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The influence of household head's skill level and digital agricultural outreach on farmers' adoption of conservation tillage technology: an empirical study based on northwestern China

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Introduction: In the digital economy era, aligning farmers' skill levels with advanced technologies is crucial for advancing agricultural informatization, and exploring the interaction between skill levels and digital promotion holds important policy value for optimizing conservation tillage technology extension strategies.
Methods: This study utilizes survey data from 487 farm households in Shanxi and Shaanxi provinces, which are important melon and fruit-producing regions in Northwest China, constructs a composite skill index, and employs a binary probit model to examine the impact of skill levels and digital promotion on the adoption of conservation tillage technologies.
Results: The findings show that higher skill levels significantly increase the adoption probability of subsoiling, integrated pest management (IPM), and organic fertilizer application. In terms of digital tools, mobile phone usage significantly promotes the adoption of subsoiling, IPM, and organic fertilizer, while computer usage only has a significant impact on organic fertilizer adoption. Additionally, digital promotion plays an intermediary role in the relationship between skill levels and technology adoption, and there is a substitution effect between mobile phone and computer usage in promoting the adoption of IPM, organic fertilizer, and straw mulching.
Discussion and insights: These results provide policy insights: differentiated promotion of digital tools based on their functional characteristics, targeted support for elderly farmers to bridge the digital divide and strengthened synergy between skills and digital tools can effectively enhance the penetration of conservation tillage technologies, which is of great significance for advancing agricultural green development and narrowing the urban-rural digital gap.

KEYWORDS
skill level, digital agricultural outreach, conservation tillage technology, mediation effect, substitution effect

1 Introduction

Under the impact of global warming, ecological disasters, particularly sandstorms in the central and western regions of China, have become increasingly frequent (Huo et al., 2025). These events have resulted in significant soil erosion and sandstorm hazards, thereby threatening agricultural production, air quality, and daily life (Ito et al., 2007). Concurrently, China faces challenges due to its large population and limited arable land. The long-term practice of "heavy use and light maintenance" of cultivated land has led to a continuous decline in both the quantity and quality of available land, as well as a deterioration of agricultural and rural water and soil resources (Chen et al., 2023). Conservation tillage technology represents a modern system for risk prevention and the improvement of cultivated land quality (Giovanni et al., 2016; Tufa et al., 2023). This approach emphasizes reduced tillage and fallow periods, sub-soiling, the application of organic fertilizers, and the use of straw mulching on the surface of cultivated land. The primary objective of conservation tillage is to address climate change, mitigate the risks associated with natural disasters, and improve the quality of cultivated land and the ecological environment (Schoengold et al., 2015). This is achieved by reducing sowing, recycling livestock and poultry waste, and utilizing crop straw to cover the surface of cultivated land, which in turn increases soil nutrients, decreases soil humification, improves soil compaction, and ultimately improves the yield and quality of agricultural products (Kosmas et al., 2001; Chen et al., 2011). Additionally, this method aims to reduce costs and consumption in agricultural production (Qiu et al., 2020). Since 1960, China has begun to introduce conservation tillage technology, successively carried out experiments and demonstrations, and issued a series of policy documents to promote conservation tillage technology, such as the "Conservation Tillage Project Construction Plan (2009–2015)" and "Key Technologies of Conservation Tillage," which have enabled conservation tillage technology to be widely applied and the area of technology adoption has expanded over the years. According to the "China Agricultural Machinery Industry Review" in 2020, the area dedicated to conservation tillage in China was 9.333 million hectares, ac-counting for only 7.5% of the total cultivated land area in the country. This represents a year-on-year increase of 1.12% compared to 2019. However, it remains significantly lower than the application levels observed in developed countries such as the United States and Canada, indicating that conservation tillage in China is still in its nascent stages.

Recently, the academic community has conducted extensive research on the adoption of conservation tillage technology among micro-households. Key factors affecting households' adoption of this technology include individual farmer characteristics, family dynamics, production and operational attributes, as well as external environmental conditions (Yu et al., 2025; Wang et al., 2025; Ngoma et al., 2021). Qiu et al. (2020) suggested that the age and educational attainment of the household head positively affect the adoption of conservation tillage technology. Yu et al. and Liu et al. demonstrated that factors such as the area of family cultivated land, income levels, and social capital are significant determinants in the adoption of conservation tillage technology (Tufa et al., 2023; Liu et al., 2021). Additionally, numerous studies focused on the effects of external environmental factors, including government support, industrial organizations, and environmental regulations, on households' adoption of conservation tillage technology (Liu et al., 2021; Miao et al., 2025). However, existing studies still have certain limitations at the methodological level. In terms of sample selection, most studies take major grain crop planting areas as the main research objects, with insufficient attention paid to major producing areas of characteristic cash crops (such as melon and fruit planting areas in northwestern China). Due to the particularities of crop characteristics and ecological environments in these regions, their logic of technology adoption may differ significantly from that in grain-producing areas (Qiu et al., 2020; Yu et al., 2025; Wang et al., 2025; Ngoma et al., 2021). In terms of variable measurement, the investigation of "household head's skill level" mostly focuses on a single dimension (such as educational level or non-agricultural work experience), failing to construct a comprehensive evaluation system covering knowledge reserves, practical abilities, social experience, and other multi-dimensional aspects, which leads to an incomplete portrayal of skill levels. This simplified measurement method may mask the internal interactions among skill elements, making it difficult to accurately reveal the mechanism of their impact on technology adoption. Farmers, as independent decision-makers, have the final decision-making power in the adoption of agricultural technologies and are the core subjects in the decision-making and promotion process. Within a single household, agricultural production management and decision-making largely depend on the personal skill level of the household head. Improving these skill levels can not only enhance the quality of agricultural practitioners but also cultivate the innovative spirit necessary to promote the advancement of agricultural production management and rural development, thereby contributing to the improvement of traditional agricultural production methods and the increase of agricultural production efficiency. Existing studies have examined the impact of household heads' skill levels on the adoption of conservation tillage technology from a single perspective, such as educational level or work experience (Gould et al., 1989; Dai et al., 2023), but they have neglected the role of household heads' comprehensive skill levels, and the specific impact mechanisms remain to be further explored. Therefore, this study takes melon and fruit growers in northwestern China as the research object and constructs a comprehensive skill index covering formal education, informal education, government service experience, migrant work experience, and farming experience. It aims to make up for the deficiencies of existing studies in terms of sample representativeness and the refinement of variable measurement, and provide a new analytical perspective for understanding technology adoption behavior in characteristic agricultural areas. Furthermore, with the emergence of the digital economy, the digital agricultural technology promotion model (i.e., "Internet + technology promotion") is progressively overcoming the temporal and spatial limitations of traditional agricultural technology dissemination (Qin et al., 2022). This model is expanding the scope of agricultural socialized services and is becoming a crucial driver of agricultural modernization. On one hand, digital agricultural promotion can mitigate information asymmetry in agriculture by providing households with management strategies related to the latest conservation tillage technology and pertinent market price information, thereby reducing the costs associated with information acquisition (Higgins and Bryant, 2020; Silvestri et al., 2021). On the other hand, digital platforms can offer households access to diverse agricultural technologies and knowledge, facilitating updates to their agricultural management concepts and methodologies (Silvestri et al., 2021; Sun and Xiang, 2024). However, the rapid evolution of digital agricultural out-reach, driven by developments in the scientific and technological revolution, necessitates a higher skill level among individuals. Given that current agricultural operators tend to be older and possess lower educational qualifications, the mismatch between individual skills and digital agricultural outreach impedes the diffusion of new technologies (Chetty et al., 2018; Van Laar et al., 2020; Zhang et al., 2022), thereby affecting the adoption rate of conservation tillage technology.

In summary, while existing research has examined the effect of individual skills possessed by the household head on the adoption of conservation tillage technology, it has largely overlooked the comprehensive skill level of the household head. Further-more, there has been limited exploration of the effects of digital agricultural outreach on conservation tillage technology, a lack of empirical data analysis, and insufficient investigation into the interplay between these two factors for adopting conservation tillage practices. To address these gaps, this paper utilizes field survey data collected from 487 melon and fruit growers in Xi'an (Shaanxi Province) and Yuncheng (Shanxi Province) in 2020 to analyze the effects and mechanisms through which skill level and digital agricultural outreach affect the adoption of conservation tillage technology. The sample of households included in this study is drawn from key regions of melon and fruit production in the northwest of China and is affiliated with agricultural colleges and universities. Additionally, regions where digital agricultural outreach initiatives were implemented earlier provide novel insights and a theoretical foundation for improving agricultural technology dissemination. The contributions of this paper, in comparison to previous studies, are twofold. Firstly, it integrates skill level, digital agricultural outreach, and conservation tillage technology into a cohesive research framework. By analyzing the effect of skill level on the adoption of various types of conservation tillage technology, the study further investigates the mechanisms through which digital agricultural outreach affects the relationship between skill level and the adoption of these technologies; Secondly, it develops a comprehensive index to measure the skill level of the household head, encompassing five dimensions: formal education, non-formal education, government service experience, migrant work experience, and farming experience. This approach elucidates the potential mechanisms through which skill level and digital agricultural outreach affect the adoption of conservation tillage technology, thereby improving the understanding of the roles that education and digital agricultural outreach play in mitigating information asymmetry and uncertainty risks associated with technology diffusion. The results hold significant implications for managing risks related to natural disasters, promoting sustainable agricultural development, and preserving a healthy ecological environment.

