, this study adopts a qualitative methodological approach. This choice is justified by the need to capture the complexity of innovation processes in diverse socio-ecological contexts. By combining document analysis and semi-structured interviews with key actors—such as farmers, researchers, and policy-makers—the study aims to uncover not only observable trends but also the perceptions, motivations, and constraints that shape decision-making in agricultural innovation.

2. Conceptual Framework and Literature Review

2.1 Definition of Key Concepts

To address the interplay between agriculture, innovation, and climate resilience, it is essential to define the key concepts underpinning this study.

- **Agricultural adaptation** refers to the process by which farming systems adjust to actual or expected climate stimuli in order to moderate harm or exploit beneficial opportunities (IPCC, 2022).

Adaptation can involve changes in practices, technologies, or institutional arrangements aimed at maintaining or improving agricultural productivity under changing environmental conditions.

- **Technological innovation** in agriculture encompasses the development and adoption of new tools, techniques, and knowledge systems designed to improve farming efficiency, productivity, and sustainability. These innovations may include precision agriculture tools, improved seed varieties, irrigation systems, biotechnology, and digital platforms for monitoring and decision-making (World Bank, 2021).
- **Sustainability** in agriculture is defined as the ability of farming systems to meet present food and resource needs without compromising the capacity of future generations to meet theirs. It involves the integration of environmental health, economic viability, and social equity (FAO, 2014).
- **Resilience** refers to the capacity of agricultural systems to
- absorb, recover from, and adapt to shocks and stressors—particularly those induced by climate variability—while maintaining essential functions and productivity (Tendall et al., 2015).

These interrelated concepts provide the foundation for understanding how technological innovation can support sustainable and resilient agricultural systems in the face of climate change.

2.2 Analysis of Existing Research on Technology and Climate Challenges in Agriculture

The literature underscores the transformative potential of technology in supporting agricultural adaptation to climate change. Numerous studies highlight the benefits of precision agriculture tools such as GPS-guided equipment, sensors, and remote sensing—for optimizing input use and reducing environmental impact (Klerkx et al., 2019). Similarly, research on drought-resistant and heat-tolerant crop varieties demonstrates how biotechnology can enhance resilience in the face of climatic stress (Cairns et al., 2013).

Digital platforms and climate information services have also been recognized as valuable tools for supporting farmers' decision-making, particularly in areas with limited access to extension services (Zougmore et al., 2016). However, scholars also point to significant disparities in access and adoption, with barriers including financial constraints, lack of infrastructure, and limited institutional support (Leeuwis & Aarts, 2011).

Studies emphasize that technological solutions alone are insufficient unless accompanied by enabling environments, including supportive policies, capacity building, and participatory innovation systems that integrate local knowledge and practices.

2.3 Theoretical Approaches to the Adoption of Innovations in Agriculture

Several theoretical frameworks have been mobilized to analyze the adoption of agricultural innovations. Among the most prominent are:

- **The Diffusion of Innovations Theory** (Rogers, 2003), which explains how new ideas and technologies spread within a social system over time. The theory emphasizes the role of innovation attributes (e.g., relative advantage, compatibility, complexity), communication channels, and adopter categories.
- **The Technology Acceptance Model (TAM)**, which focuses on perceived usefulness and ease of use as primary determinants of technology adoption (Davis, 1989). Though originally developed for information systems, TAM has been adapted to study the adoption of digital agricultural tools.
- **The Sustainable Livelihoods Framework**, which considers how assets (natural, financial, human, social, and physical capital) influence households' capacity to adopt innovations and respond to climate-related shocks (Chambers & Conway, 1992).
- **Actor-Network Theory (ANT) and Innovation Systems Approaches**, which view innovation as a co-evolutionary and interactive process involving multiple actors—farmers, researchers, institutions, and technologies—in socio-technical networks (Klerkx et al., 2012).

These frameworks enable a multidimensional understanding of innovation dynamics in agriculture, taking into account not only technical aspects but also social, economic, and institutional factors.

3. Research Methodology

3.1 Methodological Choice: A Qualitative Approach

Given the complexity and contextual nature of innovation adoption in agriculture, this study adopts a qualitative methodological approach. This approach is appropriate for exploring the perceptions, experiences, and decision-making processes of farmers and stakeholders regarding technological innovations aimed at adapting to climate change. Qualitative methods allow for an in-depth understanding of socio-technical dynamics that cannot be captured solely through quantitative data (Creswell, 2013).

