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Farmers' adoption of smart agricultural technologies for black soil conservation and utilization in China: the driving factors and its mechanism

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Smart agriculture can mitigate the degradation of black soil organic matter to ensure global food security and promote sustainable agricultural development. However, the adoption of smart agricultural technology for black soil conservation and utilization is poorly understood. This study analyzes the influence mechanisms affecting farmers' adoption intentions of one such technology, variable fertilization. We develop a structural equation model by combining the Technology Acceptance Model (TAM), Perceived Value Theory (PVT), and external factors with data from 354 farmers in Youyi State farm in the Sanjiang Plain Area, China. The results revealed that social influence (SI) was the most significant determinant of farmers' adoption intentions (AI), emphasizing the critical role of social networks, particularly information from experienced demonstration households, in shaping decisions. Additionally, both the perceived usefulness (PU) and perceived ease of use (PEOU) of variable fertilization technology (VFT) significantly and positively influenced AI. Among these, PEOU demonstrated a greater overall impact than PU. We propose strategies for demand-driven, incentive-based, and technical support mechanisms to facilitate the adoption of VFT and conclude with recommendations to promote black soil conservation and utilization technologies among farmers.

KEYWORDS

black soil conservation and utilization, smart agriculture, variable fertilization, farmers' adoption, technology acceptance model

1 Introduction

In 2022, the Food and Agriculture Organization of the United Nations (FAO) released its first global report on black soils, emphasizing their value as one of the most important natural resources.[1] Black soils are rich in organic matter and ideal for crop growth. Globally, black soil regions cover approximately 725 million hectares, about 7% of the earth's ice-free land surface. These regions are found in the Russia-Ukraine Great Plain (1.9 million square kilometers), the Mississippi Plain of the United States (2.9 million square kilometers), the Northeast Plain of

1 FAO: https://www.fao.org.

China (1.09 million square kilometers), and the Pampas of South America (0.76 million square kilometers). However, global climate change, natural disasters, population growth, and human activities have led to significant soil degradation. Most black soils have lost at least half of their soil organic carbon (SOC) stocks and suffer from severe erosion. This degradation creates nutrient imbalances and threatens global food production. Black soil must be preserved for environmental protection, sustainable agricultural development, and global food security. A series of international initiatives have highlighted the need to protect healthy black soils to ensure global food production is increased by 60% by 2050 (Rojas et al., 2016).

In the early 20th century, developed countries began experimenting with modern agricultural technologies for more efficient crop production to achieve large-scale food production (Jayaraman et al., 2015; Small, 2016). Since the 1930s, the United States and Russia have pioneered black soil conservation tillage technology to combat famine caused by excessive reclamation and sandstorms (Ao et al., 2022). These efforts included the use of large-scale plowing machinery and conservation tillage technologies, such as reduced tillage and no-tillage (Mitchell et al., 2009). These advancements have increased the net carbon sink of black soils and stabilized grain production. In the 1960s, countries like the Soviet Union, Canada, Australia, and Mexico also adopted conservation tillage technologies (Kassam et al., 2018). China has focused on conservation tillage since the late 1970s and various national departments have developed innovative black soil conservation and utilization technology. Especially smart agriculture technologies, which integrate advanced tools to create interconnected and data-driven farming ecosystems, present substantial potential to enhance black soil fertility, increase agricultural productivity, optimize resource use, and reduce environmental impacts—addressing critical challenges in sustainable agriculture (Rehman et al., 2024).

There is growing academic and practical interest in large-scale black soil conservation and utilization technologies. Farmers play a crucial role in this process, as they are the primary users and protectors of this technology. The effectiveness of black soil conservation and utilization technologies relies on farmers' intentions to adopt them (Adesina and Chianu, 2002). Farmers' adoption of new soil conservation technology is described as a diffusion process, mainly affected by family characteristics, cultivated land characteristics, and the external environment (Rogers, 1995). While it is difficult to change farmers' personal characteristics, their psychological cognitive limitations can be shifted through external influences (Zhang et al., 2020). Therefore, it is essential to consider the conditions and preferences of different farmer groups to improve overall adoption rates (Jansen et al., 2010; Schut et al., 2015). Education about technology is core to adoption, alongside external environmental interventions that affect farmers' behavioral intentions.

China State Farm, dedicated to specialized agricultural production utilizing regional water and soil resources, is crucial for national food security and agricultural modernization. However, the expansion of production scale and mechanization has led to excessive inputs, resource waste, and environmental pollution. The overuse of chemical fertilizers has resulted in the decreased black soil fertility, non-point source pollution, and increased production costs (Du et al., 2021). There is an urgent need to develop smart agriculture and promote high-quality agricultural development. Variable fertilization technology (VFT), which involves precise fertilization based on spatial data such as yield, soil properties, climate, and pest conditions, is a key component of smart agriculture (Miller et al., 2018). As an essential aspect of smart agriculture, it significantly enhances fertilizer utilization, reduces production costs, boosts farmers' income, and provides substantial economic, environmental, and social benefits. The key to enhancing the protection and utilization efficiency of black soil through variable fertilization technology lies in the effective promotion of the technology and the high adoption rate among farmers.

This paper examines the adoption intentions and promotion mechanisms for VFT, using the Youyi State farm in the Sanjiang Plain Area (the largest contiguous reclamation area in China) as the research site. Focusing on farmers as decision-makers in fertilization behavior, the study extends the Technology Acceptance Model (TAM) to investigate the influencing factors and driving mechanisms behind farmers' intention to adopt VFT, integrating both psychological perception factors and external influences. Our findings offer a scientific basis for the comprehensive promotion of black soil conservation and utilization technology, policy formulation, and sustainable agricultural development. The remainder of this paper is organized as follows: Section 2 reviews relevant literature. Section 3 introduces the theoretical framework and hypotheses. Section 4 describes the study area and data methods. Section 5 and Section 6 present the findings on farmers' intentions to adopt VFT and the driving mechanisms behind these intentions. Section 7 provides conclusions and discussion.

