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## Technology diffusion in agriculture and its economic implications for production and food security

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### Abstract

Agricultural technology adoption is widely recognized as a key driver of productivity enhancement, income growth, and food security in developing economies. This study examines the patterns, determinants, and impacts of technology adoption among farm households, with a focus on variations across farm size categories. Using primary data and econometric analysis, the study evaluates adoption levels of improved seeds, fertilizers, mechanization, ICT tools, and climate-smart practices, and assesses their effects on agricultural production, farm income, and household food security.

The results indicate significant disparities in adoption across farm sizes, with large farmers exhibiting higher adoption rates compared to small and medium farmers. Regression analysis reveals that education, farm size, extension contact, and access to credit are the key determinants of technology adoption, with extension services emerging as the most influential factor. The findings further demonstrate that adopters achieve 25-32% higher crop yields and 33-36% higher farm incomes than non-adopters. In addition, technology adoption significantly improves household food security, as reflected in higher Food Security Index values among adopters.

The diffusion pattern shows that while a majority of farmers fall within the early and late majority categories, a notable proportion remains laggards, indicating incomplete diffusion and the presence of structural and behavioral barriers. The study concludes that although agricultural technologies have substantial potential to enhance productivity and livelihoods, their adoption remains uneven due to socio-economic and institutional constraints.

The study highlights the need for strengthening extension systems, improving access to credit, promoting digital and climate-smart agriculture, and supporting smallholders through targeted policy interventions. These measures are essential to ensure inclusive and sustainable agricultural transformation.

**Keywords:** Technology adoption, agricultural productivity, farm income, food security, extension services, climate-smart agriculture, India

### 1. Introduction

Agriculture remains central to economic development, employment generation, and food security in developing economies such as India. Despite its strategic importance, the sector continues to face structural constraints, including decelerating productivity growth, climate variability, fragmentation of landholdings, and degradation of natural resources. These challenges have intensified the need for sustainable pathways to enhance agricultural performance and resilience.

In this context, technology diffusion the process through which innovations spread across farmers over time and space has emerged as a critical mechanism for agricultural transformation (Rizzo *et al.*, 2024; Zhang *et al.*, 2024) <sup>[22, 29]</sup>. Theoretical foundations of diffusion emphasize that the benefits of innovation are realized not merely through invention but through widespread adoption within a social system. However, the rate and extent of diffusion are often uneven, influenced by economic, institutional, and behavioral factors.

The nature of technological change in agriculture has undergone a significant transformation in recent years. The transition from conventional input-intensive practices to knowledge-and information-driven systems, often referred to as Agriculture 4.0, has introduced advanced tools such as precision farming, artificial intelligence (AI), Internet of Things (IoT), and big data analytics (Fragomeli *et al.*, 2024; Addorisio *et al.*, 2025) <sup>[10, 2]</sup>. These innovations have enhanced the potential to improve productivity, optimize resource use, and strengthen

resilience to climate-related risks (Manzoor *et al.*, 2025; Abdullahi *et al.*, 2025) [3, 1].

From an economic perspective, technology diffusion is a key driver of total factor productivity (TFP) growth, enabling farmers to produce more output with given levels of inputs. Empirical studies consistently show that adoption of modern agricultural technologies leads to higher crop yields, increased farm income, and improved risk management (Adnan *et al.*, 2025; Rizzo *et al.*, 2024) [3, 22]. However, the diffusion process is inherently heterogeneous, shaped by factors such as education, farm size, access to credit, extension services, and social networks (Rizzo *et al.*, 2024; Zhang *et al.*, 2024; Addorisio *et al.*, 2025) [22, 29, 2].

Beyond productivity enhancement, technology diffusion has profound implications for food security, a multidimensional concept encompassing food availability, access, utilization, and stability. Technological adoption contributes to increased food production, thereby improving availability, while higher incomes enhance access to food (Adnan *et al.*, 2025; Manzoor *et al.*, 2025) [3, 16]. Additionally, climate-smart and digital technologies improve the stability of food systems by reducing vulnerability to climatic and market shocks (Abdullahi *et al.*, 2025; Sustainable Futures, 2025) [1, 26]. These linkages highlight the critical role of technology diffusion in achieving sustainable food security outcomes.