2 Theoretical analysis and research hypotheses

2.1 Skill level and conservation tillage technology

The concept of "skill" originally originated from the German apprenticeship labor training system (Streeck, 1992). At the micro level, skills include the individual abilities, experiential knowledge, and technical expertise that workers possess or acquire through learning; at the macro level, skills involve the collective cultivation of social capabilities required for socio-economic development across various industries in a country (Liu and Tong, 2023). In terms of the impact of household heads' skill levels, their key advantages are mainly reflected as follows: firstly, they can enhance farmers' awareness of cultivated land protection, helping them fully recognize the multiple values of conservation tillage technologies to optimize land management; secondly, they can strengthen information acquisition and adaptability, and realize low-cost adoption of technologies by virtue of strong learning, innovation, and risk management capabilities; thirdly, they can generate technological spillover effects, promoting the standardized dissemination of technologies in communities to improve the overall adoption rate. This paper examines the impact of household heads' skill levels on farmers' adoption of conservation tillage technologies at the micro level. According to the human capital theory, human capital is defined as a synthesis of knowledge, work experience, and health quality possessed by the labor force, which can significantly enhance the value of the existing economy (Yang and Xun, 2019; Holden et al., 2018). The skill level of household heads is a key determinant of the quality of household human capital stock, helping to broaden cognitive horizons, enhance production capacity, and increase the income of rural households (Ingram and Neumann, 2006).

The impact of household heads' skill levels on farmers' adoption of conservation tillage technologies is reflected in multiple aspects. Firstly, household heads with higher skill levels usually have stronger cognitive and non-cognitive abilities, which can improve farmers' awareness of cultivated land protection. They have a comprehensive understanding of the economic, ecological, and social significance of conservation tillage technologies, thereby updating land management methods. This enables them to organize agricultural production and operation in accordance with the quality and market orientation of agricultural products, thereby improving the utilization rate of conservation tillage technologies. Secondly, household heads with high skill levels, especially those who have experience in migrant work, work in government departments, and received agricultural technology training, have more information channels and opportunities for skill improvement. They have strong learning ability, innovative thinking, and risk management ability, and can cope with the challenges brought by insufficient agricultural production resources and unstable economic environment (Sun et al., 2023). Therefore, they can make reasonable judgments on the investment returns of conservation tillage technologies based on their own agricultural production resource endowments, and adjust their production and operation behaviors to adopt conservation tillage technologies at a lower cost. Thirdly, skilled household heads can generate technological spillover effects, which helps them play a demonstration role and promote the systematic, comprehensive, and standardized dissemination of conservation tillage technologies in their communities. This effect can effectively solve the problems of low technical literacy and improper usage methods of ordinary farmers, thereby improving the skill levels of other farmers and increasing the possibility of wider adoption of conservation tillage technologies.

The skill level of household heads significantly impacts the adoption of multiple conservation tillage technologies: with regard to subsoiling technology, an important tillage method for improving soil structure, it requires operators to understand soil characteristics and mechanical operation principles, and high-skill household heads can quickly grasp its operation points (such as determining appropriate depth based on soil types and optimal timing), making them more likely to adopt it to enhance soil's water and fertilizer retention capacity; for Integrated Pest Management (IPM) technology, which emphasizes comprehensive control methods and ecological regulation, higher skill levels enable accurate judgment of pest occurrences, rational combination of agricultural, biological, and physical controls, and reduced reliance on chemical pesticides, leading to greater inclination toward this green technology; in terms of organic fertilizer application technology, high-skill heads, through knowledge and practice, understand nutrient content and characteristics of different organic fertilizers, formulate scientific application schemes based on soil fertility and crop needs, and actively implement it to improve soil structure and crop quality; as for straw mulching technology, effective application requires considering straw crushing degree, mulching thickness, and adaptability to local climate and crops, and skilled heads can adjust mulching methods and scale accordingly to avoid issues like pest infestation and poor permeability, thus being more willing to adopt it for moisture conservation, fertilization, and weed inhibition.

> *H1a*: The level of skill significantly impacts the adoption of subsoiling practices.
>
> *H1b*: The skill level of households significantly impacts their adoption of IPM practices.
>
> *H1c*: The skill level of households significantly impacts the implementation of organic fertilizers.
>
> *H1d*: The skill level of households significantly impacts their adoption of straw mulching practices.

2.2 Digital agricultural outreach and conservation tillage technology

With the extensive integration of digital technology in rural areas, significant digital transformations are occurring across various sectors (Deichmann et al., 2016; MacPherson et al., 2022; Dittmer et al., 2025). Therefore, the promotion of agricultural digitalization emerges as a crucial factor in improving agricultural production efficiency and serves as a vital catalyst for the dissemination of innovative agricultural technologies, thereby facilitating the development of agricultural modernization (Zhumaxanova et al., 2019; Fu and Zhang, 2022). Digital agricultural outreach effectively mitigates the information constraints faced by households. For the conservation tillage technology, it enhances both households to "want to adopt" and "be able to adopt," thereby contributing to higher adoption rates. Firstly, digital agricultural outreach enables households to access timely information regarding conservation tillage technology, fostering a sense of farmland stewardship, cultivating the principles of sustainable agricultural development (Lahiri et al., 2024), and improving the adoption rate of conservation tillage technology from the perspective of "wanting to adopt" (Silvestri et al., 2021). Digital promotion significantly addresses the challenges households face in acquiring information, broadens the channels through which agricultural information can be obtained, and enhances households' capacity to access in-formation (Asante et al., 2024). This integration of agricultural production into the information age facilitates households' access to agricultural knowledge, guiding them toward the adoption of conservation tillage technology; secondly, digital agricultural outreach exhibits substantial reach, facilitating the rapid expansion of the agricultural information service industry into rural areas (Steinke et al., 2021; Madan and Maredia, 2021). This expansion aids in optimizing households' information acquisition methods, improving the efficiency of information sharing, and narrowing the information gap (Steinke et al., 2021). To a significant extent, it mitigates information asymmetry, thereby fostering a sense of farmland protection among households and guiding them toward the adoption of conservation tillage technology; Thirdly, public health crises, such as the COVID-19 pandemic, along with extreme weather events attributed to climate change, introduce uncertainties that alter households' risk preferences and information acquisition methods, necessitating adjustments in agricultural production management strategies. In this context, digital agricultural outreach serves as the most cost-effective and convenient channel for households to acquire information during their adoption of conservation tillage technology. Therefore, digital agricultural outreach not only broadens the channels for agricultural information acquisition and mitigates information asymmetry but also strengthens households' sense of farmland stewardship (Schattman et al., 2020; Abdulai et al., 2023), thereby promoting the adoption of conservation tillage technology from the perspective of "wanting to adopt." Comprehensive and accessible information services that improve households' ability to adopt conservation tillage technology, improving their access to high-quality training services and production materials, thereby increasing the adoption rate from the perspective of "being able to adopt." Firstly, digital agricultural outreach assists households in obtaining comprehensive market information and offers personalized, diverse, and high-quality technical training and guidance. This effectively reduces the costs associated with information search and learning (Rajkhowa and Qaim, 2021), thereby facilitating access to relevant information and knowledge regarding conservation tillage technology; Secondly, when households utilize digital agricultural outreach platforms to procure materials and services related to conservation tillage technology, price transparency is improved, and market transaction risks are diminished (Schattman et al., 2020), which further supports households' adoption of conservation tillage technology. In summary, digital agricultural outreach equips households with high-quality and cost-effective training services and materials related to conservation tillage technology, thereby promoting its adoption from the perspective of "being able to adopt."

Digital agricultural outreach has a significant impact on farmers' adoption of subsoiling technology. It can timely provide key information required for the effective application of subsoiling technology, such as soil conditions, mechanical operation specifications, and operation timing. For example, it demonstrates the control of subsoiling depth for different soil types through video tutorials or pushes regional reminders of the optimal operation window, helping farmers lower the threshold for learning the technology, enhance their awareness of the technology's effects, and thus be more willing to try and adopt it. Meanwhile, digital agricultural outreach affects farmers' adoption of Integrated Pest Management (IPM) technology. Since the core of IPM technology lies in the comprehensive use of multiple control methods, farmers need to timely understand the occurrence dynamics of pests and diseases, identification methods, and green control technologies (such as the use of biological agents). Digital promotion platforms can solve the problem of farmers' delayed or incomplete information acquisition through real-time early warning, image recognition tools, and online expert guidance, enabling them to more clearly grasp the operational logic and ecological benefits of IPM technology, thereby improving their willingness to adopt it. In addition, digital agricultural outreach plays a significant role in farmers' implementation of organic fertilizer application technology. For knowledge with strong professionalism such as the selection, composting treatment, and scientific proportioning of organic fertilizers, it can help farmers understand the specific impact of organic fertilizers on soil improvement and crop quality through customized push of technical manuals and case videos (such as organic fertilizer application schemes for different crops). At the same time, it provides transparent information on purchasing channels, reduces procurement risks, and encourages farmers to implement the technology more actively. Furthermore, digital agricultural outreach affects farmers' adoption of straw mulching technology. Given that the effect of straw mulching is closely related to straw treatment methods, mulching thickness, and adaptability to local climate, it can integrate practical experiences from various regions, provide technical schemes adapted to different regions (such as moisture-preserving mulching in arid areas and breathable mulching in rainy areas), and demonstrate its actual effects of water retention and fertilization enhancement through data comparison, eliminating farmers' concerns about the risks of technology application and promoting the adoption of the technology.

> *H2a*: Digital agricultural outreach affects households' adoption of subsoiling practices.
>
> *H2b*: Digital agricultural outreach affects households' adoption of IPM practices.
>
> *H2c*: Digital agricultural outreach affects households' implementation of organic fertilizers.
>
> *H2d*: Digital agricultural outreach affects households' adoption of straw mulching practices.

