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# Mechanisms of capital endowment's influence on farmers' adoption of low-carbon fertilization technologies

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**Agriculture is critical in global greenhouse gas (GHG) emissions, making promoting low-carbon agricultural technologies essential for sustainable development. Drawing on survey data from 1,008 grain farmers in Shandong Province, this study develops a moderated mediation model within the expanded "resource–cognition–behavior" framework to explore how capital endowment affects adopting low-carbon fertilization technologies (LCFTs). The analysis reveals three key findings. First, capital endowment significantly promotes LCFT adoption, with natural capital driving organic fertilizer substitution and human capital facilitating soil testing and formula fertilization. Second, value cognition—particularly ecological value—is a crucial mediating path. Third, environmental regulation strengthens these effects through guidance and incentive-based instruments. Notably, the study introduces information capital as a novel dimension, highlighting the role of digital literacy in adoption behavior. Heterogeneity analysis further shows that environmental regulation has stronger moderating effects among large-scale farmers and those in central and eastern Shandong. This research advances the theoretical understanding of green agricultural transformation by enriching the resource-based behavioral framework and provides empirical evidence to support regionally differentiated and capital-sensitive policy design.**

**Keywords** Low-carbon fertilization technologies (LCFTs), Capital endowment, Value cognition, Environmental regulation, Technology adoption, Agricultural emissions

Agriculture is a fundamental industry that ensures national food security and is also one of the primary sources of global GHG emissions[1]. According to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), 13.5% of global carbon emissions originate from modern agricultural production activities[2]. The resulting problems, such as the frequent occurrence of extreme weather events and ecological degradation, pose serious threats to food security and the stability of ecosystems. Consequently, controlling carbon emissions has become important for countries to achieve sustainable development. Among the numerous emission-reduction pathways, low-carbon fertilization technologies (LCFTs)—including organic fertilizer substitution, soil testing and formula fertilization, and controlled-release fertilizers—constitute an important component of Nature-based Solutions (NbS). These technologies have demonstrated significant effectiveness in enhancing soil carbon sequestration, reducing greenhouse gas emissions, and improving agricultural ecological resilience[3]. However, despite governments worldwide continuously strengthening policy support and technology promotion[4–6], the adoption rate of sustainable farmland management technologies at the farmer level remains generally low, constraining the achievement of agricultural emission-reduction targets[7,8]. Therefore, from the perspective of farmers, it is of great theoretical and practical significance to explore in depth the mechanisms influencing their adoption of low-carbon technologies, in order to optimize agricultural carbon-reduction pathways, improve the efficiency of LCFTs promotion, and facilitate the green and low-carbon transition of agriculture.

Existing studies have examined the factors influencing farmers' adoption of low-carbon technologies from multiple dimensions, including farmers' characteristics[9,10], capital endowment[11–13], cognitive and psychological traits[14–18], and environmental regulation[19–23]. Xu et al. based on a farmer survey in Hainan Province, systematically

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analyzed the effects of capital endowment, ecological cognition, and environmental regulation on green production behavior, providing valuable insights into farmers' green transition mechanisms. However, existing studies still present several limitations that constrain a deeper understanding of the behavioral mechanisms underlying farmers' adoption of LCFTs. First, most research emphasizes single-level influencing factors and does not systematically examine the interaction mechanisms among capital endowment, cognitive factors, and environmental regulation. This limits the ability to uncover how internal resources and external institutions jointly shape farmers' adoption behavior through cognitive pathways. Second, prior studies have focused more on the role of ecological cognition, while paying insufficient attention to other types of value cognition—such as economic and social value cognition—which are also crucial for understanding how farmers perceive the costs, benefits, and social consequences of LCFTs. Third, in the context of digital village construction, the role of farmers' information capital is becoming increasingly prominent. However, current analytical frameworks still fail to incorporate this dimension, overlooking the growing importance of digital literacy and information access in technology adoption. Fourth, while the direct effects of environmental regulation have been widely studied, its moderating effect within the pathways linking capital endowment and cognition remains underexplored, leaving open questions about how different types of policy tools (e.g., incentive-based vs. command-based) influence cognitive activation and behavioral outcomes. To address these gaps, this study uses 1,008 farmer survey data from Shandong Province to construct a moderated mediation model within the "capital endowment–value cognition–LCFTs adoption" framework. A binary logit model is employed to empirically examine the mechanism through which capital endowment affects farmers' adoption of LCFTs, incorporating the mediating role of value cognition and the moderating role of environmental regulation, to provide a more comprehensive understanding of the formation mechanisms underlying farmers' LCFTs adoption behavior.

The main contributions of this study are as follows. First, grounded in the sustainable livelihoods framework, it systematically evaluates the impact pathways of capital endowment and its different dimensions on farmers' adoption of LCFTs, identifies the indirect mechanism through which capital endowment operates via value cognition, and extends the "resource–cognition–behavior" explanatory logic. Second, it clarifies the mediating mechanism of value cognition between capital endowment and behavioral adoption. Third, introducing environmental regulation as an institutional moderating variable identifies its moderating effect in the process through which capital endowment influences value cognition, thereby providing theoretical support for the coordinated guidance of farmers' green behavior through the synergy of "intrinsic resource endowment–external policy mechanisms." Fourth, in the context of digital village construction, this study incorporates information capital into the capital endowment framework, extending its research dimensions and highlighting the unique role of information acquisition and digital literacy in adopting LCFTs.

## Theoretical hypotheses

### Mechanism of capital endowment's influence on farmers' adoption of LCFTs

Capital endowment refers to all natural or acquired resources and capabilities farmers possess. According to the sustainable livelihoods framework, capital endowment is a key factor shaping farmers' behavior and decision-making, as most farmers make rational choices after weighing their capital endowment. For farmers, it is difficult to achieve sustainable agricultural production by relying solely on a single type of capital endowment; instead, they must possess multiple forms of capital endowment[24,25]. In general, the types of capital endowment that farmers should have to support green production include natural, material, economic, human, and social[11,26,27].

Natural endowment refers to the natural conditions available to farmers for agricultural production. Agriculture is an industry highly dependent on natural conditions. Generally, the more favorable the topography, the larger the land scale, and the more concentrated the land distribution, the better the agricultural production conditions[27]. Such conditions are more conducive to implementing large-scale operations, reducing the average cost of agricultural production, achieving economies of scale, and promoting the green transformation of agriculture[28,29].

Material endowment refers to the physical tools, infrastructure, and agricultural inputs that farmers own or can readily access to support low-carbon agriculture. The richer the material endowment, the more complete the physical conditions and production facilities for agricultural production become[30]. This enables farmers to allocate better, utilize, and maintain relevant facilities, thereby improving production efficiency while reducing trial-and-error risks and providing a solid material foundation for the green transformation of agriculture.

Economic endowment refers to the monetary accumulation of farmers, reflecting their household economic level and economic status[31]. On the one hand, adopting LCFTs requires a certain level of financial support; generally, the richer a farmer's economic endowment, the stronger their ability to afford such practices[32]. On the other hand, according to Maslow's hierarchy of needs theory, the pursuit of ecological and environmental concerns falls within the category of safety needs, and a substantial economic endowment provides the financial basis for farmers to pursue such safety needs[33].

Human endowment includes farmers' education level, health status, participation in technical training, and the number of household laborers, representing a comprehensive measure of the quantity and quality of labor[34]. Generally, the greater the number of laborers, the more effort can be devoted to low-carbon agricultural production[35], and the higher the quality of labor, the stronger the farmers' ability to learn and apply new technologies.

Social endowment refers to the degree of connection between individuals and groups[36], including social networks, social trust, social participation, and social prestige. Through mechanisms such as information diffusion[37], trust building[38], and behavioral guidance[13], social endowment effectively promotes the dissemination and adoption of LCFTs among farming communities.

