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Impact of agricultural science and technology innovation resources allocation on rural revitalization

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China's reform began in the countryside, and rural reform began in Anhui. This study uses Anhui Province, China as an example in analyzing the impact of agricultural science and technology innovation resource allocation on rural revitalization, particularly by constructing an econometric model. Results indicate that the allocation of agricultural science and technology innovation resources has a steady positive impact on rural revitalization. Improvements in the allocation of agricultural science and technology innovation resources can effectively promote the development of rural revitalization and the spatial spillover of rural development, thereby facilitating the promotion of the spillover of neighboring areas to local rural development. A nonlinear relationship exists between allocation of agricultural science and technology innovation resources and rural revitalization. Lastly, rural revitalization can only be promoted substantially when the allocation of agricultural science and technology innovation resources reaches a certain condition.

KEYWORDS

agricultural science and technology innovation, resource allocation, rural revitalization, China, Anhui Province

1 Introduction

Agriculture is the foundation of national development, and high-quality agricultural development is related to national security. "Achieving the transformation from a large agricultural country to a strong agricultural country" is the goal China pursues. Since the reform and opening-up, China's agriculture has entered a rapid development track. From 1978 to 2022, the number of employees in the primary industry decreased from 283.18 million to 176.63 million, the total output value of the primary industry increased from 101.85 billion yuan to 8.83451 trillion yuan, the total output value of agriculture, forestry, animal husbandry, and fishery increased from 137.9 billion yuan to 15.60659 trillion yuan, and grain output increased from 304.765 million tons to 686.528 million tons (National Bureau of Statistics of the People's Republic of China, 2023). China's agriculture is also crucial to the world. The added value of China's agriculture, forestry, animal husbandry, and fishery as a proportion of the world's total added value increased from 17.44% in 2001 to 30.27% in 2019, ranking first in the world. The average annual growth rate reached 10.03%, higher than the world average annual growth rate of 6.71% during the same period. The annual output of wheat, rice, fruits, vegetables, and pork, as well as their share of the global total output, also ranked first in the world (Xue and Gao, 2023).

The key to agricultural modernization is agricultural science and technology innovation. The contribution rate of China's agricultural scientific and technological progress has maintained a steady growth trend in recent years, rising from 54.5% in 2012 to over 63% in 2023. Although there is still a gap compared to the generally over 70% level of innovative countries, the overall level is already among the world's best (Li and Cheng, 2024). However, compared to the world's agricultural powerhouses, China's agricultural competitiveness still has significant shortcomings. The proportion of agricultural labor is still relatively high (23.6% in 2020, compared to less than 3% in most high-income countries), and the return on labor input is very low. At constant 2015 USD, China's per labor agricultural value added is $5,609, which is only 5% of that in the US, Israel, Canada, and 20% of the EU's overall level (Wei and Cui, 2022). Therefore, it is still necessary to emphasize the transition from factor input-driven growth to efficiency-driven growth.

Implementing the rural revitalization strategy is the most important guarantee for achieving the modernization of China's agriculture and rural areas and building a strong agricultural country. It is the current focus of China's 'agriculture, rural areas, and farmers' work, and agricultural scientific and technological innovation is the internal driving force that promotes rural revitalization. As China's rural revitalization continues to move toward a deeper level, the impact of agricultural scientific and technological innovation on rural revitalization has become increasingly prominent. Such an innovation involves various subjects and fields of the rural revitalization system, plays a significant role and has become a key core force driving rural revitalization and development. Accordingly, China has attached unprecedented importance to agricultural science and technology innovation. The '14th Five-Year Plan' for national agricultural and rural science and technology development indicated that by 2035, several world agricultural science and technology centres will be established; agricultural science and technology modernization will be characterized as high-end, intelligent and green and an agricultural science and technology power will be formed. It is foreseeable that the position of agricultural science and technology innovation in the future development of China's agriculture and rural areas will continue to be strengthened. Therefore, the position of agricultural science and technology innovation in the framework of China's agricultural and rural development in the future will continue to be strengthened.