2.3 Skill level, digital agricultural outreach, and conservation tillage technology

2.3.1 Mediation effect

Heads of households possessing a high level of skill can facilitate the adoption of digital technologies, thereby improving the likelihood that households will implement conservation tillage techniques. To improve the efficiency of adopting conservation tillage technology, it is essential for households to proactively seek relevant information and knowledge, enabling them to make timely decisions in response to fluctuations in market information. Therefore, access to market information is critical for households' decisions regarding the adoption of conservation till-age techniques. However, rural households often face disadvantages compared to other economic actors in terms of information acquisition, screening, and utilization, particularly within constrained timeframes and geographic areas. Households encounter challenges related to information asymmetry, making it difficult for them to effectively grasp and process market information in a timely manner, which subsequently affects their adoption of conservation tillage technology. Lahiri et al. (2024) demonstrated that digital agricultural outreach can transcend temporal and spatial limitations, accelerate the dissemination of information, and mitigate information asymmetry. High-skilled householders can mitigate information constraints through the utilization of digital agricultural outreach. This is evidenced by two primary results: Firstly, high-skilled individuals can leverage digital agricultural outreach to access more open and trans-parent agricultural production information, allowing them to compare and identify more accurate information and knowledge pertinent to conservation tillage technology, thereby improving the efficiency of households' selection processes; Secondly, due to the skill-biased nature of technological development, only labor with higher skill levels can swiftly adapt to and utilize new technologies (Tan and Wen, 2022). This is attributed to the fact that a higher skill level among heads of households correlates with a greater ability to utilize digital resources and technologies, which fosters the deep integration of digital technology within agricultural production. This integration promotes the dissemination and utilization of digital tools, transcending temporal and spatial boundaries, accelerating the diffusion of agricultural technology, and broadening the channels through which households can access market information. Consequently, households can acquire and process the information resources available on digital agricultural outreach platforms, leading to a more comprehensive understanding of the effects of protective technology and an increased likelihood of adopting conservation tillage techniques. Simultaneously, the developments in the scientific and technological revolution, coupled with the rapid evolution of digital agricultural outreach, highlight a mismatch between individual skills and the demands of digital agricultural outreach, particularly among older agricultural operators with lower educational levels. This mismatch can hinder the diffusion of new technologies and subsequently affect the adoption rates of conservation tillage technology. Therefore, a higher skill level among householders improves their adaptability to the evolving landscape of digital agricultural outreach and increases their proficiency in applying these digital tools, ultimately encouraging households to adopt conservation tillage technology.

The high skill level of household heads can indirectly promote the adoption of subsoiling technology through digital agricultural outreach: relying on their stronger ability to use digital tools, they can efficiently utilize digital platforms to obtain information related to subsoiling technology, such as soil data and mechanical operation specifications, accurately identify technical parameters suitable for the local area (such as subsoiling depth for different plots) through comparison and screening, make up for the temporal and spatial limitations of information acquisition in rural areas, and thus increase the probability of adopting this technology. Meanwhile, the skill level will indirectly affect the adoption of integrated pest management technology through digital agricultural outreach: household heads with high skills are more likely to adapt to the application logic of digital technology, and with the help of functions such as real-time early warning, pest identification tools, and online expert guidance on the platform, they can quickly integrate scattered pest control knowledge to form systematic technical schemes, alleviate the problem of decision-making delay caused by information asymmetry, and thus indirectly promote the adoption of this technology. In addition, the skill level of household heads has an indirect effect on the implementation of organic fertilizer application technology through digital agricultural outreach: high-skilled individuals can gain a deep understanding of knowledge related to the scientific application of organic fertilizers (such as composting technology and proportioning schemes) through digital promotion channels, use the transparent procurement information on the platform to reduce trial-and-error costs, and relying on their ability to integrate digital resources, transform technical information into practical operation plans, thereby indirectly enhancing the willingness to implement organic fertilizer application technology. Moreover, the skill level can indirectly affect the adoption of straw mulching and returning technology through digital agricultural outreach: household heads with high skills are good at using digital platforms to integrate straw treatment experiences from different regions, screen suitable mulching modes (such as straw crushing degree and returning proportion) in combination with local climate and soil characteristics, intuitively perceive the technical effects through data comparison, reduce concerns caused by insufficient information, and thus indirectly increase the possibility of adopting this technology.

> *H3a*: Skill level indirectly affects households' adoption of subsoiling practices through digital agricultural outreach.
>
> *H3b*: Skill level indirectly affects households' adoption of IPM through digital agricultural outreach.
>
> *H3c*: Skill level indirectly affects households' implementation of organic fertilizer through digital agricultural outreach.
>
> *H3d*: Skill level indirectly affects households' adoption of straw mulching and residue return through digital agricultural outreach.

2.3.2 Substitution effect

Mobile phones and computers belong to the category of "similar production fac-tors" and can both serve as media for farmers to obtain information on conservation tillage technologies. They convey the operation methods, ecological and economic benefits, and market feedback of technologies such as subsoiling, integrated pest management (IPM), and the application of organic fertilizers through forms such as graphics, videos, and online courses. Firstly, according to the theory of marginal substitution rate, when the usage cost of one tool rises (for example, the purchase and maintenance costs of a computer are relatively high), or the benefit advantage of an-other tool becomes prominent (for example, obtaining information through a mobile phone is more convenient), farmers will adjust their preference for tool usage, and a substitution relationship may be formed. Secondly, according to the theory of innovation diffusion, the information dissemination channels affect the adoption speed and scope of new technologies. As digital dissemination tools, mobile phones and computers have their own advantages and disadvantages in terms of the timeliness, coverage, and interactivity of information dissemination. If farmers find that they can obtain basic information on conservation tillage technologies more efficiently through mobile phones, they may reduce their dependence on computers, thereby affecting the diffusion path of technologies and farmers' adoption decisions. Therefore, as digital dis-semination tools, mobile phones and computers form a substitution relationship in influencing conservation tillage technologies.

There is a substitution effect between digital agricultural promotion using different tools when influencing farmers' adoption of conservation tillage technologies, which can be analyzed from two aspects: the characteristics of the tools and farmers' choice logic. First, from the perspective of cost–benefit trade-off, when the purchase and maintenance costs of computers are relatively high, or mobile phones form an obvious advantage in the convenience of information acquisition due to their portability, farmers will naturally adjust their preferences for tool usage, resulting in a substitution relationship between the tools. Second, in terms of the differences in the effectiveness of technical information dissemination, the two have their own focuses in terms of information timeliness and interactivity. If mobile phones can more quickly push regional technical early warnings or realize real-time expert consultation through social functions, farmers will find that they can obtain basic technical information more efficiently, thereby reducing their dependence on computers.

> *H4a*: Digital agricultural promotion using different tools has a substitution effect when it comes to influencing farmers' adoption of conservation tillage technologies.

3 Materials and methods

3.1 Data source

This study selects watermelon and melon growers as the main research subjects based on the following reasons: Firstly, from an economic perspective, watermelons and melons are important cash crops in China, with the highest yields globally. These crops have strong adaptability to different planting and production conditions, a short cultivation cycle, and make significant contributions to improving agricultural efficiency and farmers' incomes, thus occupying an important position in China's fruit and vegetable production sector. According to agricultural statistics, by 2020, the area under watermelon cultivation in China reached 15.281 million hectares, with an output of 62.344 million tons; in the same year, the cultivation area of melons was 3.951 million hectares, with an output of 13.808 million tons. At the research regional level, the melon industry in Yuncheng City, Shanxi Province, has formed an integrated industrial chain covering "planting-processing-e-commerce." In 2022, the related output value reached 18.6 billion yuan, accounting for 27.5% of the local total agricultural output value. The melon industry in Yanliang District, Xi'an City, Shaanxi Province, has driven employment for nearly 100,000 farming households, with an average annual increase in household income of 42,000 yuan, accounting for 41% of farmers' operating income. Compared with food crops, the output value per unit area of melon and fruit cultivation is 6–8 times that of wheat. This significant comparative benefit makes it a key driver for improving farmers' livelihoods, and the healthy development of the industry has a direct impact on regional rural revitalization. Secondly, from the perspective of ecological adaptability, the soil characteristics and planting patterns in the main melon and fruit producing areas in northwestern China have special needs for conservation tillage technology. As shallow-rooted crops, watermelons and melons have higher requirements for soil structure (such as air permeability and water retention). However, the loess in the research area has a loose texture and low organic matter content (less than 1.0% on average). Under traditional tillage methods, the annual loss of topsoil reaches 3–5 millimeters, directly leading to an increase in the rate of deformed fruits. Meanwhile, the growth cycle of these crops is concentrated in spring and summer (April–September), which coincides with the high incidence period of regional heavy rains and strong winds. The long period of exposed surface makes it a high-risk period for soil erosion. Therefore, promoting conservation tillage (such as straw mulching and no-till seeding) in melon and fruit cultivation can not only address industry pain points in a targeted manner but also make the technical application effects more easily quantifiable through changes in crop quality and yield. Finally, in terms of alignment with research objectives, this group is a typical beneficiary of digital agriculture and skill improvement policies. Compared with other cities in northwestern China, Yuncheng City in Shanxi Province and Xi'an City in Shaanxi Province have a higher level of economic development, improved rural internet infrastructure, and strong support from scientific research institutions. These factors contribute to the effective implementation of digital agricultural promotion systems, thereby significantly promoting the development of the melon industry. By 2021, Shanxi and Shaanxi Provinces had trained 424,600 high-quality farmers through a combination of online and offline skill training, and launched the "Internet +" smart rural information service action plan, with a high digital penetration rate. In the "High-Quality Farmer Cultivation Program" in Shanxi and Shaanxi, the proportion of melon and fruit growers participating in training reached 38%, significantly higher than that of grain growers (21%). In the "Internet +" agricultural products going out of villages and into cities project in these two regions, the online transaction volume of watermelons and melons accounted for 23% of the total transaction volume of fruits and vegetables, with the digital penetration rate ranking among the top. This concentration of policy intervention makes the study of the interactive effects of skill levels and digital promotion more grounded in reality, and the research conclusions are more valuable for policy formulation in similar cash crop producing areas. In summary, selecting melon and fruit growers as the research subjects is not only because of their clear status as an economic pillar but also because their industrial characteristics and technical needs in ecologically fragile areas are highly aligned with the research theme, which can provide more targeted micro-evidence for the promotion of conservation tillage technology.