Information capital refers to farmers' ability to acquire, utilize, and share information in production decision-making, including information acquisition, utilization, and sharing capacities. Information capital significantly increases farmers' probability of adopting low-carbon fertilization technologies by reducing information asymmetry[39,40] and expanding channels for skills training and technical learning[41].

Based on this, the following hypothesis is proposed:

**H1** Capital endowment has a significant positive effect on farmers' adoption of LCFTs.

## Mediating effect of value cognition

Value cognition refers to an individual's overall judgment of a given behavior's economic, ecological, and social value[42]. In the context of agricultural green transformation, whether farmers adopt LCFTs is not only constrained by their capital endowment but also influenced by their value cognition. When farmers have a vague understanding of the value of low-carbon agriculture, their perception of expected benefits weakens, their consideration of short-term costs intensifies, and resistance to adoption increases[43]. In contrast, when farmers recognize that LCFTs can improve agricultural product quality, increase yields, and protect the ecological environment, they are more inclined to adopt them[44]. Therefore, value cognition is an important factor influencing farmers' behavioral choices[45,46], and capital endowment provides the fundamental support for forming such cognition[11,47].

Specifically, farmers with abundant natural endowment tend to pay more attention to soil quality and fertility improvement due to their stronger dependence on land and long-term operational expectations. Therefore, they can better recognize and understand the potential value of LCFTs in soil restoration and ecological improvement. Second, the richer the material endowment, the better the farmers can perceive the economic value of LCFTs in terms of cost savings and efficiency enhancement. Third, greater economic endowment enhances farmers' risk resistance capacity, enabling them to evaluate the ecological and social value of LCFTs from a long-term perspective. Fourth, human endowment improves farmers' policy comprehension and environmental awareness, making them more likely to realize the positive significance of green production for the socio-ecological system. Fifth, richer social endowment allows farmers to leverage social networks and neighbor demonstration effects to accelerate the circulation of low-carbon information, thereby enhancing their value cognition of LCFTs. Sixth, the richer the information capital, the more efficient farmers are in acquiring, processing, and sharing low-carbon information, enabling them to more accurately evaluate its role in cost reduction and efficiency gains, ecological improvement, and sustainable development, thereby significantly enhancing their cognition of economic, ecological, and social values.

Accordingly, the following hypothesis is proposed:

**H2** Value cognition mediates the relationship between capital endowment and farmers' adoption of LCFTs.

## Moderating effect of environmental regulation

When adopting LCFTs, farmers incur additional time and economic costs. Suppose farmers prioritize short-term benefits while neglecting the long-term ecological and social benefits. In that case, they are more likely to choose high-carbon fertilization methods, which will harm the environment and adversely impact others, thus exhibiting negative externalities. According to externality theory and public goods theory, approaches to addressing the negative externalities of environmental pollution include government intervention and market mechanisms. However, due to the public goods nature of the rural environment, property rights are difficult to define, making it hard for market mechanisms to achieve optimal resource allocation and prone to "market failure." In addition, since rural development is still in its early stage—located on the left side of the Environmental Kuznets Curve turning point—farmers remain focused on income growth and, to some extent, forgo demands for participating in ecological governance[48]. Therefore, environmental regulation has become a key external factor driving farmers' low-carbon decision-making.

According to previous studies[26,49,50], environmental regulation can be categorized into three types: command-and-control regulation, incentive-based regulation, and guidance-oriented regulation. Specifically, command-and-control regulation mandates farmers to adopt LCFTs, with measures such as supervision, penalties, or public criticism imposed on those who fail to comply. Incentive-based regulation provides economic compensation and other benefits to farmers who adopt LCFTs. Guidance-oriented regulation involves the government offering publicity campaigns, training sessions, and demonstration activities to guide farmers toward adopting LCFTs. Environmental regulation influences farmers' adoption of LCFTs in three main ways.

First, command-and-control regulation can correct farmers' perception of the cost of environmental violations. Farmers engaging in "high-carbon" practices may incur economic and reputational losses; driven by economic rationality, loss aversion, and psychological pressure, they are more likely to adopt LCFTs.

Second, incentive-based regulation increases farmers' transfer income. As "economic actors," farmers make rational decisions on whether to adopt LCFTs based on cost–benefit analysis. Subsidies for organic fertilizers or formula fertilization can raise farmers' expected returns, thereby increasing the probability of adoption.

Third, guidance-oriented regulation can enhance farmers' technical cognition and value perception of LCFTs, strengthening their expectations regarding the feasibility of adoption and reducing psychological barriers and technical concerns during implementation.

Based on this, the following hypotheses are proposed:

**H3** Environmental regulation has a significant positive moderating effect on the relationship between capital endowment and farmers' adoption of LCFTs.

**H4** Environmental regulation has a significant positive moderating effect on the relationship between value cognition and farmers' adoption of LCFTs.

Based on the above hypotheses, this study further provides a theoretical explanation for why environmental regulation is positioned as a moderating variable in both the "capital endowment → behavior" and "value cognition → behavior" pathways. The rationale is supported by the following two theoretical perspectives:

First, according to the Sustainable Livelihoods Framework (SLF), capital endowment constitutes the fundamental basis for farmers' livelihood strategies, but whether farmers adopt low-carbon fertilization behaviors is often influenced by external institutions and policy environments. The SLF emphasizes that "livelihood strategy choice" depends not only on internal capital structures but also on the "vulnerability context" and "transforming structures" composed of institutions, policies, and organizations. Environmental regulation represents a critical component of this external structure, which adjusts farmers' ability to transform capital endowments into behavioral outcomes.

Second, from the perspectives of environmental regulation theory and externality theory, the essential function of environmental regulation is to address the typical externalities in agricultural production by influencing individual behavioral decisions through institutional arrangements. Whether through subsidies, penalties, technical guidance, or publicity and extension measures, the ultimate goal of environmental regulation is to increase the marginal benefits or reduce the marginal costs of green production behaviors. Therefore, it exerts a significant reinforcing or constraining effect on the pathways through which farmers transform "cognition" or "resources" into "behavior," manifesting as a moderating effect.

Based on the above theoretical logic, the empirical model includes two interaction terms—capital endowment × environmental regulation and value cognition × environmental regulation—to identify how different types of environmental regulation moderate the behavioral adoption pathways of low-carbon fertilization. This design systematically reveals the behavioral transformation logic under the interaction of "internal resource base × external institutional environment." The specific model structure is shown in Fig. 1.

## Research method

### Data sources

The data used in this study were obtained from a questionnaire survey on "Farmers' adoption of low-carbon technology", conducted by the research team in Shandong Province from January to March 2025. Shandong Province was selected as the survey region for three main reasons. First, it is one of China's major grain-producing provinces with large-scale and diverse agricultural operations, making it highly representative. Second, its varied topography—including plains, hills, and mountainous areas—captures heterogeneous natural and production conditions. Third, Shandong serves as a key pilot province for agricultural green transition and environmental regulation policies, with long-term implementation of soil testing and formula fertilization, straw return, and organic fertilizer substitution. These characteristics make Shandong a typical and representative case for examining farmers' low-carbon fertilization behavior and their policy responses.

The survey was conducted through one-on-one interviews with household heads or key family members involved in production decision-making. A total of 1,100 questionnaires were distributed. After excluding those with missing data or internally inconsistent information, 1,008 valid samples were retained, resulting in an effective response rate of 91.64%. The questionnaire covered: farmers' personal and household basic information, capital endowment, value cognition, adoption of LCFTs, and environmental regulation.

### Variable selection

*Dependent variable*

Adoption of LCFTs. In this study, farmers' adoption of any specific LCFT—such as organic fertilizer substitution or soil testing and formula fertilization—is considered as evidence of LCFT adoption behavior. A farmer is deemed to have adopted LCFTs if they implement either organic fertilizer substitution or soil testing and formula fertilization.

Furthermore, to assess the differential impacts of capital endowment and environmental regulation on distinct LCFTs, this study separately uses organic fertilizer substitution and soil testing and formula fertilization as specific representations of LCFT adoption behavior.

