frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 15 July 2024
DOI 10.3389/fsufs.2024.1401316

OPEN ACCESS

EDITED BY
Noshaba Aziz,
Shandong University of Technology, China

REVIEWED BY
Siphe Zantsi,
Agricultural Research Council of South Africa (ARC-SA), South Africa
Narongsak Sukma,
Siam Technology College, Thailand

*CORRESPONDENCE
Haixia Zhang
✉ zhanghx@sicau.edu.cn

RECEIVED 15 March 2024
ACCEPTED 25 June 2024
PUBLISHED 15 July 2024

CITATION
Gong W, Ma R and Zhang H (2024) Digital agricultural technology services and farmers' willingness to choose digital production technology in Sichuan province, China. *Front. Sustain. Food Syst.* 8:1401316. doi: 10.3389/fsufs.2024.1401316

Digital agricultural technology services and farmers' willingness to choose digital production technology in Sichuan province, China

Wei Gong, Ruiyao Ma and Haixia Zhang*

College of Economics, Sichuan Agricultural University, Chengdu, China

Introduction: Digital agricultural technology service has the characteristics of high efficiency, convenience and flexibility, and plays an important role in the process of Chinese agricultural digitalization, which is of great significance for realizing the modernization and intelligent development of agricultural production.

Methods: Based on micro-survey data of small-scale farmers in Sichuan Province, this study utilizes the OLS method and the mediation effect model to investigate the impact of digital agricultural technology services on farmers' willingness to adopt digital production technologies and its underlying mechanisms.

Results: The results indicate that digital agricultural technology services effectively enhance farmers' willingness to adopt digital production technologies, especially among those engaged in cooperative. Further analysis of mechanisms suggests that digital agricultural technology services influence farmers' choices of household production and management methods by expanding their information channels, enhancing their cognition of digital production technologies, and facilitating access to technology. Moreover, heterogeneous analysis reveals significant differences in the willingness of farmers with varying levels of digital literacy to adopt digital production technologies. Digital agricultural technology services have a more pronounced impact on the willingness of highly digitally literate farmers.

Discussion: The findings of this paper deepen our comprehension of the operational mechanisms of digital agricultural technology services in the context of agricultural development, and advocate for policy recommendations such as enhancing the supply of digital agricultural technology services, strengthening the role of new agricultural entities, improving farmers' digital literacy training, and enhancing policy support systems.

KEYWORDS

digital agricultural technology service, digital production technology, mechanism of action, digital literacy, theory of planned behavior, mediating effects

1 Introduction

Since the 18th National Congress of the Communist Party of China, documents such as the *Outline of Digital Village Development Strategy* and the *Action Plan for Digital Village Development (2022–2025)* have been successively issued. *The Key Points of Digital Village Development in 2023* further emphasize the acceleration of the digital transformation of the entire agricultural industry chain, highlighting the crucial role of digitalization in guiding and propelling the modernization of agriculture and rural areas. The term "Digitalization of agricultural production" refers to the

process of collecting and analyzing data to enhance the efficiency of agriculture through the utilization of information and communication technology (Bacco et al., 2019). This is primarily evident in the scale of agricultural production, mechanization, information technology, and intelligence (Du, 2023).

The digitalization of agricultural production plays an important role in the modernization of agriculture and rural areas. Digital agricultural technology services represent an information system that integrates the Internet with traditional agricultural extension services, known as the 'Internet Plus Agricultural Technology Extension' model (Gao et al., 2023). It plays an active role in improving the level of agricultural industrialization, enhancing the comprehensive quality of farmers, transforming the traditional production mode, and achieving refined agricultural production (Li, 2022). This further boosts the digitalization of agricultural production.

The digitalization of agricultural production can not only promote the organic connection between small farmers and modern agriculture (Li and Xiao, 2023), but also realize the linkage and mutual integration of primary, secondary, and tertiary industries (Liu and Fu, 2020). In recent years, China has made significant progress in agricultural digitalization, especially in infrastructure construction. However, the deep integration of the digital economy and agricultural development is still insufficient. Digital transformation in agriculture faces challenges such as reluctance, fear, and inability to switch (Niu, 2023). Farmers, as micro-entities in agricultural production, are driven, dominated, and directly affected by their intentions (Guo et al., 2018). Farmers' willingness to adopt digital production technology is very low. Currently, most Chinese farmers lack digital skills, making it challenging to meet the demands of modern digital agricultural production (Chen and Xiong, 2022). Digital agricultural technology services lag behind, with low levels of popularization and application (Li, 2022). Therefore, under the new circumstances of economic and social development, it is urgent to investigate and explore ways to increase farmers' willingness to choose digital production technology.

Digital agricultural technology services approach addresses issues such as lengthy cycles, high costs, and low efficiency associated with traditional agricultural technology extension. However, current conventional agricultural technology promotion methods are relatively single and inefficient, affecting the application of digital technology in agricultural production (Aker, 2011).

The increasing Internet penetration in rural areas of China has created a favorable environment for promoting digital agricultural technology services. According to the Statistical Report on Internet Development in China released by the China Internet Network Information Centre (CNNIC), as of December 2022, the Internet penetration rate in rural areas reached 61.9%, totaling 176 million rural broadband users. This not only means that many rural residents have become potential audiences for digital agricultural technology services but also provides a solid foundation for applying digital agronomic services.

Furthermore, digital agricultural technology services often cooperate with financial institutions (Chen et al., 2022) to provide both traditional and digital financial services to farmers, significantly improving agricultural output levels (Zeng and Qi, 2020), enhancing the efficiency and sustainability of digital agricultural production, and reducing the risk of digital technology application.

Overall, digital agricultural technology services play a crucial role in promoting the adoption of digital production technologies by farmers, fostering sustainable growth of the agricultural economy, and advancing the deep integration of digital technology and rural development (Wen and Chen, 2020).

The factors influencing farmers' adoption of digital technology in agriculture include their cognitive awareness, absorption capacity, and application proficiency in digital agricultural production technologies (Barnes et al., 2019). According to the Technology Acceptance Theory, which examines how individuals accept and adopt new technologies, this framework also applies to understanding farmers' attitudes toward digital production technologies. It encompasses farmers' awareness of how these digital technologies impact agricultural production and management, as well as their perceptions of the usability of these technologies (Steinke et al., 2019).

Additionally, the Individual-Interaction Theory suggests that factors such as farmers' beliefs, values, attitudes, expectations, and personality traits play a significant role in shaping their awareness and attitudes toward digital production technologies. These personal factors further influence their willingness to adopt these technologies. The Technology Acceptance Theory and the Individual-Interaction Theory provide insights into how farmers' perceptions and attitudes towards digital production technologies are influenced, thereby affecting their adoption behavior (Barakabitze et al., 2017).

However, Digital agricultural technology services can affect farmers' behavior choices through both direct and indirect means. Firstly, digital agricultural technology extension services can address the drawbacks of traditional extension methods, such as their singularity and limitations in terms of time and space (Norton and Alwang, 2020). They enable the visualization of technical information and facilitate two-way communication, thereby directly influencing adoption behavior (Yang et al., 2023). Secondly, by reducing search costs, improving accessibility, and lowering negotiation costs through the establishment of learning platforms, measures aimed at enhancing farmers' technical learning efficiency indirectly impact their adoption intentions (Mao et al., 2023). However, few scholars have studied the role of digital agricultural technology services in promoting the digitalization of agricultural production from the perspective of digital farm technology services. What is the effect of digital agricultural technology services on farmers' willingness to choose digital production technology? How do digital agriculture technology services influence farmers' willingness towards adopting digital production technology? These are the questions that this article aims to answer.

Currently, existing literature on analyzing the effects of digital agricultural technology services holds significant value, providing references and insights for this paper. However, there is room for supplementation and improvement.

Firstly, existing research on digital agricultural technology services mainly focuses on the macro level, involving their current status and issues (Gu et al., 2013). Research indicates that agricultural extension services provide farmers with the latest information on technology. Those who apply it tend to gain higher profits and also improve their living standards (Elias et al., 2016). Without developing a systematic theoretical framework that encompasses farmers' active participation in digital agricultural technology services.