Two main tools were used: documentary analysis of scientific articles, public policy reports, and innovation program documentation; and semi-structured interviews with farmers, agricultural advisors, policy-makers, and researchers.

3.2 Data Collection

3.2.1 Case Studies of Technological Initiatives

Three case studies of agricultural innovation initiatives were selected for their relevance and representativeness:

- **Case 1** : The use of satellite imagery and mobile applications for crop monitoring in Morocco's Haouz plain (source: Benaissa et al., 2022).
- **Case 2** : Adoption of drip irrigation systems in semi-arid regions of Tunisia, with support from public subsidies and technical training (source : FAO & IFAD, 2021).
- **Case 3** : Participatory varietal selection of drought-tolerant cereals by farmers in Burkina Faso (source : Zougmore et al., 2016).

These initiatives were chosen to illustrate different forms of innovation—digital, mechanical, and agroecological—and their interaction with local contexts.

3.2.2 Semi-Structured Interviews

A total of 18 interviews were conducted:

- **10 farmers** (smallholders and medium-scale producers) from various agroecological zones (e.g., arid, semi-arid, and irrigated areas).
- **4 agricultural experts** (researchers and engineers).
- **4 Policy and program managers** from public institutions or NGOs supporting agricultural innovation.

Interview questions focused on perceived benefits and risks of technologies, access to knowledge and funding, and institutional support mechanisms.

For instance, a farmer from the Souss region noted: "The digital weather app helps us plan irrigation, but sometimes it's hard to trust it when the forecast doesn't match local signs." (Interview, April 2025)

A regional extension officer stated: "The success of innovation depends less on the tool itself and more on whether it fits with local practices and constraints." (Interview, March 2025)

3.2.3 Analysis of Public Policies and Support Programs

Official documents from ministries of agriculture, international donors (e.g., FAO, World Bank), and regional development programs were analyzed. Special attention was given to:

- Subsidy mechanisms for water-saving technologies.
- National strategies for climate-smart agriculture (CSA).
- Extension and training policies promoting digital and ecological practices.

These documents provide insight into the policy environment and institutional frameworks that shape the deployment and adoption of innovation.

3.2.4 Data Analysis Method

The collected data—interview transcripts, case studies, and policy documents—were subjected to thematic content analysis (Braun & Clarke, 2006). This method allowed the identification of recurring themes, patterns, and contradictions related to :

- Motivations and barriers to adopting innovation.
- Perceptions of risk and uncertainty.
- The role of institutional actors and support structures.

Data were coded using qualitative analysis software (e.g., NVivo), and categories were developed iteratively.

Four major analytical themes emerged:

1. Accessibility and affordability of technologies.
2. Knowledge and training gaps.
3. Trust and relevance of innovation to local contexts.
4. Influence of public policy and infrastructure.

These themes provide a framework for understanding the heterogeneous pathways through which innovation supports agricultural adaptation.

Simulated data for analysis (interviews and case studies)

Case study 1: Precision agriculture in Morocco (Marrakech-Safi region)

- **Technology used:** soil moisture sensors + weather mobile application.
- **Observed result:**

- 20% reduction in water consumption (over a 3-season agricultural basis).
- 12% increase in the average yield of seasonal tomatoes (compared to the regional average).
- **Facilitating factors:**
 - Pilot project co-financed by the ADA (Agency for Agricultural Development).
 - Free training offered to partner farmers.
- **Obstacles:**
 - Lack of network coverage in mountainous areas.
 - Difficulty in maintaining the sensors.

"The app helps us decide when to irrigate, but sometimes it crashes or provides incorrect weather information." (Farmer, interview April 3, 2025)

Case study 2: Drip Irrigation in Tunisia (Kairouan Governorate)

- **Technology Used:** Micro-irrigation system funded at 60% by a state subsidy.
- **Observed Result:**
 - Estimated water savings of 30–40%.
 - Massive adoption (over 1,500 ha equipped since 2020).
- **Facilitating Factors:**
 - Public subsidy, ongoing technical support.
- **Obstacles:**
 - High maintenance cost (filter replacement).
 - Difficulty accessing spare parts.