Scientific and technological resources are strategic resources. Implementation of innovation-driven development strategies require markedly efficient allocation of scientific and technological innovation resources. Effective allocation of scientific and technological innovation resources is the fundamental goal of China's scientific and technological system reform (Liu and Li, 2021). However, the allocation of agricultural science and technology resources is a complex adaptive system, which is reflected in the complexities of the actual agricultural science and technology resources allocation system and agricultural science and technology resources optimization allocation process (Yang et al., 2013). Scarcity of scientific and technological resources makes the allocation the key to its effect, as the sum of resources invested in agricultural scientific and technological activities, whether or not agricultural scientific and technological resources can achieve Pareto optimality, is closely related to the high-quality development of agricultural economy (Yang et al., 2011).

Allocation level affects the role of agricultural science and technology innovation in rural revitalization. The current study focuses on this issue and uses Anhui Province, China as an example to explore the impact of agricultural science and technology innovation resource allocation on rural revitalization. Anhui Province is located in the middle and lower reaches of the Yangtze River and the Huai River, centrally positioned toward the east, with access to both the river and the sea. It borders Jiangsu Province and Zhejiang Province to the east, Hubei Province and Henan Province to the west, and Shandong Province to the north. The province spans about 450 kilometers from east to west and about 570 kilometers from north to south, covering an area of 140,100 square kilometers, which accounts for 1.46% of China's total area (National Bureau of Statistics of the People's Republic of China, 2023). By the end of 2022, Anhui had a population of 61.27 million, accounting for 4.34% of the national total. Its regional GDP was 4.5045 trillion yuan, making up 3.74% of the national total. The total output value of agriculture, forestry, animal husbandry, and fisheries was 372.23 billion yuan, representing 4.02% of the national total. Grain production totaled 41.001 million tons, accounting for 5.97% of the national total, and meat production was 4.753 million tons, accounting for 5.10% of the national total (source: National Bureau of Statistics). Anhui Province was selected as sample area for three reasons. Firstly, we are optimistic to obtain relatively more targeted research findings. China has a vast territory with significant differences between the different regions. By limiting the observation sample, we can effectively improve the pertinence of the research findings. Secondly, Anhui Province is markedly representative. On the one hand, Anhui Province is the birthplace of China's rural reform and has long been a major agricultural province. Anhui Province frequently serves as a pilot region for various agricultural and rural policies in China. On the other hand, Anhui Province is a component province of China's Yangtze River Delta (YRD) integration and a core member of the YRD scientific and technological innovation community. The Yangtze River Delta is the most important base for scientific and technological innovation in China. Thus, Anhui Province possesses the dual attributes of rural agriculture and technological innovation. Thirdly, Anhui's unique geographical characteristics make it a valuable research subject. Anhui Province is divided by the Huai River and Yangtze River into three regions: north of the Huai River (Huaibei, Bozhou, Suzhou, Bengbu, Fuyang, Huainan), between the Huai and Yangtze Rivers (Hefei, Chuzhou, Lu'an, Anqing), and south of the Yangtze River (Huangshan, Chizhou, Wuhu, Ma'anshan, Xuancheng, Tongling). The northern area is a plain, the area between the rivers is hilly, and the southern area is mountainous. These regions differ significantly in dialects, customs, and economic development, forming three relatively independent human-geographical units. This may lead to imbalanced distribution of agricultural science and technology innovation resources across different regions.

Technological innovation significantly enhances the quality of economic development (Aghion et al., 1992; Keller, 2002). Resource allocation is crucial for economic development (Restuccia et al., 2008; Hopenhayn, 2014), and this is also true for technological innovation resources. These typically include financial resources (Breschi et al., 2011), human resources (Guellec, 2004), physical resources (Allison and Long, 1990), and informational resources (Adabi et al., 2013). Even in developed countries like the United States, the United Kingdom, and Japan, the allocation of technological resources shows regional disparities (Malecki, 1993; Metcalfe, 1993; Hickok, 1999).