Secondly, most existing literature remains at the stage of empirical summarization. There is research on the use of the internet and smartphones in rural areas of developing countries, which generally finds positive effects on household welfare (Hübler and Hartje, 2016; Ma et al., 2020). Some studies have also analyzed the impact of using

training videos or call centers and interactive voice response services on farmers (Van Campenhout et al., 2017). lacking in-depth exploration of overall service evaluation and identification.

Thirdly, compared to other developing countries, existing research has focused more on the singularity and lack of effectiveness of agricultural technology services (Utami et al., 2019). Digital technologies significantly improve the income and productivity of smallholder farmers by enhancing information dissemination and market access (Bahinipati et al., 2021). Studies suggest that agricultural technology services in Indonesia have had no long-term impact on technology adoption in agriculture, yet they have a significant short-term effect (Utami et al., 2019). This is because the utilization of modern technology through extension services leads to higher productivity (Mwangi and Kariuki, 2015). In some underdeveloped countries where income depends on land and natural resources, although most people use extension services to address low productivity issues, the rate is low due to farmer illiteracy and lack of awareness (Nugraha and Osman, 2017). The existing literature has not paid enough attention to the significance of digital agricultural technology services in supporting deeper industrial integration and achieving structural changes in agricultural production.

The article's key contributions primarily lie in several areas:

Firstly, there is a considerable amount of literature discussing digital agricultural technology services and digital technologies. More and more literature emphasizes that digital technologies can significantly reduce dissemination costs, thereby lowering transaction costs, enhancing market efficiency, promoting economic growth, and reducing poverty (Torero and Von Braun, 2006; Jensen, 2007; Aker and Mbiti, 2010). Some studies suggest that providing farmers with general market and weather information via mobile phones, text messages, or internet applications can enhance agricultural productivity and market efficiency (Aker and Mbiti, 2010; Fu and Akter, 2016). There is a lack of research on the impact of digital agricultural technology services on farmers' adoption intentions and behaviors. Drawing on the theory of planned behavior, farmers' intentions are primarily influenced by behavioral attitudes, subjective norms, and perceived behavioral control, which, in turn, determine individual behaviors. This study investigates the impact of digital agricultural technology services in enhancing farmers' adoption of digital production technologies, revealing key influencing factors and pathways. This research provides valuable insights for agricultural policymakers to formulate more effective policies and strategies.

Secondly, based on analyzing whether farmers use digital agricultural technology services or not, the study by Gao et al. (2023) further examines the effectiveness of these services. The results directly respond to discussions about the digital agricultural technology service effectiveness and provide a practical basis for better applying these services to guide farmers' willingness to adopt them.

Thirdly, in terms of theoretical mechanism, existing literature often discusses the impact of digital agricultural technology services primarily from the perspective of the Technology Acceptance Model (Verma and Sinha, 2018; Castiblanco Jimenez et al., 2021). This paper innovatively incorporates the rational behavior theory and the planned behavior theory to construct a theoretical framework, providing a multifaceted exploration of the influence of digital agricultural technology services on farmers' production behavior. This paper analyzes the role of digital agricultural technology services in enhancing farmers' willingness to adopt digital production technology, focusing on production benefits and technology accessibility. It empirically analyzes and proves the existence of this mechanism.

Fourthly, from a research perspective, this paper analyzes the differences in the impact of digital agricultural technology services on farmers with varying levels of digital literacy. It details the heterogeneous role of these services for different groups of farmers, providing a decision-making basis for formulating effective digital agricultural technology service policies.

Fifthly, in terms of research value, this paper uses 214 survey data from Sichuan Province to conduct empirical tests exploring the impact of digital agricultural technology services on farmers' willingness to choose digital production technology. This not only supplements the current literature related to digital agricultural technology but also provides practical evidence for the use of these services to promote farmers' willingness to adopt digital production technology.

2 Theoretical analysis

Theory of Reasoned Action (TRA) suggests that an individual's behavior choice is closely related to psychological changes and cognitive processes (Fishbein and Ajzen, 1977). Behavioral attitudes and subjective norms can influence behavioral intentions, which, in turn, affect individual behavior. Farmers' comprehension and cognition of digital production technology will influence their willingness to adopt it, thus impacting the implementation and effectiveness of agricultural production digitization.

According to the Theory of Planned Behavior (TPB), farmers' willingness to choose digital production technologies is primarily influenced by their behavioral attitudes, subjective norms, and perceived behavioral control within the external environment. Individual behavioral intentions determine individual behavior (Zhang and Zhang, 2016). Within the framework of rational behavior and the Theory of Planned Behavior, behavioral intentions play a significant role in explaining behavioral responses. Therefore, most farmers will translate their behavioral intentions into actual behaviors, demonstrating consistency between intentions and responses (Zhan and Wang, 2023). Farmers' willingness to participate in production and management practices is influenced by their comprehension and awareness of digital production technology, leading to observable behavioral responses. This paper analyzes the impact of digital agricultural technology services on farmers' willingness to adopt digital production technology.

Digital agricultural technology services, as an extension model that combines the Internet with traditional agricultural technology extension services (Gao et al., 2023), can overcome the limitations of conventional methods. They directly affect farmers' choice behavior by achieving two-way communication of technical information and promoting adoption (Yang et al., 2023). These services also indirectly influence farmers' adoption behavior by reducing costs and establishing learning platforms to improve efficiency.

The Technology Acceptance Model (TAM) is a behavioral model in the field of information technology that is widely used to predict and explain user adoption behavior towards technology. With a robust theoretical framework and extensive empirical support, the Technology Acceptance Model (TAM) often serves as the mainstream paradigm for user acceptance of technological innovations (Sukma

and Leelasantitham, 2022). According to the Technology Acceptance Model, a user's willingness to accept new technology is influenced by perceived ease of use and perceived usefulness. There is a positive relationship between two factors: the higher the perceived ease of use and perceived usefulness, the stronger the user's willingness to accept new technology (Davis, 1989).

The impact of digital agricultural technology services refers to how they affect farmers who receive extension services. This impact is based on the theoretical role of extension services, which is to bridge the gap in technology and management. There is often a gap between farmers' current production practices and optimal production methods. Agricultural technology extension plays a crucial role in bridging this gap by disseminating information, educating farmers, promoting new technologies, and enhancing field management efficiency in practical farming applications (Swanson et al., 1972). Digital agricultural technology services can increase farmers' willingness to adopt digital production technology by enhancing their perceived usefulness and ease of use. This, in turn, promotes the adoption of digital technology among farmers. Figure 1 illustrates the structure of the theoretical framework in this paper.

3 Research hypotheses

3.1 Overall effect

By broadening the re-learning channels for farmers, agricultural technology extension aims to improve their productive capacity (Swanson et al., 1972). Digital agricultural technology services aim to interpret and demonstrate the technical aspects and management methods of advanced agricultural technology, adapting to continually changing production conditions and societal demands. With the "interconnectivity" feature of Internet information technology, digital agricultural technology services can connect multiple parties, including farmers, agricultural technicians, and agricultural experts, establishing a two-way communication system for agricultural information delivery (Wang et al., 2023).

Disseminating information and educating farmers helps bridge the gap in technology and management, consequently enhancing production efficiency. By providing real-time agricultural production information, market trends, and guidance on the latest agricultural technologies, digital agricultural technology services help farmers make more scientific production decisions and better respond to the challenges and opportunities of digital agricultural production.

From an input perspective, the widespread application of new technology mainly manifests in the continuous optimization of input structures and improvement of field management practices. With the rationalization and standardization of agricultural input factors and management practices, actual output approaches the production possibility frontier, thereby effectively enhancing technological efficiency. In this context, farmers receiving digital agricultural technology services should theoretically demonstrate higher technical efficiency in production. This indicates that agricultural technology extension services play a positive role in enhancing the technical efficiency of agriculture, which in turn stimulates an increase in farmers' preference for digital production technology as rational decision-makers.

Therefore, based on the above analyses, this study proposes Hypothesis 1:

> *H1*: Digital agricultural technology services will positively influence farmers' willingness to choose digital production technologies.

