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# Bridging the digital divide for sustainable agriculture: how digital adoption strengthens farmer livelihood resilience

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**Introduction:** Agricultural systems worldwide face intensifying pressures from climate change, market volatility, and resource degradation, making farmer livelihood resilience—the capacity to maintain and adapt livelihood strategies under disturbances—crucial for sustainable development. This study examines how digital technology adoption affects farmer livelihood resilience in China's evolving agricultural landscape.
**Methods:** We surveyed 1,395 grape farmers in Liaoning Province, China, employing a multi-stage stratified random sampling approach. Using econometric methods within a sustainable livelihoods framework, we analyzed digital adoption across three dimensions (production, sales, and financial services) and its impact on five livelihood capital types (financial, physical, natural, human, and social capital). Instrumental variable approaches addressed potential endogeneity concerns.
**Results:** Digital adoption significantly enhanced farmer livelihood resilience, with digital sales adoption showing the strongest effect, followed by production and financial services adoption. Two key mechanisms emerged: enhanced signal reception capabilities that improve market information acquisition, and strengthened signal transmission capabilities that enable farmers to demonstrate credibility to external stakeholders. Heterogeneity analysis revealed that low-to-middle income farmers experienced greater marginal benefits, with effects diminishing at higher income levels and becoming insignificant for the highest income group.
**Discussion:** While demonstrating digital technology's potential for inclusive rural development, critical challenges persist. Infrastructure requirements may exclude vulnerable groups, data extraction by platforms raises sovereignty concerns, and rapid digitalization risks eroding traditional knowledge systems. These tensions necessitate policy interventions ensuring equitable access, protecting farmer agency in data governance, and balancing technological innovation with cultural preservation.

KEYWORDS
**digital economy, livelihood, resilience, digital agriculture, signaling theory**

## 1 Introduction

Agricultural systems worldwide face intensifying pressures that challenge the sustainability of food production and rural livelihoods. Climate change increases both the frequency and severity of extreme weather events, with droughts, floods, and heat waves becoming increasingly unpredictable (Lobell et al., 2011). Market volatility compounds these environmental shocks, as globalized commodity chains expose farmers to price fluctuations beyond their control (Bellemare, 2015). Simultaneously, the degradation of essential natural resources—soil, water, and biodiversity—constrains agricultural productivity just as global food demand accelerates (Godfray et al., 2010). These intersecting pressures create a vicious cycle where smallholder farmers find themselves increasingly vulnerable to shocks they can neither anticipate nor adequately manage. The concept of livelihood resilience—the capacity to maintain, adapt, and transform livelihood strategies in response to disturbances—has thus emerged as critical for understanding how farmers navigate this landscape of compounding uncertainties (Barrett and Constas, 2014).

Digital technologies offer transformative potential for building farmer resilience in this challenging context. The rapid expansion of mobile networks, internet connectivity, and digital platforms has begun reshaping agricultural systems from production through marketing. China's ambitious digital agriculture initiatives—notably the "Digital Rural Development Strategy Outline" and "Digital Agriculture and Rural Development Plan (2019–2025)"—exemplify how nations are leveraging technology to modernize farming. Digital tools provide farmers with real-time access to weather forecasts, pest alerts, and agronomic advice, enabling more precise decision-making than traditional methods allow (Wolfert et al., 2017). E-commerce platforms break traditional market boundaries, connecting producers directly with consumers while reducing transaction costs and information asymmetries (Aker, 2011). Digital financial services expand access to credit and insurance, allowing farmers to invest in productivity improvements and protect against risks (Munyegera and Matsumoto, 2016).

The transformative power of these technologies extends beyond mere information provision. In traditional agricultural markets, farmers often struggle with information asymmetries—unable to effectively communicate their product quality to buyers or demonstrate creditworthiness to lenders. Digital platforms fundamentally alter these dynamics by enabling bidirectional information flows. Farmers not only receive market intelligence but can also project their capabilities, quality standards, and reliability to external stakeholders through digital traces, ratings, and verified production records. This shift from passive information recipients to active market participants who can signal their credibility represents a paradigm change in agricultural value chains. The integration of digital tools across production, sales, and financial domains suggests that effective information and signal management has become as crucial as traditional inputs like seeds and fertilizer.

However, emerging evidence reveals potential risks alongside these opportunities. Critical scholars warn that digital platforms may create new forms of dependency through data extraction (Fraser, 2019; Taylor, 2017), exacerbate existing inequalities by privileging digitally-literate elites (Tauzie et al., 2024), and erode traditional knowledge systems essential for long-term resilience (Hoolohan et al., 2021). These tensions between digital empowerment and potential exploitation remain unresolved in current literature.

These unresolved tensions reveal that current literature, while acknowledging both opportunities and risks, lacks comprehensive empirical frameworks to examine how digital adoption actually affects farmer resilience. Three major limitations prevent deeper understanding. First, studies tend to examine digital technologies in isolation—analyzing either mobile phones, e-commerce platforms, or digital finance—rather than investigating how farmers engage with digital ecosystems holistically across production, marketing, and financial domains. This fragmentation obscures synergies and trade-offs that emerge when farmers adopt multiple digital tools simultaneously. Second, current research inadequately distinguishes between information and signals in digital environments. While information represents raw data, signals convey credibility and intent—a distinction rooted in economic signaling theory (Connelly et al., 2011) that is crucial for understanding how digital adoption affects farmers' market positioning and bargaining power. The conflation of these concepts has prevented researchers from identifying the specific mechanisms through which digital tools enhance or undermine farmer agency. Third, the heterogeneous effects of digital adoption remain poorly understood. Studies typically report average treatment effects without examining how benefits and risks distribute across income levels, farm sizes, or demographic groups. This oversight masks potential scenarios where digital technologies help some while harming others.