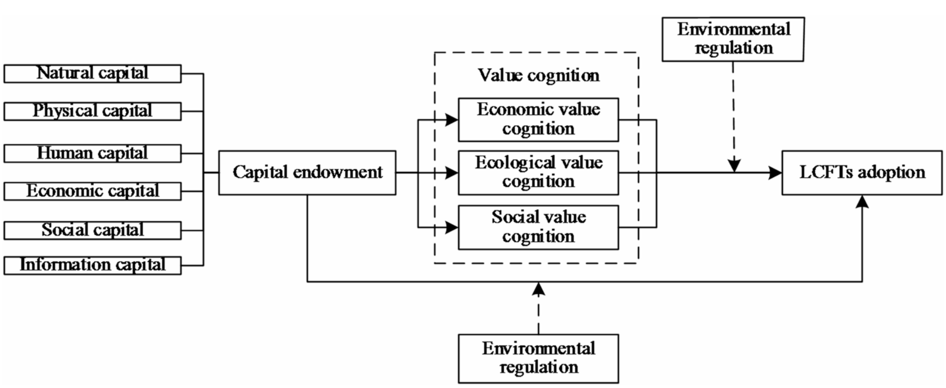


**Fig. 1**. Theoretical framework.

*Core explanatory variables*
Capital endowment. This variable is measured from six dimensions: natural endowment, material endowment, human endowment, economic endowment, social endowment, and information endowment. The specific measurement indicators are provided in Supplementary Information Table A1.

The entropy method is used to standardize the above indicators and calculate their weights, thereby objectively determining the level of each dimension of capital endowment and further calculating the total score of capital endowment. The detailed indicator system and entropy-based weights for each dimension of capital endowment are presented in Table 1.

*Value cognition* This variable is measured from three dimensions: economic value cognition, ecological value cognition, and social value cognition. The specific measurement indicators are shown in Table 2.

*Moderating variable*
Environmental regulation (ER). This variable is measured from three dimensions: command-and-control regulation, incentive-based regulation, and guidance-oriented regulation. The specific measurement indicators are provided in Supplementary Information Table A1. The entropy method is used to standardize the above indicators and calculate their weights, thereby objectively determining the level of each dimension of environmental regulation and further calculating the total score of environmental regulation. The detailed indicators and entropy-based weights of environmental regulation are shown in Table 3.

The detailed indicators and entropy-based weights of environmental regulation are shown in Table 3.

*Control variables*
This study selects factors that may influence farmers' adoption of LCFTs—such as age, gender, years of farming experience, cadre status, perception of natural disasters, and risk preference—as control variables. These variables have been widely used in prior empirical studies on agricultural technology adoption and low-carbon behavioral decisions[41,51,52]. In addition, to control for differences across regions in terms of geographical location, climatic conditions, precipitation, and other factors, regional dummy variables are included to eliminate the influence of regional differences on farmers' adoption of LCFTs.

## Model construction
*Binary logit model*
Since the dependent variable is a typical binary variable, A binary Logit regression model is introduced for data simulation. First, to explore the effect of capital endowment on farmers' decision to adopt LCFTs, the model includes only capital endowment and control variables for regression:

$$\mathrm{logit}\,(\mathrm{Y_i}) = \alpha_{\,0} + \alpha_{\,1}\mathrm{CE_i} + \alpha\,\mathrm{Control} + \epsilon_{\,i} \tag{1}$$

In Eq. (1):

| Capital type | Measurement indicator | Entropy value | Primary indicator weight | Secondary indicator weight |
|---|---|---|---|---|
| Physical Capital | Condition of field roads (+) | 0.988 | 0.1126 | 0.011 |
| | Transportation accessibility (+) | 0.989 | | 0.011 |
| | Number of machines for fertilization (+) | 0.907 | | 0.091 |
| Natural Capital | Village topography (+) | 0.978 | 0.2009 | 0.022 |
| | Farmland size (+) | 0.838 | | 0.158 |
| | Farmland quality (+) | 0.994 | | 0.007 |
| | Degree of land consolidation (+) | 0.984 | | 0.016 |
| Economic Capital | Total household income (+) | 0.961 | 0.1141 | 0.039 |
| | Income stability (+) | 0.98 | | 0.018 |
| | Financing ability (+) | 0.942 | | 0.057 |
| Human Capital | Education level (+) | 0.963 | 0.2758 | 0.036 |
| | Health condition (+) | 0.989 | | 0.011 |
| | Labor force ratio (+) | 0.968 | | 0.017 |
| | Agricultural technical training (+) | 0.781 | | 0.213 |
| Social Capital | Social trust (+) | 0.992 | 0.0836 | 0.008 |
| | Social networks (+) | 0.988 | | 0.012 |
| | Social participation (+) | 0.976 | | 0.024 |
| | Social reputation (+) | 0.959 | | 0.04 |
| Information Capital | Information acquisition ability (+) | 0.952 | 0.2131 | 0.047 |
| | Information utilization ability (+) | 0.983 | | 0.112 |
| | Information sharing ability (+) | 0.946 | | 0.053 |

**Table 1.** Weights of indicators of farmers' capital endowment.

| Variable type | Variable Name | Definition | Mean | SD |
|---|---|---|---|---|
| Dependent variable | Adoption of LCFTs | If the farmer adopts either organic fertilizer substitution or soil testing and formula fertilization: Yes = 1; No = 0 | 0.4881 | 0.5002 |
| | Organic fertilizer substitution | Yes = 1; No = 0 | 0.4594 | 0.4986 |
| | Soil testing and formula fertilization | Yes = 1; No = 0 | 0.3046 | 0.4605 |
| Independent variables | Capital endowment (CE) (6 dimensions) | Entropy-weighted index covering physical, natural, human, economic, social, and information capital | 0.2621 | 0.1064 |
| Mediating variable | Economic value cognition | Do you agree that adopting low-carbon fertilization can help increase income? Completely disagree = 1; Disagree = 2; Average = 3; Agree = 4; Completely agree = 5 | 3.2173 | 0.9131 |
| | Ecological value cognition | Do you agree that adopting low-carbon fertilization can help protect farmland ecology? Completely disagree = 1; Disagree = 2; Average = 3; Agree = 4; Completely agree = 5 | 3.6201 | 0.8866 |
| | Social value cognition | Do you agree that adopting low-carbon fertilization can help provide high-quality, safe agricultural products? Completely disagree = 1; Disagree = 2; Average = 3; Agree = 4; Completely agree = 5 | 3.4961 | 0.8958 |
| Moderating variable | Environmental regulation (3 types, 5 dimensions) | Entropy-weighted index covering:<br>Command-and-control regulation (supervision, penalties)<br>Incentive-based regulation (subsidies)<br>Guidance-based regulation (publicity, training) | 0.5442 | 0.2018 |
| Control variables | Age | Actual age of farmer (years) | 55.508 | 13.0076 |
| | Gender | Male = 1; Female = 0 | 0.5794 | 0.494 |
| | Years of farming experience | Actual years of planting experience | 32.1598 | 15.3212 |
| | Cadre status | Whether the farmer has served as a village cadre: Yes = 1; No = 0 | 0.0774 | 0.2674 |
| | Perception of natural disasters | Not at all = 1; Not severe = 2; Average = 3; Relatively severe = 4; Very severe = 5 | 4.3274 | 1.5283 |
| | Risk preference | Attitude toward risk: Strongly dislike = 1; Dislike = 2; Average = 3; Like = 4; Strongly like = 5 | 2.26 | 0.9177 |
| | Eastern region | Farmland located in Jinan, Zibo, Dongying, Yantai, Weihai, Qingdao = 1; Otherwise = 0 | 0.3522 | 0.4779 |
| | Western region | Farmland located in Zaozhuang, Binzhou, Dezhou, Liaocheng, Heze, Linyi = 1; Otherwise = 0 | 0.3294 | 0.4703 |

**Table 2**. Variable definitions and descriptive statistics.

| Variable | Measurement indicator | Entropy value | Indicator weight |
|---|---|---|---|
| Environmental regulation | Supervision (+) | 0.9826 | 0.1744 |
| | Penalty (+) | 0.9803 | 0.1975 |
| | Publicity and Promotion (+) | 0.9817 | 0.1835 |
| | Technical Guidance (+) | 0.9815 | 0.1853 |
| | Subsidy (+) | 0.9741 | 0.2596 |

**Table 3**. Weights of indicators of environmental regulation.

$Y_i$ is a binary dependent variable indicating whether farmer i adopts LCFTs. Specifically, LCFTs adoption is defined as the use of either organic fertilizer substitution or soil testing and formula fertilization. If the farmer adopts at least one of the two practices, $Y_i$ =1; otherwise, $Y_i$ =0.