2 Literature review

In the 1930s, the United States began developing conservation tillage technology under severe resource and environmental constraints. Such conservation tillage technology has long-term effects on black soil (Voorhees and Lindstrm, 1984). Scholarly research has primarily centered around conservation tillage (straw and no-tillage), soil and water conservation, and black soil health (Ike, 1986; Sturgul et al., 1990). By the late 1970s, conservation tillage had been implemented globally, with the United States, China, Russia, Canada, and Australia leading black soil conservation research (Guan, 2021; Kazeev et al., 2020; Llewellyn et al., 2012; Zhang et al., 2022). With the advent of modern information and communication technologies in agriculture, the "third green revolution" has emerged (De Baerdemaeker et al., 2023). Smart agriculture leverages information technology—such as the Internet of Things, cloud computing, big data, and artificial intelligence—to enable digitalized and information-driven management across the entire agricultural process (Blackmore and Brit Crop Protect, 1996; Trendov et al., 2019). Early research focused on technological innovations in smart agriculture for crop production (Foster et al., 2015; Zhang and Li, 2002). Later, smart technologies such as automatic guidance, sensors attached to the field, and unmanned aerial vehicles were used for variable operations like quality measurement, fertilization, and irrigation (and were gradually applied to black soil conservation and utilization). Today, smart agriculture involves various aspects of black soil conservation, including variable fertilization, vegetation conservation, precision seeding, and water-saving irrigation. Some scholars focus on the physical and chemical properties of black soil, causes of degradation, ecological management, and protection technologies of black soil (Yang et al., 2023; Yu and Zhang, 2004). Other scholars have found that farmers' psychological expectations about production and management behaviors directly affect the effectiveness of black soil conservation (Chianu and Tsujii, 2005; Guo et al., 2022). Therefore, improving farmers' intentions to adopt black soil conservation and utilization technology and promoting farmers' black soil conservation behavior has become a key issue in academic circles.

Initial research on the factors affecting farmers' adoption of black soil conservation and utilization technology focused on individual characteristics and socioeconomic factors, such as age, gender, education, farmland scale, and income (Hu et al., 2022; Mignouna et al., 2011; Xu and Zhang, 2005; Tey and Brindal, 2012). However, external environmental factors like government policy, trade agreements, market access, and social networks also influence farmers' behavioral decisions (Liu et al., 2021; Wang and Guo, 2020). In Western countries, government policies promoting agricultural environmental protection projects garnered more support from farmers to achieve better black soil conservation results (Burton et al., 2008). Chaudhuri et al. (2021) add that farmers' social networks can also provide information about sustainable practices, promote technology sharing, and address challenges in black soil conservation and utilization.

Farmers' intention to adopt technology is essentially a psychological process of perception, interest, and evaluation (Yang et al., 2023). Therefore, scholars have used psychological models like the Theory of Reasoned Action, Perceived Value Theory (PVT), and Technology Acceptance Model (TAM) to explain farmers' behavioral intentions around black soil conservation and utilization. Caffaro et al. (2020) and Fei et al. (2022) foregrounded the importance of farmers' value judgments about technology adoption, while Jorgensen and Martin (2015) used the Theory of Reasoned Action to explain how perceptions impact farmers' intentions to use irrigation systems. Khoza et al. (2021) extended TAM to determine the perceived risk in adopting conservation tillage technology and found that social processes were central to farmers' decision-making.

TAM explains individuals' acceptance of information technology based on perceived usefulness and perceived ease of use (Davis et al., 1989). However, it does not account for risk perceptions. Therefore, this study expands TAM by incorporating perceived risk factors from Perceived Value Theory (including perceived usefulness, perceived ease of use, and perceived risk). Additionally, research on technology adoption often focuses on internal psychological factors or a single external factor. However, the adoption of black soil conservation and utilization technology is a dynamic process influenced by many internal and external factors (e.g., unstable family interactions, social network coverage, and policy changes). Therefore, we consider both psychological and external factors (i.e., policy support, social influence, and household management characteristics) to better understand the behavioral factors and external environmental interventions that influence farmers' adoption of black soil conservation and utilization technology.

3 Theoretical analysis and hypotheses

3.1 TAM

The Technology Acceptance Model (TAM) was first developed by Davis (1985) based on the Theory of Reasoned Action (TRA) (Fishbein and Ajzen, 1977) and the Theory of Planned Behavior (TPB) (Ajzen, 1980). TAM considers the mediating role of two variables—perceived usefulness and perceived ease of use—on external variables and the potential use of technology (Marangunic and Granic, 2015). It is widely used to explain and predict users' acceptance of information systems. For TAM, a person's attitude about a technology and their behavioral intention to use it are influenced by the individual's "descriptive beliefs" and "reasoning beliefs," TAM assumes two specific beliefs: "perceived ease of use" and "perceived usefulness." Thus, an individual's behavioral intention is affected by behavioral attitudes, direct and indirect perceived usefulness, and perceived ease of use (Ducey and Coovert, 2016).

3.1.1 Perceived usefulness (PU)

Perceived usefulness considers whether a new technology will improve work efficiency (here, it refers to the perceived benefits of black soil conservation and utilization technology). Mohd et al. (2010) showed a significant positive correlation between PU and behavioral intention—farmers are more likely to adopt black soil conservation and utilization technology if they recognize its economic benefits (if not, their willingness decreases).

While farmers recognize the importance of black soil conservation, most still rely on large-scale fertilization to increase food production. Over time, excessive use of chemical fertilizers adversely affects soil quality through soil acidification. When farmers recognize that black soil conservation and utilization technology can save on fertilizer and improve the black soil quality, they are more willing to adopt new technologies. Therefore, we propose the following hypothesis:

> *H1*: Perceived usefulness has a significant positive impact on adoption intention.

3.1.2 Perceived ease of use (PEOU)

New technologies require time, effort, and money to learn. Therefore, perceived ease of use asks whether people find it easy to adopt new technology. A higher perceived ease of use reduces farmers' anxiety about new technologies (Sorebo and Eikebrokk, 2008), thereby enhancing their willingness to adopt. Farmers are more willing to adopt simple and easy technologies. There is also a positive correlation between perceived ease of use and perceived usefulness, with perceived ease of use indirectly affecting adoption intention through perceived usefulness (Wu and Wang, 2005). Therefore, we propose the following hypotheses:

> *H2*: Perceived ease of use has a significant positive impact on adoption intention.
>
> *H3*: Perceived ease of use has a significant positive impact on perceived usefulness.

3.1.3 External variables

The original TAM model does not explain how external variables affect individual behavioral intentions (Venkatesh and Davis, 2000). Therefore, scholars have advocated expanding TAM to understand how external variables affect an individual's psychological expectations of new technologies. Such insights have been incorporated into the model as influences on perceived usefulness and perceived ease of use (King and He, 2006). Situational factors like social influence, policy environment and household characteristics also affect behavioral intention and should be included as regulatory factors (Abbasi et al., 2011; Chang et al., 2007). Therefore, this study adds three external variables—social influence, policy support, and household management characteristics— to better explain the factors affecting farmers' intention to adopt black soil conservation and utilization technology.