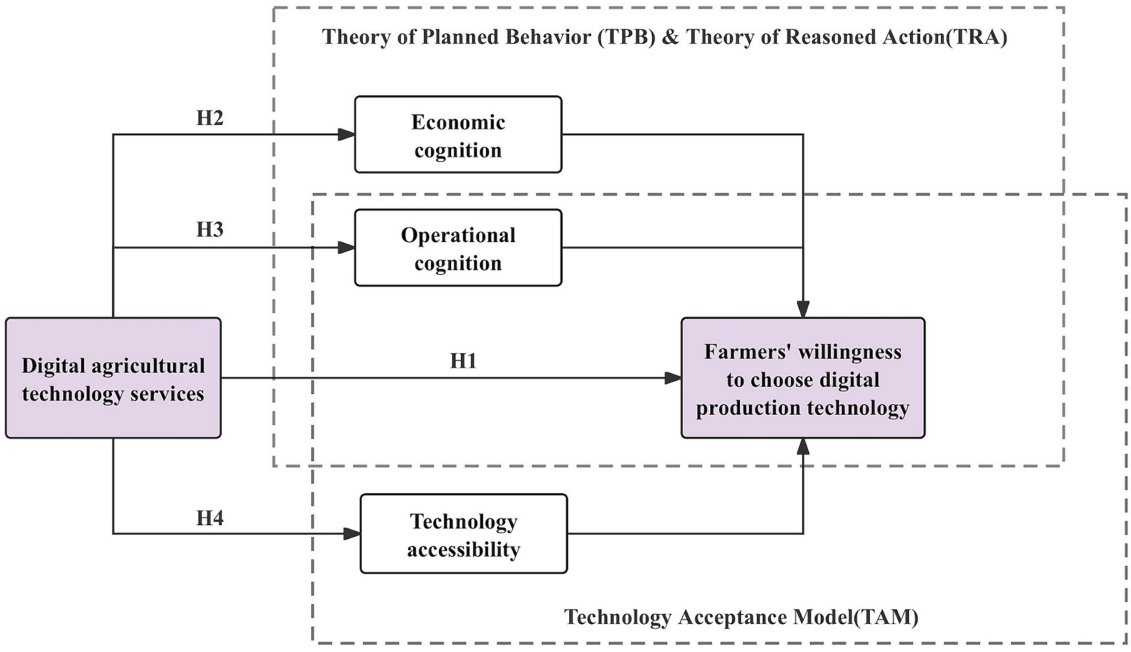

FIGURE 1
Structure of the theoretical framework.

3.2 Mediating effect

Digital agricultural technology services provide an economically viable way, and the precision of economic cognition helps to reduce production costs, improve the yield and quality of farm products, and increase the financial benefits of agriculture. As rational individuals, farmers' behavioral decisions adhere to the principle of optimization (Schultz, 1964). As rational economic beings, farmers' adoption of digital technology is mainly influenced by the expected financial benefits, and farmers are more inclined to choose digital production technology only when the expected net benefits of adopting the technology exceed those of traditional methods. Digital agricultural technology services, on the other hand, reduce farmers' learning costs for digital technologies by providing intuitive, easy-to-understand interfaces and guidance information. Farmers can master the essential operation of digital agricultural technology services through simple training or instructions, which improves farmers' operational cognition of digital production technology, thus making it more convenient to apply digital technology in agricultural production and promoting the development of digitalization of agriculture production.

Traditional agricultural technology extension services, such as demonstration, extension, and lecture training, guide farmers to adopt new technologies and strengthen their technology investment and skills (Zhou and Li, 2021), and digital agricultural technology services further enhance such technology guidance. Firstly, it expands farmers' access to information, providing them with a more comprehensive understanding of the economic and ecological value of digital production technology. This enhances economic cognition and promotes the adoption and application of digital production technology. Second, digital agricultural technology services not only guide farmers in selecting the right digital production technologies to reduce the risk of technological misuse but also alleviate income risks stemming from information asymmetry (Wei and Yang, 2022).

Digital agricultural technology service passes farm technology and information resources directly to farmers in a diversified and living way through modern communication technology, reducing the time and cost of farmers' information acquisition. Compared to traditional agricultural technology service methods, digital agricultural technology services, by shaping farmers' cognitive processes, have higher timeliness and effectiveness, enabling farmers to quickly access the latest agrarian technology knowledge and improve the technology accessibility, thus enhancing farmers' willingness to choose digital production technology. Based on the content above, this paper proposes the following hypothesis:

> *H2*: Economic cognition plays a mediating role in the influence of digital agricultural technology services on farmers' willingness to choose digital production technology.
>
> *H3*: Operational cognition plays a mediating role in the influence of digital agricultural technology services on farmers' willingness to choose digital production technology.
>
> *H4*: technology accessibility plays a mediating role in the influence of digital agricultural technology services on farmers' willingness to choose digital production technology.

4 Research design

4.1 Data source

The data used in this study come from a questionnaire survey conducted by the research group in October 2023 on farm households in Sichuan Province. Sichuan is a large agricultural province with rich and diverse agricultural industries, and occupies an important position in China's agricultural production map. In 2022, the total grain output in Sichuan was 35.105 million tonnes, accounting for 5.11% of China's grain output. The total oilseed output was 4.338 million tonnes, accounting for 11.87% of China's total oilseed output. The total fruit output was 13.805 million tonnes, accounting for 4.41% of the national total. Additionally, Sichuan produced 65.484 million pigs for slaughter, representing 9.36% of the total number of slaughtered pigs in China.

In recent years, Sichuan has witnessed rapid development in agricultural digital transformation. However, the overall level of digitization in agricultural production remains relatively low. In 2020, the overall level of digital agriculture and rural development in Sichuan Province was 38.3%, higher than the national average of 37.9% of the development level, of which the level of information technology in agricultural production in Sichuan Province is 20.02%, which is lower than the national average level (22.46%) of 2.44 percentage points (Sichuan County Agricultural and Rural Informatisation Development Level Evaluation Group, 2023).

Sichuan Province has a vast territory and complex terrain, leading to significant variations in agricultural production and digital development levels across different regions. To comprehensively reflect the situation of rural households in Sichuan Province, the research team first divided Sichuan into three regions: the Chengdu Plain area, the eastern basin hilly and low mountainous area, and the southwestern mountainous area. Secondly, to ensure the representativeness of the samples, the research team considered the levels of digital agriculture and rural development in different regions.

The research team selected cities with varying degrees of digital development from each divided area to ensure the comprehensiveness and representativeness of the research results. Based on these two principles, the research team selected Chengdu and Deyang in the Chengdu Plain area, Suining and Neijiang in the eastern basin hilly and low mountainous area, and Luzhou, Yibin, and Ya'an in the peripheral edge of the basin and the southwestern mountainous area as the study areas. In 2020, the level of agricultural informatization development in the sampled areas was as follows: Chengdu (23.59%), Deyang (12.09%), Suining (21.45%), Neijiang (13.91%), Luzhou (12.66%), Yibin (14.63%), and Ya'an (13.27%).

The data collected from the questionnaire survey encompassed details regarding the individual characteristics of farm households, household characteristics, as well as farmers' inclination towards selecting digital production technology and digital agricultural technology services. This survey collected a total of 223 questionnaires. After excluding questionnaires with missing or abnormal data, there were 214 valid responses, resulting in a questionnaire validity rate of 95.96%.

4.2 Variable definitions

Independent variable: The independent variable in this study is digital agricultural technology services, measured and characterized through

two aspects. Firstly, it involves determining whether farmers utilize digital agricultural technology services, assessed by inquiries into whether they use such services to acquire agricultural-related information. Secondly, it includes evaluating the effectiveness of digital agricultural technology services, characterized by the subjective assessment of the information obtained by farmers.

Regarding the specific measurement of digital agricultural technology services and their effectiveness, this paper draws on the experience of Mao et al. (2023). Firstly, "do you utilize digital agricultural technology services (such as WeChat groups, official accounts, or short videos) to access information related to the digitization of agricultural production (e.g., the use of digital agricultural production technology)?" To determine whether farmers use digital agricultural technology services to access information related to agriculture, the study will also evaluate their effectiveness. This will be done through the following question: "Do you think it is effective to obtain information regarding the digitalization of agricultural production through digital agricultural technology services (such as WeChat groups, official accounts, or short videos)?"