$CE_i$ denotes the composite index of capital endowment for farmer i;

Control is a vector of control variables including individual and household characteristics (e.g., age, gender, farming experience, cadre status, disaster perception, and risk preference);

$\alpha_0$ is the intercept term. $\alpha_1$ and $\alpha$ are the estimated coefficients for the explanatory variables. If capital endowment has a positive effect on farmers' LCFTs adoption, $a_1$ should be positive and statistically significant.

$\varepsilon_i$ is the random error term, assumed to follow a logistic distribution.

*Mediation effect model*

On the basis of the baseline model (1), a mediation effect model is constructed to verify research hypothesis H2, as shown in Eqs. (2) and (3).

$$VC_i = \beta_0 + \beta_1 CE_i + \beta \text{ Control} + \mu_i \tag{2}$$

$$\text{logit}\,(Y_i) = \gamma_0 + \gamma_1 CE_i + \gamma_2 VC_i + \gamma \text{ Control} + \delta_i \tag{3}$$

In Eqs. (2) and (3):

$VC_i$ denotes the composite score of value cognition for farmer i, which includes economic value cognition, ecological value cognition, and social value cognition;

$CE_i$ is the capital endowment index, as defined earlier;

Control is a vector of control variables as in the baseline model;

$\beta_0$, $\beta_1$, $\beta$, and $\mu_i$ are the intercept, coefficients, and error term in the mediator regression model (Eq. 2);

$\gamma_0$, $\gamma_1$, $\gamma_2$, $\gamma$, and $\delta_i$ are the intercept, coefficients, and residual error in the final outcome regression (Eq. 3), where the mediating effect of value cognition is evaluated.

*Moderation effect model*
Following the definition of moderation effect proposed by Wen Zhonglin et al., the moderation effect is constructed based on the baseline Model (1). An interaction term between capital endowment and environmental regulation is introduced into Model (1) to test the moderating effect of environmental regulation on the relationship between capital endowment and farmers' adoption of LCFTs.

To avoid multicollinearity problems, the original variables are mean-centered before constructing the interaction terms. The identified models are as follows:

$$\text{logit}\left(Y_i\right) = \sigma_0 + \sigma_1 CE_i + \sigma_2 ER_i + \sigma_3 CE_i \times ER_i + \sigma\, \text{Control} + \phi_i \tag{4}$$

In Eq. (4):
$CE_i$ denotes capital endowment;
$ER_i$ represents environmental regulation;
$CE_i \times ER_i$ is the interaction term used to examine moderating effect;
Control includes the control variables defined in Eq. (1);
$\sigma_0$, $\sigma_1$, $\sigma_2$, $\sigma_3$, $\sigma$ are regression coefficients, while $\varphi_i$ is the random error term.

*Moderated mediation effect model*
To further examine the conditional indirect effect of capital endowment on farmers' adoption behavior through value cognition under varying levels of environmental regulation, a moderated mediation model is specified as shown in Eq. (5).

This model allows us to evaluate whether the mediating effect of value cognition is moderated by environmental regulation.

$$\text{logit}\left(Y_i\right) = \tau_0 + \tau_1 CE_i + \tau_2 VC_i + \tau_3 ER_i + \tau_4 VC_i \times ER_i + \tau\, \text{Control} + \omega_i \tag{5}$$

In Eq. (5):
$CE_i$ denotes capital endowment;
$VC_i$ is the mediating variable representing value cognition;
$ER_i$ represents environmental regulation;
$VC_i \times ER_i$ is the interaction term used to examine moderating effect;
Control includes the control variables defined in Eq. (1);
$\tau_0$, $\tau_1$, $\tau_2$, $\tau_3$, $\tau_4$, and $\tau$ are regression coefficients, while $\omega_i$ is the random error term.

## Empirical analysis
### Impact of capital endowment on farmers' adoption of LCFTs
All variables were tested for multicollinearity using Stata 15.0. The obtained VIF values ranged from 1.04 to 2.50, with an average value of 1.45, all less than 10, indicating no multicollinearity among the selected variables and the independence requirement was satisfied.

Columns (1), (3), and (5) of Table 4 show that capital endowment has a significant positive effect on farmers' adoption of LCFTs, including organic fertilizer substitution as well as soil testing and formula fertilization, indicating that the higher the overall level of farmers' capital endowment, the more inclined they are to adopt LCFTs. Columns (2), (4), and (6) of Table 4 further reveal the effects of different dimensions of capital endowment on the three types of fertilization practices, which verifies research hypothesis H1.

The regression results reveal that natural capital, human capital, economic capital, social capital, and information capital significantly and positively influence farmers' adoption of LCFTs, including both organic fertilizer substitution and soil testing and formula fertilization. However, physical capital shows a significant effect only on the adoption of organic fertilizers, with no significant impact on soil testing and formula fertilization. These results indicate that the influence of capital endowment on LCFTs adoption varies across dimensions and technology types. Specifically, natural capital has the strongest effect on organic fertilizer substitution, while human capital plays a dominant role in the adoption of soil testing and formula fertilization. Detailed explanations of these findings are presented in Supplementary Information B.

At the same time, environmental regulation, years of farming experience, and cadre status positively influence the adoption of LCFTs, whereas the perception of natural disasters and risk preference exert significant negative effects. These findings highlight the importance of policy intervention and farmer experience in encouraging low-carbon technology adoption. While disaster risk perceptions discourage investment, those with stronger leadership roles or more farming experience are better positioned to adopt sustainable practices, even in challenging environments. For detailed interpretations of these control variable results, see Supplementary Information C.

### Endogeneity treatment
Although the preceding analysis incorporates certain individual, household, and regional characteristics of farmers as control variables in the model estimation, it is still theoretically impossible to completely rule out endogeneity problems caused by reverse causality, selection bias, and measurement error.

To address the potential endogeneity between capital endowment and farmers' adoption of LCFTs, this study first applies the entropy weight method to calculate a composite index of capital endowment, thereby reducing