Social influence (SI) is defined as the degree to which people in the surrounding environment believes that a person should use a new technology (Venkatesh et al., 2003). Individual behavioral intention is influenced by the behaviors of other people in one's social network, with social influence playing a complex role in adoption decisions (Ajzen and Driver, 1991). Social influence significantly shapes perceived usefulness and perceived ease of use (Adnan et al., 2017). The opinions of neighbors, friends, demonstration households, and farm workers influence farmers' perceptions of black soil conservation and utilization technology availability and risk (Li, 2012). We propose the following hypotheses:

> *H4a*: Social influence has a significant impact on perceived usefulness.
>
> *H4b*: Social influence has a significant impact on perceived ease of use.

Policy support (PS) considers government incentives and normative systems. Farmers, as rational economic agents, make decisions to maximize their interests. Therefore, government subsidies for agricultural machinery significantly promote farmers' adoption of new technologies (e.g., conservation tillage) (Guo et al., 2022). Improved government policy support for black soil conservation and utilization technology alleviated farmers' funding and capacity issues, boosting their confidence and promoting adoption intentions. We propose the following hypotheses about the regulatory role of policy environment variables:

> *H5a*: Policy support has a significant impact on perceived usefulness.
>
> *H5b*: Policy support has a significant impact on perceived ease of use.

Household management characteristics (HMC) research shows that the scale of cultivated land management significantly impacts farmers' adoption of new technologies (Xia et al., 2019). Larger farms allow farmers to leverage economies of scale that encourage black soil conservation and utilization technology. Farming income also affects whether farmers can afford technical investments. Therefore, we propose the following hypotheses:

> *H6a*: Household management characteristics have a significant impact on perceived usefulness.
>
> *H6b*: Household management characteristics have a significant impact on perceived ease of use.

3.2 Perceived value theory

Zeithaml (1988) first proposed the Perceived Value Theory to posit that consumers' behavioral intentions depend on the perceived value of products and services. This theory hinges on the trade-off between perceived benefits and perceived risk. Farmers are generally risk-averse and have low awareness and acceptance of new technologies, so any risk farmers perceive significantly affects their adoption intentions (Wang and Wang, 2021). Therefore, we incorporated perceived risk into the influencing factors.

Perceived risk (PR) refers to an individual's attitude about potential risks that may arise from adopting new technologies (Zhang et al., 2012). Perceived risk is a determinant of technology acceptance (Poortvliet et al., 2018). Farmers' perceptions of risk might convince them that adopting black soil conservation and utilization technology is difficult and, thus, inhibit their perceived ease of use (Wang and Wang, 2021). However, a favorable external environment might positively influence farmers' risk perception. Therefore, we propose the following hypotheses:

> *H4c*: Social influence has a significant impact on perceived risk.
>
> *H5c*: Policy support has a significant impact on perceived risk.
>
> *H6c*: Household management characteristics have a significant impact on perceived risk.
>
> *H7*: Perceived risk has a significant negative impact on adoption intention.
>
> *H8*: Perceived Risk has a significant negative impact on perceived ease of use.

4 Materials and methods

4.1 Study area

The Sanjiang Plain is a crucial commercial grain supply base for China. In 2023, its total grain output is projected to reach 2.99 million tons, with the commodity rate surpassing 90%. Moreover, it serves as an essential strategic hub for agricultural modernization. It is a central demonstration zone for black soil conservation and utilization technologies, as well as a leader in research on smart agricultural technologies. This study was conducted at the Youyi State Farm situated in the Sanjiang Plain Area, between 46°28′N and 46°58′N, 131°27′E–132°15′E. It encompasses 11 management areas and 90 operation stations. It is an agricultural organization composed of numerous small farms operated by individuals, who are able to make their own farming-related decisions. The total agricultural output value reached 3.54 billion yuan, reflecting an average annual increase of 22.5% compared to 2020 (Beidahuang Agricultural Reclamation Group Co., Ltd, 2023). Youyi Farm is a model area for black soil conservation and utilization due to its concentrated and contiguous cultivated land, rich black soil resources, and high degree of agricultural mechanization and it serves as a key demonstration site for black soil conservation and utilization technology.

4.2 Data source

The research team conducted a field survey at Youyi Farm in September 2023. The study area encompassed all 11 management areas, with approximately 30 people randomly sampled from each area. The interviews were conducted face-to-face to accommodate farmers of all education levels. The questionnaire collected information in four areas: household characteristics, agricultural production conditions, fertilization conditions, and understanding of VFT. A total of 363 questionnaires were collected; 354 of these questionnaires were valid, resulting in a 97.5% recovery rate. Additional interviews with farm managers and management area leaders provided deeper insights into the farm's black soil conservation and utilization technology measures.

We examined the factors influencing farmers' willingness to adopt VFT using the TAM and PVT frameworks. After consulting existing research (Ajzen and Driver, 1991) and considering the empirical situation, we developed six latent variables: perceived usefulness, perceived ease of use, perceived risk, social influence, policy support, and household management characteristics. The questionnaire utilized a five-point Likert scale ("very disagree," "disagree," "general," "agree," and "very agree"). The management characteristics (i.e., cultivated land area and annual household income) were expressed quantitatively, while the demand degree for precision fertilization was assigned a rating of 1–5. Adoption intention was measured as "unwilling" (0) or "willing" (1). The specific index variables and statistics are presented in Table 1.

4.3 Structural equation model

The structural equation model (SEM) is a multivariate statistical technology that outperforms traditional measurement methods in assessing multiple causal relationships between observed variables, latent variables, and error variables (Wang et al., 2019). Unlike traditional methods, SEM allows both independent and dependent variables to contain measurement errors. The SEM consists of two parts: the measurement model, which reflects the relationship between latent variables and observed variables, and the structural model, which reflects the interaction between latent variables. The following equations were established to explore the relationship between farmers' intention to adopt VFT and various abstract variables:

$$\eta = \mathrm{B}\eta + \Gamma\xi + \zeta \tag{1}$$

$$X = \Lambda_x \xi + \sigma \tag{2}$$

$$Y = \Lambda_y \eta + \varepsilon \tag{3}$$

In Equation 1, η represents the endogenous latent variable, and ξ represents the exogenous latent variable. In this study, the exogenous latent variables are PU, PEOU, PR, and the external variables. The endogenous latent variable is the farmer's intention to adopt VFT. Γ represents the influence of exogenous latent variables on endogenous latent variables; B represents the relationship between endogenous latent variables; ζ is the error vector. In Equations 2, 3, X and Y are the observable variables of ξ and η, respectively. Λ_x and Λ_y reflect the factor loading coefficients of x to ξ and y to η, respectively. σ and ε represent the measurement errors of x and y, respectively.

