



Digital Transformation in Agriculture and Smallholder Farmer Empowerment: Evidence from Una District, Himachal Pradesh, India

Dr. Sham Singh

Department of Economics, Government College Una, Himachal Pradesh

Abstract

Smart agriculture adoption has emerged as an important pathway for enhancing agricultural productivity, promoting efficient resource utilization, and improving the socio-economic conditions of smallholder farmers. This study examines the role of smart agriculture technologies in improving crop productivity, farm income, resource-use efficiency, and farmer empowerment in Una District of Himachal Pradesh, India. The study is based on primary data collected from 230 small and marginal farmers through a structured survey questionnaire. The collected data were analysed using descriptive statistics and inferential statistical techniques to assess the relationship between smart agriculture adoption and key agricultural outcomes. The findings reveal that farmers adopting smart agriculture practices, including Internet of Things (IoT)-based applications, Artificial Intelligence (AI), precision farming techniques, and mobile-based agricultural advisory services, experience improvements in farm productivity, income generation, input-use efficiency, and access to agricultural information. Adoption of these technologies has also strengthened farmers' decision-making capacity by improving access to weather forecasts, market information, and scientific farm management practices. However, the diffusion of smart agriculture remains constrained by several factors, including limited digital literacy, inadequate internet connectivity, high initial investment costs, fragmented landholdings, and insufficient technical support. The study highlights that strengthening digital infrastructure, enhancing farmers' technological awareness, providing affordable access to smart farming solutions, and developing effective extension mechanisms are essential for promoting inclusive and sustainable agricultural transformation. The findings provide useful policy insights for encouraging technology-driven agricultural development and improving the livelihood security of smallholder farmers in hill regions.

Keywords: Smart Agriculture; Digital Agriculture; Precision Farming; Smallholder Farmers; Farmer Empowerment; Rural Development

Introduction

Agriculture remains a fundamental pillar of the Indian economy, contributing significantly to food security, employment generation, rural livelihoods, and overall economic development. A large proportion of India's population continues to depend directly or indirectly on agriculture and allied activities as an important source of income and livelihood. Despite its crucial role, the agricultural sector faces several structural and emerging challenges, including declining farm profitability, fragmented landholdings, climate variability, increasing

input costs, and inefficient utilization of natural resources. These challenges are particularly severe for small and marginal farmers, who constitute the majority of India's farming community and often operate under resource-constrained conditions.

Smallholder farmers generally cultivate fragmented and small-sized land parcels with limited access to financial resources, modern technologies, institutional credit, and efficient market networks. These constraints restrict mechanization, reduce production efficiency, and increase vulnerability to climatic uncertainties. Rising

prices of agricultural inputs, inadequate irrigation facilities, weak extension services, fluctuating market prices, and limited bargaining power further affect farm income and livelihood security. In recent years, climate change has intensified these challenges through irregular rainfall patterns, prolonged dry periods, increasing temperatures, and frequent extreme weather events, resulting in higher production risks and uncertainty in agricultural outcomes.

In this context, rapid technological advancement has created new opportunities for transforming agricultural systems. Smart agriculture, also known as digital agriculture or precision agriculture, integrates modern information and communication technologies with agricultural production and farm management practices. Technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Global Positioning System (GPS), Geographic Information Systems (GIS), remote sensing, drones, sensors, satellite-based monitoring systems, and mobile-based advisory platforms enable farmers to access real-time information related to soil conditions, weather forecasts, crop health, irrigation requirements, pest management, and market conditions. These technologies facilitate scientific decision-making, improve farm management practices, and promote efficient utilization of agricultural resources.

The adoption of smart agriculture provides multiple economic, environmental, and social benefits. Precision-based application of water, fertilizers, pesticides, and other agricultural inputs helps reduce resource wastage while improving productivity and production efficiency. Digital advisory services enable farmers to receive timely information regarding weather conditions, disease management, and market opportunities, thereby reducing production risks and improving marketing decisions. Consequently, smart agriculture has the potential to enhance farm income, promote sustainable resource management, strengthen climate resilience, and improve the overall socio-economic well-being of rural farming communities.