| Variable name | LCFTs (1) | (2) | Organic fertilizer substitution (3) | (4) | Soil testing and formula fertilization (5) | (6) |
|---|---|---|---|---|---|---|
| CE | 7.2*** (8.45) | | 6.4593*** (7.81) | | 8.9884*** (9.93) | |
| Physical capital | | 0.9828** (2.14) | | 0.9695** (2.15) | | 0.3921 (0.82) |
| Natural capital | | 1.8906* (1.72) | | 1.8412*(1.7) | | 2.5127** (2.19) |
| Human capital | | 1.6964*** (3.84) | | 1.4544*** (3.36) | | 2.8392*** (6.45) |
| Economic capital | | 2.0046*** (5.39) | | 1.8005*** (4.9) | | 1.8924*** (4.76) |
| Social capital | | 0.6978* (1.66) | | 0.7226* (1.73) | | 1.3076*** (2.83) |
| Information capital | | 1.1941*** (3.18) | | 1.0559*** (2.85) | | 1.2571*** (3.13) |
| Environmental regulation | 1.2298*** (3.08) | 1.3238*** (3.12) | 1.5446*** (3.86) | 1.5912*** (3.74) | 1.0682** (2.4) | 1.1469** (2.41) |
| Age | 0.0116 (1.39) | 0.0134 (1.59) | 0.007 (0.84) | 0.0087 (1.03) | 0.0096 (1.03) | 0.0106 (1.11) |
| Gender | 0.149 (1.07) | 0.1274 (0.9) | 0.1782 (1.28) | 0.1551 (1.1) | 0.1531 (0.98) | 0.1076 (0.67) |
| Years of farming experience | 0.015** (2.11) | 0.0148** (2.06) | 0.0148** (2.09) | 0.0145** (2.01) | 0.0162** (2.02) | 0.0149* (1.83) |
| Cadre status | 0.8673*** (3.03) | 0.8635*** (2.97) | 0.7154*** (2.61) | 0.699** (2.51) | 0.7981*** (2.93) | 0.7894*** (2.85) |
| Perception of natural disasters | -0.0895** (-1.96) | -0.0853* (-1.84) | -0.0842* (-1.85) | -0.0785* (-1.7) | -0.098* (-1.92) | -0.0993* (-1.9) |
| Risk preference | -0.2043** (-2.36) | -0.1785** (-1.96) | -0.2129** (-2.46) | -0.1909** (-2.1) | -0.207** (-2.16) | -0.1581 (-1.56) |
| Eastern region | 0.2573 (1.54) | 0.2294 (1.35) | 0.2663 (1.59) | 0.2355 (1.39) | 0.1037 (0.56) | 0.0564 (0.3) |
| Western region | 0.2211 (1.31) | 0.241 (1.4) | 0.2067 (1.23) | 0.2202 (1.28) | -0.024 (-0.13) | -0.043 (-0.22) |
| $LRx^2(F)$ | 150.77 | 175.39 | 140.13 | 163.11 | 184.81 | 207.8 |
| Log likelihood | -623.02081 | -610.7092 | -625.2905 | -613.7989 | -527.1946 | -515.6981 |
| Pseudo $R^2$ | 0.1079 | 0.1256 | 0.1008 | 0.1173 | 0.1491 | 0.1677 |
| N | 1008 | 1008 | 1008 | 1008 | 1008 | 1008 |

**Table 4**. Basic regression. T value in parentheses $*p<0.1$, $**p<0.05$, $***p<0.01$.

| | Endogeneity test for capital endowment: Coefficient | t-value | Standard Error |
|---|---|---|---|
| First-stage regression results: | | | |
| Instrumental variable (capital endowment) | 0.343*** | 4.61 | 0.07 |
| F | 23.93*** | | |
| Second-stage regression results: | | | |
| Capital endowment | 2.325** | 2.15 | 1.08 |
| Control variables | Controlled | | |
| Endogeneity tests: | | | |
| Durbin test | 0.494 ($P=0.482$) | | |
| Wu-Hausman test | 0.488 ($P=0.485$) | | |

**Table 5**. Endogeneity test results. T value in parentheses $*p<0.1$, $**p<0.05$, $***p<0.01$.

the possible endogeneity risk associated with single-dimension measures of capital endowment. In addition, the instrumental variable (IV) approach is employed for endogeneity testing. Specifically, the "average capital endowment level of other sample farmers within the same village" is selected as the instrumental variable[32,53]. Neighboring farmers often engage in strong information exchange and sharing, and this average level can significantly reflect an individual's capital endowment status, satisfying the relevance condition. At the same time, since this average reflects others' situations and does not directly affect an individual's adoption of LCFTs, it meets the exogeneity requirement.

Table 5 reports the results of the endogeneity tests. The first-stage regression results indicate that the instrumental variable is significantly correlated with the endogenous variables at the 1% level, with an F-statistic of 23.93, exceeding the threshold value of 10, suggesting no weak instrument problem exists. After controlling for potential endogeneity bias, the second-stage regression results show that capital endowment still exerts a significant positive impact on farmers' adoption of LCFTs. The endogeneity test results suggest that capital endowment can be regarded as an exogenous variable, making it suitable for conventional regression analysis.

## Mediating effect

To further examine the mediating role of value cognition in the relationship between capital endowment and farmers' adoption of LCFTs, this study employs the Process macro in SPSS 26.0 and applies the Bootstrap method to test the mediating effects of economic value cognition (EVC), social value cognition (SVC), and ecological value cognition (ELVC). The results are presented in Table 6.

The results of the mediating effect test in Table 6 indicate that economic value cognition, social value cognition, and ecological value cognition play significant mediating roles between capital endowment and the adoption of LCFTs, supporting research hypothesis H2. The possible reasons are as follows: First, farmers with higher levels of capital endowment can not only assess the input–output balance of low-carbon technologies more accurately, thereby positively influencing their adoption of LCFTs by enhancing their economic value cognition[54], but also understand the social contributions and environmental benefits of adopting such technologies[55]. This understanding, in turn, triggers farmers' moral norms and sense of social responsibility[56,57], motivating them to engage in low-carbon practices out of a sense of responsibility toward future generations and socio-ecological well-being.

## Moderating effect

To further examine the moderating role of environmental regulation (ER) in the relationship between capital endowment and the adoption of LCFTs, this study constructs a dual-path moderating effect model by introducing an interaction term between environmental regulation and capital endowment, as well as an interaction term between environmental regulation and value cognition. The empirical results are presented in Table 7.

### *Moderating effect of environmental regulation on the relationship between capital endowment and the adoption of LCFTs*

Model (1) shows that environmental regulation can significantly enhance the impact of capital endowment on farmers' adoption of LCFTs. In other words, under a context of stronger environmental regulation, farmers with higher capital endowment are more likely to adopt LCFTs. Further decomposing capital endowment into its five dimensions.

Models (2) to (7) show that the interaction terms between environmental regulation and natural capital, human capital, economic capital, social capital and information capital are all positive and significant at the 10% level or above. This suggests that environmental regulation has a significant positive moderating effect on the relationships between these four types of capital endowment and farmers' adoption of LCFTs. These findings indicate that external institutional interventions can activate farmers' capital endowment, thereby jointly driving the transition and upgrading toward low-carbon fertilization in agriculture. This result supports the research hypothesis H3.

It is worth noting that the moderating effect of environmental regulation on the relationship between physical capital and the adoption of LCFTs is not statistically significant. This suggests that the instrumental attributes of physical capital may not translate into a substantial impact under regulatory pressure.

To further compare the relative strength of environmental regulation's moderating effects across different dimensions of capital endowment on farmers' adoption of LCFTs, this study calculates the marginal effect differences based on the interaction term regression results. The shaded areas in Fig. 2 illustrate the magnitude of the moderating effects.

As shown in Fig. 2, on the one hand, environmental regulation exerts the strongest moderating effect on the relationship between human capital and the adoption of LCFTs. This may be because farmers with higher levels of human capital are better able to understand policy content, grasp regulatory requirements, and possess stronger implementation capabilities, thereby making them more responsive to environmental regulations.

On the other hand, the moderating effect of environmental regulation on the relationship between natural capital and the adoption of LCFTs is the weakest. This may be attributed to the fact that natural capital has a relatively strong direct effect on the adoption of low-carbon fertilization technologies, while its compatibility with environmental regulation is relatively low, making it difficult to adjust through short-term policy interventions.