This study addresses these critical gaps through a comprehensive empirical investigation of 1,395 grape farmers in Liaoning Province, China, examining how digital adoption affects livelihood resilience while acknowledging both its transformative potential and inherent risks. We make four key contributions. First, we examine digital adoption holistically across production, sales, and financial services, revealing synergies and complementarities that single-technology studies miss. Second, we advance theoretical understanding by applying signaling theory to distinguish between information acquisition and signal transmission capabilities. This novel framework illuminates how digital tools not only provide farmers with market intelligence but also enable them to project credibility and quality to external stakeholders—a mechanism previously overlooked yet fundamental to understanding digital empowerment. Third, through rigorous heterogeneity analysis, we uncover how digital adoption's impacts vary across income distributions and capital dimensions, demonstrating that benefits concentrate among certain groups while others face marginal gains or potential exclusion. Finally, we provide a balanced assessment that integrates our positive empirical findings with critical perspectives on digital agriculture's risks and limitations, offering empirical grounding for policies that promote inclusive rather than extractive digital transformation.

The paper proceeds as follows: Section 2 develops our theoretical framework; Section 3 describes data and methods; Section 4 presents empirical results; Section 5 critically discusses implications; and Section 6 concludes with policy recommendations for inclusive digital transformation.

## 2 Theoretical basis and research hypothesis

### 2.1 Conceptual framework of farmer livelihood resilience

Livelihood resilience refers to the ability of individuals or households to maintain and enhance their livelihood conditions when facing external shocks, encompassing both risk adaptation capabilities and the capacity for proactive response and recovery

(Barrett and Constas, 2014). The multidimensional nature of livelihood resilience and its complex determinants present significant measurement challenges. Researchers typically construct livelihood resilience indicator systems based on the well-established sustainable livelihood framework (Li and Wu, 2020). This framework categorizes household livelihood capital into five dimensions: natural, physical, financial, human, and social capital, which aligns well with the complexity of livelihood resilience. More importantly, the sustainable livelihood framework not only focuses on capital assets but also provides a lens for observing the transformation of various resilience dimensions and their interaction with the external environment, consistent with the systemic adaptability and transformation capacity emphasized in agricultural production.

The sustainable livelihood framework's strength lies in its dynamic and systemic nature. In particular, the framework elucidates the underlying logic and internal mechanisms of farmer livelihood resilience. Farmers operate within a vulnerable environment shaped by natural disasters, market fluctuations, and policy changes. They rely on their core livelihood capital to form livelihood outcomes through the selection and adjustment of livelihood strategies. This dynamic perspective effectively captures the evolution of farmers' livelihood strategies, which is crucial for understanding the formation mechanisms of livelihood resilience (Ellis, 2000). On the other hand, the framework provides a theoretical basis for assessing how policies and market environments affect farmer livelihoods, making it particularly applicable for studying the impact of emerging factors such as the digital economy (Yang et al., 2024).

## 2.2 Mechanisms of digital adoption's impact on farmer livelihood resilience

In the context of global digitalization, digital technologies are profoundly restructuring the organizational structure of production and market operation mechanisms across industries. Agriculture, as a fundamental sector of the national economy, is experiencing unprecedented opportunities for digital transformation.

From a value chain perspective, the agricultural value chain encompasses three core segments: production, circulation, and sales. This structure reflects the complete process from value creation to value realization in agricultural products. Driven by digital technology, most agricultural product circulation segments have achieved relatively high levels of standardization and scale, no longer serving as major constraints (Yin and Ye, 2024). In contrast, financial services, as a key element in value chain operation, have more significant impacts on farmers' production, operation, and livelihood resilience. Access to adequate financial support directly determines farmers' ability to acquire production factors and expand operations. Meanwhile, timely financial support can effectively help farmers cope with external shocks such as natural disasters and market fluctuations, enhancing their risk prevention capabilities.

Driven by digital technology, the agricultural value chain is exhibiting novel development characteristics. Farmers achieve precise management of production processes through smart devices and agricultural apps, improving production efficiency and product quality. They expand sales channels through e-commerce platforms, breaking geographical constraints to directly access consumer markets and expand market influence. The development of digital inclusive finance has significantly lowered barriers to accessing funds, providing strong support for coordinated operation across value chain segments. These changes demonstrate deepening digital adoption among farmers, with notable improvements in production efficiency, market reach, and financial access. Based on this, our study systematically examines farmers' digital adoption and its effects from three dimensions: production, sales, and financial services.

### 2.2.1 Direct effects of digital adoption on livelihood resilience

Digital adoption influences farmers' livelihood capital accumulation across multiple dimensions, facilitating the transition of their livelihood resilience from lower to higher levels. Regarding physical capital, farmers adopt facility agriculture to replace traditional open-field cultivation and employ smart devices (such as temperature and humidity sensors and automatic control systems) to monitor crop growth information and regulate greenhouse environments. These changes mark farmers' transition from traditional experience-based management to data-driven precise management (Trendov et al., 2019), significantly improving resource utilization efficiency and production precision (Mehrabi et al., 2021). In terms of human capital, farmers acquire essential digital skills and agricultural knowledge through agricultural information apps and online training, enhancing their ability to acquire and process information (Misaki et al., 2018) while laying the foundation for continuous learning and technology adaptation. For financial capital, the use of digital payments and online financial services has introduced many farmers to formal financial systems for the first time, improving their fund management capabilities and access to microfinance (Sekabira and Qaim, 2017). Social capital accumulation is achieved through basic e-commerce platform and social media usage, enabling farmers to break geographical constraints and establish new market networks and information exchange channels (Kos and Kloppenburg, 2019). Regarding natural capital, digitalization improves farmers' awareness and management of natural resources by providing basic meteorological and soil information, promoting the transition from extensive to intensive management practices. This provides essential support for farmers to maintain their competitive position in the market. Therefore, we propose:

H1: Digital adoption promotes the accumulation of financial, physical, natural, human, and social capital, leading to higher livelihood resilience outcomes.

### 2.2.2 Signal mechanisms in digital adoption

In the current era of information explosion, farmers face the dual challenge of information overload and limited processing capacity. This contradiction between information overload and capability constraints exacerbates information asymmetry between farmers and markets (Akerlof, 1978). Signaling theory suggests that economic agents can mitigate the adverse effects of information asymmetry by receiving and transmitting credible signals (Spence, 1978). In the digital economy environment, information and signals are closely related but fundamentally distinct concepts. Information represents objective data and facts with general applicability and passivity, while signals are specific content that economic agents consciously filter, refine, and transmit from massive information, characterized by selectivity and proactivity. For farmers, signals represent specific information they intentionally receive or transmit to enhance their capabilities, demonstrate credibility, or showcase product quality.