The research group conducted a preliminary survey in Shaanxi and Shanxi Provinces in October 2020, followed by a formal survey in December of the same year. A multi-stage sampling method was employed for sample selection during the field sur-vey. The sampling process was divided into three stages. In the first stage, the survey team selected Xi'an City in Shaanxi Province and Yuncheng City in Shanxi Province as the sample areas. This selection was based on a comprehensive assessment of the watermelon and melon cultivation areas in Northwest China, as well as the variations in local economic conditions and external environmental factors. Notably, Xi'an City serves as the largest production base for early spring melons in Northwest China, with the planting area for Yanliang melons reaching 4,400 hectares, an output of 271,400,000 kg, and an annual output value exceeding 700 million yuan. This production also stimulates the planting area in other counties and districts, which exceeds 6,670 hectares. Conversely, Yuncheng City is recognized for its melon industry, which is a characteristic advantageous and leading agricultural sector. The "Xia Le" watermelon variety from Yuncheng has received geographical indication status for agricultural products in China and is included in the brand catalog of Chinese agricultural products. In the second stage, the counties and districts under the jurisdiction of Xi'an City and Yuncheng City were ranked according to their watermelon and melon outputs, from highest to lowest. Based on the principle of equidistant sampling, 1 ~ 2 counties were selected from each region, and 2 ~ 5 townships were randomly chosen within each county, resulting in a total of 10 townships. In the third stage, 7 ~ 15 villages were randomly selected from each township, culminating in the selection of 33 sample villages. Subsequently, 10 ~ 20 rural households from each sample village were randomly chosen for face-to-face questionnaire surveys, leading to a total of 500 sample rural households. The data collected from this questionnaire survey encompassed various aspects, including the personal characteristics of household heads, household endowment characteristics, inputs and outputs related to melon production, the status of natural disasters, agri-cultural insurance, and government support. The data pertains to the year 2020. Out of the 500 distributed questionnaires, 487 valid responses were obtained, resulting in an effective response rate of 97.4% (see Figure 1).

3.2 Model settings

The equations should be inserted in editable format from the equation editor.

3.2.1 Benchmark model

This study employs a benchmark model to examine the effect of skill level and digital agricultural outreach on households' adoption of conservation tillage techniques. Drawing on the research conducted by Li and Chen (2017), the analysis identifies subsoiling, IPM, organic fertilizer, and straw mulching as the Explained variable, additionally, skill level and digital agricultural outreach are designated as the core explanatory variables. A binary Probit model is utilized for the regression analysis.

$$Y_i = \alpha_0 + \alpha_1 T_i + \alpha_2 I_i + \alpha_3 P_i + \beta C_i + \varepsilon_i \tag{1}$$

In Equation 1, where Y_i is the Explained variable, Indicates whether households adopt conservation tillage technology; T_i is skill level; I_i and P_i are mobile phones and computers utilization in digital agricultural outreach, respectively; C_i is the other control variables; ε_i is the random disturbance term; while $\alpha_1, \alpha_2, \alpha_3$ and β are the regression coefficients.

3.2.2 Mediation effect model

To examine the mediating effect, this study adopts the mediation analysis framework proposed by Wen and Ye (2014) to investigate the mechanism underlying the interaction between skill level, digital agricultural outreach, and the adoption of conservation tillage techniques. Specifically, the model aims to determine whether digital agricultural outreach serves as an intermediary variable that transmits the effect of skill level on households' adoption behavior. The following equations describe the structure of the mediation model:

$$Y_i = \alpha_0 + \alpha_1 T_i + \beta C_i + \varepsilon_i \tag{2}$$

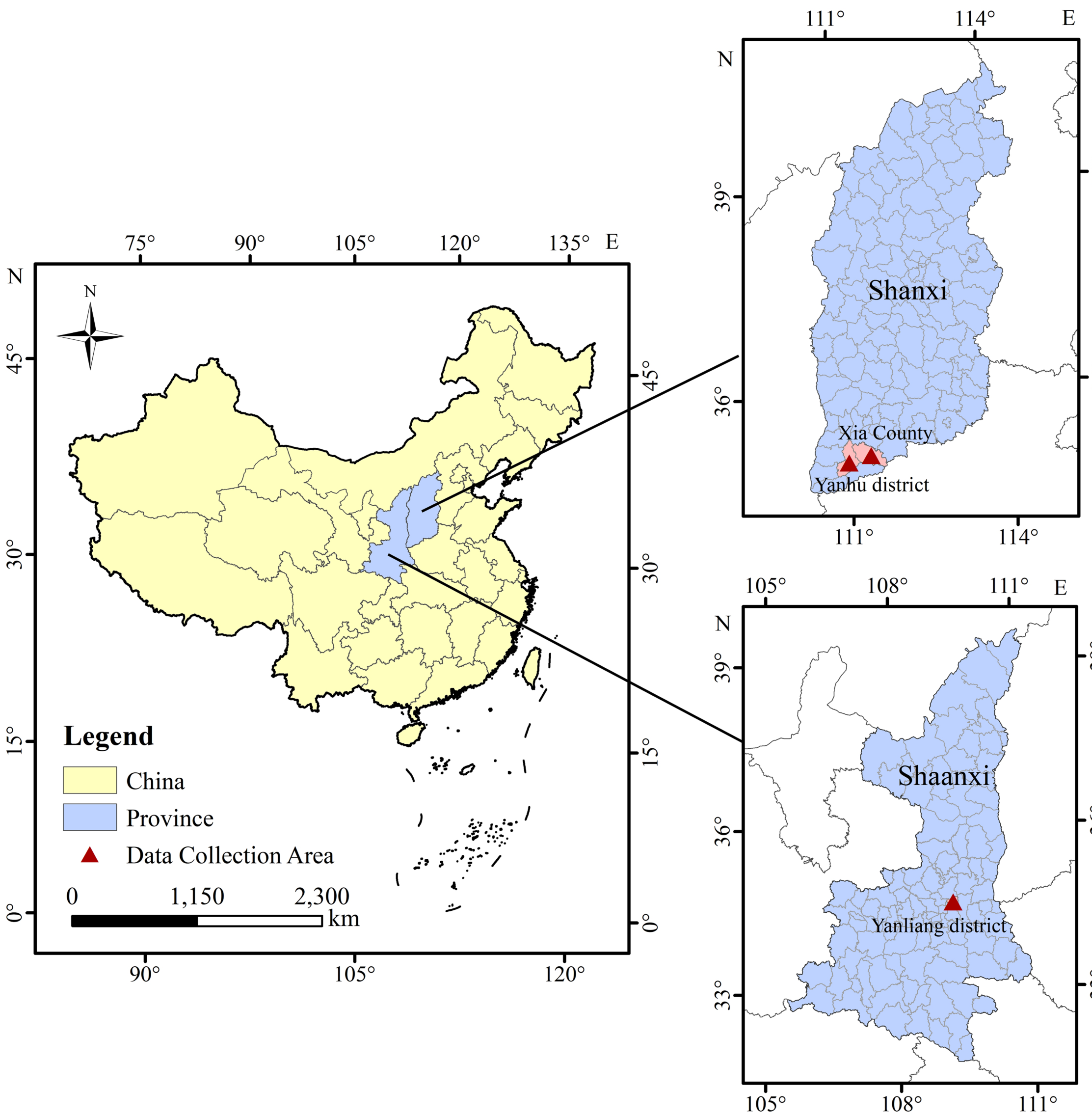

FIGURE 1
Overview of the research area.

$$I_i = \alpha_0 + \alpha_1 T_i + + \beta C_i + \varepsilon_i \tag{3}$$

$$P_i = \alpha_0 + \alpha_1 T_i + \beta C_i + \varepsilon_i \tag{4}$$

$$Y_i = \alpha_0 + \alpha_1 T_i + \alpha_2 I_i + \beta C_i + \varepsilon_i \tag{5}$$

$$Y_i = \alpha_0 + \alpha_1 T_i + \alpha_3 P_i + \beta C_i + \varepsilon_i \tag{6}$$

In Equations 1–6, where I_i and P_i are the mobile phones and computers utilization for the promotion of agricultural digital initiatives, which serve as the mediating variables. The remaining variables retain the definitions provided previously. The primary rationale for employing the bootstrap test to assess the mediating effect of digital agricultural outreach is that this self-sampling method not only evaluates the significance of the mediating variables but also mitigates the potential "masking effect" within the mediating effect pathway.

3.2.3 Substitution relationship

To explore the potential substitution relationship between different modes of digital agricultural outreach, this study introduces an interaction term between mobile phone utilization and computer utilization in the empirical model. Specifically, the objective is to determine whether these two digital channels function as substitutes in affecting households' adoption of conservation tillage technologies. By incorporating an interaction term, the model facilitates an examination of the combined effect of mobile phone and computer utilization on technology adoption behaviors, extending beyond their respective individual effects. The model specification is expressed as follows:

$$Y_i = \alpha_0 + \alpha_1 T_i + \alpha_2 I_i + \alpha_3 P_i + \alpha_4 I_i \times P_i + \beta C_i + \varepsilon_i \tag{7}$$

In Equation 7, where $I_i \times P_i$ is the interaction term between mobile phone utilization and computer utilization and α_4 is the regression model associated with this interaction term. Furthermore, if the regression coefficient of α_4 is statistically significant, it indicates the presence of a substitution relationship.