Dependent variable: The dependent variable of this paper is farmers' willingness to choose digital production technology. By asking farmers if they are willing to adopt digital production technology in crop cultivation, livestock breeding, aquaculture, seed breeding, and other agricultural production areas, values ranging from 1 to 5 points are assigned. These values represent a spectrum from" unwilling" to "very willing."

Mediating variable: In this study, we examine benefit cognition and technological accessibility as mediating variables. Benefit cognition assesses the extent to which farmers perceive the economic benefits and operational cognitions brought about by digital production technologies. On the other hand, technological accessibility measures how easily farmers perceive acquiring information related to digital production technologies.

First, theoretical analysis suggests that digital agricultural technology services can enhance farmers' benefit cognition of production digitization, thereby influencing their behavioral responses. The level of farmers' cognition of the economic benefits of the technology and their comprehension of the technology at the operational level determine the challenges farmers encounter in implementing digital production. This paper categorizes farmers' benefit cognition into economic cognition and operational cognition, respectively, utilizing questionnaires such as: "Do you believe that using digital production technology is advantageous for increasing agricultural income?" "Do you think you can fully learn, understand, and apply digital production technology?" "Do you agree that developing digital production technology is not difficult?" With higher values indicating that farmers believe that the economic effects of producing digital technology are higher.

Second, digital agricultural technology services can reduce the cost and risk of adopting digital production technologies, thus promoting farmers' willingness to choose digital production technologies. This can be measured by the questionnaire" Do you think it is easy to access information about digital production technologies?" The higher the value, the higher the accessibility of the technology.

Control variable: Referring to relevant studies (e.g., Gao et al., 2023; Mao et al., 2023; Wang et al., 2023; Yang et al., 2023). The control variables in this study mainly include the factors of individual characteristics of farm households (including the gender of the householder, age of the householder, education level of the householder, and health status of the householder), household characteristics (including household labor force, and level of an annual income of the household), management characteristics (area of cultivated land, and the number of cultivated land parcels), and other characteristics (human relations, and whether or not the household participates in specialized farmers' cooperatives). Variable definitions are shown in Supplementary Table S1.

4.3 Model structuring

4.3.1 Baseline regression model

To examine the impact of digital agricultural technology services on the willingness of farmers to choose digital production technology, the baseline regression model in this study uses Ordinary Least Squares (OLS) method of estimation, which is a classic linear regression method. Its principle is to estimate model parameters by minimizing the sum of squared residuals between the actual observed values in the data and the model's predicted values. Additionally, OLS regression coefficients can be directly interpreted as the average change in the dependent variable per unit change in the independent variable, making them intuitive and easy to understand. Furthermore, the relationships between variables may approximate linearity. OLS is capable of capturing this approximate linear relationship and providing corresponding interpretations. The Equation (1) set in this study is as follows:

$$Y_i=\alpha_0+\alpha_1 X_i+\alpha \text{Control}_i+\varepsilon_i \quad (1)$$

Where i denotes the farm household and Y_i denotes the willingness of the farm household to choose digital production technology, X_i denotes the factors affecting the willingness of the farm household to choose digital production technology, including the digital agricultural technology service and the effectiveness of the digital agricultural technology service. Control_i denotes the sample's characteristics, household characteristics, management characteristics, and other factors affecting farmers' willingness to choose digital production technologies ε_i is the error term α_0 is a constant term, α_1 , α_2 are to be estimated coefficients.

4.3.2 Mediated effect model

To further investigate the mechanism of the influence of digital agricultural technology services on farmers' willingness to choose digital production technology, this paper sets up a mediated effect model. Equations (2)–(4) are established as follows:

$$Y_i=\alpha_0+\alpha_1 X_i+\alpha \text{Control}_i+\varepsilon_i \quad (2)$$

$$M_i=\beta_0+\beta_1 X_i+\beta \text{Control}_i+\varepsilon_i \quad (3)$$

$$Y_i=\beta_0+\beta_1' X_i+\beta_2 M_i+\beta \text{Control}_i+\varepsilon_i \quad (4)$$

Where Y_i denotes the willingness of the farm household to choose digital production technology; M_i denotes the Mediating variable, including economic cognition, operational cognition and technology accessibility; β_0 is a constant term; β_1, β_1',β_2 are to be estimated coefficients.

5 Results and discussion

5.1 Descriptive statistics

Supplementary Table S1 depicts the traits of farmers and their agricultural production. A total of 214 farm households were interviewed for this study. The survey results show that 50 percent of the householders are headed by males and 50 percent by females, and they are generally older, with an average age of 46 years. The education level of the farmers was typically low, with more than 70 percent having only a junior high school education or below. In the research area, the mean value of farmers' willingness to choose digital production technology is 0.355. It is necessary to analyze further the factors affecting farmers' willingness to choose digital production technology to promote the sustainable development of digitalization of production in the appropriate areas; nearly half of the farmers have participated in digital agricultural technology activities related to digitalization of production, and the mean value of the effectiveness of the promotional activities is 3.187; the mean values of economic and operational cognition of farmers on production digitization were 3.262 and 3.150, respectively, indicating that the sample farmers in the research area have a certain degree of cognition and understanding of production digitization. The mean value of technology accessibility is 2.883, indicating that the cost of acquiring information about production digitization is relatively low. The descriptive statistics for the variables are presented in Supplementary Table S1.

5.2 Baseline regression analysis

This study utilizes Stata 17.0 for empirical analysis, the results are shown in Supplementary Table S2. The results from column (1) and (2) indicate that the use of digital agricultural technology services has a significant and positive impact on farmers' willingness to adopt digital production technologies. The results are statistically significant. Furthermore, in column (3) (4), it is found that the effectiveness of digital agricultural technology services also significantly impacts farmers' willingness to adopt digital production technologies. Specifically, farmers who acquire knowledge about digital production technologies through digital agricultural technology services demonstrate an enhanced willingness to adopt such technologies. This result validates Hypothesis 1. The underlying implication aligns with theoretical analysis: digital agricultural technology services facilitate real-time dissemination of information related to digital production technologies online, enabling farmers to learn and manage technology according to their specific needs. This facilitates visualization and two-way communication, thereby more effectively guiding farmers' adoption behaviors (Gao et al., 2023; Yang et al., 2023). This empirical evidence supports the role of digital agricultural technology services in enhancing farmers' digitalization levels.

Furthermore, the estimated results of the control variables also provide valuable insights. The participation of households in cooperatives significantly influences farmers' level of digitalization, as evidenced by the tendency of cooperative-participating farmers to adopt digital production technologies more readily. This conclusion aligns with the findings of Yang et al. (2023). One possible reason for this phenomenon could be that traditional smallholder farmers aim to maximize their overall household income. To mitigate production risks and increase agricultural income, they often maintain diversified production operations. Consequently, they may be less willing to incur higher investment costs to adopt digital production technologies. In contrast, the production focus of new agricultural entities is primarily on agriculture rather than diversification, making them more inclined to adopt new agricultural technologies. Additionally, farmers involved in new agricultural entities typically have broader channels for acquiring information and expanding social networks, which facilitates their access to information and resources concerning emerging technologies. Farmers can access technical information through industry associations, cooperatives, training courses, and other channels, which facilitates their understanding and adoption of emerging technologies.

However, farmers with more extensive land holdings are less inclined to adopt digitalization. This result contradicts common expectations. It is widely assumed that farmers with larger land holdings would be more inclined to adopt digital production technologies because such technologies can assist them in managing and utilizing large-scale farmland more effectively through data analysis, intelligent equipment, and automated processes, enhancing the quality and efficiency of agricultural production. The possible reason is that the larger the cultivated land area, the more conservative the farmers are. This could be due to the fact that the return on technology investment may not be immediately obvious, or the investment recovery period is longer. Large-scale operations will bring higher management difficulty and risk, thus inhibiting farmers' willingness to choose digital technology. It may also be due to the fact that the data for this study is only from Sichuan Province, China, which slightly compromises the representativeness of the research conclusion. Sichuan Province may have unique agricultural development, land use patterns, and characteristics of farmers. These factors may lead to the weak applicability of the conclusion in other regions.