Digital adoption enhances farmers' market response capabilities through signal empowerment, which comprises two key dimensions: signal reception and transmission. Digital adoption primarily enhances farmers' signal reception capabilities. Signaling theory emphasizes that market participants need to identify and filter valuable signals for optimal decision-making in information-overloaded environments (Chen and Yu, 2024). Digital adoption enhances farmers' signal identification and filtering capabilities, improving their efficiency in extracting key signals from complex market environments. For instance, digital production adoption provides farmers with more precise signal filtering methods, enabling accurate identification of technical guidance and risk warning signals from large volumes of information; digital sales adoption enhances farmers' market signal acquisition methods, enabling more timely and comprehensive access to consumer demand and price change information; digital financial services adoption effectively improves farmers' resource signal acquisition channels, helping them receive more comprehensive information about policy support and financing opportunities.

Equally important, digital adoption enhances farmers' signal transmission capabilities. Signaling theory posits that market participants can demonstrate their advantages through transmitting credible signals to gain more favorable positions in competition (Connelly et al., 2011). Digital adoption enhances the efficacy of farmers' signal transmission in the market while strengthening the credibility and influence of their information dissemination (Zhao and Xu, 2023). More precisely, digital production adoption enables farmers to obtain standardized production records and quality monitoring data through digital production equipment, enhancing the credibility of their production management signals and more effectively demonstrating their production standardization and product quality; digital sales adoption allows farmers to break through geographical constraints in traditional sales, gaining broader market reach opportunities while enhancing the credibility of product and brand signals through platform certification and user review mechanisms; digital financial services adoption enables farmers to accumulate standardized transaction records and credit data, strengthening the persuasiveness of their development potential signals.

The enhancement of signal reception and transmission capabilities contributes to strengthening farmer livelihood resilience. On one hand, improved signal reception capabilities enable farmers to more accurately identify external environmental changes, including predicting market risks and seizing development opportunities. This optimization of resource allocation decisions and improvement of risk response capabilities helps increase farmers' livelihood adaptability and resource utilization efficiency, thereby enhancing their livelihood resilience (Wang et al., 2024). On the other hand, enhanced signal transmission capabilities make farmers' information advantages more prominent in market competition, improving their bargaining power and influence in resource acquisition processes. This strengthens their position in acquiring key resources such as technology and funding, thereby enhancing the sustainability of their livelihood development and ultimately increasing their livelihood resilience. This coordinated enhancement of signal reception and transmission capabilities ultimately strengthens farmer livelihood resilience by optimizing resource acquisition and utilization efficiency across multiple dimensions, including human, social, financial, physical, and natural capital. Therefore, we propose the following hypotheses:

H2: Digital adoption enhances farmer livelihood resilience by improving their signal reception capabilities.

H3: Digital adoption enhances farmer livelihood resilience by strengthening their signal transmission capabilities.

## 2.3 Research framework

Figure 1 presents our analytical framework that combines sustainable livelihoods theory with signaling mechanisms to explain how digital adoption enhances livelihood resilience.

First, we conceptualize digital adoption as a multidimensional construct across production, sales, and financial services. Unlike previous studies examining technologies in isolation, our framework captures synergistic effects of comprehensive digital engagement, recognizing that resilience emerges from integrated capabilities rather than single interventions. This holistic approach recognizes that resilience emerges from coordinated transformation across value chains, not isolated technological adoptions.

Second, we introduce signaling theory as a novel mechanism linking digital adoption to livelihood resilience. While existing literature emphasizes information access as the primary benefit of digital technologies, we distinguish between passive information receipt and active signal management. Our framework posits that digital adoption enhances resilience through dual pathways: strengthening farmers' ability to receive critical signals (market prices, weather warnings, policy changes) and amplifying their capacity to transmit credible signals (product quality, production standards, creditworthiness) to markets and institutions. This signal-based perspective reveals how digital technologies fundamentally alter farmers' position within agricultural networks, transforming them from isolated producers to connected market participants.

As illustrated in Figure 1, the framework operationalizes these relationships through measurable pathways: digital adoption (independent variable) influences five dimensions of livelihood capital (financial, physical, natural, human, and social), mediated by enhanced signal capabilities, ultimately determining livelihood resilience outcomes (dependent variable). This structure enables

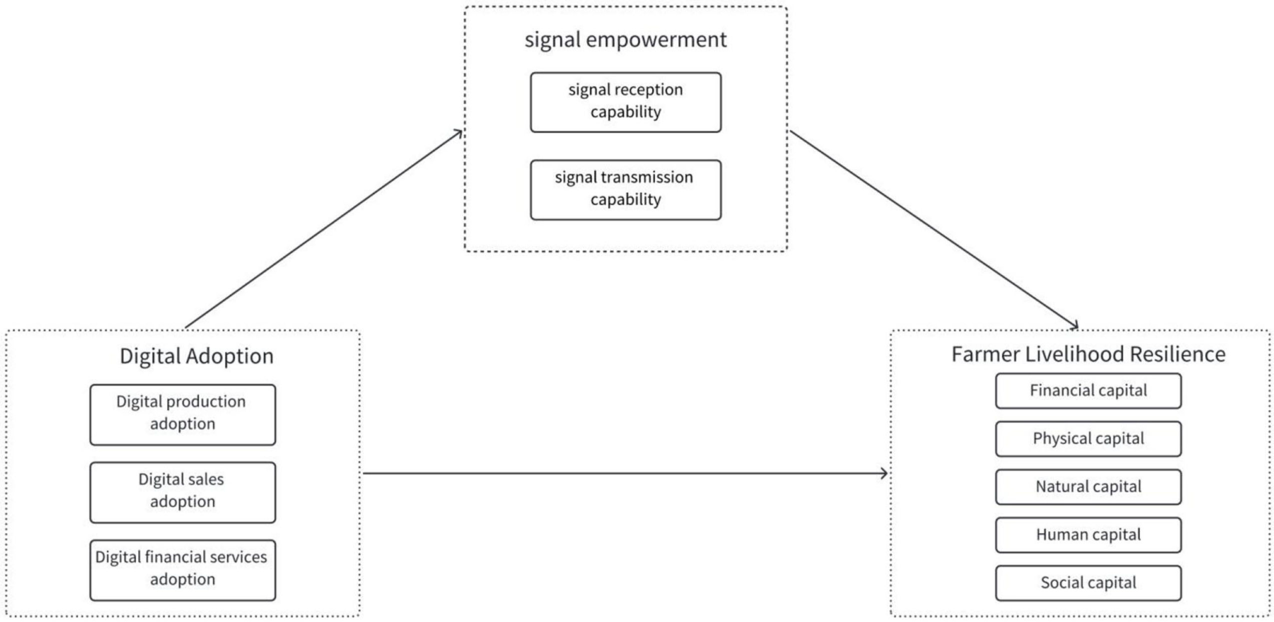


FIGURE 1
Research framework of digital adoption on farmer livelihood resilience.