In recent years, digital agriculture has further accelerated the diffusion process by facilitating access to real-time information and advisory services. Mobile-based platforms, remote sensing, and AI-driven tools enable farmers to make informed decisions regarding crop management, input use, and market participation (Manzoor *et al.*, 2025; Abdullahi *et al.*, 2025) [16, 1]. Nevertheless, the adoption of such technologies remains constrained by infrastructural gaps, digital illiteracy, and affordability issues, particularly among small and marginal farmers (Zhang *et al.*, 2024; Addorisio *et al.*, 2025) [29, 2]. This has resulted in a persistent digital divide, which may reinforce existing inequalities in agricultural outcomes.

Despite the growing availability of advanced technologies, their diffusion remains uneven across regions and farm categories. Smallholder farmers often face significant barriers, including limited financial resources, inadequate institutional support, and higher exposure to production risks (Zhang *et al.*, 2024; Rizzo *et al.*, 2024) [29, 22]. Consequently, disparities in productivity, income, and food security persist, limiting the overall impact of technological progress. Moreover, technology adoption is increasingly recognized as a systemic process influenced by institutional frameworks, governance structures, and knowledge dissemination mechanisms (Addorisio *et al.*, 2025; Fragomeli *et al.*, 2024) [2, 10].

Although existing literature provides valuable insights into the determinants and impacts of technology adoption, a significant research gap remains. Many studies are based on macro-level or secondary data, which often fail to capture the heterogeneity of adoption behavior and its localized economic implications. There is limited empirical evidence linking technology diffusion simultaneously with production outcomes and household-level food security using primary data. This gap is particularly relevant in the context of developing regions, where socio-economic diversity and institutional constraints play a crucial role in shaping adoption dynamics.

Against this backdrop, the present study seeks to provide a comprehensive micro-level analysis of technology diffusion in agriculture. By utilizing primary data from farm households, the study examines the extent and determinants of technology adoption and evaluates its economic implications for agricultural production and food security. The findings are expected to contribute to the existing body of literature and provide policy-relevant insights for promoting inclusive and sustainable agricultural development. The study is guided by the following specific objectives:

1. To analyze the extent of technology diffusion among farmers
2. To identify the determinants influencing technology adoption
3. To assess the impact of technology adoption on agricultural production
4. To evaluate the implications of technology adoption for household food security

## 2. Literature Review

### 2.1 Conceptual Foundations of Technology Diffusion in Agriculture

The theory of technology diffusion, rooted in innovation diffusion frameworks, emphasizes that adoption is a dynamic and social process influenced by communication channels, time, and the characteristics of adopters. In agriculture, diffusion determines how quickly and widely innovations such as improved seeds, mechanization, and digital tools are adopted across farming communities. Recent studies highlight that diffusion is not merely a function of technological availability but also of institutional support and socio-economic conditions (Rizzo *et al.*, 2024; Addorisio *et al.*, 2025) [22, 2].

The transition toward digital and smart agriculture systems has further expanded the scope of diffusion by integrating advanced technologies such as AI, IoT, and precision farming (Fragomeli *et al.*, 2024; Manzoor *et al.*, 2025) [10, 16]. These innovations enable efficient resource use and real-time decision-making, thereby enhancing farm productivity and resilience (Abdullahi *et al.*, 2025) [1]. However, the diffusion process remains uneven due to structural constraints and differential access to information (Zhang *et al.*, 2024) [29].

### 2.2 Determinants of Technology Adoption

A substantial body of empirical literature identifies key determinants influencing farmers' adoption behavior. Education is consistently found to be a critical factor, as it enhances farmers' ability to understand and utilize new technologies effectively (Rizzo *et al.*, 2024; Zhang *et al.*, 2024) [22, 29]. Farm size also plays an important role, with larger farmers more likely to adopt due to greater access to capital and lower risk exposure (Birthal *et al.*, 2023; Addorisio *et al.*, 2025) [8, 2].