Most of the existing studies on the allocation of agricultural science and technology innovation resources in China have used various methods to calculate, evaluate and analyse allocation efficiency (Liu et al., 2022; Li et al., 2019; Zhang et al., 2018). Although these studies are important, no further analysis on the impact on rural revitalization has been performed after calculating the allocation efficiency of agricultural science and technology innovation resources. Some studies have focused on the impact of China's agricultural science and technology innovation resources on agriculture and rural development, and have explored the relationship between agricultural science and technology resources and agricultural economic development. For example, the paper believes that increasing expenditure on agricultural science and technology activities, cultivating agricultural technical personnel and improving the utilization efficiency of agricultural machinery are important path choices for promoting agricultural economic development (Yang et al., 2011). The paper found that the number of agricultural science and technology patents granted, number of new agricultural varieties and number of agricultural science and technology papers are prerequisites for promoting agricultural economic growth (Chen, 2016). On the one hand, this research stream is long-standing. On the other hand, the statistical and measurement methods used are relatively simple, only revealing the correlation between agricultural science and technology innovation resources and agriculture and rural areas. Additionally, some studies have analyzed specific input factors in the allocation of agricultural science and technology innovation resources, such as human capital and financial capital investment in agricultural science and technology innovation (Deng and Wang, 2020) and scientific and technological personnel (Hu et al., 2022). They conclude that there is still room for improvement in the effect of these input factors. Although the objective of this type of research is markedly focused and microscopic, there are some deficiencies in the integrity.

Evidently, the impact of the allocation of agricultural science and technology innovation resources on rural revitalization should be further analyzed. Although some studies have analyzed the role path and internal mechanism of agricultural science and technology innovation driving rural revitalization (Song et al., 2020; Chai, 2021), only a few studies have involved the allocation of agricultural science and technology innovation resources in terms of quantity. Although studies have also been conducted on the relationship between the allocation of agricultural science and technology innovation resources and the coordinated development of industrial structure (Shen et al., 2017), relatively more people have only discussed this issue in part within the framework of 'scientific and technological innovation empowering rural revitalization'. The paper analyzed that the optimization effect of industrial structure brought by the allocation function of scientific and technological innovation resources guarantees the promotion of the rural revitalization strategy in the research on the effective supply and docking of scientific and technological innovation promoting rural revitalization (Song and Liu, 2020). The paper believes that optimising the allocation of rural science and technology resources and strengthening the construction of rural science and technology software and hardware are important contents of the modernization of rural governance enabled by scientific and technological innovation (Cui, 2022). The analyses of these studies on the impact of agricultural science and technology innovation resource allocation on rural revitalization are relatively fragmented, rather than complete, independent and comprehensive studies. Hence, there is still room for improvement in the research depth.

Overall, the reference value of the existing research results in exploring the impact of the allocation of agricultural science and technology innovation resources on rural revitalization in China is relatively limited in terms of the number and depth of research. The reference of the current study to previous research is mainly reflected in the calculation of the efficiency of the allocation of agricultural science and technology innovation resources, whilst the other parts are significantly original. This study particularly analyses the spatial effect. The analysis of non-linear relationship and treatment of endogeneity have provided new and robust research findings. The development of this study has certain supplement and deepening significance to the research in this field.

2 Theoretical mechanisms and research hypotheses

Technological innovation is the endogenous driving force for economic growth (Romer, 1986), and agricultural science and technology innovation is the source of power for rural revitalization. At present, agricultural science and technology innovation resources are limited and scarce, only partially meeting development needs. Therefore, their rational allocation must be emphasized to maximize economic and social benefits.