empirical testing while maintaining theoretical coherence, bridging the gap between abstract digitalization concepts and concrete rural development outcomes.

# 3 Research design

## 3.1 Data source

The research data derives from a survey of specialty agriculture farmers conducted by our research team in Liaoning Province from June to July 2023. We focus on grape farmers as they represent commercial crop producers who typically have stronger market orientation and face unique resilience challenges, making them suitable subjects for studying digital adoption impacts. We employed a multi-stage stratified random sampling approach. First, we selected main grape-producing counties in Liaoning.[1] Second, we stratified townships within selected counties based on: (1) grape production scale, selecting townships where grape cultivation represents a significant agricultural activity, (2) geographic representation across Liaoning's different grape-producing zones, and (3) varying levels of digital infrastructure development, ultimately selecting 18 townships. Third, we randomly selected 3–4 villages per township from within grape-producing areas (65 villages total). While our initial sampling plan targeted 10–20 grape households per village, actual sample sizes varied based on village size and grape cultivation density, reflecting the natural variation in grape farming concentration across villages. This yielded 1,412 initial responses. After data cleaning, we obtained 1,395 valid observations (98.8% effective rate).

1 Huanren County was excluded because it specializes in ice wine grapes for winemaking rather than table grapes for fresh consumption, operating under fundamentally different market structures and cultivation practices incompatible with our analysis.

## 3.2 Variable selection and measurement

### 3.2.1 Dependent variable

The dependent variable in this study is the farmer livelihood resilience level, assessed using the household livelihood resilience approach (HLRA) (Quandt et al., 2019). This method, based on the sustainable livelihood analysis framework, aggregates livelihood resilience into a multidimensional construct encompassing five types of capital: financial, physical, natural, human, and social. Considering potential regional heterogeneity, while maintaining the core HLRA framework, we adapted the indicator system based on our research subjects' characteristics and data availability, selecting 19 indicators to construct a corresponding secondary indicator system, as shown in Table 1. The indicator selection and measurement primarily reference studies by Han et al. (2024), Fan and Cong (2024), and Gao et al. (2024).

To avoid bias from subjective weight determination, we applied the entropy method for indicator weighting. Additionally, in the robustness test section, we reconstructed the livelihood resilience indicator using equal weighting for further validation.

### 3.2.2 Independent variables

The core independent variable is digital adoption, including production, sales, and financial services aspects. We measure digital production adoption based on whether farmers "can employ digital information methods such as mobile phones and computers to manage production processes in grape production, operation,

TABLE 1 Farmer livelihood resilience indicator system.

| First-level indicators | Second-level indicators | Indicator definition |
|---|---|---|
| Financial capital | Insurance participation | Whether the household has purchased agricultural insurance |
| | Loan access | Whether to borrow money from relatives and friends or to take out a bank loan for planting grapes |
| Physical capital | Use of agricultural machinery | Whether owns mechanical equipment |
| | Cultivation facilities | Whether owns greenhouses |
| | Storage facilities | Whether owns cold storage |
| | Processing facilities | Whether has space suitable for grape sorting and packaging |
| Natural capital | Land area | Total household land area |
| | Land quality | Soil fertility or grape cultivation suitability of largest plot |
| | Natural disaster risk | Whether experienced major natural disasters in past 3 years |
| | Land access ability | Whether rents land from others |
| Human capital | Health status | Household members' health conditions |
| | Cultivation skills | Understanding of grape cultivation techniques (compared to other villagers) |
| | Labor capacity | Total household labor force (members aged 18–65) |
| | Education level | Farmer's education years (1–5 representing primary school and below, middle school, high school/technical school, college, undergraduate, graduate) |
| Social capital | Peer network | Number of relatives and friends growing grapes |
| | Market network | Number of known grape buyers and cooperatives |
| | Social network | Number of relatives and friends visiting during Spring Festival |
| | Membership in organizations | Whether serves as village cadre |

management, and sales," with a value of 1 if the answer is "yes" and 0 otherwise. Digital sales adoption is measured by whether farmers "use WeChat, QQ social circles or e-commerce platforms like JD.com, Taobao, or live streaming platforms like Douyin, Kuaishou to sell agricultural products," with a value of 1 if the answer is "yes" and 0 otherwise. Digital financial services adoption is measured by whether farmers "use third-party payment services like WeChat Pay, Alipay, or digital credit products like Ant Credit Pay, JD IOU, WeChat Micro Loan, P2P lending platforms in production and operation activities," with a value of 1 if the answer is "yes" and 0 otherwise. Following Su (Su et al., 2024), we use a binary approach to measure farmers' digital adoption status, where digital adoption equals 1 if the farmer answers "yes" to at least one of these three items, and 0 otherwise.

This binary measurement approach is selected based on the following considerations: First, the key to digital adoption lies in overcoming the initial barrier of the "digital divide," where adoption in any dimension indicates that farmers have acquired fundamental digital technology usage capabilities. Second, farmers' digital transformation typically shows gradual characteristics, where adoption in a single dimension often serves as an important starting point for comprehensive digitalization. Third, this treatment method clearly reflects whether farmers have achieved the critical leap in digital adoption, facilitating the assessment of its overall impact on livelihood resilience.