Access to institutional credit significantly facilitates adoption by enabling investment in modern inputs and machinery (Adnan *et al.*, 2025; Feder *et al.*, 2023) [3, 11]. Similarly, extension services and information dissemination mechanisms are crucial in reducing uncertainty and promoting awareness (Krishnan & Patnam, 2022; Manzoor *et al.*, 2025) [14, 16]. Social networks and peer effects also influence adoption decisions, as farmers often rely on

community experiences and demonstration effects (Zhang *et al.*, 2024) <sup>[29]</sup>.

Despite these enabling factors, barriers such as high costs, lack of infrastructure, and risk aversion continue to hinder adoption, particularly among small and marginal farmers (Abdullahi *et al.*, 2025; Addorisio *et al.*, 2025) <sup>[1, 2]</sup>. This highlights the need for inclusive and context-specific policy interventions.

### 2.3 Impact of Technology Adoption on Agricultural Production

The adoption of agricultural technologies has been widely associated with improvements in crop productivity and efficiency. Empirical studies demonstrate that modern inputs and mechanization significantly enhance yield levels and reduce labor constraints (Birthal *et al.*, 2023; Adnan *et al.*, 2025) <sup>[8, 3]</sup>. Similarly, precision farming technologies optimize input use, thereby increasing output while minimizing costs (Fragomeli *et al.*, 2024) <sup>[10]</sup>.

Digital technologies, including mobile-based advisory systems and remote sensing tools, provide farmers with timely information, enabling better crop management practices and reducing production risks (Manzoor *et al.*, 2025; Abdullahi *et al.*, 2025) <sup>[16, 1]</sup>. These technologies also contribute to improved resilience against climate variability by facilitating adaptive decision-making.

However, the magnitude of productivity gains varies across farm categories and regions, reflecting differences in access to resources and institutional support (Zhang *et al.*, 2024; Rizzo *et al.*, 2024) <sup>[29, 22]</sup>.

### 2.4 Technology Diffusion and Food Security

Technology adoption has significant implications for food security, particularly in developing economies. By increasing agricultural productivity, technological innovations enhance food availability at both household and aggregate levels (Adnan *et al.*, 2025; Sustainable Futures, 2025) <sup>[3, 26]</sup>. Increased farm income resulting from higher productivity improves households' economic access to food (Manzoor *et al.*, 2025) <sup>[16]</sup>.

Climate-smart technologies further contribute to the stability of food systems by mitigating risks associated with climate change and market fluctuations (Abdullahi *et al.*, 2025) <sup>[1]</sup>. Moreover, improved agricultural practices enhance food utilization by promoting diversified and nutritious diets. Despite these benefits, uneven diffusion of technology may lead to disparities in food security outcomes, particularly among smallholder farmers (Zhang *et al.*, 2024; Addorisio *et al.*, 2025) <sup>[29, 2]</sup>. This underscores the importance of inclusive diffusion strategies.

### 2.5 Research Gap

Although existing literature provides extensive insights into the determinants and impacts of technology adoption, several gaps remain. First, many studies rely on macro-level or secondary data, limiting their ability to capture farm-level heterogeneity. Second, there is limited integration of production and food security outcomes within a single analytical framework. Third, the role of digital technologies in shaping adoption behavior and economic outcomes is still evolving and requires further empirical investigation. Therefore, there is a need for micro-level studies using primary data to analyze the extent, determinants, and

economic implications of technology diffusion, particularly in the context of developing regions.

## 3. Methodology

### 3.1 Study Area and Sampling

The present study was conducted in the Rayalaseema region of Andhra Pradesh, which is characterized by semi-arid climatic conditions, frequent droughts, and a predominance of smallholder farming systems. The region provides a suitable context for analyzing agricultural livelihoods, technology adoption, and income dynamics under varying resource conditions. A total sample of 240 farm households was selected for the study. The sampling design followed a multistage random sampling technique to ensure representativeness and minimize selection bias.