3.3 Variable selection

3.3.1 Explained variable

Conservation tillage technology constitutes a comprehensive technical system that encompasses various methodologies aimed at improving soil fertility and water retention capacity, increasing soil organic matter, and improving resilience to environmental risks. Key components of this system include low tillage, no-tillage, subsoiling, IPM, the application of organic fertilizers, and straw mulching (Giovanni et al., 2016; Tufa et al., 2023). However, the roots, stems, and leaves of watermelon plants secrete excessive phenolic compounds, which can diminish chlorophyll content, exert toxic impacts on the plants themselves, and ultimately reduce yield. In this study, the explained variables comprised four types of conservation tillage techniques: subsoiling, IPM, organic fertilizer application, and straw mulching. To assess the adoption of these practices, households were asked the following questions: "Do you perform subsoiling during the planting process of watermelons or melons?," "Do you perform subsoiling during the planting process of watermelons or melons?," "Do you use integrated pest control in the watermelon or melon planting process?," "Do you use organic fertilizer in the watermelon or melon planting process?," and "Do you use straw mulching in the watermelon or melon planting process?" The adoption of the specified measure is assigned a value of 1, while non-adoption is assigned a value of 0.

3.3.2 Core explanatory variables

The core explanatory variables in this study include digital agricultural extension and skill level. In terms of measuring digital agricultural extension, drawing on the research of Xiong et al. (2025), this study focuses on the dimension of using digital promotion tools to measure the indicators of digital promotion. From the perspective of the types of digital tools actually accessed and used by farmers, the usage of digital promotion tools is characterized by two core items: "Do you obtain agricultural information, knowledge, and material information through mobile-based digital tools such as WeChat groups, official accounts, and agricultural Apps on your mobile phone?" and "Do you obtain agricultural information, knowledge, and material information through computer-based digital tools such as browsing computer web pages and web searches?" These items correspond, respectively, to farmers' usage behaviors of two mainstream digital promotion tools: mobile-terminal and computer-terminal tools, both adopting a 0–1 assignment method. If a farmer answers "yes," it is assigned a value of 1 (indicating that they have used such digital promotion tools); if the answer is "no," it is assigned a value of 0 (indicating that they have not used such digital promotion tools). By quantifying the usage of digital tools on different terminals, the actual application status of tools by farmers in the process of digital promotion is clearly depicted, laying a foundation for subsequent analysis of the effects of digital promotion. In terms of measuring the household head's skill level, this study refers to the research framework of Wasono et al. (2024) and optimizes it in combination with the research context, selecting 6 sub-indicators to construct an evaluation system, specifically including: the household head's education level (reflecting the foundation of knowledge reserve), years of farming (reflecting the accumulation of agricultural production experience), whether having received agricultural technical training (measuring the channel for professional skill improvement), whether having non-agricultural work experience (reflecting diversified abilities and market cognition), the number of mobile phone contacts (characterizing the scale of social network and information acquisition ability), and physical health status (the basic condition for ensuring the effective exertion of skills). Based on the indicator evaluation system of the household head's skill level, and to avoid multicollinearity among selected variables, principal component analysis is conducted on the 6 measurement indicators of skill level. The selection of skill level variables is shown in Table 1. The six sub-indicators comprehensively cover the entire process of "acquisition, transformation, application, and guarantee" of the household head's skill level from six dimensions: "cognitive foundation (education) - practical accumulation (farming experience) - professional training (technical participation) - cross-border migration (non-agricultural experience) - resource support (social

TABLE 1 Definition and descriptive statistics of skill level variables.

Variable	Indicator	Definition and coding	Mean	Standard deviation
Household head's skill level	Years of education	Number of years of formal education completed by the household head.	8.1293	2.5815
	Farming experience	Years of crop cultivation: ≤ 5 years = 0; > 5 years = 1	1.0472	2.4620
	Agricultural technical participation	Participation in formal agricultural training: Yes = 1; No = 0	0.1909	0.3934
	Non-agricultural work experience	Has held non-agricultural employment: Yes = 1; No = 0	0.6448	0.4791
	Social relationship	Number of contacts in the household head's mobile phone as of the survey time (person)	160.59	152.3483
	Health condition	Self-assessed health: Sick = 1; Average = 2; Excellent = 3	2.8090	0.4380

relationship) - execution guarantee (health)," and together constitute a systematic measurement of the household head's comprehensive skill level.

According to the definition of skill level presented in this paper, and to mitigate the issue of multicollinearity in variable selection, principal component analysis was conducted on six measures of skill level. Table 1 outlines the selection of skill level variables. The results indicated that the Kaiser-Meyer-Olkin (KMO) index for the six sub-indicators of the head of household's skill level was 0.601, and the approximate chi-square value from the Bartlett's test of sphericity was 215.736 ($p < 0.001$), suggesting that the skill level variables of the head of household were appropriate for factor analysis. The factor analysis was initially performed on the six indicators representing the skill level of the head of household to derive the corresponding eigenvalues and variance contribution rates. Two common factors with eigenvalues greater than 1 were extracted, resulting in a cumulative variance contribution rate of 50.35%. This result indicates that the two principal components can effectively be utilized to evaluate and assess the skill level index of the head of household. The extracted common factors and their respective variance contribution rates were used to calculate the skill level index of the head of household, as represented by Fm1 = (F1 * 33.175 + F2 * 17.18%) / 50.35%. Based on this formula, the actual skill levels of the household heads in the sample farmers are measured to range from −2.5 to 6.9. In essence, the household head's skill level index is a dimensionless data (generally distributed around 0). Specifically, a higher score indicates a higher skill level of the household head; conversely, a lower score indicates a lower skill level of the household head.

3.3.3 Control variables

To consider potential confounding factors that may affect the relationship between the household head's skill level, digital agricultural outreach, and the adoption of conservation tillage techniques, this study incorporates a comprehensive set of control variables informed by existing literature. These include personal characteristics of the household head (e.g., age and attitudes toward market prospects); (2) household-level factors (e.g., labor force size, income structure, Cultivated area, participation in cooperatives, and exposure to natural disasters); and (3) external environmental conditions (e.g., the receipt of government agricultural subsidies). To ensure the reliability of the results, alternative model specifications with varied control variable combinations were employed, and the robustness of the estimation results was confirmed. The full list of variables and their descriptive statistics is summarized in Table 2.

4 Results

To take part in the Resource Identification Initiative, please use the corresponding catalog number and RRID in your current manuscript. For more information about the project and for steps on how to search for an RRID, please click here. The primary steps of the empirical analysis conducted in this study are delineated as follows: Firstly, the effect of skill level and digital agricultural outreach on various types of conservation tillage techniques is examined; Secondly, the study aims to verify the mediating role of digital agricultural outreach in the relationship between skill level and the adoption of conservation tillage technology by households; Thirdly, the complementary effects of different types of digital agricultural outreach on households' adoption of conservation tillage techniques are analyzed. Prior to estimating the regression, a multicollinearity test was conducted, with results indicating that the variance inflation factor (VIF) values for each variable were below 2, thereby suggesting the absence of multicollinearity issues among the variables. In Tables 3–5, Wald's chi-square value is significant at the 1% level, indicating a good fit for the model.

4.1 Regression results of skill level and digital agricultural outreach affecting households' adoption of conservation tillage techniques

Models 1–4 in Table 6 present the empirical results assessing the effect of skill level and digital agricultural outreach on households' adoption of conservation tillage technologies. The results indicate that skill level is positively and significantly associated with the adoption of subsoiling, IPM, and organic fertilizer at the 10, 5, and 1% significance levels, respectively. These results suggest that households with higher skill levels are more likely to adopt these conservation practices. This may be attributed to their greater awareness of the ecological and economic benefits of such techniques, as well as their stronger learning capacity and ability to incorporate new knowledge. Consequently, Hypotheses H1a, H1b, and H1c are supported. However, the effect of skill level on straw mulching adoption is not statistically significant. This result likely stems from crop-specific constraints, as watermelon straw has toxic properties that can harm the plant itself, making its use for mulching uncommon. Furthermore, substituting with straw from other crops would increase input costs. Therefore, more skilled households are less likely to adopt straw mulching in this context, aligning with practical observations.

In terms of digital agricultural promotion, the use of mobile phones is significantly and positively correlated with the adoption of subsoiling, integrated pest management (IPM), and organic fertilizers at the 1% significance level, which confirms its significant impact. In contrast, the use of computers is only significantly associated with the adoption of organic fertilizers at the 10% significance level. These results verify part of Hypothesis H2. Compared with computers, mobile phone-based promotion has higher accessibility, lower cost, and greater ease of use in rural areas, making its promotion more effective. In addition, the expansion and upgrading of rural digital infrastructure have facilitated the more timely and accurate dissemination of agricultural knowledge and technical information, enhancing farmers' ability to access relevant resources. This, in turn, has increased their awareness of farmland protection and promoted the adoption of conservation tillage measures.

In terms of household head characteristics, the age of the household head has a significantly negative impact on the adoption of integrated pest management (IPM), while its effects on the other three technologies are not statistically significant. This indicates that older farmers are less likely to adopt IPM technology, possibly because they have a weaker ability to learn new pest control technologies and are more reliant on traditional methods. Conversely, the household head's risk attitude has a significantly positive impact on subsoiling, meaning that farmers who are more willing to take risks are more inclined to try subsoiling technology, which requires

TABLE 2 Descriptive statistics of variables.