Recognizing the importance of digital transformation in agriculture, the Government of India and various agricultural institutions have initiated several programmes to encourage technology-based farming practices. These initiatives include digital extension services, capacity-building programmes, financial support mechanisms, and promotion of climate-smart agricultural practices. However, despite increasing policy emphasis, the adoption of smart agriculture technologies among small and marginal farmers remains limited due to several socio-economic and infrastructural constraints.

Limited digital literacy, inadequate internet connectivity, high initial investment requirements, lack of technical knowledge, insufficient institutional support, and fragmented landholdings continue to restrict the widespread adoption of digital agricultural technologies. Many rural households face difficulties in accessing and effectively utilizing advanced technological solutions due to financial and skill-related limitations. These challenges create a gap between the availability of agricultural innovations and their actual adoption at the farm level.

Previous studies have highlighted the positive contribution of digital agriculture towards improving agricultural productivity, reducing input costs, and enhancing resource-use efficiency. Reports by international organizations such as the Food and Agriculture Organization (FAO) and the World Bank have emphasized the role of digital technologies in promoting sustainable agricultural development and improving farmers' livelihoods. Recent empirical studies also indicate that technologies such as IoT-based monitoring systems, Artificial Intelligence applications, and precision farming techniques can enhance crop management and farm profitability. However, existing research has largely focused on individual technologies or specific agricultural outcomes, while limited studies have examined the combined impact of smart agriculture adoption on productivity, income generation, resource-use efficiency, access to information, and farmer empowerment, particularly among smallholder farmers in rural and hill regions of India.

Hill states such as Himachal Pradesh present unique agricultural conditions characterized by geographical constraints, fragmented landholdings, climatic uncertainties, and limited access to advanced agricultural infrastructure. These factors make the adoption and effectiveness of smart agriculture technologies an important area of investigation. Una district of Himachal Pradesh provides an appropriate setting for analysing these issues as agriculture remains an important livelihood activity, while farmers face challenges related to small operational holdings, rising input costs, changing climatic conditions, and market uncertainties. At the same time, improving digital connectivity and availability of mobile-based agricultural services provide new opportunities for technology-driven agricultural transformation.

Considering these research gaps and regional challenges, the present study examines the role of smart agriculture adoption in improving the productivity, income, resource-use efficiency, and empowerment of small and marginal farmers in Una District of Himachal Pradesh. The study also identifies the major socio-

economic and infrastructural constraints affecting the adoption of digital agricultural technologies. The findings are expected to provide empirical evidence for policymakers, agricultural extension agencies, and development institutions in designing inclusive strategies for promoting sustainable and technology-driven agricultural development among smallholder farming communities.

Review of Literature

The increasing integration of digital technologies into agriculture has attracted significant attention among researchers, policymakers, and development institutions due to their potential to transform agricultural production systems and improve rural livelihoods. Smart agriculture represents a technology-driven approach that combines advanced tools such as the Internet of Things (IoT), Artificial Intelligence (AI), remote sensing, Geographic Information Systems (GIS), drones, sensors, and mobile-based advisory services to facilitate data-based decision-making in farming. These technologies enable farmers to monitor crop conditions, manage agricultural inputs efficiently, reduce production risks, and enhance farm productivity and profitability.

Food and Agriculture Organization (FAO, 2020) highlighted that digital agriculture plays a crucial role in achieving sustainable agricultural development by improving production efficiency, reducing input wastage, enhancing climate resilience, and strengthening the capacity of farmers to respond to emerging agricultural challenges. Similarly, the **World Bank (2019)** emphasized that digital innovations improve access to agricultural information, strengthen market linkages, increase financial inclusion, and support income enhancement among smallholder farmers, particularly in developing economies.