### *Moderating effect of environmental regulation on the relationship between value cognition and the adoption of LCFTs*

As shown in Models (8), (9), and (10), the interaction terms between environmental regulation and economic value cognition, ecological value cognition, and social value cognition are all positive and statistically significant

| Category | Path | Effect value | Standard error | 95% Confidence interval | |
|---|---|---|---|---|---|
| | | | | Lower limit | Upper limit |
| Direct effect | CE → adoption | 7.476*** | 0.8574 | 5.7956 | 9.1564 |
| Mediating effect (EVC) | CE → EVC → adoption | 0.7791 | 0.2312 | 0.374 | 1.2771 |
| Total effect | CE → adoption | 8.2551 | – | – | – |
| Direct effect | CE → adoption | 7.4006*** | 0.8566 | 5.7217 | 9.0795 |
| Mediating effect (SVC) | CE → SVC → adoption | 0.8934 | 0.2282 | 0.4824 | 1.3905 |
| Total effect | CE → adoption | 8.294 | – | – | – |
| Direct effect | CE → adoption | 7.3032*** | 0.8602 | 5.6172 | 8.9893 |
| Mediating effect (ELVC) | CE → ELVC → adoption | 1.0939 | 0.2382 | 0.6676 | 1.6118 |
| Total effect | CE → adoption | 8.3971 | – | – | – |

**Table 6.** Mediating effect test. T value in parentheses $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

| | Moderating effect on the relationship between capital endowment and LCFTs | | | | | | | Moderating effect on the relationship between value cognition and LCFTs | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
| CE × ER | 11.515*** (3.07) | | | | | | | | | |
| Natural capital × ER | | 11.382** (2.1) | | | | | | | | |
| Physical capital ×ER | | | 3.182 (1.59) | | | | | | | |
| Human capital × ER | | | | 6.606*** (2.81) | | | | | | |
| Economic capital × ER | | | | | 3.679** (2.13) | | | | | |
| Social capital × ER | | | | | | 2.661* (1.73) | | | | |
| Information capital × ER | | | | | | | 2.736* (1.86) | | | |
| Economic value cognition × ER | | | | | | | | 0.917*** (2.74) | | |
| Ecological value cognition × ER | | | | | | | | | 1.113*** (3.2) | |
| Social value cognition × ER | | | | | | | | | | 0.89*** (2.72) |
| Control variables | Controlled | Controlled | | | | | | | | |
| LRx$^2$(F) | 160.79 | 82.76 | 96.12 | 114.91 | 127.46 | 90.8 | 96.31 | 105.16 | 127.37 | 109.97 |
| Log likelihood | -618*** | -657*** | -650*** | -641*** | -635*** | -653*** | -650*** | -646*** | -635*** | -643 |
| Pseudo R$^2$ | 0.1151 | 0.0592 | 0.0688 | 0.0823 | 0.0912 | 0.065 | 0.069 | 0.0753 | 0.0912 | 0.0787 |
| N | 1008 | 1008 | 1008 | 1008 | 1008 | 1008 | 1008 | 1008 | 1008 | 1008 |

**Table 7**. Moderating effect test. T value in parentheses *$p<0.1$, **$p<0.05$, ***$p<0.01$.

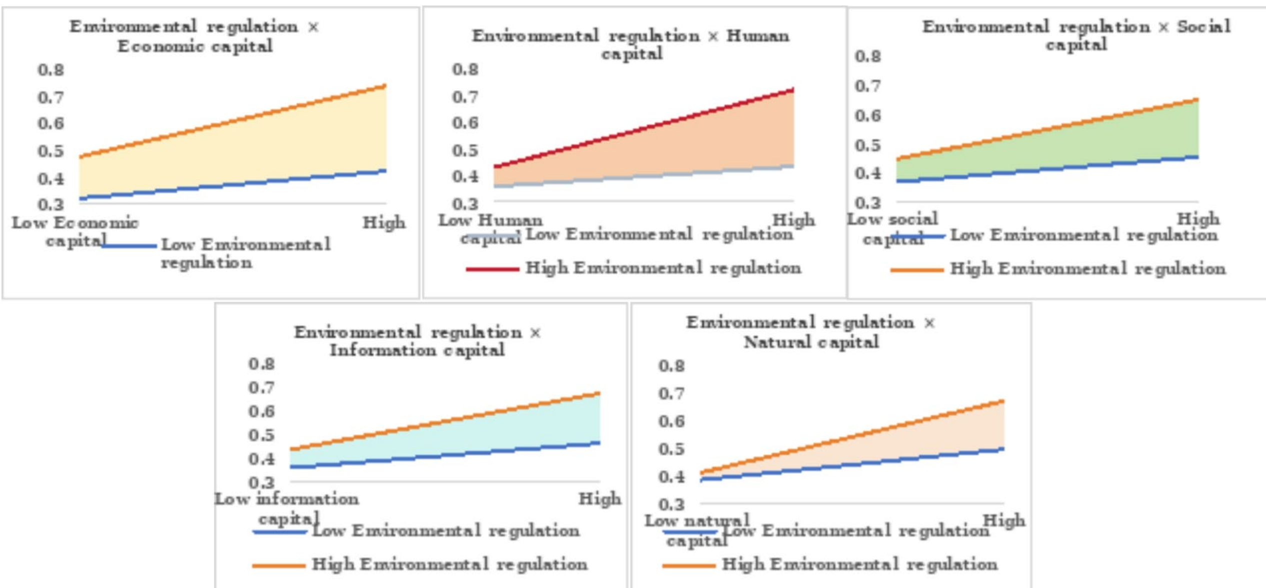


**Fig. 2**. Moderating effects of environmental regulation on capital endowment and tech adoption.

at the 10% level or higher. This indicates that environmental regulation exerts a significant positive moderating effect on the relationship between value cognition and farmers' adoption of LCFTs, suggesting that institutional interventions can activate farmers' value cognition, thereby jointly promoting the transformation and upgrading toward low-carbon fertilization in agriculture. These results confirm research hypothesis H4. The shaded area in Fig. 3 indicates the magnitude of the moderating effect of environmental regulation in the process by which value cognition influences farmers' adoption of LCFTs.

As shown in Fig. 3, environmental regulation has the strongest moderating effect on the relationship between ecological value cognition and the adoption of LCFTs. From the perspective of behavioral psychology, ecological value cognition embodies individuals' internal moral norms and pro-environmental identity, serving as a key

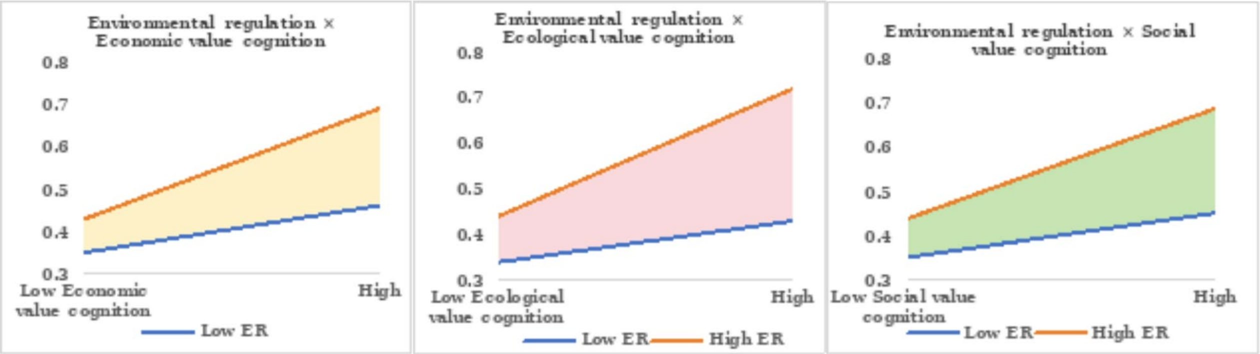


**Fig. 3**. Moderating effects of environmental regulation on value cognition and tech adoption.

| Variable name | Small-scale (1) | Medium-scale (2) | Large-scale (3) | Western Shandong (4) | Central Shandong (5) | Eastern Shandong (6) |
|---|---|---|---|---|---|---|
| CE × ER | 8.594 (0.78) | 7.394 (1.01) | 27.261*** (3.63) | 11.182 (1.39) | 13.701* (1.82) | 16.319** (2.28) |
| Control variables | Controlled | Controlled | Controlled | Controlled | Controlled | Controlled |
| LR$x^2$(F) | 63.96 | 55.78 | 66.11 | 41.75 | 53.64 | 77.36 |
| Log likelihood | -178.47 | -254.19 | -165.6 | -209.2*** | -193.77 | -206.98*** |
| Pseudo $R^2$ | 0.152 | 0.0989 | 0.1664 | 0.0907 | 0.1216 | 0.1574 |
| N | 312 | 407 | 289 | 332 | 321 | 355 |

**Table 8**. Heterogeneity analysis. T value in parentheses *$p<0.1$, **$p<0.05$, ***$p<0.01$.

psychological driver of sustainable behavior[58]. When external regulatory signals align with individuals' internal moral beliefs, a resonance mechanism between internal and external social norms is activated[59], whereby the consistency effect further enhances behavioral motivation[60]. Therefore, environmental regulation strengthens the moral and cognitive resonance of ecological values, resulting in a more pronounced moderating effect in this pathway.