In the first stage, districts were selected purposively based on the intensity of agricultural activities and diversity in farming systems. In the second stage, mandals and villages were selected randomly. In the final stage, farm households were selected using simple random sampling from the identified villages. The sampled households were categorized based on operational landholding size into three groups:

- Small farmers: 120 households (up to 2 hectares)
- Medium farmers: 80 households (2-4 hectares)
- Large farmers: 40 households (above 4 hectares)

This stratification enabled a comparative analysis of socio-economic characteristics, technology adoption behavior, and livelihood outcomes across different farm size categories.

### 3.2 Data Collection

The study primarily relies on primary data collected directly from selected farm households using a structured questionnaire schedule. The questionnaire was carefully designed and pre-tested to ensure clarity, relevance, and consistency of responses across different categories of farmers.

The data collection instrument covered key dimensions relevant to the objectives of the study, including:

- Socio-economic characteristics: Information on age, education, household size, landholding pattern, farming experience, livestock possession, and access to institutional support.
- Technology adoption: Level of adoption of agricultural technologies such as improved seed varieties, irrigation practices, fertilizers, mechanization, and climate-resilient practices.
- Production and income: Crop-wise production details, input use, yield levels, cost of cultivation, gross and net returns, and off-farm income sources.
- Food consumption and livelihood indicators: Household food consumption patterns, dietary diversity, expenditure on food and non-food items, and overall livelihood security.

The data were collected through face-to-face interviews with farm household heads or the primary decision-makers in agriculture to ensure accuracy and reliability of responses. Cross-verification techniques were applied wherever possible to minimize recall bias and improve data quality.

3.3 Analytical Tools

The study employs a combination of descriptive and econometric tools to examine technology adoption behavior and its impact on production, income, and food security outcomes among farm households. The analytical framework is structured as follows:

(i) Adoption Index

The level of agricultural technology adoption among farm households is measured using an Adoption Index (AI). This index captures the extent to which a farmer has adopted recommended agricultural technologies across different components such as seeds, fertilizers, irrigation, and mechanization. Each technology component is assigned a score based on adoption status, and the index is computed as:

$$AI = \frac{\sum Ai}{\sum Ti}$$

where *Ai* represents the number of adopted technologies and *Ti* represents the total number of recommended technologies. The index ranges from 0 to 1, where higher values indicate greater adoption intensity.

(ii) Multiple Regression Model

A Multiple Linear Regression Model is used to identify the determinants of technology adoption intensity and its impact on key outcome variables such as productivity and income. The general form of the model is specified as:

$$Y = \beta_0 + \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \beta_4X_4.....\beta_nX_n. + \epsilon$$

- Where  
Y = Technology adoption index  
X1 = Education  
X2 = Farm size  
X3 = Extension contact  
X4 = Credit Access

$\beta_n$  are coefficients, and  $\epsilon$  is the error term. This model helps in quantifying the marginal effects of different factors influencing agricultural outcomes.

(iii) Food Security Index

The Food Security Index (FSI) is constructed to assess household-level food security status. It integrates dimensions such as food availability, access, and consumption adequacy. The index is computed using standardized indicators of calorie intake, dietary diversity, and food expenditure patterns.

The index is generally expressed as:

$$FSI = \frac{A\text{Ctual Food Consumption}}{R\text{ecomended Food requirement}}$$

4. Results

4.1 Demographic and Socio-Economic Profile

The socio-economic characteristics of the sampled households reveal considerable heterogeneity across farm size categories. The average age of farmers ranges from 45 to 50 years, indicating a relatively experienced farming population. Education levels increase with farm size,

suggesting that human capital plays a crucial role in farm decision-making and innovation uptake (Table 1). Similar patterns have been observed in recent empirical studies, where education significantly enhances farmers' capacity to process information and adopt improved technologies (Rizzo *et al.*, 2024; Andersen *et al.*, 2024; Islam *et al.*, 2024) [22, 5, 13].