Shukla (2024) examined the role of Artificial Intelligence and Internet of Things-based applications in agriculture and found that smart monitoring systems significantly improve crop management, irrigation scheduling, and resource-use efficiency. The study highlighted that real-time data availability enables farmers to make informed decisions regarding farm operations. However, the study also identified digital illiteracy, high technological costs, and inadequate technical knowledge as major barriers limiting the adoption of smart agricultural solutions among small farmers.

Behuria et al. (2025) analysed the contribution of precision agriculture technologies towards improving agricultural productivity and sustainability. The findings revealed that precision farming practices enhance the efficiency of fertilizer, pesticide, and water utilization by enabling accurate and need-based application of inputs.

The study further emphasized that wider adoption of precision agriculture requires affordable technologies, improved digital infrastructure, and effective capacity-building programmes for farmers.

Singh and Singh (2024) investigated the effectiveness of IoT-enabled agricultural systems and observed that sensor-based technologies improve farm performance through continuous monitoring of soil moisture, climatic conditions, and crop health indicators. The study concluded that digital farming technologies contribute to reducing production uncertainties, improving input efficiency, and enhancing overall agricultural productivity.

Sachdeva and Anand (2025) examined the economic implications of smart agriculture and found that technology adoption positively influences farm profitability through improved resource management, timely decision-making, and reduction in production costs. The authors emphasized that government support, financial incentives, digital extension services, and institutional mechanisms are essential for encouraging smallholder farmers to adopt modern agricultural technologies.

Samantaray (2025) focused on the role of institutional support in promoting digital agriculture and highlighted the importance of Farmer Producer Organizations (FPOs) in facilitating technology access, improving credit availability, strengthening extension services, and enhancing farmers' participation in organized markets. The study suggested that collective institutional arrangements can play a significant role in overcoming adoption barriers faced by small and marginal farmers.

Indian Council of Agricultural Research (ICAR) have emphasized the increasing vulnerability of Indian agriculture due to climate change, reflected through irregular rainfall patterns, rising temperatures, water stress, and frequent extreme weather events. These reports advocate the promotion of climate-smart and digital agricultural practices as effective mechanisms for improving agricultural resilience, conserving natural resources, and ensuring sustainable livelihood opportunities for farming communities.

Overall, the existing literature establishes that smart agriculture has significant potential to improve agricultural productivity, resource-use efficiency, farm profitability, market access, and sustainability. However, the effectiveness of these technologies is largely influenced by socio-economic conditions, digital infrastructure, institutional support, technical capabilities, and farmers' readiness to adopt innovative practices.

Research Gap

Existing studies have largely focused on individual smart agriculture technologies such as AI, IoT, and precision farming, with limited attention to their integrated use and broader socio-economic outcomes. The impact of smart agriculture on farmer empowerment, decision-making, access to information, market participation, income, and livelihood improvement remains insufficiently explored, particularly among small and marginal farmers. Furthermore, empirical evidence from hilly regions such as Himachal Pradesh is limited, despite challenges related to fragmented landholdings, geographical constraints, climate variability, poor internet connectivity, digital illiteracy, high initial costs, and inadequate technical support. There is also limited understanding of the socio-economic and institutional factors that influence farmers' willingness and capacity to adopt smart agricultural technologies. Therefore, the present study addresses these gaps by examining the impact of smart agriculture adoption on productivity, farm income, resource-use efficiency, and farmer empowerment, while also identifying the major barriers and determinants of technology adoption among small and marginal farmers in Una District, Himachal Pradesh. The study aims to contribute to the development of more inclusive, sustainable, and region-specific strategies for digital transformation in agriculture.

Objectives of the Study

- To examine the adoption pattern of smart agriculture among small and marginal farmers in Una District of Himachal Pradesh.
- To analyse the impact of smart agriculture adoption on productivity, farm income, and resource-use efficiency.
- To assess the role of smart agriculture in enhancing farmer empowerment and identify major adoption barriers.