5.3 Endogenous problem

Using digital agricultural technology services itself is a kind of farmers' behavioral decision-making. Firstly, there may be an omission problem in the selection of variables in the model, and some variables are challenging to be measured accurately (such as farmers' risk attitudes, innovation capacity). These factors can affect both digital agricultural technology services and farmers' willingness to choose digital production technologies. Secondly, there is a reverse causation problem, that is, the adoption of digital production technologies may lead to a demand for digital agricultural technology services by farmers. Considering the possible endogeneity problem, this paper further adopts the instrumental variable method for the endogeneity test. Referring to Yang et al. (2023), This paper uses the convenience of digital agricultural technology services as an instrumental variable.

Firstly, there is a strong correlation between digital agricultural technology service convenience and digital agricultural technology service. Secondly, digital agricultural technology service convenience is independent of farmers' willingness to choose digital production technology, which satisfies the exogeneity condition required for instrumental variables.

The two-stage least square method (2SLS) was adopted in this paper. The results in Supplementary Table S3 show that after controlling endogeneity, digital agricultural technology services still positively effect dependent variables, which is consistent with the results of previous studies. According to the weak instrumental variables test, the minimum eigenvalue of the first stage is greater than the critical value at the 1% bias level. The *F* values in the first stage are 40.13 and 45.23, respectively, which are bigger than the critical value of 10. This indicates that there is no issue with weak instrumental variables (Supplementary Table S3).

The economic logic of the above empirical results is reflected in two aspects. On the one hand, digital agricultural technology service is a way for the country to provide agriculture-related services to farmers by using digital promotion means, and its goal is to promote the digital transformation of agricultural production, and to become an essential force in promoting the transformation and upgrading of agriculture and realizing the development of agricultural modernization. Through digital agricultural technology services, farmers can access agricultural technology information more conveniently, thus improving their understanding of new technologies and accelerating the practical application of agricultural science and technology achievements. This approach not only takes advantage of digitalization and enhances the efficiency of information transfer, but also helps promote the development of digital agriculture and the modernization of agricultural production.

On the other hand, the spread of the Internet in rural areas and the use of information tools such as mobile phones have significantly reduced the cost of information access for farmers, increased their exposure to new agricultural technologies, and strengthened their understanding of market needs. The externality of this information transmission provides farmers with a basis for more scientific decision-making.

5.4 Mediating effects

Farmers usually consider several factors when deciding whether to choose digital production technology, This paper explores the indirect mechanism by which digital agricultural services influence farmers' willingness to adopt digital production technology. It examines this phenomenon from the perspectives of economic cognition, operational cognition, and technological accessibility, building upon the significant positive effect that digital agricultural technology services have on farmers' willingness to adopt digital production technology. Based on this, this paper uses the Stepwise Regression Method to verify the above three action paths, and the results are shown in Supplementary Table S4.

5.4.1 Economic cognition

In Supplementary Table S4, the estimation results in columns (9), (10), (15), and (16) indicate that economic cognition mediates the relationship between digital agricultural technology services and farmers' willingness to adopt digital production technologies. Regression results from columns (9) and (10) reveal that digital agricultural technology services are statistically significant, with a positive estimated coefficient, indicating a significant positive impact of these services on economic cognition. Similarly, regression results from columns (15) and (16) show that the effectiveness of digital agricultural technology services also significantly and positively influences farmers' economic cognition regarding digital production technologies, thereby enhancing farmers' willingness to adopt such technologies through economic cognition. This mechanism is confirmed.

Empirical findings suggest that digital agricultural technology services disseminate relevant information related to production material procurement, market sales, technical learning, meteorological content, and other aspects to many farmers through various platforms, thereby enhancing farmers' economic cognition and increasing their expectations of economic returns. It provides a basis for farmers' decision-making regarding adopting digital production technologies (Gao et al., 2023). Thus, research hypothesis H2 is supported.

5.4.2 Operational cognition

The estimation results in columns (11), (12), (17), and (18) of Supplementary Table S4 show the mediating role of operational cognition. Firstly, model (11) is set to analyze whether digital agricultural technology services enhance or reduce operational cognition. From the results in column (11), it's evident that digital agricultural technology services can improve farmers' operational cognition of digital production technology. The results in column (12) show that by introducing the variable of operational cognition, digital agricultural technology services still significantly and positively affect their willingness to choose digital production technology, and the results pass the significance tests of 1%. When farmers think it is easy to adopt digital production technology, their willingness to choose digital production technology increases. The results in columns (17) and (18) show that the effectiveness of digital agricultural technology promotion positively influences farmers' operational cognition. According to the results, operational cognition plays a partial mediating role in the relationship between digital agricultural technology services and farmers' willingness to choose digital production technology. Hypothesis H3 is confirmed.

Farmers access various types of information through digital agricultural technology services, including information obtained from websites, blogs, social media, and mobile applications. By sharing agricultural information, farmers can enhance their operational awareness, understand the diverse needs and specific operations of current agricultural technology services, stay updated on the latest trends, and efficiently carry out production tasks (Steinke et al., 2019).

5.4.3 Technology accessibility

Columns (13), (14), (19), and (20) present the results of tests with technology accessibility as the mediating variable. Column (13) analyzes whether digital agricultural technology services enhance or reduce technology accessibility. Based on the findings presented in column (12), it is evident that digital agricultural technology services contribute to enhancing technology accessibility. From the results in column (14), it can be found that after introducing the variable of technology accessibility, digital agricultural technology services still have a significant positive effect on farmers' willingness to choose

digital production technology, and technology accessibility has a significant positive impact on farmers' willingness to choose digital production technology.

This result indicates that there is a mechanism by which digital agricultural technology services promote farmers' willingness to choose digital production technology through increased technological accessibility. Hypothesis H4 is supported. Digital agricultural technology services utilize tools such as mobile phones and computers to broaden access to various sources of information (Yang et al., 2019), optimize the allocation of agricultural technology resources (Osman et al., 2020), reduce the difficulty of information acquisition, thereby lowering the cost of technology acquisition, and increasing technological accessibility. The increased technology accessibility reduces the entry barrier for farmers to adopt digital tools and services, thereby promoting their enthusiasm for choosing digital production technology. It is also conducive to the widespread promotion of digitization in agricultural production.

5.5 Heterogeneity analysis; based on different digital literacy

Digital literacy refers to an individual's comprehensive ability to discover, access, evaluate, integrate, and communicate information quickly and effectively in a digital environment using Internet information technology tools (Mao et al., 2023). The digital literacy of farmers is increasingly critical in the process of digitalizing their production response. Drawing on Mao et al. (2023), this paper examines whether digital agricultural technology services have varying effects on the selection of digital production technologies among farmers with different levels of digital literacy. The importance of the Internet to farmers is utilized as a measure of their digital literacy.

Farmers with high levels of digital literacy are likely to have stronger skills acquisition and application capabilities. They can understand and apply digital production technologies more efficiently and integrate more quickly into the technical training and information sharing provided by digital agronomic services. Conversely, farmers with lower levels of digital literacy may require additional training and support to effectively utilize digital agricultural technology services.

Secondly, the level of digital literacy also affects farmers' ability to access and process information. Farmers with high digital literacy are better at acquiring and processing digital information. They can better understand and assess the advantages and disadvantages of different digital production technologies, making informed choices accordingly. Farmers with lower digital literacy may struggle to understand and apply digital information, making them less receptive to digital production technologies.

Implementing digital agricultural technology services necessitates specific resources and facility support, including internet connectivity and smart devices. Farmers with high digital literacy are more likely to possess the capability to access and utilize these facilities and resources, thereby increasing their likelihood of adopting digital production technologies. A key aspect is the capacity of such services to mitigate the limited comprehension of technology applications and the constraints related to information resources when adopting new technologies, particularly in the selection of digital production technologies.

It is deduced that farmers possessing higher digital literacy are more inclined to utilize digital agricultural technology services to their full extent, consequently exerting a more pronounced positive influence on their preference for digital production technologies. To further validate this inference, the paper categorizes the sample into high and low digital literacy groups based on their responses to the questionnaire regarding the importance of the Internet. Subsequently, group regression analysis is conducted, and the results are presented in Table 1.