The allocation of agricultural science and technology innovation resources occurs during specific agricultural science and technology activities. The goal is to maximize the use of these resources, enhance system operational efficiency, and obtain the maximum output with minimal input. This process ensures the effective distribution and coordination of various agricultural science and technology resources among different activity entities, regions, industries, activity stages, as well as among agricultural enterprises, higher education institutions, research units, and farmers, ultimately achieving effective transformation of agricultural outcomes (Yang, 2011). The purpose of optimizing the allocation of agricultural science and technology innovation resources is to achieve a better input–output ratio. During its Pareto improvement process, the optimized allocation allows agricultural science and technology innovation personnel, funding, and information resources to be utilized to the maximum extent, improving output efficiency. This enhances agricultural science and technology innovation capabilities, thereby providing stronger development momentum for agriculture and rural development.

From the perspective of agricultural science and technology innovation resource allocation output, improved efficiency raises output levels, bringing more and better knowledge innovation, technological innovation, and management innovation outputs. This advancement in agricultural science and technology innovation enhances the capacity to supply agricultural science and technology for rural revitalization, providing a higher-quality technological environment for agricultural and rural development. On one hand, it increases the quantity of technological supply, providing more technological products for agriculture and rural areas, enriching the technological choices available for rural revitalization entities. On the other hand, it improves the level of technological supply by upgrading and updating existing agricultural technological products. This provides rural revitalization entities with more advanced and convenient technological tools and methods, helping them solve various technical problems in production and life, driving rural revitalization toward a green and smart direction, and achieving high-quality development of agriculture and rural areas. Thirdly, the improvement of agricultural science and technology supply levels will, in turn, raise the quality of rural revitalization entities. By guiding them to actively choose and adapt to more advanced agricultural technological products, their knowledge and technical levels will gradually increase. This cultivates scientific thinking, broadens technological perspectives, and transforms production concepts, overall enhancing the scientific literacy of rural revitalization entities, thereby leading rural revitalization development. Fourthly, through the demonstration effect, the allocation of agricultural science and technology innovation resources will influence less developed areas to look up to and learn from more advanced regions, thereby driving the development of rural revitalization in less developed areas.

Therefore, this paper proposes the hypothesis that the allocation of agricultural science and technology innovation resources has a significant promoting effect on rural revitalization.

3 Materials and methods

3.1 Variable selection

The explanatory variable is rural revitalization. In this study, the rural development comprehensive index is used as proxy variable of rural revitalization. This index is an indicator system composed of 3 secondary and 17 tertiary indicators. On the basis of dimensionless standardization of the preceding indicators, the entropy method is used to determine the weights of indicators at all levels.

The core independent variable is the allocation efficiency of agricultural scientific and technological innovation resources. This study uses three-stage DEA to measure it. Input indicators used in the calculation process include the full-time equivalent of agricultural R&D personnel and internal expenditure of agricultural R&D funds; and output indicators include the number of patents granted, number of scientific and technological papers published and total output value of agriculture, forestry, animal husbandry and fishery. In the second stage of the SFA model analysis, environmental variables considered include openness to the outside world (expressed in total import and export volume/GDP), economic development level (expressed in *per capita* GDP), higher education level (expressed in the number of full-time teachers in ordinary colleges and universities), financial support (expressed in financial expenditure on science and technology/total financial expenditure) and Internet penetration rate (expressed by the number of Internet broadband access of households).

To accurately analyse the impact of the allocation of agricultural science and technology innovation resources on rural revitalization, the following control variables are considered in the equation: (1) level of financial support, measured by the percentage of fiscal expenditure on agriculture and total fiscal expenditure; (2) bank liquidity level, measured by the percentage of total loans to total deposits; (3) level of fixed asset investment, measured by the percentage of fixed asset investment in agriculture, forestry, animal husbandry and fishery to fixed asset investment; (4) level of foreign capital utilization, measured by the amount of foreign capital actually utilized and (5) education level of the region, measured by the *per capita* education years table. The meaning of variables is shown in Table 1.