Materials and Methods

Research Design

The study adopted a descriptive and empirical research design to examine smart agriculture adoption among small and marginal farmers in Una District of Himachal Pradesh, India. Primary data were collected from 230 farming households to analyse the relationship between smart agriculture adoption and socio-economic outcomes, including agricultural productivity, farm income, resource-use efficiency, market access, and farmer empowerment. The collected data were analysed using descriptive and inferential statistical techniques.

A conceptual framework was developed to examine the association between smart agriculture adoption and farmers' socio-economic outcomes.

Study Area

The study was conducted in Una District of Himachal Pradesh, located in the lower Shivalik average elevation of about 369 metres above sea level. Agriculture remains an important region. The district lies at approximately 31°28' N latitude and 76°16' E longitude, with an livelihood activity in the region, with a large number of households dependent on farming and allied activities. The agricultural system is predominantly characterized by small landholdings, rainfed cultivation, and increasing efforts towards adoption of modern agricultural technologies.

Study Variables

The study focused on small and marginal farmers of Una District. Marginal farmers were defined as those owning less than 1 hectare of land, while small farmers owned 1–2 hectares. Smart agriculture adoption was considered the key independent variable, including technologies such as Internet of Things (IoT), Artificial Intelligence (AI), precision farming practices, and mobile-based agricultural advisory services. The dependent variables included agricultural productivity, farm income, resource-use efficiency, and farmer empowerment. Factors such as digital literacy, internet connectivity, technology cost, government support, and training facilities were considered influencing variables.

Sampling Technique and Sample Size

A multistage random sampling technique was adopted for selecting respondents. A total sample of 230 small and marginal farmers was selected from Una District to ensure adequate representation of different categories of farmers.

Data Collection Tool and Validation

Primary data were collected through a structured questionnaire prepared after reviewing relevant literature and consulting experts in the field. The questionnaire was pre-tested among selected farmers to ensure clarity, reliability, and suitability before final data collection.

Reliability of Instrument

The reliability of the research instrument was tested using Cronbach's alpha coefficient. The results indicated satisfactory internal consistency of the scale used for measuring smart agriculture adoption and related socio-economic indicators.

Statistical Tools Used

The collected data were analysed using IBM SPSS Statistics and Microsoft Excel. Descriptive statistics were used to analyse the socio-economic characteristics of respondents. Percentage analysis was applied to measure technology adoption patterns and outcomes. Inferential statistical tools, including Chi-square test, t-test, correlation analysis, and regression analysis, were used to examine the relationship between smart agriculture adoption and socio-economic outcomes of farmers.

Size of Landholding

Farmers were classified according to the Agricultural Census of India. Marginal farmers were those owning less than 0–1 hectare, small farmers 1–2 hectares, semi-medium farmers 2–4 hectares, medium farmers 4–10 hectares, and large farmers above 10 hectares of land. This classification helped analyse variations in resource availability and socio-economic conditions among different farmer categories.

Hypotheses of the Study

H01: Smart agriculture adoption has no significant relationship with agricultural productivity of small and marginal farmers.

H02: Smart agriculture adoption has no significant relationship with farm income and resource-use efficiency.

H03: Socio-economic and infrastructural factors do not significantly influence the adoption of smart agriculture among farmers.

Results and Discussion

Socio-economic Classification of Respondents: The study was based on a sample of 230 small and marginal farmers from Una District of Himachal Pradesh. Among the total respondents, 68.00 percent were marginal farmers and 32.00 percent were small farmers. The dominance of marginal farmers in the sample reflects the prevailing pattern of fragmented and small-sized landholdings in the study area. The socio-economic characteristics of respondents indicate the resource constraints faced by smallholder farmers in adopting modern agricultural technologies.