### 3.2.3 Mechanism variables

Based on our theoretical analysis of how digital adoption affects livelihood resilience, we define mechanism variables as signal empowerment, specifically encompassing signal reception capability and signal transmission capability. These are primarily identified through two survey questions: "How many types of agricultural information do you regularly obtain through mobile phones and computers?" and "Do you share agriculture-related pictures, articles, or videos in your social media circles?" The specific assignments are shown in Table 2.

### 3.2.4 Control variables

To control for potential confounding factors affecting farmer livelihood resilience, we include control variables related to respondent personal characteristics and household characteristics. Specifically, for respondent characteristics, we include age, age squared, gender, marital status, political status, and risk preference. For household characteristics, we include household members' health status and the proportion of labor force. We also control for county-level regional variables. The specific definitions are shown in Table 2.

## 3.3 Model setting

### 3.3.1 Baseline regression model

To estimate the impact of digital adoption on farmer livelihood resilience, we specify the following model:

$$Y_i = \alpha_0 DE_{mi} + \beta_0 X_i + \varepsilon_i \tag{1}$$

In Equation 1, $Y_i$denotes the dependent variable measuring the livelihood resilience of farmer $i$; $DE_{mi}$ represents the core explanatory variable where $m$ equals 1, 2, 3, or 4, representing the overall digital adoption status of farmer $i$, digital production adoption, digital sales adoption, and digital financial services adoption, respectively;$X_i$includes control variables for individual characteristics, household characteristics, and regional characteristics; $\alpha_0$ and $\beta_0$ are coefficients to be estimated; $\varepsilon_i$ is the random disturbance term.

### 3.3.2 Mechanism testing model

Following Jiang (2022), we employ a two-step mediation analysis to examine the impact of core explanatory

TABLE 2 Descriptive statistics of key variables.

| Variable | Definition | Mean | Max | Min |
|---|---|---|---|---|
| Livelihood resilience | Composite index based on the farmer livelihood resilience indicator system in Table 1. Continuous. | 0.21 | 0.79 | 0.02 |
| Digital adoption | Adoption in digital production, sales, or financial services. Yes = 1, No = 0. | 0.84 | 1 | 0 |
| Digital production adoption | Use of IoT or digital tools (e.g., smartphones, computers) in grape production management. Yes = 1, No = 0. | 0.11 | 1 | 0 |
| Digital sales adoption | Use of WeChat, QQ, JD.com, Taobao, Douyin, or Kuaishou for agricultural product sales. Yes = 1, No = 0. | 0.13 | 1 | 0 |
| Digital financial services adoption | Use of third-party payments (WeChat Pay, Alipay) or digital credit products (Ant Credit Pay, JD IOU). Yes = 1, No = 0. | 0.83 | 1 | 0 |
| Signal reception capability | Number of types of agricultural information regularly obtained (e.g., market prices, policy info, weather conditions). Count (0 to 6). | 3.23 | 6 | 0 |
| Signal transmission capability | Whether respondents share agricultural-related content (e.g., images, articles, videos) on social media. Yes = 1, No = 0. | 0.46 | 1 | 0 |
| Age | Age of the household financial decision-maker in years. Continuous. | 53.59 | 81 | 22 |
| Age squared | Square of the household financial decision-maker's age. Continuous. | 2971.35 | 6561 | 484 |
| Gender | Gender of the household financial decision-maker. Male = 1, Female = 0. | 0.67 | 1 | 0 |
| Marital status | Marital status of the household financial decision-maker. Married = 1, Other = 0. | 0.96 | 1 | 0 |
| Political status | Whether the decision-maker is a member of the Communist Party. Party member = 1, Non-party member = 0. | 0.14 | 1 | 0 |
| Risk preference | Willingness to adopt new agricultural technologies (higher scores indicate a greater willingness to take risks). 1 (low) to 4 (high). | 2.70 | 4 | 1 |
| Household health status | Whether any household member experienced a major illness in the past year. Yes = 1, No = 0. | 0.04 | 1 | 0 |
| Labor force ratio | Proportion of labor force to total household members. Percentage (%). | 0.73 | 1 | 0 |
| Total household income | Total household income in 2023 (in 10,000 yuan). Continuous. | 13.56 | 1 | 78 |
| Beizhen county | Whether the household is located in Beizhen. Yes = 1, No = 0. | 0.45 | 1 | 0 |
| Gaizhou county | Whether the household is located in Gaizhou. Yes = 1, No = 0. | 0.34 | 1 | 0 |
| Lingyuan county | Whether the household is located in Lingyuan. Yes = 1, No = 0. | 0.08 | 1 | 0 |
| Dengta county | Whether the household is located in Dengta. Yes = 1, No = 0. | 0.02 | 1 | 0 |
| Faku county | Whether the household is located in Faku. Yes = 1, No = 0. | 0.06 | 1 | 0 |
| Sujiatun county | Whether the household is located in Sujiatun. Yes = 1, No = 0. | 0.05 | 1 | 0 |

variables on mediating variables. The specification is as follows:

$$M_{ni} = \gamma_1 DE_{mi} + \gamma_2 X_i + \mu_i \tag{2}$$

In Equation 2, $n$ represents mechanism variables, with $n$ taking values 1 and 2, respectively representing farmer $i's$ signal reception capability and signal transmission capability; $\gamma_1$ and $\gamma_2$ are parameters to be estimated; $\mu_i$ is the random disturbance term; and the meaning of $X_i$ is the same as in Equation 1.

# 4 Results

## 4.1 Basic regression analysis

To empirically test the impact of digital adoption on farmer livelihood resilience, we conduct regression analysis using Ordinary Least Squares (OLS) based on Model (1) and apply robust standard errors to address potential heteroscedasticity. The regression results are shown in Table 3. After controlling for individual characteristics, household characteristics, and county fixed effects, digital adoption and its three dimensions—digital production adoption, digital sales adoption, and digital financial services adoption—all exhibit significant positive effects on farmer livelihood resilience at the 1% statistical level, validating Hypothesis H1. Results from Equation 1 show that digital adoption increases the livelihood resilience index by 0.035 units relative to non-adopters. Examining individual dimensions, digital sales adoption demonstrates the largest enhancement effect on livelihood resilience, with an average increase of 0.034 units, followed by digital production adoption and digital financial services adoption, with average increases of 0.030 and 0.029 units, respectively.