3.2 Model building

3.2.1 Reference equation

This study uses the robust least square method, generalized least square method, random panel model and fixed panel model to estimate the benchmark equation, which is presented as follows:

$$\ln y_i = \alpha_i + \beta_i \ln x_i + \mu_i \tag{1}$$

where y_i represents the comprehensive index of rural development; x_i, independent variable; α_i, constant term; β_i, estimation coefficient of the independent variable and μ_i, error term.

3.2.2 Robustness test

This study uses two methods for robustness analysis. Firstly, the spatial impact of agricultural science and technology innovation resource allocation on rural revitalization is investigated from the spatial measurement perspective. Secondly, the non-linear impact of the allocation of agricultural science and technology innovation resources on rural revitalization is investigated from the non-linearity perspective.

3.2.2.1 Spatial econometric model

This study constructs relevant models based on the spatial panel models proposed by Anselin (1988) and Elhorst (2003).

3.2.2.1.1 Spatial autocorrelation test

Moran's I is used to conduct global spatial autocorrelation test to assess whether or not the variables have spatial dependence. The form of the constructed index is as follows:

$$\mathrm{I} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}\left(X_i - \bar{X}\right)\left(X_j - \bar{X}\right)}{S^2 \sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}} \tag{2}$$

$$S2 = \frac{\sum_{i=1}^{n}\left(X_i - \bar{X}\right)^2}{n}, \bar{X} = \frac{\sum_{i=1}^{n} X_i}{n} \tag{3}$$

where I represents the spatial autocorrelation coefficient and value range is [−1,1]: I < 0 indicates a spatial negative correlation, I > 0 indicates a spatial positive correlation and I = 0 indicates no spatial correlation; X_i, observed value in area i; X_j, observed value in area j; n, number of sample areas; W_{ij}, spatial weight matrix; S^2, sample variance and $\bar{X}$, sample mean.

3.2.2.1.2 Spatial autocorrelation model (SAR)

The spatial autocorrelation (SAR) model reveals the spatial spillover and diffusion effect of the comprehensive index of rural

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TABLE 1 Equation variables.

Dependent variable	Comprehensive Rural Development Index (y)	Industry development	Gross output value of agriculture, forestry, animal husbandry and fishery/gross regional product value
			Number of rural employees/rural population
			Total power of agricultural machinery
			effective irrigation area
			Rural electricity consumption
		Rural environment	Usage of agricultural plastic film
			Fertilizer usage
			Pesticide usage
			Afforestation area
			Proportion of days when air quality is better than Level 2
		Peasant life	Tap water penetration rate
			Village clinics Number of village doctors and health workers
			Actual rural *per capita*l disposable income/town
			Actual rural residents' consumption expenditure/cities
			Minimum subsistence allowance for rural residents/rural population
			Postal rural delivery line
Core argument	Allocation Efficiency of Agricultural Science and Technology Innovation (x1)	Input indicator	Agricultural R&D personnel FTE
			Internal expenditure of agricultural R&D funds
		Output indicators	Number of patents granted
			Number of scientific papers published
			Gross output value of agriculture, forestry, animal husbandry and fishery
Control variable	Level of financial support (x2)	Fiscal expenditure on agriculture/total fiscal expenditure	
	Bank liquidity level (x3)	Total loans/deposits	
	Fixed asset investment level (x4)	Fixed assets investment/fixed assets investment in agriculture, forestry, animal husbandry and fishery	
	Level of utilization of foreign capital (x5)	Actual foreign capital utilized	
	Regional Education Level (x6)	Years of education per capita	

development in the sample area. The specific model constructed by this research is as follows:

$$\ln y_{it} = \alpha_{it} + \rho W \ln y_{it} + \beta_{it} \ln x_{it} + \varepsilon_{it} \quad (4)$$

where y_{it} represents the dependent variable; X_{it}, independent variable; i, sample area; t, sample time; α_{it}, individual effect and W, $n \times n$-order spatial weight matrix. This study uses the spatial weight matrix constructed by the geographical distance between cities in Anhui Province. Given that the geographical distance between cities is fixed for a long time and will not change owing to the influence of economic and social activities, this treatment can avoid the endogenous problem of the model to a certain extent. Meanwhile, Wy_{it} represents the spatial autoregressive term of the dependent variable; ρ, spatial autoregressive coefficient and ε_{it}, vector of the random error term.