Category	Variable	Definition and coding	Mean	Standard deviation
Conservation tillage technology	Subsoiling	Whether the household has adopted subsoiling: Yes = 1, No = 0	0.8021	0.3353
	IPM	Whether the household has adopted IPM: Yes = 1, No = 0	0.6850	0.4646
	Organic fertilizer application	Whether the household has applied organic fertilizer: Yes = 1, No = 0	0.7284	0.4470
	Straw mulching	Whether the household practices straw mulching (return to field): Yes = 1, No = 0	0.4661	0.4993
Household Head's Skill Level	Skill Level	Composite index derived from six indicators including education, experience, and training	−2.4604	6.8022
Digital agricultural outreach	Mobile phone utilization	Access to agricultural info via mobile apps/WeChat/public accounts: Yes = 1, No = 0	0.6488	0.4778
	Computer utilization	Access to agricultural info via computer/web browsing: Yes = 1, No = 0	0.1314	0.3382
Respondent characteristics	Age	Age of the household head (year)	51.5236	8.6985
	Risk attitude	Investment preference: High risk with high return = 1, Moderate risk with moderate return = 2, Reduced risk with relatively low return = 3, No risk with stable return = 4	2.7720	0.9490
	Agricultural insurance	Whether the household has agricultural insurance: Yes = 1, No = 0	0.2525	0.4349
Household characteristics	Number of labors	Number of working-age household members	3.2833	1.0152
	Cultivated area	Area of watermelon/muskmelon cultivation (hectare)	1.0535	0.7992
	Income from melon/fruits	Share of melon/fruit income in total household income in 2020 (%)	0.5662	0.2901
	Soil quality	Soil quality: Extremely poor = 1, Relatively poor = 2, Average = 3, Relatively good = 4, Extremely good = 5	3.3696	1.0515
	Land transfer	Whether the household participated in land transfer: Yes = 1, No = 0	0.6509	0.4771
	Cooperative participation	Whether the household participates in a cooperative: Yes = 1, No = 0	0.3491	0.6738
External environment	Government subsidies	Received government subsidies for agricultural tech in 2020: Yes = 1, No = 0	0.7659	0.4238
	Number of natural disasters	Number of natural disaster events experienced by the household in the last 3 years	1.2895	1.2653
Geographic location	Regional dummy variable	Region: Shaanxi = 1, Shanxi = 0	0.4681	0.4994

upfront investment and yields long-term returns. However, risk attitude has no significant impact on the other three technologies, which may be due to the fact that the short-term benefits of these technologies are more predictable. In terms of production conditions, soil quality shows a significantly negative impact on all four technologies. This suggests that farmers with poorer soil quality are more motivated to adopt conservation tillage technologies to improve soil fertility, which is consistent with the actual need to address soil degradation through technologies such as organic fertilizer application and subsoiling. Nevertheless, cultivated area and income from melons/fruits have no significant correlation with these four technologies, indicating that in the context of this study, farm size and fruit income level are not direct determinants of farmers' adoption of these conservation tillage measures. In terms of institutional factors, government subsidies have a significantly positive impact on all four technologies. This confirms that financial incentives can effectively reduce the cost threshold for farmers to adopt conservation tillage technologies, especially for technologies with higher upfront costs such as IPM and straw mulching. Participation in cooperatives has a significantly positive impact on straw mulching because cooperatives can promote collective procurement of straw and technical training, reducing the individual implementation costs for farmers, but it has no significant impact on other technologies. Land transfer has a significantly positive impact on IPM, possibly because operators after land transfer are more inclined to adopt standardized management measures such as IPM to ensure stable yields, but land transfer has no significant impact on other technologies. The number of natural disasters has a significantly positive impact on IPM and straw mulching, indicating that farmers who have experienced more disasters are more likely to adopt these risk-mitigating technologies. IPM helps reduce pest losses after disasters, while straw mulching can enhance soil water retention capacity and resilience. Regional dummy variables have a significantly positive impact on subsoiling, organic fertilizer application, and straw mulching, reflecting regional differences in technology promotion policies, natural conditions, and agricultural infrastructure. For

TABLE 3 Regression results of mediation effect test.

Influence path	Bootstrap test			Significance of mediating effect
	Indirect effect	95% confidence interval		
		Lower limit	Upper limit	
A. Skill level → Mobile phone utilization → Subsoiling	0.0173* (0.0062)	0.0052	0.0294	Significant
B. Skill level → Mobile phone utilization →IPM	0.0269* (0.0084)	0.0114	0.0424	Significant
C. Skill level →Mobile phone utilization → Organic fertilizer application	0.0254* (0.0085)	0.0089	0.0419	Significant
D. Skill level → Mobile phone utilization → Straw mulching	0.0001 (0.0051)	−0.0095	0.0096	Not significant
E. Skill level → Computer utilization → Subsoiling	0.0014 (0.0021)	−0.0026	0.0054	Not significant
F. Skill level → Computer utilization → IPM	0.0022 (0.0026)	−0.0029	0.0072	Not significant
G. Skill level → Computer utilization → Organic fertilizer application	0.0050 (0.0031)	−0.0017	0.0117	Not significant
H. Skill level → Computer utilization → Straw mulching	0.0032 (0.0031)	−0.0026	0.0091	Not significant

*, **, and *** indicate significance at the 10, 5, and 1% levels, respectively. The numbers in parentheses are standard errors.

example, in areas with greater agricultural promotion efforts or higher ecological protection requirements, the adoption rates of these technologies may be higher. Overall, the regression results highlight the key roles of government subsidies, soil quality, and regional factors in promoting the adoption of conservation tillage technologies, while the impacts of household characteristics such as age and risk attitude vary by technology type. These findings emphasize the need for targeted policy interventions, such as increasing subsidies for high-cost technologies and strengthening cooperative-led technical training, to improve farmers' adoption of conservation tillage measures.

4.2 Mediation effect test

In this study, the self-sampling method, specifically the bootstrap technique, was employed to assess the significance of the mediating effect. According to the assumptions underlying the self-sampling test method, a confidence interval that does not encompass zero indicates a significant mediating effect. Specifically, if both the upper and lower limits of the confidence interval are either positive or negative, this suggests a significant positive or negative mediating effect, respectively. Conversely, if the confidence interval includes zero (i.g., evidenced by the upper and lower bounds having different signs) this violates the assumption that the confidence interval should not include zero, thereby indicating that the mediating effect is not significant.

In Table 3, the mediating effect was quantified at 0.0173, with a confidence interval ranging from [0.0052, 0.0294]. This result is statistically significant at the 95% confidence level, suggesting that mobile phone utilization, as promoted by agricultural digital initiatives, exerts a significant positive mediating effect on the relationship between skill level and subsoiling practices. Furthermore, the mediating effect was determined to be 0.0269, with confidence intervals of [0.0114, 0.0424] for the skill level-mobile phone utilization-IPM pathway. This result is also significant at the 95% confidence level, indicating that mobile phone utilization, facilitated by digital agricultural outreach, positively mediates the effect of skill level on IPM practices. In the relationship involving skill level, mobile phone utilization, and organic fertilizer application, the mediating effect was calculated at 0.0089, with a confidence interval of [0.0089, 0.0419], which is significant at the 95% confidence level. This suggests that mobile phone utilization for digital agricultural outreach has a significant positive mediating effect on the relationship between skill level and the implementation of organic fertilizers. However, in the analysis of the skill level-mobile phone utilization relationship concerning straw mulching, the assumption of "confidence interval does not include zero" was violated, indicating the absence of a mediating effect. This may be attributed to the observation during the research that the mechanization of straw mulching has largely been achieved, with certain villages receiving direct mechanization services from the government. Consequently, households may overlook the need for information search or cost assessment. Additionally, the relationship of skill level → mobile phone utilization → straw mulching also violated the assumption regarding the confidence interval not containing zero, suggesting a lack of mediating effect. This may be due to the higher costs, complexity, and lower penetration of computers in rural areas. The regression results in Table 3 support the validity of part of Hypothesis H4a.

The mediating effect of the path "skill level → mobile phone utilization → straw mulching" is not significant [indirect effect = 0.0001, 95% confidence interval (−0.0095, 0.0096) includes 0]. In addition to the high mechanization level of straw mulching and the direct provision of services by the government reducing farmers' demand for information search, it is also related to the particularity of watermelon cultivation. Watermelon straw contains toxic substances and is not suitable for returning to the field, while using straw from other crops will increase costs. This practical obstacle weakens the connection between "information acquisition via mobile phones" and

TABLE 4 Regression results of substitution effect test.

Variable	Model 5	Model 6	Model 7	Model 8
Skill level	0.2170* (0.1148)	0.2170** (0.1032)	0.3475*** (0.1071)	0.1004 (0.1012)
Mobile phone utilization	0.6388*** (0.1751)	0.7695*** (0.1533)	0.7056*** (0.1507)	0.1357 (0.1738)
Computer utilization	0.3381 (0.4379)	1.2345** (0.5321)	1.3308** (0.5374)	1.1794** (0.4828)
Substitution effect	−0.1091 (0.5718)	−1.2981** (0.6001)	−1.1915** (0.5975)	−1.1647** (0.5431)
Controlled variable	Controlled	Controlled	Controlled	Controlled
Wald χ^2	51.29	112.54	77.93	181.78
Prob > χ^2	0.0000	0.0000	0.0000	0.0000
Pseudo R^2	0.1543	0.2491	0.162	0.3907
Log likelihood	−172.5568	−227.6048	−240.1032	−204.9919

*, **, and *** indicate significance at the 10, 5, and 1% levels, respectively. The numbers in parentheses are standard errors.