Smart Agriculture Adoption and Productivity Outcomes: The findings indicate that adoption of smart agriculture practices has a positive association with productivity-related outcomes among small and marginal farmers. Farmers adopting smart agricultural technologies reported improvements in access to weather information, scientific farm management practices, input-use efficiency, crop quality, and reduction in

production risks. The results suggest that digital agricultural tools assist farmers in making timely and informed decisions, thereby contributing to improved agricultural performance.

Small farmers showed relatively higher adoption levels and perceived benefits compared to marginal farmers, which may be attributed to better resource availability, greater investment capacity, and improved access to information and training facilities.

Smart Agriculture Adoption, Farm Income and Resource-use Efficiency: The results reveal that smart agriculture adoption contributes positively to farm income and efficient utilization of agricultural resources. Farmers using digital advisory services, precision farming techniques, and improved farm management practices reported better utilization of water, fertilizers, seeds, and other inputs. Adoption of smart technologies was also associated with reduced cultivation costs, improved productivity, and better access to market information.

These findings indicate that smart agriculture can support sustainable agricultural development by improving economic returns and promoting efficient resource management among smallholder farmers.

Farmer Empowerment through Smart Agriculture Adoption: The study further examined the role of smart agriculture in enhancing farmer empowerment. The findings indicate that digital agricultural technologies improved farmers' access to information, decision-making ability, and awareness regarding weather conditions, crop management practices, and market opportunities. Farmers adopting smart agriculture practices demonstrated greater confidence in farm-related decisions and improved engagement with agricultural information sources.

However, the extent of empowerment varied according to farmers' digital literacy, availability of internet facilities, and access to technical support.

Barriers Affecting Adoption of Digital Agriculture: The study identified several constraints affecting the adoption of smart agriculture technologies. Digital literacy emerged as the major barrier, followed by inadequate internet connectivity, lack of awareness, high technology costs, limited technical training, and small operational landholdings. These constraints indicate that technological availability alone is insufficient unless supported by appropriate infrastructure, capacity building, and institutional assistance.

Hypothesis Testing Results

The Chi-square test result ($\chi^2 = 18.50$, $p < 0.05$) indicates a statistically significant association between smart agriculture adoption and agricultural productivity. Therefore, the null hypothesis stating that smart agriculture adoption has no significant relationship with productivity is rejected. Similarly, the t-test result ($t = 4.21$, $p < 0.01$) confirms a significant difference in productivity outcomes between farmers adopting smart agriculture technologies and those with lower or no adoption levels.

Regression Analysis of Productivity Model

The regression analysis indicates a strong positive relationship between smart agriculture adoption variables and agricultural productivity ($R = 0.82$). The model explains approximately 67.00 percent variation in productivity outcomes ($R^2 = 0.67$), suggesting that adoption of smart agricultural practices significantly contributes to improving farm productivity.

Regression Analysis of Adoption Constraints

The regression model analysing adoption constraints shows a strong relationship between socio-economic and infrastructural factors and smart agriculture adoption behaviour ($R = 0.76$). The model explains 58.00 percent variation in adoption levels ($R^2 = 0.58$), indicating that factors such as digital literacy, internet availability, technology cost, and training support significantly influence farmers' adoption decisions.

Discussion

Smart Agriculture Adoption and Productivity Improvement of Small and Marginal Farmers: The positive association between smart agriculture adoption and productivity outcomes indicates that digital technologies can improve farm management practices and operational efficiency among small and marginal farmers. Access to timely information related to weather conditions, crop health, irrigation requirements, and input management enables farmers to make informed decisions and optimize the use of agricultural resources. The comparatively better performance of small farmers may be attributed to their relatively higher capacity to access financial resources, digital services, and technological support. These findings are consistent with the studies of Shukla (2024), Singh and Singh (2024), and Behuria et al. (2025), which reported that digital technologies, IoT-based systems, and precision farming practices contribute significantly to improving agricultural productivity and resource-use efficiency.