5 Results

5.1 Descriptive statistics

By investigating and analyzing the individual characteristics of farmers (e.g., age, education, farming experience, cultivated land area, etc.), we can gain a comprehensive understanding of farmers' profiles. This provides a solid foundation for further analysis of the factors influencing farmers' intention to adopt VFT. We found that 81.6% of farmers were willing to adopt VFT. The mean age of farmers was 47 years, with the largest proportion (42.98%) in the age category of 45–55 years. Most respondents were middle-aged. Most respondents had a low level of education: 7.16% had elementary school or below, while 49.86% had only lower secondary school education. However, some farmers (19.56%) had obtained a college or higher degree. The mean farming experience was 23 years, and the average annual household income was 269,900 yuan. Notably, 15.53% of the farmers had an annual household income exceeding 500,000 yuan, indicating that these farmers were large plantation growers with significant agricultural revenue. The mean cultivated land area was 13.45 hectares; 50% of the farmers had fewer than 10 hectares. Most of the farmers owned drylands (69.52%), while 24.21% owned paddy fields. A small number (6.27%) owned both drylands and paddy fields.

5.2 Assessment of measurement model

We first validated the measurement model and then the structural model. We used SPSS 26.0 software to conduct an exploratory factor analysis, obtaining a KMO value of 0.902 ($p < 0.001$), indicating suitability for factor analysis (generally, KMO > 0.5 is considered acceptable). To verify the rationality of the data dimensions, six common factors were extracted through factor rotation, with a cumulative variance contribution rate of 65.524% (>50%), consistent with the scale dimensions shown in Table 1. We performed a Confirmatory Factor Analysis (CFA) to evaluate the scales' reliability and validity, including composite reliability (CR), average variance extracted (AVE), and discriminant validity indicators.

According to Bagozzi et al. (1981), Cronbach's alpha coefficient (>0.6) and CR measure the internal consistency of each dimensional indicator. High CR values indicated high internal consistency, with 0.7 being the minimally acceptable threshold. The square root value of AVE for each construct must be greater than its correlation with other constructs, and AVE values must be higher than 0.5. As shown in Table 2, Cronbach's alpha values ranged from 0.608 to 0.847, and CR values ranged from 0.814 to 0.962, indicating that the construct is reliable. All AVE values were greater than 0.5, suggesting acceptable convergent validity. AVE values were larger than all other cross-correlations for the sample (Table 3). Additionally, the goodness of fit criteria for the structural model were evaluated using Amos 26.0, as indicated in Table 4. The Chi-square value (Chi-square = 1.855, p-value

TABLE 1 Latent variables, measurement items, and descriptive statistics.

Latent variable	Observational variable	Category coding	Variable description	Mean	Standard deviation
Perceived usefulness	Variable fertilization technology can save input costs.	PU1	1 = very disagree; 2 = disagree; 3 = general; 4 = agree; 5 = very agree	3.70	1.04
	Variable fertilization technology is conducive to increasing production.	PU2		3.65	1.06
	Variable fertilization technology can effectively improve crop quality.	PU3		3.53	1.05
	Variable fertilization technology can effectively improve soil quality.	PU4		3.60	0.97
	Variable fertilization technology can effectively improve the quality of the ecological environment.	PU5		3.41	1.14
Perceived ease of use	I think variable fertilization technology is easy to master.	PEOU1		3.14	1.15
	Under current economic conditions, I can afford the capital investment for variable fertilization technology.	PEOU2		2.82	1.17
	The variable fertilization technology application is very convenient, can save time and effort, and improve efficiency.	PEOU3		3.51	1.13
	I have enough time and energy to adopt variable fertilization technology.	PEOU4		3.23	1.18
	With adequate publicity on the farm, I will be more willing to use variable fertilization technology.	PEOU5		3.60	1.04
	With adequate training on the farm, it will be easier for me to master the principles of variable fertilization technology.	PEOU6		3.68	1.07
Perceived risk	I am worried about the complexity of variable fertilization technology.	PR1		2.97	1.12
	I am concerned about the high cost of modifying agricultural machinery for variable fertilization technology.	PR2		2.93	1.16
	I am worried about the difficulty in leasing agricultural machinery and equipment for variable fertilization technology.	PR3		2.95	1.11
	I am worried that variable fertilization technology will not significantly increase profits.	PR4		2.93	1.13
Policy support	The government's green fertilization policy will encourage me to adopt variable fertilization technology.	PS1		3.79	0.97
	The government's subsidy for the transformation of variable fertilization agricultural machinery and equipment will encourage me to adopt variable fertilization technology.	PS2		4.05	0.97
	The government's preferential policies on capital loans will encourage me to adopt variable fertilization technology.	PS3		3.65	1.14
Social influence	I will refer to the guidance provided by farm managers when deciding whether to adopt variable fertilization technology.	SI1		3.39	1.11

(Continued)

TABLE 1 (Continued)

Latent variable	Observational variable	Category coding	Variable description	Mean	Standard deviation
	Whether I am willing to adopt variable fertilization technology, I will be influenced by my family, friends, and neighbors.	SI2		3.89	1.03
	Whether I am willing to adopt variable fertilization technology, I will be influenced by the demonstration households.	SI3		3.66	1.07
	I will be influenced by the guidance of technicians or expert teams when deciding whether to adopt variable fertilization technology.	SI4		3.84	1.05
Household management characteristics	Cultivated area	CA	hm^2	13.55	12.20
	Annual household income	FAI	yuan	269,900	268,300
	The need for variable fertilization technology	PF	1 = very unnecessary; 2 = unnecessary; 3 = general; 4 = necessary; 5 = very necessary	3.81	1.13
Adoption intention	Are you willing to adopt variable fertilization technology?	AI	0 = unwilling; 1 = willing	0.82	0.39

TABLE 2 Item loadings, CR, AVE and Cronbach's alpha.