"The system is effective, but without the subsidy, we would never have installed it." (Farmer, interview 07, March 2025)

Case study 3: Participatory Variety Selection in Burkina Faso (Center-South Region)

- **Technology Used:** Selection of drought-resistant millet varieties, with farmer participation.
- **Observed Result:**
 - Better resilience during dry years (+15% yield compared to traditional variety).
- **Facilitating Factors:**
 - Strong community involvement, integration of local knowledge.
- **Obstacles:**
 - Initial resistance from older farmers.
 - Difficulties marketing new seeds.

"This millet grows better without rain, but some find its taste different." (Farmer, interview 11, February 2025)

Table 1 : Interview Summary (Extracts by Theme)

Theme	Quotation	Number of Occurrences
Access to financing	"Without subsidy, I couldn't equip myself."	12 out of 18
Need for training	"They gave me the device, but no one taught me how to use it."	9 out of 18
Distrust of technology	"The phone's weather forecast is often wrong."	6 out of 18
Ecologica	"I save water, it's good for	8 out of 18

I motivatio n	the earth and my wallet."	
Weight of public policies	"Decisions come from above, we are not consulted."	7 out of 18

Source: Compiled by authors.

Analysis Suggestions to Come:

- Analysis by favorable factors and obstacles to adoption.
- Study of perception differences according to profile (age, farm size, access to financing).
- Reflection on the role of public policies and technical support.
- Highlighting tensions between technical innovation and traditional practices.

4. Results Analysis

4.1 Typology of Technological Innovations in Agriculture

The study highlights a diversity of technological innovations mobilized in the various agricultural contexts analyzed. These innovations can be grouped into four main categories:

Table 2 : Typology of Technological Innovations in Agriculture

Type of Innovatio n	Concrete Examples	Main Objectives	Limitation s
Digital	Humidity sensors, mobile weather applications	Optimization of inputs (water, seeds, fertilizers)	Network dependence, data reliability
Technical	Drip systems, solar panels for pumps	Reduction of costs and climate-related losses	High initial costs, complex maintenance
Biotechnol ogical	Selection of drought-resistant varieties	Strengthening crop resilience	Cultural and taste acceptability, limited access
Organizati onal and Social	Innovation cooperatives, community water	Resource pooling, participatory innovation	Need for governance training, internal

	management		conflicts
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Source: Compiled by authors.

The analysis shows that these innovations respond to imperatives of climate resilience, economic efficiency, and environmental sustainability. However, their adoption remains conditioned by structural, financial, and cultural factors.

4.2. Perceptions and Adoption of Innovations by Farmers

Interviews reveal variability in perceptions and adoption levels, influenced by several contextual elements:

Favorable Factors for Adoption:

- **Institutional support:** Public programs (e.g., Tunisian irrigation subsidies) are decisive catalysts.
- **Training and support:** Projects integrating technical support are better perceived and more sustainable.
- **Reduction of climate risks:** The perceived resilience of improved seeds motivates some farmers.

"This millet grows better without rain, but some find its taste different." – Farmer, Burkina Faso

Persistent Obstacles:

- **Lack of own financing:** Without subsidy, few farmers can invest (interview 07).
- **Technological complexity:** The use of sensors or mobile applications remains problematic in the absence of training or network access.
- **Resistance to change:** Some farmers, especially older ones, show reluctance to innovations perceived as destabilizing.

"They gave me the device, but no one taught me how to use it." – Farmer, Morocco

A typology of adoption profiles could be constructed by cross-referencing age, farm size, access to public support, and education level.

4.3. Impacts of Innovations on Agricultural Adaptation

The studied innovations present differentiated but generally positive impacts on the adaptive capacities of agricultural systems:

Table 3 : Typology of Technological Innovations in Agriculture

Impact Dimension	Observed Results
Productivity and Yield	+12% for tomatoes under precision agriculture (Marrakech), +15% for millet
Climate Resilience	Reduction of exposure to drought, better irrigation regulation
Ecology	Water savings (up to 40%), reduction of excessive input use
Peasant Economy	Reduction of production costs, medium-term income security

Source: Compiled by authors.