Table 1: Socio-Economic Profile of Respondent Farmers

| Particulars       | Small    | Medium   | Large    | Overall  |
|-------------------|----------|----------|----------|----------|
| Avg. Age (years)  | 45       | 48       | 50       | 47       |
| Education (years) | 6        | 8        | 10       | 7.8      |
| Farm Size (ha)    | 1.2      | 3.5      | 7.8      | 2.9      |
| Annual Income (₹) | 1,20,000 | 2,80,000 | 6,50,000 | 2,75,000 |

Farm size and income disparities are also evident, with large farmers possessing significantly higher resource endowments. This finding aligns with recent evidence indicating that resource-rich farmers are more capable of bearing risks associated with technology adoption and are more likely to invest in modern inputs (Wang *et al.*, 2025; Bang and Han, 2025) [27, 6]. Moreover, socio-economic factors such as income, education, and landholding size remain dominant predictors of adoption behavior in developing economies (Mthethwa *et al.*, 2022; Serote *et al.*, 2023; Makamane *et al.*, 2023) [20, 24, 17].

4.2 Pattern of Agricultural Technology Adoption among Small, Medium, and Large Farmers

The adoption pattern demonstrates a clear scale bias, with large farmers exhibiting higher adoption rates across all technologies. While improved seeds and fertilizers show widespread adoption, advanced technologies such as mechanization, ICT tools, and climate-smart practices remain unevenly distributed (Table 2).

Table 2: Technology Adoption Levels

| Technology              | Small (%) | Medium (%) | Large (%) | Overall (%) |
|-------------------------|-----------|------------|-----------|-------------|
| Improved Seeds          | 62        | 78         | 90        | 72          |
| Fertilizer Use          | 85        | 92         | 95        | 89          |
| Mechanization           | 35        | 65         | 88        | 52          |
| ICT/Digital Tools       | 22        | 48         | 70        | 38          |
| Climate-smart Practices | 30        | 52         | 68        | 44          |

Recent literature confirms that adoption of digital and climate-smart technologies in low-and middle-income countries is constrained by infrastructure, knowledge gaps, and financial barriers (Manzoor *et al.*, 2025; Amoussouhoui *et al.*, 2024; Zakaria *et al.*, 2020) [16, 4, 28]. Similarly, studies highlight that adoption is influenced by perceived usefulness, cost, and compatibility with existing farming systems (Li *et al.*, 2020; Ronaghi and Forouharfar, 2020; Zheng *et al.*, 2022) [15, 23, 30].

The relatively low adoption of ICT tools (38%) and climate-smart practices (44%) indicates that these technologies are still in the early diffusion stage, particularly among smallholders. This is consistent with recent reviews emphasizing that sustainable innovations often face behavioral and institutional barriers despite their long-term benefits (Rizzo *et al.*, 2024; Becerra-Encinales *et al.*, 2024) [22, 7].

4.3 Determinants of Adoption Behavior in Agricultural Technology Use

The regression results ( $R^2 = 0.68$ ) indicate a strong explanatory power of the model. Education, farm size, extension contact, and credit access significantly influence adoption decisions (Table 3). Education positively affects adoption, supporting recent findings that knowledge and awareness significantly enhance farmers' willingness to adopt innovations (Rizzo *et al.*, 2024; Muromba *et al.*, 2025) <sup>[22, 21]</sup>.

Table 3: Determinants of Technology Adoption (Regression Results)

| Variables         | Coefficient | t-value |
|-------------------|-------------|---------|
| Constant          | 0.45        | 2.12    |
| Education         | 0.32***     | 4.85    |
| Farm Size         | 0.28***     | 3.96    |
| Extension Contact | 0.41***     | 5.12    |
| Credit Access     | 0.36***     | 4.44    |
| R <sup>2</sup>    | 0.68        | —       |

(\*\*\*) Significant at 1%

Farm size also plays a critical role, as larger farms benefit from economies of scale and higher risk-bearing capacity (Bang and Han, 2025) <sup>[6]</sup>. Extension contact emerges as the most influential determinant, reinforcing recent evidence that effective extension systems are central to technology dissemination in developing countries (Becerra-Encinales *et al.*, 2024) <sup>[7]</sup>. Similarly, access to credit significantly enhances adoption by relaxing liquidity constraints, particularly for capital-intensive technologies (Wang *et al.*, 2025) <sup>[27]</sup>. Recent studies also emphasize the importance of institutional support, cooperatives, and government interventions in facilitating adoption (Hoang and Tran, 2023; Miine *et al.*, 2023; Meng *et al.*, 2023) <sup>[12, 19, 18]</sup>.