Variables	Items	Item loading	CR	AVE	Cronbach's alpha
Perceived Usefulness (PU)	PU1	0.671	0.838	0.510	0.751
	PU2	0.729			
	PU3	0.626			
	PU4	0.751			
	PU5	0.782			
Perceived Ease of Use (PEOU)	PEOU1	0.666	0.862	0.514	0.831
	PEOU2	0.745			
	PEOU3	0.601			
	PEOU4	0.633			
	PEOU5	0.797			
	PEOU6	0.829			
Perceived Risk (PR)	PR1	0.820	0.833	0.561	0.608
	PR2	0.858			
	PR3	0.598			
	PR4	0.690			
Policy Support (PS)	PS1	0.773	0.814	0.594	0.787
	PS2	0.756			
	PS3	0.782			
Social Influence (SI)	SI1	0.742	0.836	0.560	0.847
	SI2	0.727			
	SI3	0.776			
	SI4	0.748			
Household Management Characteristics (HMC)	CA	0.968	0.926	0.808	0.609
	FAI	0.968			
	PF	0.742			

TABLE 3 Correlations and average variance extracted (AVE).

	PS	SI	HMC	PR	PU	PEOU
PS	**0.771**					
SI	0.558	**0.748**				
HMC	0.385	0.366	**0.899**			
PR	0.57	−0.745	−0.027	**0.749**		
PU	0.376	0.642	0.014	0.151	**0.714**	
PEOU	0.224	0.235	0.046	0.071	0.392	**0.717**

The bold value is the square root value of AVE.

TABLE 4 Models evaluation overall fit measurement.

Goodness of fit measure	Recommended values	Model results
Chi-square/degree of freedom (X^2/df)	<5	1.855
Root mean square error of approximation (RMSEA)	<0.05	0.049
Goodness of fit (GFI)	>0.9	0.900
Root mean square residual (RMR)	<0.08	0.042
Normed fit index (NFI)	>0.9	0.900
Comparative fit index (CFI)	>0.9	0.945
Incremental fit index (IFI)	>0.9	0.946
Parsimonious normed fit index (PNFI)	>0.5	0.766
Comparative parsimony correction index (PCFI)	>0.5	0.814
Adjust goodness of fit (AGFI)	>0.9	0.869
Parsimonious goodness fit index (PGFI)	>0.5	0.714

<0.001) and various fit indices met the requirements of model construction, implying that the model has a good fit. The results showed that the model has acceptable internal consistency, reliability, convergent validity, and discriminant validity. Our data fits the hypothetical model well and can be used to analyze the structural model.

5.3 Factors influencing farmers' adoption intentions to use VFT

After we validated the measurement models, we used the structural model to test the hypotheses. We used SEM to analyze the major factors influencing farmers' intentions to adopt VFT. The results from the path analysis of the hypotheses are presented in Table 5 and Figure 1. The results show that PU ($\beta = 0.338$, $p < 0.001$) and PEOU ($\beta = 0.230$, $p < 0.001$) had positive and statistically significant impacts on AI, confirming hypotheses H1 and H2. PEOU directly affects farmers' intention to adopt VFT and indirectly affects AI via PU ($\beta = 0.407$, $p < 0.001$), supporting H3. We did not find a significant impact of PR ($\beta = -0.025$, $p = 0.620$) on AI, leading to the rejection of hypothesis H7. However, PR ($\beta = -0.034$, $p < 0.001$) was found to have a negative significant impact on PEOU and indirectly affect AI via PEOU, supporting H8.

Most external variables significantly affected the farmers' adoption intention through PU, PEOU and PR. Social influence (SI) was found to have a positive impact on PU ($\beta = 0.665$, $p < 0.01$) and PEOU ($\beta = 0.583$, $p < 0.001$) and a negative impact on PR ($\beta = -0.186$, $p < 0.001$), supporting H4a, H4b and H4c. Similarly, policy support (PS) positively affected PU ($\beta = 0.529$, $p < 0.05$) and PEOU ($\beta = 0.179$, $p < 0.001$) and negatively affected PR ($\beta = -0.207$, $p < 0.001$), consistent with hypotheses H5a, H5b and H5c. Finally, household management characteristics (HMC) significantly impacted PEOU ($\beta = 0.049$, $p < 0.001$) and PR ($\beta = -0.090$, $p < 0.001$), supporting H6b and H6c. However, HMC ($\beta = 0.029$, $p = 0.547$) had no significant effect on PU (H6a was rejected). The findings demonstrated that SI had the greatest direct effect on PU and PEOU—positive reputations, delivered through acquaintance networks, significantly affected farmers' perceptions of VFT.

This study also examined the total effects of some explanatory variables on the dependent variables. Table 6 presents a comparison of the effect sizes of the paths from the external variables to AI and from PU, PEOU, and PR to AI. PU (0.34) had the greatest direct impact on AI of all the variables, including PEOU (0.23) and PR (−0.03). However, our study found that the indirect effect value of PEOU on AI through PU was 0.137, and the total effect value of PEOU on AI was 0.367, leading to a higher total effect value than PU (0.338) on AI. The external variables had no direct effect on AI, but they all indirectly affected AI through PU, PEOU, and PR. The external variables displayed multiple paths of impact on AI, so their total effect should not be underestimated. The total effect of SI on AI, through PU, PEOU, and PR, was 0.444—much higher than the total effect of PS (0.075) and HMC (0.031) on AI. In summary, the total effect of all variables on AI was, from highest to lowest: SI, PEOU, PU, PS, PR, and HMC.

TABLE 5 Results of hypotheses testing.

Hypotheses				Std. Estimate	S.E.	C.R.	*p*	Result
H1	AI	←	PU	0.338	0.098	1.999	***	Support
H2	AI	←	PEOU	0.230	0.075	1.450	***	Support
H3	PU	←	PEOU	0.407	0.22	1.688	***	Support
H4a	PU	←	SI	0.665	0.292	2.346	**	Support
H4b	PEOU	←	SI	0.583	0.193	3.940	***	Support
H4c	PR	←	SI	−0.186	0.244	−0.502	***	Support
H5a	PU	←	PS	0.529	0.257	1.406	*	Support
H5b	PEOU	←	PS	0.179	0.168	0.890	***	Support
H5c	PR	←	PS	−0.207	0.214	−0.547	***	Support
H6a	PU	←	HMC	0.029	0.030	0.603	0.547	Reject
H6b	PEOU	←	HMC	0.049	0.032	1.275	***	Support
H6c	PR	←	HMC	−0.090	0.043	−1.173	***	Support
H7	AI	←	PR	−0.025	0.036	−0.496	0.620	Reject
H8	PEOU	←	PR	−0.034	0.044	−1.170	***	Support

*, **, and *** indicate significance at the 5%, 1%, and 0.1% levels, respectively.