Smart Agriculture Adoption, Farm Income and Resource-use Efficiency: The improvement in farm income and resource-use efficiency suggests that smart agriculture contributes to sustainable economic benefits for smallholder farmers. Efficient utilization of water, fertilizers, seeds, and other agricultural inputs helps reduce production costs and improve profitability. Moreover, access to digital market information enables farmers to make better marketing decisions and improve their participation in agricultural markets.

These findings support the observations of FAO (2020) and the World Bank (2019), which highlighted the role of digital agriculture in improving farm efficiency, reducing production risks, and enhancing farmers' livelihoods. Similar findings were reported by Sachdeva and Anand (2025), who emphasized that technology-based agricultural practices improve resource management and farm profitability.

Role of Smart Agriculture in Farmer Empowerment: The findings indicate that smart agriculture adoption contributes not only to productivity improvement but also to farmer empowerment by improving access to information, enhancing decision-making capacity, and increasing awareness about scientific farming practices. Digital advisory platforms, weather forecasting services, and market information systems enable farmers to take timely decisions regarding crop planning, input use, and marketing strategies.

However, the extent of empowerment depends on farmers' digital literacy, affordability of technology, internet accessibility, and availability of technical support. Therefore, improving digital skills and strengthening extension services are essential for ensuring inclusive benefits of smart agriculture among smallholder farmers.

Barriers Affecting the Adoption of Digital Agriculture: Despite the potential advantages of smart agriculture, adoption remains limited due to various socio-economic and infrastructural constraints. Digital illiteracy, inadequate internet connectivity, high technology costs, lack of awareness, and insufficient training opportunities were identified as major barriers affecting technology adoption among farmers.

These findings are consistent with Shukla (2024) and Behuria et al. (2025), who highlighted that financial limitations, inadequate technical knowledge, and weak digital infrastructure restrict the adoption of smart farming technologies among small farmers. The results also support the observations of the Organisation for Economic Co-operation and Development (OECD, 2021), which emphasized the importance of digital infrastructure, institutional support, and capacity-building programmes for promoting agricultural technology adoption.

Challenges Faced During Data Collection

The study has certain limitations that should be considered while interpreting the findings.

Limited Awareness about Smart Agriculture: Some farmers had limited awareness regarding smart agriculture technologies, including digital advisory services, precision farming, and IoT-based agricultural applications. This created challenges in understanding the concepts and assessing their adoption level.

Reluctance in Providing Information: Some respondents were hesitant to provide detailed information regarding farm income, technology usage, and agricultural practices. Such hesitation may have influenced the accuracy of responses to some extent.

Understanding of Technical Concepts: Many farmers faced difficulties in understanding technical terms related to digital agriculture and modern farming technologies. The researcher had to explain certain questions in simple language to ensure better comprehension.

Time Constraints during Field Survey: The availability of farmers was limited due to their agricultural activities and seasonal workload. This created challenges in conducting detailed interactions and completing the survey within the planned time period.

Limited Financial and Logistical Resources: Due to limitations of available resources, the study was restricted to selected respondents from Una District. A larger sample covering more geographical areas could provide broader insights.

Variation in Education and Digital Literacy: The respondents differed significantly in educational background and digital literacy levels. These variations influenced their understanding, accessibility, and ability to adopt smart agriculture technologies.

Policy Suggestions

Based on the findings of the study, the following policy measures are suggested to promote inclusive and sustainable adoption of smart agriculture among small and marginal farmers:

Enhancing Digital Literacy and Awareness: Regular training programmes, awareness campaigns, and capacity-building initiatives should be organized to improve farmers' understanding and effective use of smart agriculture technologies.

Ensuring Affordable Access to Technology: Government support through subsidies, financial assistance, and affordable technology solutions should be provided to enable small and marginal farmers to adopt digital agricultural practices.

Strengthening Rural Digital Infrastructure: Improvement in internet connectivity, electricity supply, and digital service networks in rural areas is essential for ensuring effective implementation of smart agriculture technologies.