4.4 Productivity Effects of Agricultural Technology Adoption across Farm Sizes

The results indicate that adopters achieve significantly higher yields compared to non-adopters across all farm categories (Table 4). Yield increases range from 25% to 32%, demonstrating the effectiveness of improved technologies in enhancing productivity.

Table 4: Impact on Agricultural Production

| Category | Non-Adopters Yield (q/ha) | Adopters Yield (q/ha) | % Increase |
|----------|---------------------------|-----------------------|------------|
| Small    | 32                        | 40                    | 25%        |
| Medium   | 38                        | 50                    | 32%        |
| Large    | 42                        | 55                    | 31%        |

Recent empirical studies confirm that adoption of improved seeds, mechanization, and climate-smart practices leads to substantial productivity gains through improved input-use efficiency and agronomic management (Mthethwa *et al.*, 2022; Serote *et al.*, 2023; Makamane *et al.*, 2023) <sup>[20, 24, 17]</sup>. Additionally, digital agriculture tools such as precision farming and weather-based advisory systems have been shown to significantly improve crop performance (Manzoor *et al.*, 2025) <sup>[16]</sup>.

4.5 Impact of Technology Adoption on Farm Income Across Farm Size Categories

Technology adoption leads to a substantial increase in farm income across all categories, with gains ranging from 33% to 36%. These findings highlight the strong economic benefits of adopting modern agricultural technologies (Table 5). Recent studies indicate that technology adoption enhances income not only through increased productivity but also through improved market access, reduced costs, and better risk management (Islam *et al.*, 2024; Andersen *et al.*, 2024) <sup>[13, 5]</sup>.

Table 5: Impact on Farm Income

| Category | Non-Adopters Income (₹) | Adopters Income (₹) | % Increase |
|----------|-------------------------|---------------------|------------|
| Small    | 1,20,000                | 1,60,000            | 33%        |
| Medium   | 2,80,000                | 3,80,000            | 36%        |
| Large    | 6,50,000                | 8,80,000            | 35%        |

Furthermore, access to financial services and digital platforms has been found to strengthen farm profitability and resilience (Wang *et al.*, 2025; Sharma *et al.*, 2025) <sup>[27, 25]</sup>.

4.6 Food Security Analysis

The Food Security Index (FSI) shows a marked improvement among adopters across all farm categories. This indicates that technology adoption contributes significantly to both food availability and economic access. The Food Security Index (FSI) reveals a strong positive relationship between technology adoption and household food security. Among small farmers, FSI increases from 0.52 to 0.71, while medium and large farmers experience increases from 0.61 to 0.80 and 0.68 to 0.88, respectively (Table 6).

Table 6: Food Security Index (FSI)

| Category | Non-Adopters | Adopters |
|----------|--------------|----------|
| Small    | 0.52         | 0.71     |
| Medium   | 0.61         | 0.80     |
| Large    | 0.68         | 0.88     |

Recent literature strongly supports the link between technology adoption and food security outcomes, particularly in the context of climate variability and resource constraints (Mthethwa *et al.*, 2022; Serote *et al.*, 2023) <sup>[20, 24]</sup>. Climate-smart agriculture and digital advisory systems have been shown to enhance resilience, reduce vulnerability, and stabilize food supply (Manzoor *et al.*, 2025) <sup>[16]</sup>.

4.7 Technology Diffusion Dynamics among Farmers

The diffusion pattern follows the classical innovation adoption lifecycle, with the majority of farmers falling within the early and late majority categories. However, the presence of 15% laggards indicates incomplete diffusion (Table 7).

Table 7: Technology Diffusion Pattern

| Stage          | % Farmers |
|----------------|-----------|
| Innovators     | 8         |
| Early Adopters | 22        |
| Early Majority | 30        |
| Late Majority  | 25        |
| Laggards       | 15        |

Recent studies confirm that diffusion of agricultural technologies is often gradual and influenced by social networks, institutional support, and behavioral factors (Rizzo *et al.*, 2024; Muromba *et al.*, 2025) <sup>[22, 21]</sup>.