## Heterogeneity analysis

To further identify the differences in responses of farmers with different planting scales to the interaction between environmental regulation and capital endowment, this study conducts regressions separately for three scale groups: large, medium, and small. Following the classification in existing research[48,61], farmers with a planting area of less than or equal to 3 mu are defined as small-scale farmers, those with 3–10 mu as medium-scale farmers, and those with 10 mu or more as large-scale farmers.

The results in Table 8 show that the interaction term between capital endowment and environmental regulation has a significantly positive moderating effect in the large-scale farmer group, but is insignificant for medium- and small-scale farmers. This may be because large-scale farmers are more responsive to environmental regulation due to higher policy awareness, lower marginal costs, and stronger capacity to adopt LCFTs.

To examine the regional differences in the moderating effect of environmental regulation on the relationship between capital endowment and farmers' adoption of LCFTs, this study further estimates interaction effect models for the western, central, and eastern regions of Shandong Province. The results show that in the Central Shandong and Eastern Shandong regions, environmental regulation has a significant positive moderating effect on the influence of capital endowment on farmers' adoption of LCFTs, whereas in the western region, the moderating effect is not significant. This may be related to differences among regions in terms of topographical conditions, ecological vulnerability, the stringency of environmental regulations, and the average level of farmers' capital endowment.

## Robustness checks

*Variable substitution*

The intensity of the adoption of LCFTs—defined as the simultaneous adoption of both organic fertilizer substitution and soil testing and formula fertilization—was used as the dependent variable. After controlling for control variables, a Logit regression was performed, and the results are reported in columns (1)–(2) of Table 9.

*Winsorization to eliminate outliers*

The Winsorize method was applied to all continuous explanatory variables—capital endowment, environmental regulation, age, and years of farming experience—at the 1% and 99% quantiles, in order to mitigate the influence of extreme values. Regressions were then re-estimated using the processed data, with the results presented in columns (3)–(4) of Table 9.

| Variable name | Variable substitution (adoption intensity) (1) | (2) | Winsorization test (3) | (4) | PCA-based robustness test (5) | (6) |
|---|---|---|---|---|---|---|
| Capital endowment | 9.516*** (10.66) | | 7.661*** (9.13) | | 0.994*** (0.166) | |
| Physical capital | | 0.612 (1.26) | | 1.026** (2.24) | | 0.242* (0.138) |
| Natural capital | | 2.499** (2.16) | | 2.977** (2.55) | | 0.354* (0.19) |
| Human capital | | 2.724*** (6.17) | | 1.656*** (3.73) | | 0.132* (0.068) |
| Economic capital | | 1.71*** (4.24) | | 1.965*** (5.29) | | 0.303*** (0.06) |
| Social capital | | 1.876*** (4.15) | | 1.05*** (2.6) | | 0.125** (0.054) |
| Information capital | | 1.369*** (3.35) | | 1.259*** (3.36) | | 0.194*** (0.06) |
| Control variables | Controlled | Controlled | Controlled | Controlled | 已控制 | 已控制 |
| LR$x^2$(F) | 170.33 | 194.46 | 145.29 | 173.78 | 86.47 | 157.66 |
| Log likelihood | -508.48*** | -496.42*** | -625.76*** | -611.52*** | -655.17*** | -619.59*** |
| Pseudo $R^2$ | 0.1435 | 0.1638 | 0.104 | 0.1244 | 0.0619 | 0.1129 |
| N | 1008 | 1008 | 1008 | 1008 | 1008 | 1008 |

**Table 9**. Robustness test results. T value in parentheses $*p<0.1$, $**p<0.05$, $***p<0.01$.

| Matching method | ATT estimate | S.E. | t-value | Matched sample size | Mean bias reduction |
|---|---|---|---|---|---|
| Capital endowment | 0.5774 | 0.0507 | 3.4 | 575 | 32.5% → 7.9% |

**Table 10**. PSM Estimation results.

*PCA-based robustness test*

To verify the robustness of the weighting method for the capital endowment indicators, this study re-estimated the composite scores of overall and dimensional capital endowments using Principal Component Analysis (PCA). The PCA-derived scores replaced the entropy-weighted indices in the regression models, and the corresponding results are reported in columns (5)–(6) of Table 9.

The results of these three robustness checks indicate that the signs and significance levels of the coefficients for capital endowment and environmental regulation remain essentially unchanged, thereby confirming the robustness of the empirical findings.

*Propensity score matching (PSM)*

Using the median as the cutoff to construct treatment and control groups, the nearest neighbor matching method (caliper = 0.05) was applied to perform pairwise matching to estimate the net effect of capital endowment. Table 10 presents the matching results.

Table 10 shows that, after PSM matching, the standardized bias of all covariates was substantially reduced (from 32.5% to 7.9%), and the ATT estimate was significant (0.5774). This indicates that, after controlling for observable variables, the adoption of LCFTs among farmers with high capital endowment was 57.74% higher than that of their counterparts. This conclusion is consistent with the main regression results, confirming the significant robustness of the positive effect of capital endowment on the adoption of LCFTs by farmers.

## Discussion

### Impact of core explanatory variable

Capital endowment and its various dimensions all have significant positive effects on the adoption of LCFTs. This indicates that a higher level of capital endowment can provide the necessary capacity for farmers to choose LCFTs, supporting the basic proposition of the sustainable livelihood framework that "capital accumulation can promote sustainable decision-making behavior"[62]. Among these dimensions, natural and human capital exert particularly strong influences on different LCFT types.

Natural capital exerts the strongest influence on the adoption of organic fertilizer substitution, as favorable terrain and concentrated landholdings enhance mechanization efficiency and reduce application costs[63]. Previous studies have shown that soil characteristics significantly affect the marginal productivity of fertilizer inputs[64], and since organic fertilizer is a restorative and accumulative input, it relies more heavily on natural capital. Therefore, policy measures should prioritize organic fertilizer promotion in areas with favorable terrain and land concentration to enhance technological accessibility and reduce costs.

In contrast, human capital plays the most critical role in the adoption of soil testing and formula fertilization, which is a knowledge-intensive practice requiring strong cognitive ability and technical literacy. It determines farmers' capacity to understand and apply the technology, making it a crucial support for implementation[65]. Farmers with higher education and technical training are better equipped to understand soil test results and follow fertilizer recommendations, resulting in higher adoption rates[66,67]. Hence, strengthening farmers' knowledge and technical literacy remains essential for expanding the effective coverage of soil testing and formula fertilization.

These findings highlight that different forms of capital endowment are not uniformly effective across LCFT types. Resource-intensive technologies like organic fertilizers rely more on natural and physical assets, while information- and decision-intensive technologies such as soil testing and formula fertilization requires greater human capital input.

### Impact of mediating variable

First, economic value cognition exerts a significant mediating effect between capital endowment and farmers' adoption of LCFTs. The reason is that a higher level of capital endowment can strengthen farmers' risk tolerance and investment capacity, thereby increasing their expectations of the future economic returns from LCFTs and, in turn, stimulating adoption intentions. Even under high capital endowment, imperfect market pricing and subsidy mechanisms may weaken farmers' perception of economic value due to the technology's positive externalities.