This suggests that the digital economy significantly strengthens farmers‘ ability to cope with market risks by optimizing resource allocation efficiency in production, sales, and financial utilization. The prominent role of digital sales adoption reflects the key impact of direct market access on enhancing livelihood resilience, while the adoption of digital technologies in production and financial services builds farmers' comprehensive risk response capabilities

TABLE 3 Impact of digital adoption on farmer livelihood resilience.

| Variable | Dependent variable | | | |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| Digital adoption | 0.035*** (0.009) | | | |
| Digital production adoption | | 0.030*** (0.009) | | |
| Digital sales adoption | | | 0.034*** (0.008) | |
| Digital financial services adoption | | | | 0.029*** (0.008) |
| Individual-level controls | Y | Y | Y | Y |
| Household-level controls | Y | Y | Y | Y |
| County fixed effects | Y | Y | Y | Y |
| $N$ | 1,395 | 1,395 | 1,395 | 1,395 |
| $R^2$ | 0.172 | 0.177 | 0.186 | 0.169 |

Robust standard errors are reported in parentheses. ***$p < 0.01$, **$p<0.05$, *$p < 0.1$.

TABLE 4 Endogeneity test.

| Variable | First-stage | Second-stage |
|---|---|---|
| | Digital adoption | Livelihood resilience |
| Digital adoption | | 0.095** (0.042) |
| Instrumental variable | 0.109*** (0.013) | |
| Individual-level controls | Y | Y |
| Household-level controls | Y | Y |
| County fixed effects | Y | Y |
| $N$ | 1,395 | 1,395 |
| $R^2$ | 0.363 | 0.207 |
| Kleibergen-Paap rk Wald F-statistic | 67.385 | |
| Kleibergen-Paap rk LM statistic | 43.207*** | |

Robust standard errors are reported in parentheses. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

through technical support and financial access. These positive effects should be interpreted as capturing current benefits in China's evolving digital agriculture landscape, where farmers are still realizing gains from overcoming traditional market inefficiencies.

## 4.2 Endogeneity problem and robustness test

### 4.2.1 Endogenous problems

Considering potential endogeneity concerns arising from omitted variable bias, reverse causality, and measurement errors—where farmers with higher livelihood resilience levels might be more capable and willing to participate in the digital economy—we adopt an instrumental variable (IV) approach to address these concerns. We select the mobile signal strength in the respondent's area as an instrumental variable. Regarding correlation, mobile signal strength is highly correlated with the endogenous variable (digital adoption). Signal strength directly influences farmers' convenience and quality of digital adoption, as better signal conditions significantly increase farmers' willingness and frequency to utilize agricultural apps, e-commerce platforms, and other digital tools.

In terms of exogeneity, signal strength satisfies the exogeneity requirement as it is primarily determined by regional factors such as terrain, population density, and communication infrastructure, with no direct relationship to individual farmers' livelihood resilience levels. While wealthier regions might have better signal coverage, this effect can be effectively controlled through regional fixed effects. Moreover, the impact of signal strength on livelihood resilience operates primarily through digital adoption, with other potential influences (such as communication convenience) being relatively weak, satisfying the exclusion restriction requirement for instrumental variables.

Table 4 reports the instrumental variable regression results. The first-stage regression results reveal that the instrumental variable is significantly positively associated with the potentially endogenous variable at the 1% level, and the Kleibergen-Paap rk LM statistic $p$-value is $<0.01$, confirming that the instrumental variable satisfies the correlation condition. The first-stage F-statistic is 67.385, exceeding the critical value of the Cragg-Donald statistic, indicating that the weak instrument problem is not a concern. The second-stage regression results show that the coefficient direction and significance level of livelihood resilience remain consistent with the baseline regression results, indicating that digital adoption continues to exert a significant positive impact on farmer livelihood resilience. After addressing endogeneity concerns through instrumental variables, further validating Hypothesis H1.

### 4.2.2 Robustness test

To further verify the robustness of our estimation results, we implement three alternative approaches: restricting the analysis dataset through 5% winsorization of core variables, excluding samples of farmers aged above 65 years, and adjusting the weighting method for the livelihood resilience index calculation. The specific results are presented in Table 5. Columns (1)–(3) report the estimation results using the restricted dataset, age-limited sample, and alternative weighting method, respectively. The results consistently show that digital adoption maintains its significant positive effect on farmer livelihood resilience, with coefficients remaining stable across different specifications. These findings further support the robustness of our baseline regression results.

### 4.2.3 Mechanism check

The regression results above establish that digital adoption has a significant positive impact on farmer livelihood resilience. We next examine how does digital adoption generate this impact through specific mechanisms? Below, we explore how digital adoption

TABLE 5 Robustness test.

| Variable | Restricted dataset (1) | Excluding sample of farmers older than 65 years (2) | Alternative weighting method (3) |
|---|---|---|---|
| Digital adoption | 0.040** (0.009) | 0.042*** (0.011) | 0.032** (0.007) |
| Individual-level controls | Y | Y | Y |
| Household-level controls | Y | Y | Y |
| County fixed effects | Y | Y | Y |
| $N$ | 1,395 | 1,209 | 1,395 |
| $R^2$ | 0.167 | 0.234 | 0.302 |

Robust standard errors are reported in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

enhances farmer livelihood resilience through the stages of signal reception and transmission.

As shown in the empirical results in Table 6, all three aspects of digital adoption—digital sales adoption, digital financial services adoption, and digital production adoption—exert significant positive effects on farmers' signal reception capability and signal transmission capability at the 1% statistical level, thereby enhancing their livelihood resilience.

Regarding signal reception, digital adoption shows particularly significant effects. Through adoption in online financial services, farmers can more efficiently access market and financial information; digital sales adoption enhances farmers' sensitivity to market demands; while digital production adoption, though showing relatively smaller impact, significantly improves farmers' ability to acquire production technology information. Regarding signal transmission, digital adoption also demonstrates significant positive effects, albeit with smaller magnitude compared to reception capability. The three forms of adoption provide farmers with lower-cost information dissemination channels through digital platforms and social media, enhancing their ability to transmit credible signals to markets, policy makers, and cooperation partners.