Barriers such as risk aversion, lack of awareness, and financial constraints continue to limit full-scale adoption, particularly among smallholders (Becerra-Encinales *et al.*, 2024) <sup>[7]</sup>.

#### 4.8 Synthesis and Policy Implications

The findings clearly demonstrate that technology adoption significantly enhances agricultural productivity, income, and food security. However, adoption remains uneven due to structural and institutional constraints. Recent literature emphasizes that improving extension systems, expanding access to credit, and strengthening institutional support are critical for accelerating adoption (Wang *et al.*, 2025; Becerra-Encinales *et al.*, 2024) <sup>[27, 7]</sup>.

Additionally, promoting digital agriculture and climate-smart practices requires targeted interventions, capacity building, and policy support to ensure inclusive and sustainable agricultural transformation (Manzoor *et al.*, 2025; Rizzo *et al.*, 2024) <sup>[16, 22]</sup>.

#### 5. Discussion

The present study provides robust empirical evidence on the role of technology adoption in enhancing agricultural productivity, farm income, and household food security. The findings reveal that adoption is not only a technical decision but also a socio-economic and institutional process shaped by farmer characteristics, resource endowments, and access to support systems.

A key insight from the study is the positive association between socio-economic status and technology adoption. Farmers with higher levels of education and larger landholdings were more likely to adopt improved technologies. This supports recent empirical evidence that human capital enhances farmers' ability to process information, evaluate risks, and implement innovations effectively (Rizzo *et al.*, 2024; Andersen *et al.*, 2024) <sup>[22, 5]</sup>. Similarly, larger farm size enables economies of scale and greater risk-bearing capacity, which are critical for adopting capital-intensive technologies (Wang *et al.*, 2025; Bang and Han, 2025) <sup>[27, 6]</sup>. However, this also indicates a structural bias, where smallholders remain disadvantaged in accessing and utilizing modern technologies, potentially widening rural inequalities.

The analysis further highlights the critical role of institutional factors, particularly extension services and access to credit. Extension contact emerged as the most significant determinant of adoption, underscoring the importance of knowledge dissemination and advisory support. This finding aligns with recent studies emphasizing that effective extension systems act as a bridge between research and farmers, accelerating the diffusion of innovations (Becerra-Encinales *et al.*, 2024; Muromba *et al.*, 2025) <sup>[7, 21]</sup>. Likewise, access to credit significantly influences adoption decisions by alleviating liquidity constraints, especially for resource-poor farmers (Islam *et al.*, 2024; Sharma *et al.*, 2025) <sup>[13, 25]</sup>. These results reinforce the argument that strengthening institutional support mechanisms is essential for promoting inclusive agricultural transformation.

The study also demonstrates that technology adoption leads to substantial productivity gains, with adopters achieving 25-32% higher yields compared to non-adopters. These findings are consistent with recent literature showing that improved seeds, mechanization, and climate-smart practices enhance input-use efficiency and agronomic performance (Mthethwa *et al.*, 2022; Serote *et al.*, 2023) <sup>[20, 24]</sup>. Notably, medium farmers exhibited slightly higher productivity gains, suggesting that optimal resource utilization and management efficiency play a crucial role in realizing the benefits of technology adoption.

In terms of economic outcomes, the results confirm that technology adoption significantly increases farm income, with gains ranging from 33% to 36%. This supports the growing body of evidence that agricultural innovations not only improve productivity but also enhance profitability through cost efficiency, better market integration, and risk reduction (Andersen *et al.*, 2024; Wang *et al.*, 2025) <sup>[5, 7]</sup>. The relatively higher income gains among medium farmers may indicate diminishing marginal returns at higher scales and constraints among smallholders, highlighting the need for targeted policy interventions.