Second, social value cognition plays a significant mediating effect between capital endowment and farmers' adoption of LCFTs. Farmers with higher capital endowment tend to possess stronger information and policy comprehension abilities, making it easier for them to internalize the green development philosophy.

Third, ecological value cognition also plays a significant mediating role between capital endowment and farmers' adoption of LCFTs. Farmers with higher capital endowment are more likely to recognize LCFTs' ecological benefits, such as improving soil structure and reducing pollution. At the same time, stronger ecological value cognition can directly stimulate farmers' sense of environmental responsibility and moral obligation[68]. This finding is consistent with the core proposition of the Value–Belief–Norm (VBN) theory, which posits that individuals' pro-environmental behaviors often stem from internalized environmental values and a sense of moral responsibility[58].

Overall, enhancing farmers' economic, social, and ecological value cognition is essential for transforming LCFT promotion from policy-driven to value-driven.

### Impact of moderating variable

Environmental regulation strengthens the positive impact of capital endowment on farmers' adoption of LCFTs, indicating that farmers with higher capital endowment are more willing to adopt LCFTs under regulatory incentives. The moderating effect is most pronounced between human capital and LCFT adoption, as farmers with higher human capital can better interpret policy signals and translate them into practical actions[69].

In contrast, the moderating effect on natural capital is weakest because land scale and soil fertility are relatively fixed in the short term, leaving limited room for amplification through regulatory measures. The moderating effect on physical capital is also insignificant, possibly because its utility depends mainly on existing infrastructure and market conditions rather than regulatory intensity.

At the same time, environmental regulation plays a significant positive moderating role in the influence of value cognition on farmers' adoption of LCFTs. Among these, the effect is strongest in the ecological value cognition pathway, where policy guidance enhances farmers' environmental awareness and strengthens adoption willingness. This finding is consistent with the study by Song (2025)[48] and further confirms the mechanism that "external constraints reinforce internal cognition, and internal cognition stimulates behavioral motivation."

### Heterogeneity of the moderating effect

The moderating effect of environmental regulation exhibits heterogeneity across farmer types and regions. It is more pronounced among large-scale farmers with stronger capital endowment and greater sensitivity to regulatory incentives, while remaining insignificant among small- and medium-scale farmers due to land fragmentation and limited adaptability to LCFTs. Regionally, the moderating effect also varies due to differences in endowment structures and technological adaptability (Xu et al., 2025)[70]. It is stronger in Central and Eastern Shandong, where regulatory intensity is higher and farmers' capital endowment is generally stronger, and weaker in the Western region due to lower policy pressure and a more constrained resource base.

## Conclusions and recommendations

### Conclusions

Based on 1,008 household survey samples from Shandong Province, this study employs a binary Logit model to empirically examine the relationships among capital endowment, value cognition, environmental regulation, and farmers' adoption of LCFTs. The main conclusions are as follows:

First, capital endowment and its various dimensions significantly and positively influence farmers' adoption of LCFTs. Among the different dimensions, natural capital exerts the greatest effect on organic fertilizer substitution, whereas human capital has the strongest influence on soil testing and formula fertilization.

Second, economic value cognition, social value cognition, and ecological value cognition all play significant mediating roles between capital endowment and the adoption of LCFTs.

Third, environmental regulation has a significant positive moderating effect on the relationships between capital endowment, value cognition, and the adoption of LCFTs. In terms of the magnitude of the moderating effect, environmental regulation has the strongest positive moderation between human capital and the adoption of LCFTs, and between ecological value cognition and the adoption of LCFTs.

Fourth, the moderating effect of environmental regulation exhibits heterogeneous impacts. On the one hand, compared with small- and medium-scale farmers, environmental regulation significantly enhances the influence of capital endowment on large-scale farmers' adoption of LCFTs; on the other hand, compared with the western region, environmental regulation significantly strengthens the influence of capital endowment on the adoption of LCFTs by farmers in the central and eastern regions.

## Recommendations

First, leverage the foundational role of capital endowment. Enhance farmers' capital endowment and strengthen their capacity for green production through measures such as vocational farmer training, agricultural technical services, land transfer and scale operations, and the development of digital villages.

Second, strengthen the cultivation and guidance of value cognition. Highlight the ecological benefits and environmental responsibility of low-carbon fertilization in policy publicity, and further enhance farmers' economic value cognition through market linkages, subsidies, credit, insurance, and other supportive measures.

Third, improve the overall effectiveness of environmental regulation. Utilize multiple approaches—including technical training, ecological compensation, and punitive measures—to reinforce farmers' understanding and recognition of environmental policies, thereby transforming regulatory pressure into motivation for adoption.

Fourth, differentiated and targeted measures. Strengthen the positive guiding role of environmental regulation for large-scale farmers and those in the central and eastern regions of Shandong, while further enhancing the capital endowment base of small- and medium-scale farmers and those in the western region.

## Limitations and outlook of the study

Based on cross-sectional data, examines the relationships among capital endowment, value cognition, environmental regulation, and the adoption of LCFTs, making it difficult to capture the dynamic changes in these relationships over time. Future research could incorporate panel data or long-term tracking surveys to explore the stability and evolutionary patterns of the roles of value cognition and environmental regulation at different stages of adoption (initial trial, continued use, and technological upgrading).

At the same time, although this study verifies the mediating effect of value cognition in the relationship between capital endowment and adoption behavior, as well as the moderating effect of environmental regulation, the interaction mechanism between the two has not been fully explored. Future studies could employ hybrid models combining chain mediation and moderation to analyze how the "capital endowment–value cognition–adoption intention–adoption behavior" pathway changes under varying intensities of environmental regulation, thereby revealing the complementarities and substitution effects between policy instruments and cognitive factors.

Finally, the analysis in this study focuses primarily on the individual level, overlooking the systematic influence of differences in village, community, and regional policies. Future research could adopt a multilevel analytical framework that incorporates village-level collective values, social norms, and the enforcement strength of local environmental regulations into the model, in order to examine the spillover and spatial spillover effects of these contextual factors on individual adoption behavior.

In addition, it should be noted that although this study focuses on Shandong Province, the findings are not limited to regional characteristics. As a major agricultural province with diverse topography, production scales, and policy environments, Shandong highly represents China's grain-producing regions. Therefore, the mechanism identified in this study—how capital endowment and environmental regulation jointly influence farmers' low-carbon fertilization behavior—has universal theoretical significance and may apply to other developing countries undergoing low-carbon agricultural transitions. Future studies could further validate this mechanism through multi-regional or cross-country comparative analyses.

# Declarations

## Ethical approval

All participants were adult farmers who voluntarily agreed to take part in the survey. Before starting the questionnaire, participants were provided with a written statement on the first page explaining the purpose of the research, the anonymous and confidential handling of data, and their right to participate voluntarily. As the survey was conducted anonymously and posed minimal risk to participants, signed informed consent forms were not collected; instead, verbal informed consent was obtained from all participants before the interviews commenced. According to the Ethical Review Methods for Life Sciences and Medical Research Involving Humans issued by the National Health Commission of China in February 2023, written consent and ethics approval may be waived for minimal-risk studies involving anonymized data (full text available at: https://www.gov.cn/zhengce/2023-02/28/content_5743660.htm). All methods were performed in accordance with the relevant guidelines and regulations.

## Data availability

The raw data and analysis files used to support the findings of this study are available from the corresponding author upon request.

Received: 30 August 2025; Accepted: 18 November 2025
Published online: 23 November 2025

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## Funding

This research was funded by the National Social Science Foundation Key Project, Research on the Optimization of China's Agricultural Insurance Policy Based on the "Trinity" of Scale, Structure, and Efficiency, grant number 23AGL026.

## Declarations

## Competing interests

The authors declare no competing interests.

## Additional information

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1038/s41598-025-29655-2.

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