Notably, the impact of digital adoption on signal reception capability is significantly greater than its effect on signal transmission capability. This difference reflects that farmers find it easier to utilize tools to improve information acquisition efficiency in the digitalization process, while enhancing transmission capability relies on more complex skill development and experience accumulation. This asymmetry may also reflect the current stage of digital platform development in rural China, where platforms are designed primarily as information delivery systems rather than genuine two-way communication channels. These findings validate both Hypothesis H2 and H3, confirming that digital adoption enhances farmer livelihood resilience through dual mechanisms of signal empowerment—both reception and transmission—though with varying magnitudes of impact.

### 4.2.4 Heterogeneity tests

#### 4.2.4.1 Effects across income levels

Previous research indicates that digital adoption is an important means of influencing income. Then, in the process of improving farmer livelihood resilience levels, does digital adoption have differential impacts on farmers with different income levels? Using quantile regression, we select five representative quantile points-—10th, 25th, 50th, 75th, and 90th percentiles—to analyze the heterogeneous effects of digital adoption on farmer livelihood resilience across different income levels. Table 7 shows that, except for the 90th percentile, digital adoption has a significant positive effect on farmer livelihood resilience across all quantiles, with the most significant enhancement effect on low-to-middle income farmers. Specifically, digital adoption exhibit the strongest marginal effect on farmers at the 25th percentile of income levels, though this effect gradually weakens as income levels increase; for farmers with median and relatively higher income levels, the positive impact remains substantial but diminishing. However, for farmers with the highest income levels (90th percentile), the marginal effect of digital adoption is not significant, likely reflecting a ceiling effect where these high-income farmers have already optimized their operations through established networks and credit channels. This suggests digital adoption primarily serves an equalizing function—helping disadvantaged farmers catch up rather than extending the advantages of already-successful ones.

These heterogeneous effects align with the diminishing marginal returns principle in economics—low-to-middle income farmers experience larger gains because they start from a lower base, with greater room for improvement. This 'late-mover advantage' explains why structural concerns raised in critical literature coexist with positive empirical findings: immediate welfare gains from overcoming traditional market failures can occur even within imperfect digital systems.

#### 4.2.4.2 Effects across capital dimensions

Digital adoption demonstrates significant accumulation effects across all types of livelihood capital, though with varying magnitudes. Results in Table 8 show that digital adoption exhibits relatively stronger effects on social capital, natural capital, physical capital, and financial capital, while its impact on human capital is comparatively smaller. Specifically, digital adoption primarily enhances social dimension resilience by improving farmers' network construction capabilities, as they utilize digital platforms to expand industry networks and market connections, increasing organizational adoption and strengthening social support for risk response. In the natural dimension, digital technology improves farmers' land use efficiency and disaster response capabilities, improving their adaptability in natural resource management. Regarding physical capital, digital economy reduces barriers for farmers to acquire and

TABLE 6 Signal mechanism test of digital adoption.

| Variable | Signal reception capability | | | | Signal transmission capability | | | |
|---|---|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (1) | (2) | (3) | (4) |
| Digital adoption | 1.568*** (0.093) | | | | 0.260*** (0.041) | | | |
| Digital production adoption | | 0.546*** (0.102) | | | | 0.167*** (0.042) | | |
| Digital sales adoption | | | 1.219*** (0.096) | | | | 0.151*** (0.041) | |
| Digital financial services adoption | | | | 1.426*** (0.091) | | | | 0.247*** (0.040) |
| Individual controls | Y | Y | Y | Y | Y | Y | Y | Y |
| Household controls | Y | Y | Y | Y | Y | Y | Y | Y |
| County fixed effects | Y | Y | Y | Y | Y | Y | Y | Y |
| *N* | 1,395 | 1,395 | 1,395 | 1,395 | 1,395 | 1,395 | 1,395 | 1,395 |
| $R^2$ | 0.442 | 0.340 | 0.397 | 0.427 | 0.164 | 0.149 | 0.147 | 0.163 |

Robust standard errors are reported in parentheses. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

TABLE 7 Heterogeneous effects of digital adoption on farmer livelihood resilience.

| Variable | Income level quintiles | | | | |
|---|---|---|---|---|---|
| | 10th (1) | 25th (2) | 50th (3) | 75th (4) | 90th (5) |
| Digital adoption | 0.019** (0.009) | 0.039*** (0.011) | 0.034** (0.013) | 0.030*** (0.011) | 0.016 (0.021) |
| Individual-level controls | Y | Y | Y | Y | Y |
| Household-level controls | Y | Y | Y | Y | Y |
| County fixed effects | Y | Y | Y | Y | Y |
| *N* | 1,395 | 1,395 | 1,395 | 1,395 | 1,395 |

Robust standard errors are reported in parentheses. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

improve production facilities, strengthening their production system's risk resistance capacity. For financial capital, digital technology optimizes farmers' insurance adoption and credit access channels, enhancing their financial security resilience. While digital adoption shows statistically significant positive effects on human capital, the magnitude is relatively smaller compared to other capital dimensions, likely because improvements in health status, education level, and labor skill development require longer time periods, making it difficult to achieve fundamental improvements through short-term digital adoption.

# 5 Discussion

## 5.1 Opportunities and challenges

While our findings demonstrate significant positive effects of digital adoption on farmer livelihood resilience, critical examination reveals that this technological transformation is far from neutral or universally beneficial.

Our heterogeneity analysis showing stronger benefits for low-to-middle income farmers appears encouraging, yet this finding requires nuanced interpretation. Meaningful engagement with digital technologies goes beyond mere access—it depends on users' "technological frames" shaped by their experiences, resources, and capabilities (Engås's et al., 2023). This insight is particularly relevant when considering observations from Malawi, where digital platforms inadvertently created a new "achikumbe elite"—educated, urbanized youth who could leverage these tools while others were left behind (Tauzie et al., 2024). Our results may reflect a similar dynamic: while low-to-middle income farmers show greater marginal benefits when they successfully adopt, this assumes they can overcome the initial barriers to meaningful engagement. The stronger effect of digital sales adoption in our study likely privileges those with existing market knowledge and digital literacy, potentially widening rather than closing rural inequalities.