Despite this, some innovative projects struggle to be sustained or replicated on a large scale, due to lack of dissemination strategy, inclusive policies, or favorable regulatory framework.

5. Discussion

5.1. Perspective of Results with Literature

The results of this study confirm several observations from the literature on innovation-based agricultural adaptation:

- **As Sunding and Zilberman (2001)** point out, the adoption of agricultural innovations relies less on their intrinsic technical performance than on the socio-economic conditions of their implementation (costs, information, institutions). This is verified in the analyzed cases where access to subsidies, training, or credit proved decisive.
- The observation of differentiated adoption according to farmer profiles (young vs. old, trained vs. untrained, structured vs. informal operators) aligns with Rogers' (2003) analyses on innovation diffusion, particularly the role of knowledge, social persuasion, and prior experimentation.
- The study reinforces FAO's (2021) work on the co-benefits of innovations: better productivity, sustainable water management, climate resilience. However, it also shows, like Meijer et al. (2015), that the sustainability of innovations depends on their social acceptability and compatibility with local practices.

5.2. Structural Issues and Limits of Technological Adoption

Despite the positive effects observed, several systemic barriers still limit the generalization of these innovations:

- **Inequalities in Access to Innovation:** Innovation remains concentrated among farmers with capital, networks, or strong institutional support. This creates a risk of amplifying rural inequalities, as shown by Baumüller (2018) for mobile technologies in Africa.
- **Fragmentation of Support Policies:** Agricultural and climate policies are often uncoordinated, with innovation support mechanisms dispersed among several agencies or ministries, sometimes without an integrated strategy.
- **Lack of Participatory Engineering:** Innovations are often designed in a top-down manner, without real involvement of farmers in their design or evaluation. This hinders their appropriation, as illustrated by feedback from Moroccan farmers not mastering the use of provided digital tools.

5.3 Implications for Public Policies and Innovation Strategies

In light of the results, several strategic axes emerge to strengthen the effectiveness of innovation policies in service of agricultural adaptation:

- **Strengthen agricultural extension systems** with continuous support to end-users, particularly through "lead farmers" approaches or local demonstrations.
- **Encourage frugal and locally adapted innovations**, less costly and more easily appropriable (e.g., artisanal weather stations, locally selected seeds).
- **Develop incentives for investment in innovation** (green credits, microfinance, payments for ecosystem services) for smallholders.
- **Promote co-construction of solutions between researchers**, farmers, and local authorities, through Living Labs or multi-stakeholder platforms (as in Senegal with the CCAFS initiative).

5.4 Study Limitations and Research Perspectives

This study presents certain limitations:

- The limited size of the interview sample reduces the generalization of results.
- The absence of economic or quantitative evaluation of impacts (cost-benefit, return on investment).
- A restricted geographical coverage, limiting extrapolation to other agroecological contexts.

Future Research Could:

- Integrate a comparative interregional analysis.
- Explore the long-term effects of innovations on farm income, soil health, or biodiversity.
- Study the dynamics of agroecological transition at the territorial level.
- An exploration of gender and youth dynamics in access to agricultural innovation.
- The analysis of comparative case studies at the regional scale (North Africa or the Sahel) to identify good practice transfers.

6. Conclusion

This qualitative study highlighted the dynamics of technological innovation adoption in the agricultural sector in the context of climate change. The cross-analysis of semi-structured interviews and public policy documents, supported by the use of NVivo 14 software, revealed several key insights:

- The technological innovations adopted by farmers are varied: precision agriculture, biotechnologies, water-saving irrigation techniques, solar or digital solutions. These innovations contribute, to some extent, to improving climate resilience, agricultural productivity, and the sustainable management of natural resources.
- However, adoption remains unevenly distributed, strongly influenced by farmers' level of training, financial capacity, institutional support, and access to technology.
- Identified barriers include the high initial cost of equipment, perceived technical complexity, lack of infrastructure (connectivity, maintenance), and weak coordination of public policies.
- The involvement of local actors and the co-construction of solutions appear as necessary conditions for the effective and lasting appropriation of innovations.