6 Driving mechanisms for the adoption of variable fertilization technology

While VFT was still in the early stages on the farm, we found that the main factors influencing farmers' intention to adopt VFT were a lack of significant favorability about this technology and a failure to meet their actual needs. Therefore, farmer behavioral intentions and decision-making directly affect the implementation of technology. The large-scale implementation of VFT ought to consider how external dynamic mechanisms affect farmers' behavioral intentions. This section explores three such mechanisms—demand-driven mechanism, incentive-based mechanism, and technical support mechanism—to encourage a more effective implementation of VFT.

6.1 Demand-driven mechanism

Agricultural technology passively accepted by farmers generally leads to issues of technical homogenization. The demand-driven mechanism promotes the application of VFT based on farmers' actual needs. Under this system, problems encountered by farmers are quickly reported to agricultural technology promotion centers, and solutions are developed by research and development (R&D) institutions. Farmers' acceptance of VFT converts theoretical results into productivity. Factors such as farmer skills, knowledge, economic status, and cultivated land area affect psychological expectations of VFT, resulting in variations in PEOU. Farmers with high mechanization levels may prioritize VFT's cost-saving and profit-maximizing features. In contrast, small-scale farmers may exhibit blind conformity; their needs focus on minimizing investment and maximizing benefits, and they are easily affected by social networks.

The demand-driven mechanism includes the R&D system, extension system, and farmer system, where the farmer system determines the operation direction of the R&D and extension systems. The extension system, composed of promotion personnel, connects with the farmer and R&D systems through training, experimentation, and information feedback. The agricultural technology promotion center strengthens testing and demonstration activities to address farmers' technical needs. This approach directly reflects the economic benefits of VFT, improves farmers' awareness, and leverages social networks to spread positive reputations. Extension personnel listen carefully to farmer feedback, provide reliable information for the R&D system, and become a medium of interaction between technological personnel and farmers. The R&D system, composed of universities and research institute personnel, focus on the actual needs of VFT obtained by the extension system, especially whether this technology meets the needs of farmers with varying amounts of land. The R&D system and extension system also carry out technical implementation guarantees according to the technical needs of farmers. The farmer feedback direct promotion personnel and scientific researchers in a bottom-up information transmission path.

6.2 Incentive-based mechanism

State-owned farms depend on both state and market influences. They should leverage advantages in agricultural machinery, technology, scale, and brand management. The incentive-based mechanism formulates benefit distribution policies and behavioral norms to achieve grain production goals and indirectly facilitate new agricultural technologies' effective implementation.

VFT reduces chemical fertilizer use and improves black soil quality but does not generate obvious external benefits for farmers immediately. Farmers' primary concerns are the costs of VFT and agricultural machinery subsidies since adopting VFT may require modifying existing machinery or purchasing costly new equipment. Despite supportive policies, farmers often face long subsidy cycles and insufficient subsidy amounts. Given the unique administrative management of state-owned farms, Beidahuang Group, the parent company of state farms in Heilongjiang, can adjust subsidy policies for

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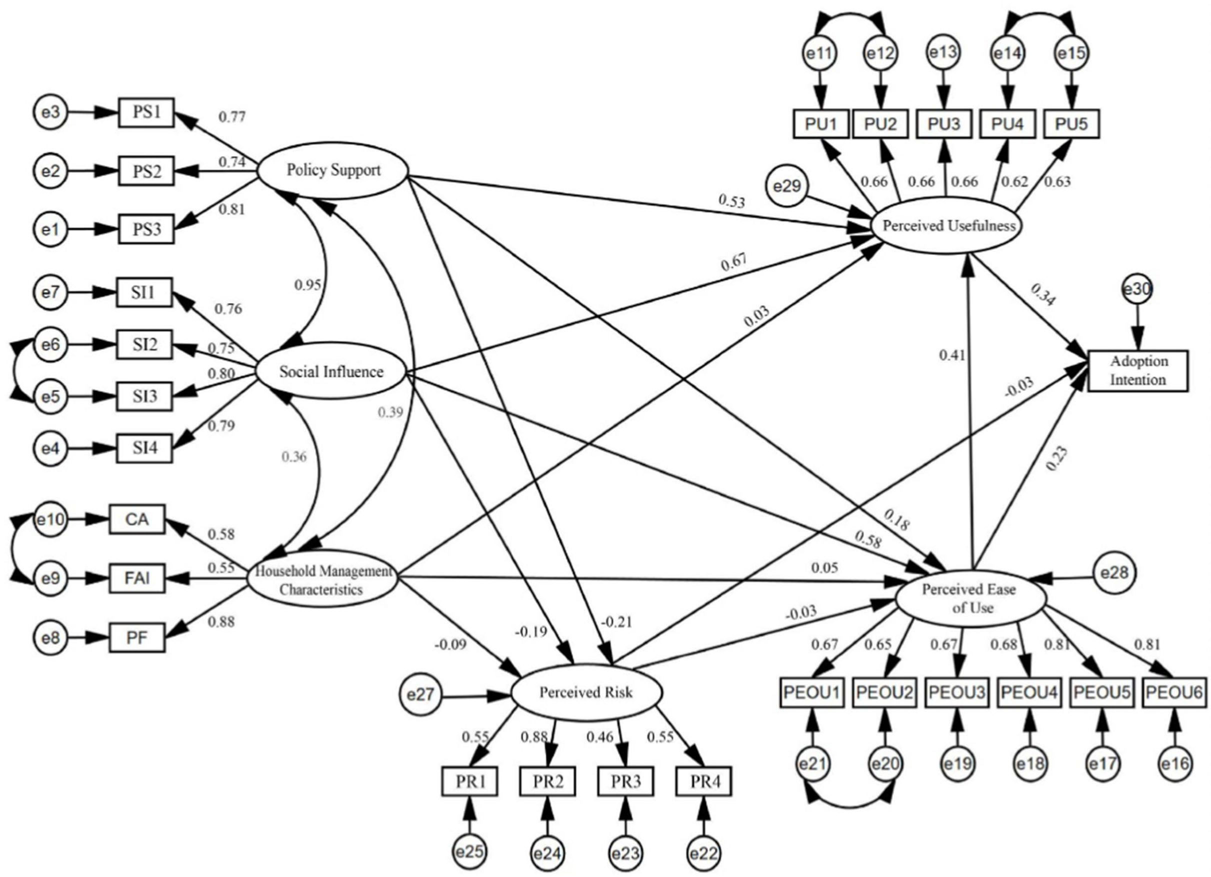