TABLE 5 Regression results of substitution model.

Variable	Model 9	Model 10	Model 11	Model 12
Skill level	0.4751** (0.2160)	0.3837** (0.1826)	0.5903*** (0.1842)	0.1894 (0.1695)
Mobile phone utilization	1.1123*** (0.3068)	1.1430*** (0.2475)	1.0422*** (0.2460)	0.0270 (0.2878)
Computer utilization	0.5072 (0.5666)	0.5326 (0.4411)	0.8489* (0.4421)	0.4828 (0.3935)
Controlled variable	Controlled	Controlled	Controlled	Controlled
Wald χ^2	49.91	97.41	70.93	146.66
Prob > χ^2	0.0000	0.0000	0.0000	0.0000
Pseudo R^2	0.1577	0.2498	0.1644	0.3902
Log likelihood	−171.8447	−277.3963	−239.4102	−205.1779

*, **, and *** indicate significance at the 10, 5, and 1% levels, respectively. The numbers in parentheses are standard errors.

"adoption of straw mulching." Even if high-skilled farmers obtain relevant information through mobile phones, it is difficult to translate it into actual adoption behavior, resulting in the breakdown of the mediating chain. The mediating effects of the paths "skill level → computer utilization → subsoiling," "skill level → computer utilization → IPM," "skill level → computer utilization → organic fertilizer application," and "skill level → computer utilization → straw mulching" are all not significant. The core reason is that the penetration rate of computers in rural areas is much lower than that of mobile phones, and limited by factors such as network stability and operational complexity, their information dissemination efficiency and matching degree with farmers' needs are relatively low. For example, subsoiling relies on mechanical operation experience and real-time equipment rental information, IPM requires guidance on field dynamic monitoring, and organic fertilizer application is more dependent on information about local supply channels. These needs are more appropriately met through mobile phones or offline interpersonal networks. In contrast, computer information is mostly macro policies or technical theories, lacking timeliness and practicality. Even if high-skilled farmers use computers, it is difficult to convert the obtained information into technology adoption behavior, leading to the failure of the mediating chain "skill level → computer utilization → technology adoption." In summary, the insignificant mediating effect of computer utilization in all paths is mainly due to its low penetration rate in rural areas and the limitations of information dissemination. The insignificant mediating effect of paths related to straw mulching is further affected by the practical operational constraints brought by crop characteristics. Both factors jointly lead to the breakdown of the mediating chain.

4.3 Substitution effect test

The estimation results in Table 4 indicate that the coefficients of the interaction terms for mobile phone and computer utilization in regressions 5~8 are 1.2981, −1.1915, and −1.1647, respectively, with all coefficients being statistically significant at the 5% level. According to the interaction coefficient analysis method outlined in the relevant literature (Sun and Xiang, 2024), these results suggest a substitution relationship between mobile phone and computer utilization for the digital agricultural outreach, as well as in the adoption of IPM, organic fertilizers, and straw mulching techniques that affect households' implementation of conservation tillage practices. The above results verify Hypothesis H4a. A plausible explanation for this phenomenon is that both mobile phones and computers serve as channels for information acquisition, exhibiting overlapping functionalities. However, mobile phones offer different advantages over computers, such as lower costs associated with information acquisition and greater convenience.

4.4 Robustness test

This study conducted several robustness tests informed by existing research. Firstly, the model specification was altered by substituting the Probit model with the Logit model; secondly, the control variables were modified; specifically, the risk attitude, originally represented as an ordinal variable, was replaced with agricultural insurance, which is categorized as a categorical variable; thirdly, subsampling was employed to mitigate the impact of extreme values. The focus of this research is primarily on smallholder households, leading to the exclusion of sample households managing areas exceeding 30 mu from the regression analysis. The outcomes of the robustness tests are largely consistent with the results of the benchmark regression, thereby providing strong support for the hypotheses posited in the previous study. The results of the robustness tests are outlined in Tables 5–8.

5 Conclusions and policy implications

5.1 Conclusion

Based on the survey data of farmers in Xi'an City, Shaanxi Province and Yuncheng City, Shanxi Province in 2020, this paper examines the

TABLE 6 Regression results of skill level and digital promotion on households' adoption of conservation tillage technologies.

Variable	Model 1	Model 2	Model 3	Model 4
Skill level	0.2174* (0.1148)	0.2160** (0.1041)	0.3419*** (0.1067)	0.0974 (0.0999)
Mobile phone utilization	0.6292*** (0.1677)	0.6708*** (0.1460)	0.6186*** (0.1443)	0.0159 (0.1637)
Computer utilization	0.2751 (0.2836)	0.2823 (0.2399)	0.4555* (0.2354)	0.2814 (0.2192)
Age	−0.0065 (0.0099)	−0.0243*** (0.0091)	−0.0056 (0.0087)	0.0062 (0.0091)
Risk attitude	0.1497* (0.0811)	−0.0186 (0.0756)	0.0616 (0.0716)	−0.0955 (0.0771)
Number of labor force	−0.0170 (0.0765)	−0.1028 (0.0701)	0.0432 (0.0684)	0.0222 (0.0763)
Cultivated area	0.0469 (0.1322)	−0.0292 (0.1163)	0.1718 (0.1216)	−0.0180 (0.1116)
Income from melon/fruits	0.0386 (0.2998)	−0.4232 (0.2610)	0.3972 (0.2575)	0.2549 (0.2743)
Soil quality	−0.1818** (0.0865)	−0.4526*** (0.0791)	−0.1298* (0.0719)	−0.3944*** (0.0773)
Land transfer	0.2236 (0.1778)	0.3573** (0.1591)	0.1197 (0.1538)	−0.1816 (0.1649)
Cooperative participation	0.2416 (0.1806)	0.2139 (0.1453)	0.0942 (0.0865)	0.3857** (0.1737)
Government subsidies	0.3044* (0.1735)	0.5459*** (0.1614)	0.3038** (0.1544)	0.4454** (0.1768)
Number of natural disasters	0.0640 (0.0625)	0.1899*** (0.0598)	−0.0713 (0.0552)	0.1130* (0.0582)
Regional dummy variable	0.6036*** (0.1849)	0.1056 (0.1580)	0.2847* (0.1488)	2.1185*** (0.1811)
Wald χ^2	51.29	112.54	77.93	181.78
Prob > χ^2	0.0000	0.0000	0.0000	0.0000
Pseudo R^2	0.1543	0.2491	0.1620	0.3907
Log likelihood	−172.5568	−227.6048	−240.1032	−204.9919

*, **, and *** indicate significance at the 10, 5, and 1% levels, respectively. The numbers in parentheses are standard errors.

TABLE 7 Regression results of alternative control variables.

Variable	Model 13	Model 14	Model 15	Model 16
Skill level	0.2007* (0.1135)	0.2249** (0.1040)	0.3408*** (0.1063)	0.1133 (0.0990)
Mobile phone utilization	0.6215*** (0.1668)	0.6859*** (0.1467)	0.6231*** (0.1445)	0.0256 (0.1636)
Computer utilization	0.2749 (0.2841)	0.3049 (0.2407)	0.4675** (0.2365)	0.2984 (0.2191)
Controlled variable	Controlled	Controlled	Controlled	Controlled
Wald χ^2	49.50	113.24	78.64	179.92
Prob > χ^2	0.0000	0.0000	0.0000	0.0000
Pseudo R^2	0.1474	0.2512	0.1631	0.3891
Log likelihood	−173.9591	−226.9634	−239.7795	−205.5410

*, **, and *** indicate significance at the 10, 5, and 1% levels, respectively. The numbers in parentheses are standard errors.

TABLE 8 Regression results of subsamples.

Variable	Model 17	Model 18	Model 19	Model 20
Skill level	0.2523** (0.1196)	0.1940* (0.1116)	0.3256*** (0.1095)	0.1290 (0.1159)
Mobile phone utilization	0.6218*** (0.1744)	0.6865*** (0.1504)	0.5932*** (0.1499)	0.0352 (0.1686)
Computer utilization	0.1404 (0.2950)	0.3834 (0.2599)	0.4840* (0.2525)	0.1968 (0.2318)
Controlled variable	Controlled	Controlled	Controlled	Controlled
Wald χ^2	51.58	103.53	76.22	170.99
Prob > χ^2	0.0000	0.0000	0.0000	0.0000
Pseudo R^2	0.1673	0.2402	0.1671	0.3850
Log likelihood	−159.5153	−216.3450	−223.8409	−192.6235

*, **, and *** indicate significance at the 10, 5, and 1% levels, respectively. The numbers in parentheses are standard errors.

impact of skill levels and digital promotion on farmers' adoption of conservation tillage technologies. This not only expands the research on the influencing factors and mechanisms of conservation tillage technologies but also provides an important reference for examining how skill improvement and digital promotion can improve farmers' economic benefits and better meet their production and living needs. The study finds that skill levels can significantly promote farmers' adoption of subsoiling, integrated pest management, and organic fertilizer application in conservation tillage technologies; in digital promotion, the use of mobile phones can significantly promote farmers' adoption of subsoiling, integrated pest management, and organic fertilizer application in conservation tillage technologies, while the use of computers can only significantly promote the implementation of organic fertilizer application; digital promotion plays an intermediary role in the process of skill levels affecting conservation tillage technologies; there is a substitution relationship between the use of mobile phones and computers in digital promotion in influencing farmers' adoption of integrated pest management, organic fertilizer application, and straw returning and mulching in conservation tillage technologies.