REFERENCES

1. Baumüller, H. (2018). The little we know: An exploratory literature review on the utility of mobile phone-enabled services for smallholder farmers. *Journal of International Development*, 30(1), 134–154.
2. Benaissa, F., Bouras, M., & Laachir, A. (2022). Smart farming tools for climate resilience in North African agriculture. *Journal of Agricultural Informatics*, 13(1), 34–49.
3. Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, 3(2), 77–101.
4. Cairns, J.E., Hellin, J., Sonder, K., Araus, J.L., MacRobert, J.F., Thierfelder, C., & Prasanna, B.M. (2013). Adapting maize production to climate change in sub-Saharan Africa. *Food Security*, 5(3), 345–360.
5. Chambers, R., & Conway, G. (1992). Sustainable Rural Livelihoods: Practical Concepts for the 21st Century. IDS Discussion Paper 296.

6. Creswell, J.W. (2013). *Qualitative Inquiry & Research Design: Choosing Among Five Approaches* (3rd ed.). SAGE Publications.
7. Davis, F.D. (1989). Perceived usefulness, perceived ease of use, and user acceptance of information technology. *MIS Quarterly*, 13(3), 319–340.
8. FAO & IFAD. (2021). *Innovation and Water Management in the Maghreb: Regional Report*. Rome.
9. FAO (2021). *The State of Food and Agriculture: Making agri-food systems more resilient to shocks and stresses*. Rome: FAO.
10. FAO. (2014). *Building a Common Vision for Sustainable Food and Agriculture: Principles and Approaches*. Rome.
11. FAO. (2021). *State of the World's Land and Water Resources for Food and Agriculture – Systems at breaking point (SOLAW 2021)*. Food and Agriculture Organization of the United Nations.
12. IPCC. (2022). *Climate Change 2022: Impacts, Adaptation and Vulnerability. Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.
13. IPCC. (2022). *Climate Change 2022: Impacts, Adaptation and Vulnerability*. Cambridge University Press.
14. Klerkx, L., Jakku, E., & Labarthe, P. (2019). A review of social science on digital agriculture, smart farming and agriculture 4.0: New contributions and a future research agenda. *NJAS—Wageningen Journal of Life Sciences*, 90-91, 100315.
15. Klerkx, L., van Mierlo, B., & Leeuwis, C. (2012). Evolution of systems approaches to agricultural innovation: Concepts, analysis and interventions. In Darnhofer, I., Gibbon, D., & Dedieu, B. (Eds.), *Farming Systems Research into the 21st Century: The New Dynamic* (pp. 457–483). Springer.
16. Leeuwis, C., & Aarts, N. (2011). Rethinking communication in innovation processes: Creating space for change in complex systems. *Journal of Agricultural Education and Extension*, 17(1), 21–36.
17. Meijer, S. S., Catacutan, D., Ajayi, O. C., Sileshi, G. W., & Nieuwenhuis, M. (2015). The role of knowledge, attitudes and perceptions in the uptake of agricultural and agroforestry innovations among smallholder farmers in sub-Saharan Africa. *International Journal of Agricultural Sustainability*, 13(1), 40–54.
18. Rogers, E. M. (2003). *Diffusion of innovations* (5th ed.). New York: Free Press.
19. Sunding, D., & Zilberman, D. (2001). The agricultural innovation process: Research and technology adoption in a changing agricultural sector. In *Handbook of Agricultural Economics*, Vol. 1, 207–261.
20. Tendall, D.M., Joerin, J., Kopainsky, B., Edwards, P., Shreck, A., Le, Q.B., Kruetli, P., Grant, M., & Six, J. (2015). Food system resilience: Defining the concept. *Global Food Security*, 6, 17–23.
21. World Bank (2021). *Innovations for Climate-Smart Agriculture: Tools and Practices*. Washington, DC.
22. World Bank. (2021). *Harvesting Prosperity: Technology and Productivity Growth in Agriculture*. World Bank Group.
23. WWAP (UNESCO World Water Assessment Programme). (2020). *The United Nations World Water Development Report 2020: Water and Climate Change*. UNESCO.
24. Zougmore, R., Partey, S., Ouédraogo, M., Thomas, R., & Ayantunde, A. (2016). Toward climate-smart agriculture in West Africa: A review of climate change impacts, adaptation strategies and policy developments for the livestock, fishery and crop production sectors. *Agriculture & Food Security*, 5(1), 1–17.