FIGURE 1
Structural equation modeling and path coefficients between variables.

agricultural branches within national policy compliance. It is essential to implement subsidies for purchasing variable fertilization equipment, categorize machinery by modification and purchase to adjust subsidy amounts. Beidahuang Group might also provide low-interest loans for agricultural machinery. It is suggested that demonstration households participating in the pilot projects receive free upgrades for variable fertilization machinery and allocated subsidy funds. Meanwhile, farmers can evaluate promotion personnel and institutions based on service effectiveness. The farm implements an incentive chain for VFT, establishes performance systems and project management systems within the agricultural technology service center, and links promotion personnel's labor performance to technology promotion outcomes.

Policy-driven incentives can significantly enhance farmers' adoption intention, but full policy implementation and large-scale adoption require constraint mechanisms around behavioral norms. During our interviews with farm managers, we learned that farmers could select a unified supply and purchase model for seeds, fertilizers, and other production means implemented by the farm. Hence, there is a need to establish reasonable pricing for seeds, fertilizers, pesticide, agricultural machinery, etc. It is also urgent to establish and improve the management rules and regulations of agricultural technology promotion to ensure that the relevant subsidies for VFT can be implemented to reduce farmers' anxiety about the risk of VFT funds. While the cooperation between farms and agricultural machinery companies is mainly profit-oriented, it should heed fair and just competition, control the quality and price of agricultural machinery, and strictly formulate a matching accountability mechanism. This would promote the effective implementation of VFT and ultimately contribute to a top-down interest transmission path.

6.3 Technical support mechanism

VFT is independently developed by university and research institutions cooperating with farms. The effective transformation of its scientific and technological achievements depends on whether farms and agricultural machinery enterprises have become a community of interest and whether the effectiveness of VFT meets the needs of farmers' agricultural production. The survey revealed VFT issues like imperfect mechanical precision, insensitive signal induction, and equipment blockage due to muddy soil. Therefore, technical personnel promptly communicate with farmers, report to cooperative enterprises, and improve the prescription map. Farms need agricultural machinery manufacturers to address equipment problems effectively.

The promotion process spreads from demonstration households to surrounding regions. Initially, farmers' PU of VFT was low, necessitating effective technology transfer to improve adoption intention. The farm allowed the agricultural technology promotion center personnel to distribute relevant data to the farmers. Technical achievements were publicized through the internet, self-media, and seminars to mobilize farmers to visit the demonstration area. At the

TABLE 6 Direct and indirect effects on variables.

Variable	Effect											
	PU			PEOU			PR			AI		
	Direct	Indirect	Total	Direct	Indirect	Total	Direct	Indirect	Total	Direct	Indirect	Total
PS	0.529*	0.076*	0.605*	0.179***	0.007***	0.186***	−0.207***		−0.207***		0.075***	0.075***
SI	0.665**	0.237**	0.902***	0.583***	0.006***	0.589***	−0.186***		−0.186***		0.444***	0.444***
HMC	0.029	0.02	0.049	0.049***	0.003***	0.052***	−0.09***		−0.09***		0.031*	0.031*
PR		−0.013***	−0.013***	−0.034***		−0.034***				−0.025	−0.024	−0.049
PEOU	0.407***		0.407***							0.23***	0.137***	0.367***
PU										0.338***		0.338***

*, **, and *** indicate significance at the 5%, 1%, and 0.1% levels, respectively.

same time, the farm mobilized promotion personnel to carry out technical demonstration and training activities and discuss the VFT experience by organizing expert lectures and demonstration household exchange meetings. These events cultivated the habit of providing active and timely feedback to the agricultural technology promotion center.

In summary, the successful implementation and promotion of VFT should prioritize the involvement of the government and the Beidahuang Group. These entities play a crucial role in formulating relevant policies and providing financial incentives to support the black soil conservation and utilization strategy. Additionally, they facilitate the advancement and optimization of VFT in colleges and scientific research institutions. Ensuring reasonable benefit guarantees for VFT will help meet farmers' demand for its adoption. Simultaneously, the agricultural technology promotion center enhances the technical support system and subsidy policies for VFT by collecting and submitting farmers' feedback during its implementation to higher authorities. This feedback loop enables continuous improvement in VFT application. As a result, a two-way technological communication framework is created between the incentive-based mechanism, the technical support mechanism, and the demand-driven system (Figure 2).

7 Conclusions and discussion

This study offers an extended framework to analyze the driving forces behind farmers' adoption intention of VFT using TAM supplemented by PVT and external factors. The SEM was used to predict farmers' intention to adopt VFT through the mediation of PU and PEOU. We found that social influence had the most significant impact, meaning that a social network was necessary to persuade most farmers to adopt VFT. This finding echoes previous work on how farmers benefit from opportunities to communicate and learn from each other (Caffaro et al., 2020; Krishnan and Patnam, 2014). Farmers valued reliable information from demonstration households, relatives, friends, promotion centers and researcher who had already adopted or been familiar with VFT.

When farmers received useful information about VFT, they were more likely to make behavioral intention decisions about it. Perceived usefulness and perceived ease of use both had a significant positive impact on adoption intention (see also Nguyen Khanh et al., 2022; Rezaei et al., 2020). Perceived ease of use had a higher path coefficient than perceived usefulness for the total effect indicating that in the early stage of promotion, farmers' willingness to adopt this technology depended heavily on their perceived ability to use it. If farmers perceived that the technology was difficult or impossible to adopt, their willingness significantly weakened. Therefore, agricultural technology promotion centers should focus on demonstrating how VFT can increase economic benefits and reduce production cost. We also found that perceived risk did not have a direct effect on adoption intention. However, it can indirectly influence adoption intention through perceived ease of use, which aligns with the findings of Wang and Wang (2021). This is likely because the case study farm had full insurance for food crops such as rice, corn, and soybeans in response to natural disasters, as well as an "insurance + futures" planting income insurance project to ensure maximum economic benefits for farmers. Our study also confirmed that policy support significantly impacts adoption intention.