5.2 Policy implications

Based on the above research conclusions, the following three suggestions are put forward: (1) Promote the application of digital tools in a differentiated manner to adapt to technical characteristics and usage scenarios. Based on the functional differences between mobile phones and computers in technology adoption, it is necessary to optimize the promotion paths in a targeted manner. Mobile phones play a significant role in subsoiling, integrated pest management, and organic fertilizer technologies and have a relatively wide popularity, so priority should be given to developing lightweight applications. For subsoiling technology, relevant soil testing programs can be designed to support farmers in recommending operation depth through taking photos and linking to agricultural machinery scheduling services; for integrated pest management, identification and early warning functions can be added to integrate historical data and push prevention tips in advance. At the same time, appropriate subsidies should be given to the traffic fees of agricultural applications, and the subsidies should be linked to technology adoption. Farmers who adopt relevant technologies can obtain additional traffic support. Computers have advantages in data analysis in organic fertilizer technology but have limited popularity, so precise support is needed. Appropriate subsidies can be provided for the purchase of computers by large-scale planting entities, requiring the supporting use of relevant analysis software; digital service platforms can be built at township agricultural technology stations, equipped with public equipment and professional personnel to provide small farmers with soil nutrient inquiry and fertilization scheme design services, ensuring regular opening for convenient use. (2) Focus on the needs of elderly farmers to bridge the digital divide. To address the problem that elderly farmers have weak ability to use digital tools, efforts should be made from two aspects: tool adaptation and ability improvement. Promote mainstream agricultural applications to add operation modes suitable for the elderly, retain core functions for technologies such as organic fertilizers that elderly farmers pay attention to, simplify interface design, enlarge display content, support dialect voice interaction, and reduce operation steps. Develop remote assistance functions to allow family members to help set technical reminders or make consultation appointments. Establish village-level assistance teams, and young people can guide elderly farmers one-on-one in using basic mobile phone functions, such as scanning packages to obtain application instructions and taking photos of crops to send for consultation. Training adopts the form of field practice combined with paper diagrams, and provides agricultural material rewards to elderly farmers who continue to use digital tools to enhance their enthusiasm for participation. (3) Strengthen the synergy between skills and digital tools to achieve layered and precise empowerment. Considering the promoting effect of skill levels on the use of digital tools, it is necessary to optimize the support system for different skill groups. For farmers with weak skill foundations, focus on promoting easy-to-operate mobile tools, provide video-based technical guidance, push key information through short messages, and simultaneously achieve information coverage with the help of village bulletin boards. For farmers with higher skill levels, guide them to use professional computer-based tools, rely on county-level platforms to provide soil analysis and technical scheme design services, and combine technical training to improve the depth of tool use. Through layered guidance, promote the integration of skill improvement and digital tool application, and facilitate the effective penetration of conservation tillage technologies among different groups.

6 Discussion

6.1 Specificity and limitations of the research region

Based on micro-data from melon and fruit growers in Shanxi and Shaanxi Provinces, this study reveals the mechanism by which farmers' skill levels and digital agricultural extension influence the adoption of conservation tillage technology. It confirms that improved skills significantly enhance the probability of technology adoption by strengthening the ability to use digital tools, optimizing technical cognition, and improving risk response capabilities. Meanwhile, digital agricultural extension plays a dual regulatory role of "capacity amplification" and "information empowerment" in this process. These findings not only provide new evidence for understanding the laws of technology diffusion in characteristic agricultural regions but also offer a micro-foundation for formulating policies related to sustainable agricultural development in ecologically fragile areas. However, further discussions are needed regarding the specificity and limitations of the research region. (1) Specificity of crop types. The research focuses on cash crops such as watermelons and melons in the study area. These crops have high economic benefits (with a unit-area output value 6–8 times that of food crops) and strong market orientation, making farmers more sensitive to the cost–benefit of technology adoption. Compared with food crop growers, melon and fruit growers are more inclined to adopt conservation tillage technology to improve quality (e.g., reducing the rate of misshapen fruits) and reduce ecological risks (e.g., yield reduction caused by soil erosion). In contrast, in food crop regions, due to limited profit margins, the motivation for technology adoption is more dependent on policy subsidies (Liu et al., 2021). In addition, as shallow-rooted crops, watermelons and melons have special requirements for soil permeability and water retention, which makes the effects of technologies such as no-tillage more easily perceived through changes in yield and quality. This is different from the response mechanism of deep-rooted crops such as wheat and corn to tillage technologies (Qin et al., 2022). (2) Uniqueness of the ecological environment. The sample areas in Shanxi and Shaanxi Provinces are located in the Yellow River Basin, with a typical continental monsoon climate and loess as the main soil type. This area faces serious soil erosion problems, resulting in loose soil and fragile farmland ecological environment, and agricultural production is particularly vulnerable to the impact of climate change. Therefore, the "anti-erosion" function of conservation tillage has become the core driving force for technology adoption (Wang et al., 2025). In the black soil region of Northeast China, the core demand for conservation tillage is to alleviate soil compaction and the decline of organic matter (Miao et al., 2025); in the red soil region of South China, the main goal is to improve acidic soil and enhance fertilizer retention capacity (Ngoma et al., 2021). Differences in ecological needs may lead to different paths of influence of skill levels and digital extension. For example, in the black soil region, farmers have higher skill requirements for "no-tillage sowing depth control," and digital tools need to focus on soil compaction monitoring rather than erosion early warning. (3) Regional differences in policy and technological environments. The coverage rate of the "Internet + Smart Rural" project in the research area reaches 78%, and the participation rate of online agricultural technology training is 1.5 times the average level in Northwest China (data from the Ministry of Agriculture and Rural Affairs of China, 2021). This advanced digital infrastructure makes the "skill-digital" interaction effect more significant. In regions with weak digital infrastructure (such as remote mountainous areas in the west), even if farmers have high skill levels, it may be difficult to translate into technology adoption behavior due to insufficient access to digital tools (Van Laar et al., 2020); on the contrary, in regions with perfect digital facilities but low farmer skills (such as the eastern plain grain region), there may be a dilemma of "excess digital services but insufficient utilization" (Zhang et al., 2022). (4) There may be omitted variables in the model specification. Institutional factors such as "participation in agricultural cooperatives" and "land lease duration" have not been included in the control variables of this study. The main reasons for their exclusion are as follows: First, the core of this study focuses on the interactive mechanism between "skill level and digital promotion." Institutional factors, as more exogenous environmental variables, may dilute the effect of core explanatory variables if forcibly included. Second, the coverage rate of agricultural cooperatives in the sample area is relatively low, and land leasing is dominated by short-term transfers, resulting in limited data variability, which may affect the stability of estimation results. Future studies can expand the sample scope and further discuss and test institutional factors in regions where such factors are more prominent (e.g., areas with dense cooperatives or large-scale land transfer areas).

6.2 Future research directions

Although the results of this study have regional specificity, its core logic (with skill level as the foundation, digital extension as the medium, and technical demand as the guide) can provide reference for other regions. The enhancement of universality depends on the deepening of cross-regional comparative studies: (1) Comparison of crop type dimensions. Future research can select growers of different types of crops such as wheat (northern dry farming areas), rice (southern paddy fields), and tea (mountain cash crops) to analyze the differentiated needs of skill elements. For example, food crop growers may rely more on "mechanical operation skills," while cash crop growers need more "quality control and market information analysis skills"; the content of digital extension should also vary according to crops. For instance, for rice growers, the focus is on pushing "water-saving irrigation technology," and for tea growers, the dissemination of "ecological prevention and control knowledge" is strengthened. (2) Expansion of climate and soil type dimensions. In arid and semi-arid regions (such as Gansu and Ningxia), we can explore "how skill levels affect the coordinated adoption of conservation tillage (such as plastic film mulching for moisture conservation) and drought-resistant technologies"; in the black soil region of Northeast China, we can analyze "the role of digital tools in the large-scale promotion of straw returning technology." By comparing the technology adoption mechanisms under different climate zones (monsoon/continental / plateau climate) and soil types (loess/black soil/red soil), we can extract the analytical laws of "skill-digital-technology." (3) Gradient analysis of policy intervention intensity. In the future, we can compare the differences in marginal effects between skill training and digital infrastructure investment in regions with different maturity of digital agricultural extension (such as eastern developed regions vs. western underdeveloped regions), so as to provide a basis for "differentiated resource allocation."

Therefore, the main limitation of this study is the regional constraint of sample representativeness. The technology adoption behavior of melon and fruit growers in Shanxi and Shaanxi is limited by local crop characteristics, ecological pressure, and policy environment, so the results are difficult to be directly extended to other regions of the country. In addition, cross-sectional data are difficult to capture the dynamic evolution effect of skill level and digital extension. In the future, tracking surveys can be used to analyze the interaction between long-term skill accumulation and technological iteration (such as intelligent conservation tillage equipment). Despite these limitations, this study still provides key insights for understanding the technology adoption behavior of cash crop growers in ecologically fragile areas. For similar areas in the Yellow River Basin of China, the policy combination of "skill training + digital precision extension" can be directly used for reference; for regions with large differences, it is necessary to make adaptive adjustments based on the analytical framework of this study and combined with local crop, ecological, and technical characteristics. Ultimately, multi-regional and multi-crop comparative studies will provide more comprehensive scientific support for building a "localized" conservation tillage promotion system.

Data availability statement

The datasets presented in this article are not readily available because other participants are not allowed to make them public. Requests to access the datasets should be directed to feixiang2022@nxu.edu.cn.

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

XD: Conceptualization, Data curation, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. LL: Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Validation, Writing – review & editing. QL: Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Resources, Supervision, Visualization, Writing – review & editing. CB: Formal analysis, Project administration, Software, Supervision, Validation, Writing – review & editing.

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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.

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