The enhancement of signal transmission capabilities, while improving market access, raises profound concerns about power and control. Precision agriculture has been provocatively framed as a contemporary "data grab," where platforms extract immense value from farmers' data while providing limited transparency or sharing of profits (Fraser, 2019). This resonates with calls for "data justice," which recognizes the fundamental tension between gaining visibility in digital markets and losing control over one's information (Taylor, 2017). Our finding that digital

TABLE 8 Digital adoption and heterogeneous effects on livelihood capital.

| Variable | Financial capital (1) | Physical capital (2) | Natural capital (3) | Human capital (4) | Social capital (5) |
|---|---|---|---|---|---|
| Digital adoption | 0.006*** (0.002) | 0.008*** (0.002) | 0.009** (0.002) | 0.002*** (0.001) | 0.010*** (0.003) |
| Individual-level controls | Y | Y | Y | Y | Y |
| Household-level controls | Y | Y | Y | Y | Y |
| County fixed effects | Y | Y | Y | Y | Y |
| *N* | 1,395 | 1,395 | 1,395 | 1,395 | 1,395 |

Robust standard errors are reported in parentheses. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

financial services significantly enhance resilience exemplifies this paradox: farmers gain crucial access to credit and insurance, yet simultaneously surrender detailed information about their production patterns, financial behaviors, and social networks to platform companies. They become data subjects in an asymmetric relationship where the terms of exchange remain opaque.

Perhaps most concerning is how digital adoption may fundamentally alter rural social fabric while appearing to strengthen it. Digital transformations are never merely technical but are "socio-technical" processes that can disrupt established knowledge systems and community relationships (Hoolohan et al., 2021), often reproducing existing inequalities including gender disparities (Duguma et al., 2022).

These critical concerns and our positive findings are not contradictory but capture different dimensions of digital transformation. The benefits we document—particularly for low-to-middle income farmers—represent short-term gains from overcoming traditional market failures, while the risks we identify concern long-term structural dependencies. Our cross-sectional data captures a transitional moment where benefits outweigh costs, yet this balance may shift as digital platforms consolidate control.

## 5.2 Policy directions

These critical perspectives do not negate our positive findings but rather demand a more sophisticated understanding of how to harness digital technologies for genuinely inclusive rural development.

The path forward requires moving beyond simplistic notions of "access" to ensure meaningful engagement. Drawing on Engås's et al. (2023) framework, policies must recognize and work with farmers' diverse technological frames rather than imposing one-size-fits-all solutions. This means developing platforms that align with resource-poor farmers' existing practices and knowledge systems, while providing culturally appropriate support that builds genuine digital capabilities rather than mere technical skills. The differential benefits across income levels in our study underscore that universal approaches will likely exacerbate rather than alleviate inequalities.

Addressing data sovereignty concerns requires fundamental restructuring of digital agricultural ecosystems. Fraser's (2019) vision of farmer-controlled data cooperatives and Taylor's (2017) framework for data justice point toward institutional innovations that return agency to farmers. Rather than passive data subjects, farmers should become active participants who understand, control, and benefit from their information. This necessitates not only technical solutions but also regulatory frameworks ensuring transparency, fair value distribution, and protection against algorithmic discrimination.

Finally, digital transformation must be reconceptualized not as an inevitable technological progression but as a contested socio-political process with profound implications for rural futures. The specific institutional and agricultural context in Liaoning—with its established grape industry and farmer cooperatives—provides important insights that may inform digital transformation strategies in other agricultural regions. In contexts with weaker institutional support or deeper digital divides, the risks these scholars identify could overwhelm potential benefits. Our findings confirm that digital adoption can enhance livelihood resilience, particularly for vulnerable groups, but realizing this potential requires deliberate efforts to ensure meaningful engagement, protect farmer agency, preserve valuable traditional knowledge, and prevent the emergence of new forms of digital exclusion.

# 6 Conclusions

This study examined how digital adoption affects farmer livelihood resilience using survey data from 1,395 grape farmers in Liaoning Province, China. Our findings provide empirical evidence for the transformative potential of digital technologies in agriculture while highlighting critical implementation challenges.

Our results demonstrate that digital adoption significantly enhances farmer livelihood resilience across production, sales, and financial service dimensions, with digital sales adoption showing the strongest effects. The mechanism analysis reveals that these benefits operate through dual pathways: enhanced signal reception capabilities that improve market information acquisition, and strengthened signal transmission capabilities that enable farmers to demonstrate credibility to external stakeholders. Notably, low-to-middle income farmers experience greater marginal benefits from digital adoption, suggesting potential for reducing rural inequalities.

However, these findings must be interpreted with caution. While our cross-sectional analysis captures immediate benefits from overcoming traditional market inefficiencies, it cannot address longer-term concerns about data sovereignty, algorithmic dependencies, and the erosion of traditional knowledge systems that may emerge as digital platforms consolidate control.

Moreover, our cross-sectional design inherently limits our ability to assess how these digital adoption effects evolve over time. Longitudinal research tracking farmers over multiple years is needed to determine whether the positive effects we document—particularly for low-to-middle income farmers—represent sustainable improvements or temporary gains during the current phase of digital transformation.

To realize the benefits of agricultural digitalization while mitigating risks, policy interventions should focus on three priorities. First, establish farmer data cooperatives that negotiate fair value-sharing agreements with platforms and provide legal support against algorithmic discrimination. Second, implement differentiated support programs that provide lower-income farmers with subsidized devices and practical training while offering advanced digital marketing skills to those already online. Third, mandate platform transparency requirements including clear pricing algorithms, data portability standards, and accessible dispute resolution mechanisms. These targeted interventions can help ensure that digital transformation strengthens rather than undermines resilient rural livelihoods.

Future research should employ longitudinal designs to track the evolution of digital dependencies, explore alternative platform governance models, and investigate how different institutional contexts shape digitalization outcomes. Only through continued critical examination can we understand how to harness digital technologies for genuinely inclusive agricultural development.

## Data availability statement

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

## Ethics statement

The studies involving humans were approved by Ethics Committee of Shenyang Agricultural University. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

## Author contributions

ZL: Data curation, Methodology, Writing – review & editing, Conceptualization, Software, Writing – original draft. ZJ: Resources, Writing – review & editing, Funding acquisition. XY: Data curation, Writing – review & editing, Conceptualization, Software, Resources, Funding acquisition, Validation.

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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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