In this paper, the sample farmers is divided into two groups, and the Seemingly Unrelated Regressions (SUR) test is applied to control for possible correlations between different samples. Models (21) and (23) in Table 1 demonstrate that digital agricultural technology services significantly influence the willingness of farmers with high digital literacy, with Chow test F statistics of 4.22 and 4.71, respectively. The results indicate that the impact of digital literacy on the willingness of farmers to choose digital production technologies is more significant when farmers with high digital literacy are using digital agricultural technology services.

5.6 Robustness checks

To ensure the robustness of the previous regression results, this paper replaces the dependent variable in the robustness test. Specifically, the willingness to choose digital production technology

TABLE 1 Heterogeneous responses by digital literacy.

Variable	High-digital literacy farmers (21)	Low-digital literacy farmers (22)	High-digital literacy farmers (23)	Low-digital literacy farmers (24)
Digital agricultural technology services	0.359** (0.172)	0.235 (0.172)		
Digital agricultural technology service Effectiveness			0.280** (0.120)	0.546*** (0.137)
Control variable	Yes	Yes	Yes	Yes
Sample size	78	136	78	136
R^2	0.065	0.150	0.092	0.266
Chow test F statistics	4.22***		4.71***	

*, ** and *** indicate significance at the10, 5 and 1% levels, respectively. Robust standard errors are in parentheses.

in the baseline regression is substituted with the question, "Are you willing to take the initiative to learn technology and knowledge about digital production and then carry out digital production?" The equation represents a regression of whether or not to use digital agricultural technology services on the willingness to engage in digital production according to standard scientific practices. The results, significant at the 1% statistical level, reveal a positive estimated coefficient, indicating that using digital agricultural technology services can enhance farmers' inclination towards digital production with standard scientific methods. These findings align with those obtained from the baseline regression. The results are presented in Table 2.

6 Discussion

Digital agricultural technology services and their effectiveness can positively influence farmers' willingness to adopt digital production technology, primarily by impacting farmers' economic cognition, operational cognition, and technological accessibility. The influence of digital agricultural technology services varies among farmers with different levels of digital literacy. Existing research suggests that digital agricultural technology services are a vital factor influencing farmers' adoption behavior (Cunguara and Darnhofer, 2011). Digital agricultural technology services serve as a new driving force for agricultural modernization, playing a crucial role in helping farmers learn about new agricultural technologies, adjusting their livelihood decisions, and optimizing resource allocation (Shen, 2019).

From a theoretical standpoint, digital agricultural technology services not only reduce information search time (Steinke et al., 2019) but also enhance flexibility in technology application, providing comprehensive support for farmers to master new agricultural technologies (Tadesse and Bahiigwa, 2015). Farmers utilize digital agricultural technology services to communicate with the outside world, improving their decision-making grasp before technology selection and their ability to exchange information during the technology selection process, thereby reducing information negotiation costs.

Empirically, existing research has only analyzed the impact of digital agricultural technology services on farmers' adoption of green production technology using fruit tree planters as an example (Gao et al., 2023), as well as the analysis of the impact of digital agricultural technology services on farmers' adoption of rice-prawn cropping patterns (Yang et al., 2023). Most studies remain at the theoretical level and require further empirical confirmation. Moreover, there is a lack of in-depth investigation into the impact of digital agricultural technology services on the digitization of agricultural production.

TABLE 2 Robustness check.

Variable	Model(25)	Model(26)
Digital agricultural technology services	0.509*** (0.125)	
Digital agricultural technology service Effectiveness		0.503*** (0.088)
Control variable	Yes	Yes
sample size	214	214
R^2	0.153	0.266

*, ** and *** indicate significance at the10, 5 and 1% levels, respectively. Robust standard errors are in parentheses.

This study conducted supplementary research based on existing literature, exploring the influence of digital agricultural technology services on farmers' willingness to adopt digital production technologies, and validated relevant inferences using field survey data. Firstly, through the analysis of micro-level farmer data, a deeper understanding of digital agricultural technology services was gained, providing a more comprehensive understanding of literature in related fields. Secondly, previous studies lacked in-depth research on the effectiveness of digital agricultural technology services for farmers. However, in reality, the effectiveness of these services directly impacts farmers' choices of production technologies, which also holds more direct economic significance.

The results of this study indicate that utilizing digital agricultural technology services and the higher effectiveness of theseservices will encourage farmers to choose digital production technology. Digital agricultural technology services providedigital agricultural consultation, technical training, and online support for farmers. This helps farmers understand and master the operational methods and application scenarios of digital technology, improving their technical acceptance and accessibility. Moreover, effective digital agricultural technology services can enhance farmers' production efficiency and agricultural income. Through precise management and intelligent decision support of digital technology, farmers can optimize the processes of planting, breeding, and management. This can help reduce resource wastage, improve yield and quality, and ultimately lead to better economic returns.

Furthermore, digital agricultural technology services promote information sharing and social influence among farmers. When farmers observe their peers succeeding in adopting digital technology and sharing their experiences and cases through digital agricultural technology services, they may feel more motivated and confident to try and adopt similar digital production technologies. This practical guidance has been beneficial for farmers.

The research conclusion also shows that farmers who engage in new agricultural entities are often more willing to adopt emerging technologies. Farmers who engage in new agricultural entities usually have broaderaccess to information and social networks. They may face greater economic motivation and competitive pressure, so they need to improve production efficiency and reduce costs to maintain their competitive advantage. Therefore, farmers are more willing to adopt emerging technologies to cope with market competition and improve agricultural management efficiency. In addition, digital agricultural services have a greater impact on farmers with high digital literacy. The reasons may include their better technical understanding and application ability, higher technical acceptance and willingness to adopt, wider information acquisition channels and social networks, stronger self-learning and adaptability, and higher technological innovation ability.

These conclusions also provide a basis for the government to formulate relevant policies. The government is enhancing policy formulation by focusing on improving the supply of digital agricultural technology services, empowering new agricultural entities, enhancing farmers' digital literacy training, and improving the policy support system.

The conclusion of this study not only offers practical guidance and policy suggestions for farmers and the government but also provides an important feedback mechanism for technology providers. Through

research results, technology developers can gain a deep understanding of farmers' demands and feedback on digital technology, enabling them to adjust and update their technical products promptly. This two-way feedback mechanism can not only promote the continuous improvement and innovation of digital technology but also better meet the actual needs of farmers, thereby fostering the modernization and intelligent development of agricultural production.

The article has certain limitations. Firstly, it employs cross-sectional data to study the impact and efficacy of digital agricultural technology services, whereas utilizing panel data could better address potential endogeneity issues within the model. Therefore, in future research, the research group will consider conducting a follow-up survey on the investigated farmers and collecting panel data to further expand the research on the factors influencing farmers' willingness to adopt digital production technology. Secondly, the samples in this paper are all from Sichuan Province, China. The agricultural production situations vary significantly across different countries and regions, which may compromise the representativeness of the research conclusions. In future research, the scope of expanded samples can be further broadened to investigate the impact of digital agricultural technology services. Thirdly, the measurement methods of digital agricultural services in this paper are not comprehensive enough. Subsequent research could consider incorporating additional indicators such as the service life of digital agricultural services for farmers and the significancethey attribute to these services. This would enhance the measurement of digital agricultural services and their effectiveness.

7 Conclusion and policy implications

7.1 Conclusion

In the context of today's rapid development of new media, digital agriculture is developing at a high speed. Farmers are increasingly inclined to use digital platforms such as WeChat, mobile applications (apps), and websites to access agricultural technology services. Digital platforms have become one of the primary ways for farmers to obtain agricultural information. Developing and perfecting digital agricultural technology services is of great practical significance in addressing the issues of farmers' low willingness to adopt digital production technology, inadequate ability to utilize digital production technology, and ineffective digital development of agricultural production. Existing research has already demonstrated that digital agricultural technology services can broaden farmers' information channels and reduce the costs associated with adopting technology. However, current studies often focus more on the impact of digital agricultural technology services on farmers' selection of green production technologies, with little discussion on their influence on the digitization of agricultural production and the adoption of digital production technologies. Furthermore, there is a lack of exploration into the theoretical mechanisms underlying these phenomena.

Based on this, this paper analyses the impact of digital agricultural technology services on farmers' willingness to choose agricultural digital production technology and its mechanism of action through a questionnaire survey of 214 households in Sichuan Province. The findings of this study offer a panoramic view of how digital agricultural technology services facilitate the digitization of agricultural production.