Promoting Collective Approaches for Technology Adoption: Farmer groups, Self Help Groups (SHGs), and Farmer Producer Organizations (FPOs) should be encouraged to facilitate collective learning, resource sharing, and wider adoption of digital agricultural practices.

Strengthening Agricultural Extension Services: Agricultural extension systems should be improved by providing regular technical guidance, field demonstrations, and continuous support to farmers regarding smart farming solutions.

Encouraging Multi-stakeholder Collaboration: Greater collaboration among government agencies, agricultural research institutions, universities, technology providers, and private sector organizations should be promoted to develop affordable, farmer-friendly, and region-specific smart agriculture solutions.

Limitations of the Study

The study has certain limitations that should be considered while interpreting the findings:

Geographical Limitation: The study is confined to Una District of Himachal Pradesh; therefore, the findings may not be fully generalizable to other regions with different agricultural, socio-economic, and technological conditions.

Sample Size Limitation: The study is based on a sample of 230 households, which may not completely represent the diversity of all categories of farmers across the wider agricultural landscape.

Primary Data Constraints: The study relies mainly on primary data collected through questionnaires. Therefore, the findings may be influenced by respondents' perceptions, recall errors, and accuracy of information provided by farmers.

Time and Resource Constraints: Due to limitations of time and available resources, the study was restricted in terms of extensive field coverage and detailed data collection.

Dynamic Nature of Digital Agriculture: Digital agricultural technologies are rapidly evolving; therefore, changes in technology availability, affordability, and adoption patterns may influence the long-term relevance of the findings.

Limited Variables Considered: The study focuses on selected variables related to smart agriculture adoption, productivity, income, resource efficiency, and farmer empowerment. Other possible influencing factors may require further investigation.

Conclusion

The study concludes that smart agriculture adoption has a positive association with agricultural productivity, farm income, resource-use efficiency, and farmer empowerment among small and marginal farmers in Una District of Himachal Pradesh. Technologies such as Internet of Things (IoT), Artificial Intelligence (AI), precision farming, and digital advisory platforms have improved farm management practices, access to agricultural information, and decision-making capacity of farmers. However, the adoption of smart agriculture remains limited due to challenges such as digital illiteracy, inadequate internet connectivity, high technology costs, and limited technical support. The findings suggest that strengthening rural digital infrastructure, enhancing farmers' digital skills, providing affordable technology solutions, and improving agricultural extension services are essential for promoting inclusive and sustainable digital transformation in agriculture. The study highlights that smart agriculture can play an important role in improving the livelihoods of smallholder farmers by increasing productivity, enhancing resource efficiency, and empowering farmers through better access to information and improved decision-making opportunities.

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Tables

Table 1. Socio-economic classification of respondents based on farm size

Category	Number of Farmers	Percentage
Marginal Farmers	156	68.00
Small Farmers	74	32.00
Total	230	100.00

Source: Primary Survey Data from Una District, Himachal Pradesh, 2025

Table 2: Impact of smart agriculture on productivity of sample farmers

Variables	Marginal Farmers	Small Farmers	All Farmers
X_1	67 (42.95%)	37 (50.00%)	104 (45.22%)
X_2	59 (37.82%)	33 (44.59%)	92 (40.00%)
X_3	45 (28.85%)	24 (32.43%)	69 (30.00%)
X_4	37 (23.72%)	21 (28.38%)	58 (25.22%)
X_5	33 (21.15%)	18 (24.32%)	51 (22.17%)
X_6	27 (17.31%)	14 (18.92%)	41 (17.83%)

Source: Primary Survey Data from Una District, Himachal Pradesh, 2025

X_1 =Technology Adoption (IoT, AI, Precision Farming), X_2 =Market & Weather Information Access, X_3 =Input Efficiency, X_4 =Risk Reduction, X_5 =Productivity Improvement, X_6 =Crop Quality Improvement