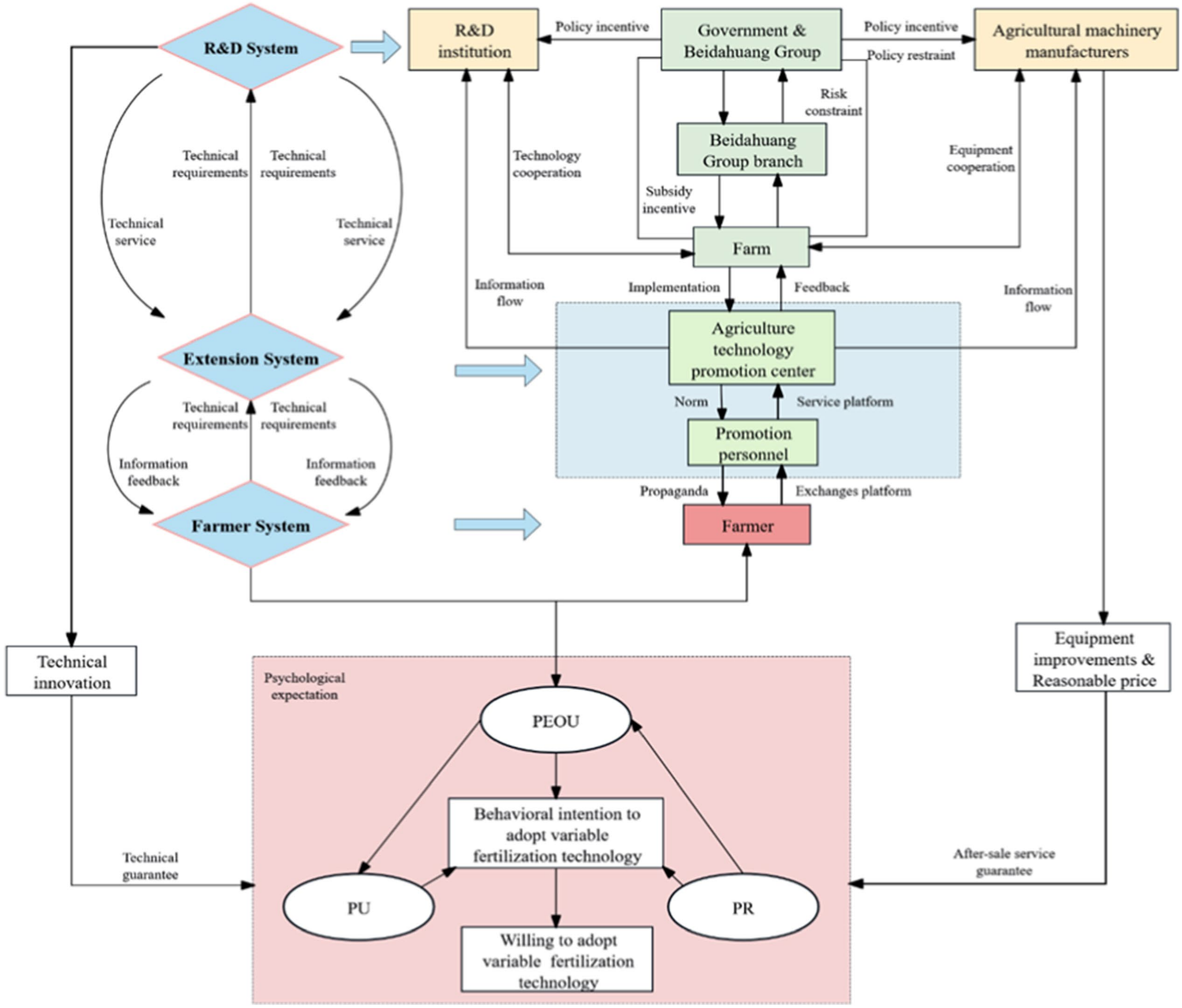

FIGURE 2
The driving mechanisms of the adoption of variable fertilization technology.

We conclude with recommendations for promoting black soil conservation and utilization technology. Firstly, it is necessary to establish technical management mechanisms and implement classification management for the various innovative black soil conservation and utilization technologies (i.e., how each performs in soil and water conservation, water saving and fertilizer saving, variety breeding, tillage methods, and disaster prevention). A diversified subsidy strategy also could be implemented to increase subsidies for agricultural machinery purchases, land fertility protection, crop rotation subsidies, etc. Improving the grain subsidy system and guiding farmers to adjust planting structures according to market demand will reduce production costs and enhance competitiveness. As it becomes increasingly evident that more sustainable approaches are needed to maintain reasonable grain prices and safeguard the benefits of grain farmers. At the same time, preferential policies in finance, credit, and insurance would be strengthened to increase investment in black soil conservation and utilization technology funds, encourage commercial banks to participate in agricultural credit, and jointly establish a low-interest loan system for agricultural machinery, a sound agricultural insurance system, and more comprehensive risk guarantees when implementing black soil conservation and utilization technology.

Second, focusing on the farm-level, a bottom-up information transmission path could usher technical feedback from farmers using black soil conservation and utilization technology to promotion personnel and R&D teams. Farms invite technical R&D experts for demonstrations and guidance, and promotion centers solve farmers' problems by passing technical blind spots on to the R&D team. The promotion center use internet platforms and self-media to release public information on black soil conservation technology knowledge, advantages, models, and implementation measures. Regular online videos, offline exchange meetings, and expert lectures can improve farmers' mastery of black soil conservation and utilization technology. It is best to perform personalized recommendations about black soil conservation and utilization technology based on a farmer's land quality and agricultural production conditions to ensure comprehensive information dissemination. Finally, it is of great necessity to make full use of mechanized state-owned farms, establish a black soil conservation and utilization technology demonstration area, and conduct field tests to share views and experiences of demonstration households. This would form an "acquaintance network" among demonstration households, neighbors, relatives, and friends. Such a network will help farmers conveniently understand the principles and advantages and enhance their recognition, autonomy, and enthusiasm for black soil conservation and utilization technology.

Data availability statement

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

Author contributions

JY: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft. JL: Conceptualization, Formal analysis, Investigation, Supervision, Writing – review & editing, Data curation. KL: Writing – review & editing. SH: Investigation, Writing – review & editing. YL: Investigation, Writing – original draft. ZZ: Investigation, Writing – original draft.

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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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