Firstly, the research findings indicate that digital agricultural technology services significantly promote farmers' willingness to adopt digital production technologies, with significant statistical significance. Furthermore, by selecting the convenience of promoting digital agricultural technology services as an instrumental variable, the study maximally addresses endogeneity issues caused by neglecting certain variables or misalignment of causality, thus ensuring the robustness of the core conclusions.

Secondly, the willingness of farmers to adopt digital production technologies is primarily enhanced by digital agricultural technology services through three pathways: enhancing economic cognition, operational cognition, and technological accessibility. Empirical tests confirm the validity of these three hypotheses, forming the primary mechanism through which digital agricultural technology services influence farmers' willingness to adopt digital production technologies.

Finally, the impact of digital agricultural technology services on farmers with different levels of digital literacy exhibits specific heterogeneity, with a more significant effect observed among farmers with higher digital literacy when using digital agricultural technology services to influence their willingness to adopt digital production technologies.

This research has significantly contributed to the existing literature by providing a detailed micro-data analysis on the subject, improving understanding of the topic. It also serves as a valuable resource for advancing digital agricultural technology services to facilitate the digital transformation of agricultural practices. The data not only benefit farmers by providing practical insights but also assist governments in shaping agricultural policies. The findings of this study can guide policymakers in implementing more impactful measures, leading to overall enhancements in the agricultural industry. The implications of this research extend beyond China and hold universal relevance and practical value for agricultural agencies worldwide.

7.2 Policy implications

Based on empirical research, this article proposes the following policy recommendations to promote farmers' adoption of digital production technologies and enhance the level of digitalization in agricultural production:

First, Governments and relevant institutions should intensify efforts to promote and popularize digital agricultural technology services. It includes accelerating investment in digital infrastructure in rural areas, such as high-speed internet access and communication networks, to ensure that farmers can access digital agricultural technology services and tools, thereby reducing barriers to technology acquisition.

Second, Governments should strengthen the ability to adapt the supply and demand of digital agricultural technology services. Firstly, we need to accurately grasp the demand characteristics of different farmers for digital agricultural technology services and promptly innovate services with more targeted approaches. Secondly, the government needs to adjust the provision of digital agricultural technology services according to the digitalization level and resource distribution of farmers in different regions, and implement service innovation based on regional characteristics.

Third, Governments should actively leverage the advantages of new agricultural business entities such as rural cooperatives and launch digital literacy training programs. These programs can cover basic digital skills such as computer usage, Internet browsing, email, and basic knowledge of social media, helping farmers master basic digital skills and operational cognition, making it easier for them to use digital agricultural technology tools.

Fourth, Governments should establish sound monitoring and evaluation mechanisms, strengthen the review of agricultural technology services published on internet platforms, and improve the accuracy and effectiveness of digital agricultural technology services. Tracking the effects of digital agricultural technology services, promptly identifying problems, and rectifying them is essential.

Fifth, Governments should improve the policy support system and actively play a leading role in establishing a sound policy environment. While adhering to the overall direction of the rural digitalization policy, it is necessary to focus on optimizing various related sub-policies and promote corresponding changes in the fields of "agriculture, rural areas, and farmers" through careful adjustments. Additionally, local governments should formulate more specific and flexible policies based on the development status of local digital agricultural technology services and the actual needs of farmers, which helps enhance the adaptability, targeting, and effectiveness of policy instruments, ensuring the practical and effective implementation of digital agricultural technology service policies.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the [patients/ participants OR patients/participants legal guardian/next of kin] was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

WG: Formal analysis, Methodology, Software, Visualization, Writing – original draft. RM: Conceptualization, Investigation, Project administration, Validation, Visualization, Writing – original draft. HZ: Funding acquisition, Methodology, Project administration, Resources, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. National Social Science Fund Project "Innovative Research on Social Policies to Support the livelihood of agricultural Migrant Population in Ethnic minority Areas" (23BSH035); National Social Science Fund Project "Research on Building Long-term Mechanism of Cultivated Land Cultivation Use Control under Food Security Goal" (23XJY006); Sichuan Science and Technology Plan Project "Research on Building a Higher Level 'Tianfu Granary' in a New Era" (2023JDR0111); University students innovation and entrepreneurship provincial project "Research on farmer Response and Promotion Mechanism of Digitalization of Agricultural Production -- Based on research in Sichuan Province" (S202310626095).

Acknowledgments

The authors gratefully acknowledge Xingduan Du, an outstanding researcher from Sichuan Academy of Agricultural Sciences for his valuable suggestions and discussions.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2024.1401316/full#supplementary-material

References

Aker, J. C. (2011). Dial "a" for agriculture: a review of information and communication technologies for agricultural extension in developing countries. *Agric. Econ.* 42, 631–647. doi: 10.1111/j.1574-0862.2011.00545.x

Aker, J. C., and Mbiti, I. (2010). Mobile phones and economic development in Africa. *J. Econ. Perspect.* 24, 207–232. doi: 10.1257/jep.24.3.207

Bacco, M., Barsocchi, P., Ferro, E., Gotta, A., and Ruggeri, M. (2019). The digitisation of agriculture: a survey of research activities on smart farming. *Array* 3-4:100009. doi: 10.1016/j.array.2019.100009

Bahinipati, C. S., Kumar, V., and Viswanathan, P. K. (2021). An evidence-based systematic review on farmers' adaptation strategies in India. *Food Security,* 13, 399–418.

Barakabitze, A. A., Fue, K. G., and Sanga, C. A. (2017). The use of participatory approaches in develo** ICT-based systems for disseminating agricultural knowledge and information for farmers in develo** countries: the case of Tanzania. *Electr. J. Inform. Syst. Dev.* 78, 1–23.

Barnes, A. P., Soto, I., Eory, V., Beck, B., Balafoutis, A., Sánchez, B., et al. (2019). Exploring the adoption of precision agricultural technologies: a cross regional study of EU farmers. *Land Use Policy* 80, 163–174. doi: 10.1016/j.landusepol.2018.10.004

Castiblanco Jimenez, I. A., Cepeda García, L. C., Marcolin, F., Violante, M. G., and Vezzetti, E. (2021). Validation of a TAM extension in agriculture: exploring the determinants of acceptance of an e-learning platform. *Appl. Sci.* 11:4672. doi: 10.3390/app11104672

Chen, J., and Xiong, L. G. (2022). Research on the connotation, role mechanism, challenges, and promotion path of digital agriculture. *Southwest Finance* 10, 92–102.

Chen, K., Ye, M. H., and Wang, T. J. (2022). How do digital financial services affect the development of agricultural insurance?--empirical evidence from 24 major agricultural provinces. *Lanzhou J.* 4, 64–78.

Cunguara, B., and Darnhofer, I. (2011). Assessing the impact of improved agricultural on household income in rural Mozambique. *Food Policy* 36, 378–390. doi: 10.1016/j.foodpol.2011.03.002

Davis, F. D. (1989). Perceived usefulness, perceived ease of use, and user acceptance of information technology. *MIS Q.* 13, 319–340. doi: 10.2307/249008

Du, Y. H. (2023). Digital transformation path of the whole agricultural industry chain based on China's national conditions. *China Circul. Econ.* 37, 36–48. doi: 10.14089/j.cnki.cn11-3664/f.2023.12.004

Elias, A., Nohmi, M., Yasunobu, K., and Ishida, A. (2016). Farmers'Satisfaction with agricultural extension S ervice and its influencing factors: A case study in north West Ethiopia. *Appl. Econ. Perspect. Policy* 18, 39–53.

Fishbein, M., and Ajzen, I. (1977). Belief, attitude, intention and behaviour: an introduction to theory and research. Addison-Wesley, Reading MA. *Philos. Rhetor.* 41, 842–844.