Table 3: Effect of smart agriculture on farmers' income & resource efficiency

Variables	Marginal Farmers	Small Farmers	All Farmers
X_1	67 (42.95%)	37 (50.00%)	104 (45.22%)
X_2	52 (33.33%)	30 (40.54%)	82 (35.65%)
X_3	33 (21.15%)	18 (24.32%)	51 (22.17%)
X_4	45 (28.85%)	24 (32.43%)	69 (30.00%)
X_5	40 (25.64%)	22 (29.73%)	62 (26.96%)
X_6	59 (37.82%)	33 (44.59%)	92 (40.00%)

Source: Primary Survey Data from Una District, Himachal Pradesh, 2025

X_1 =Level of Smart Agriculture Adoption, X_2 =Farmers' Income Improvement, X_3 =Crop Productivity (Yield per acre), X_4 =Input Use Efficiency (water, fertilizer, seeds), X_5 =Cost of Cultivation (Reduction), X_6 =Market Access & Price Realization

Table 4: Barriers in adoption of digital agriculture

Variables	Marginal Farmers	Small Farmers	All Farmers
X_1	78 (50.00%)	34 (45.95%)	112 (48.70%)
X_2	65 (41.67%)	30 (40.54%)	95 (41.30%)
X_3	72 (46.15%)	33 (44.59%)	105 (45.65%)
X_4	70 (44.87%)	29 (39.19%)	99 (43.04%)
X_5	60 (38.46%)	27 (36.49%)	87 (37.83%)
X_6	55 (35.26%)	25 (33.78%)	80 (34.78%)

Source: Primary Survey Data from Una District, Himachal Pradesh, 2025

X_1 =Lack of Digital Literacy, X_2 =High Cost of Technology, X_3 =Poor Internet Connectivity, X_4 =Lack of Awareness, X_5 = Limited Training Support, X_6 =Small Landholding Constraint

Table 5: Hypothesis testing results

Component	Test	Value	Significance
Productivity Impact	Chi-square (χ^2)	18.50	$P < 0.05$
Productivity Improvement	t-test	4.21	$P < 0.01$

Table 6. Regression Results of Productivity Model (Smart Agriculture Impact)

Variable	β (Coefficient)	t-value	P-value	Interpretation
Constant	1.25	—	—	Baseline productivity level
X_1 (Technology Adoption)	0.42	4.85	<0.01	Highly significant positive effect
X_2 (Market & Weather Information)	0.38	4.12	<0.01	Significant positive effect
X_3 (Input Efficiency)	0.30	3.76	<0.05	Moderately significant effect
X_4 (Risk Reduction)	0.35	4.01	<0.01	Strong significant effect
R Square (R^2)	0.67			
Adjusted R Square	0.65			
Regression Equation	$Y_1 = 1.25 + 0.42X_1 + 0.38X_2 + 0.30X_3 + 0.35X_4 + \mu$			

Table 7. Regression Results of Adoption Barriers Model (Digital Agriculture Constraints)

Variable	β (Coefficient)	t-value	P-value	Interpretation
Constant	1.20	—	—	Baseline level of adoption
X_1 (Lack of Digital Literacy)	0.40	4.60	<0.01	Strong positive constraint on adoption
X_2 (High Cost of Technology)	0.35	4.10	<0.01	Significant barrier
X_3 (Poor Internet Connectivity)	0.38	4.25	<0.01	Highly significant infrastructural barrier
X_4 (Lack of Awareness)	0.32	3.90	<0.05	Moderate significant barrier
X_5 (Limited Training Support)	0.30	3.70	<0.05	Moderate barrier
X_6 (Small Landholding Constraint)	0.28	3.45	<0.05	Weak but significant constraint
R Square (R^2)	0.58			
Adjusted R Square	0.56			
Regression Equation	$Y_2 = 1.20 + 0.40X_1 + 0.35X_2 + 0.38X_3 + 0.32X_4 + 0.30X_5 + 0.28X_6 + \mu$			

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