A particularly important contribution of this study is the analysis of food security outcomes, which shows a marked improvement in the Food Security Index among adopters. This finding underscores the multidimensional impact of technology adoption, extending beyond production and income to household welfare and nutritional security. Recent studies similarly emphasize that climate-smart and digital agricultural technologies contribute to resilience by stabilizing yields and improving access to food (Manzoor *et al.*, 2025; Rizzo *et al.*, 2024) <sup>[16, 22]</sup>. Thus, technology adoption emerges as a critical pathway for achieving sustainable development goals related to food security and poverty reduction.

The diffusion analysis reveals that the majority of farmers fall within the early and late majority categories, while a significant proportion (15%) remains laggards. This indicates that technology diffusion is ongoing but incomplete, with persistent barriers limiting full-scale adoption. Behavioral factors such as risk aversion, lack of awareness, and resistance to change, along with structural constraints like limited access to credit and extension services, continue to hinder adoption among certain groups (Becerra-Encinales *et al.*, 2024; Muromba *et al.*, 2025) <sup>[7, 21]</sup>. This pattern is consistent with the diffusion of innovations framework, which suggests that adoption follows a gradual, non-linear process influenced by social, economic, and institutional factors.

From a policy perspective, the findings highlight the need for a multi-dimensional approach to promote technology adoption. While improving access to inputs and technologies is important, equal emphasis must be placed on strengthening extension systems, enhancing financial inclusion, and building farmers' capacity through education and training. Special attention should be given to smallholders, who face the greatest constraints yet have the most to gain from adoption. Promoting collective approaches such as farmer producer organizations (FPOs), cooperative mechanization, and digital advisory platforms can help bridge existing gaps and ensure inclusive growth.

Overall, the study contributes to the growing literature on agricultural transformation by providing empirical evidence on the interconnected effects of technology adoption on

productivity, income, and food security. It reinforces the view that technological change, when supported by appropriate institutional frameworks, can serve as a powerful driver of rural development. However, achieving widespread and equitable adoption requires addressing both structural inequalities and behavioral constraints, thereby ensuring that the benefits of innovation reach all segments of the farming community.

## 6. Conclusion

This study examined the patterns, determinants, and impacts of agricultural technology adoption across different farm size categories, with a particular focus on productivity, income, and household food security. The findings provide strong empirical evidence that technology adoption plays a transformative role in enhancing agricultural performance and rural livelihoods. The results reveal that adoption is significantly influenced by socio-economic and institutional factors, particularly education, farm size, extension contact, and access to credit. Among these, extension services and financial access emerged as the most critical drivers, highlighting the importance of strengthening institutional support systems. At the same time, disparities in adoption across farm sizes indicate that smallholders continue to face structural constraints, limiting their ability to benefit from modern technologies.

The study further demonstrates that adoption leads to substantial improvements in agricultural productivity, with yield increases ranging from 25% to 32%. These gains translate into significant income enhancements, with adopters earning 33% to 36% higher incomes compared to non-adopters. Importantly, technology adoption also contributes to improved household food security, as reflected in higher Food Security Index values among adopters. This underscores the multidimensional benefits of agricultural innovations, extending beyond production to overall welfare and resilience.

Despite these positive outcomes, the diffusion analysis indicates that technology adoption remains incomplete, with a considerable proportion of farmers still categorized as late adopters and laggards. This suggests the presence of persistent barriers, including limited awareness, risk aversion, inadequate access to credit, and weak extension outreach. Addressing these challenges is essential for achieving widespread and inclusive adoption. From a policy perspective, the findings emphasize the need for a comprehensive and inclusive approach to agricultural development. Strengthening extension systems, expanding access to affordable credit, promoting digital and climate-smart technologies, and supporting smallholders through targeted interventions are critical for accelerating adoption. In addition, fostering collective action through farmer organizations and improving rural infrastructure can further enhance technology diffusion.

In conclusion, agricultural technology adoption serves as a key pathway for improving productivity, increasing farm income, and enhancing food security. However, realizing its full potential requires coordinated efforts to address socio-economic disparities and institutional gaps. Future research may focus on integrating behavioral factors, digital innovation ecosystems, and climate resilience dimensions to further deepen the understanding of technology adoption in agriculture.

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