Fu, X., and Akter, S. (2016). The impact of mobile phone technology on agricultural extension services delivery: evidence from India. *J. Dev. Stud.* 52, 1561–1576. doi: 10.1080/00220388.2016.1146700

Gao, T. Z., Feng, H., and Lu, Q. (2023). Did digital agrotechnology extension services promote farmers' green production technology choices - based on micro-survey data from three provinces in the Yellow River Basin. *Agric. Technol. Econ.* 9, 23–38. doi: 10.13246/j.cnki.jae.20220425.001

Gu, J., Zou, Y., and Wang, J. F. (2013). Application status and development countermeasures of modern information technology in the transforming of agricultural scientific and technological achievements in China. *Southern Agric. J.* 44, 1746–1750.

Guo, G. (2021). "Digital" agriculture for rural revitalization. *Coop. Econ. Technol.* 23, 38–39. doi: 10.13665/j.cnki.hzjjykj.2021.23.014

Guo, Y. N., Li, S. P., and Zhang, J. (2018). From willingness to behaviour: the impact of information access on farmers' pro-environmental behaviour. *Ecol. Econ.* 34, 191–196.

Hübler, M., and Hartje, R. (2016). Are smartphones smart for economic development? *Econ. Lett.* 141, 130–133. doi: 10.1016/j.econlet.2016.02.001

Jensen, R. (2007). The digital provide: information (technology), market performance, and welfare in the south Indian fisheries sector. *Q. J. Econ.* 122, 879–924. doi: 10.1162/qjec.122.3.879

Li, Q. R. (2022). Development strategy of digital agriculture in the context of rural revitalization. *Agric. Econ.* 10, 17–18.

Li, Q., and Xiao, Z. Y. (2023). Practical exploration and mechanism innovation of digital transformation of agricultural production - a typical case analysis based on Zhejiang. *J. Jiangnan Univ.* 22, 64–76.

Liu, C., and Fu, L. (2020). Research on information technology, data elements and modernisation of rural governance system and governance capacity. *J. Jiangnan Univ.* 19, 67–76.

Ma, W., Nie, P., Zhang, P., and Renwick, A. (2020). Impact of internet use on economic well-being of rural households: evidence from China. *Rev. Dev. Econ.* 24, 503–523. doi: 10.1111/rode.12645

Mao, H., Liu, S. W., Peng, P., et al. (2023). Digital extension and Farmers' Fertiliser reduction-an empirical analysis from the Main apple producing areas in Shaanxi Province. *China Rural Econ.* 2, 66–84. doi: 10.20077/j.cnki.11-1262/f.2023.02.006

Mwangi, M., and Kariuki, S. (2015). Factors determini ing adoption of new agricultural technology by smallholder farmers in developing g countries. *J. Econ. Sustain. Dev.* 6:5.

Niu, S. Q. (2023). Comprehensive considerations and promotion strategies for developing digital agriculture in China in the context of rural revitalisation. *J. Mudanjiang Univ.* 32, 8–16. doi: 10.15907/j.cnki.23-1450.2023.07.010

Norton, G. W., and Alwang, J. (2020). Changes in agricultural extension and implications for farmer adoption of new practices. *Appl. Econ. Perspect. Policy* 42, 8–20. doi: 10.1002/aepp.13008

Nugraha, A. T., and Osman, N. H. (2017). The energy-economic growth Nexus in Indonesia. *J. Bus. Manag. Account.* 7, 61–75. doi: 10.32890/jbma2017.7.2.8819

Osman, T. D., Ansahb, I. G. K., Donkohb, S. A., Mullinsd, K. Y., Taylorf, M. S., Tettehb, B. K. D., et al. (2020). Effects of technology dissemination approaches on agricultural technology uptake and utilization in northern Ghana. *Technol. Soc.* 62:101294. doi: 10.1016/j.techsoc.2020.101294

Schultz, T. W. (1964). Transforming traditional agriculture. New Haven: Yale University Press.

Shen, F. W. (2019). Research on the multiple synergistic model of agricultural science and technology extension services--experience of developed countries and inspiration for China. *Econ. Syst. Reform* 6, 172–178.

Sichuan County Agricultural and Rural Informatisation Development Level Evaluation Group (2023). "Report on digital agriculture and rural development in Sichuan counties in 2021" in Sichuan digital economy development report (2023). eds. K. Houquan and L. Yangchun (Beijing: Social Science Literature Press), 270–294.

Steinke, J., Achieng, J. O., Hammond, J., Kebede, S. S., Mengistu, D. K., Mgimiloko, M. G., et al. (2019). Household-specific targeting of agricultural advice via mobile phones: feasibility of a minimum data approach for smallholder context. *Comput. Electron. Agric.* 162, 991–1000. doi: 10.1016/j.compag.2019.05.026

Sukma, N., and Leelasantitham, A. (2022). Understanding online behavior towards community water user participation: a perspective of a develo** country. *PLoS One* 17:e0270137. doi: 10.1371/journal.pone.0270137

Swanson, B. E., Bentz, R. P., and Sofranko, A. J. (1972). Improving agricultural extension: a reference manual. *Agric. Educ.* 374.

Tadesse, G., and Bahiigwa, G. (2015). Mobile phones and farmers' marketing decisions in Ethiopia. *World Dev.* 68, 296–307. doi: 10.1016/j.worlddev.2014.12.010

Torero, M., and Von Braun, J. (Eds.). (2006). *Information and communication technologies for development and poverty reduction: The potential of telecommunications*. Intl Food Policy Res Inst.

Utami, C. W., Indrianto, A. T. L., and Pratama, I. (2019). Agricultural technology adoption in Indonesia: The role of the agriculture extension service, the rural financing and the institutional context of the lender.

Van Campenhout, B., Vandevelde, S., Walukano, W., and Van Asten, P. (2017). Agricultural extension messages using video on portable devices increased knowledge about seed selection, storage and handling among smallholder potato farmers in southwestern Uganda. *PLoS One* 12:e0169557. doi: 10.1371/journal.pone.0169557

Verma, P., and Sinha, N. (2018). Integrating perceived economic wellbeing to technology acceptance model: the case of mobile based agricultural extension service. *Technol. Forecast. Soc. Chang.* 126, 207–216. doi: 10.1016/j.techfore.2017.08.013

Wang, J. X., Luo, X. F., Tang, L., et al. (2023). Online versus offline: the influence of agricultural extension methods on farmers' biopesticide application behaviour. *China Agric. Resour. Zoning* 44, 43–53.

Wei, B. B., and Yang, Z. H. (2022). Government extension, relational networks and Farmers' adoption behaviour of ecological farming technology. *Chin. J. Ecol. Agric.* 30, 2036–2049.

Wen, T., and Chen, Y. M. (2020). Integrated development of digital economy and agricultural and rural economy: practice mode, realistic obstacles and breakthrough path. *Probl. Agric. Econ.* 7, 118–129.

Yang, X. J., Qi, Z. H., and Yang, C. Y. (2023). Do public agrotechnology extension and digital agrotechnology services promote farmers' adoption of rice-shrimp co-cropping model. *Agric. Technol. Econ.* 1–17. doi: 10.13246/j.cnki.jae.20230613.004

Yang, X. J., Qi, Z. H., Yang, C. Y., et al. (2021). Can new agricultural management entities promote the popularization of ecological agricultural technologies?- a case study of rice-crab co-culture technology. *Resour. Environ. Yangtze Basin* 30, 2545–2556.

Yang, G., Zhao, D., and Yu, L. (2019). Influence of a new agricultural technology extension mode on Farmers'Technology adoption behavior in China. Haoran Yang. *J. Rural. Stud.* 76, 173–183. doi: 10.1016/j.jrurstud.2020.04.016

Zeng, X. Y., and Qi, H. Q. (2020). Mechanism and structural effects of digital financial development on agricultural output. *Guizhou Soc Sci.* 371, 162–168.

Zhan, J., and Wang, X. Y. (2023). Behavioural intention and Behavioural response of Farmers' participation in digital finance-an empirical study based on 676 Farmers' survey data in Hunan Province. *Res. World* 1, 70–79.

Zhang, Y. Y., and Zhang, Z. J. (2016). Bias analysis of Farmers' outsourcing demand willingness and choice behaviour in production segment-empirical evidence based on Rice production data in Jiangsu and Jiangxi provinces. *J. Huazhong Agric. Univ.* 2, 9–14.

Zhou, S. D., and Li, X. Z. (2021). Farmer characteristics, external environment and scientific fertiliser application. *J. South China Agric. Univ.* 20, 50–58.