3.2.2.1.3 Spatial error model

The spatial error model (SEM) reveals the impact of the observation value error of the comprehensive rural development index of the adjacent areas on the comprehensive rural development index of the local area. The specific model built in this research is as follows:

$$\ln y_{it} = \alpha_{it} + \beta_{it} \ln X_{it} + \varepsilon_{it} \quad (5)$$

$$\varepsilon_{it} = \lambda W \varepsilon_{it} + \mu_{it} \quad (6)$$

$$\mu \sim N\left(0, \sigma^2 I\right) \quad (7)$$

where λ is the spatial error coefficient, and the meanings represented by the remaining parameters are the same as those in Equation 4.

3.2.2.2 Threshold regression

This study uses the threshold (PTR) model proposed by Hansen (1999) as basis in constructing a panel threshold model to further analyse the robustness of the benchmark equation. The PTR model uses threshold variables to group the observation values. When the value of threshold variables exceeds the critical value, the state of regression coefficient will change accordingly. In the estimation process, for the significance test of the threshold effect, the bootstrap method is used to obtain the progressive distribution and construct its p value thereafter. The maximum likelihood method is used for the authenticity test of the threshold estimate.

The following single threshold model is established with the allocation of agricultural science and technology innovation resources as threshold variable:

$$\ln y_i = \alpha_i + \beta_1 \ln x_1\left(x_1 \le \theta_1\right) + \beta_2 \ln x_1\left(x_1 > \theta_1\right) + \beta_{3i} \ln x_{2i} + \mu_i \quad (8)$$

where $\theta_i$is the threshold value. According to the test result of the threshold effect, if there are two threshold values, then a double threshold model should be buil:

$$\ln y_i = \alpha_i + \beta_1 \ln x_1\left(x_1 \le \theta_1\right) + \beta_2 \ln x_1\left(\theta_1 < x_1 \le \theta_2\right) + \beta_3 \ln x_1\left(x_1 > \theta_2\right) + \beta_{4i} \ln x_{2i} + \mu_i \quad (9)$$

When there are more threshold values, expansion processing can be performed according to Equations 8,9 to obtain the corresponding models.

3.2.3 Endogenous test

The endogenous problem is not considered in the estimation process of the benchmark equation, which leads to biased and inconsistent coefficient estimation of the benchmark equation. This study considers the endogenous problem in the benchmark equation and uses two methods to test the endogeneity of the benchmark equation. The first method introduces the dependent variable with a lag of one period into the benchmark equation, builds a dynamic panel model, and uses the generalized method of moments (GMM) proposed by Hansen (1982) for estimation. The second method uses the two-stage least squares method (IV-2SLS) of instrumental variables proposed by Basmann (1957) and Theil (1971) for estimation. The estimation results of the preceding two equations are mutually verified.

3.2.3.1 Generalized moment estimation

Generalized moment estimation (GMM) includes first difference GMM and system GMM. This study selects system GMM for analysis. The reason is that the differential GMM firstly eliminates the fixed effect in the original equation through the first-order difference. Nevertheless, there is still a sequence correlation between the lag dependent variable and error term. In the selection of instrumental variables, the lag level variable of explanatory variables is taken as the instrumental variable of differential variables. When this method is used in the economic growth equation, it can eliminate the disregarded individual effects, but it can also eliminate endogenous problems caused by independence. However, the problem of the difference GMM estimation is that it requires the lag level variable as a tool variable to substantially explain the difference variable. Moreover, the estimation coefficient may be biased when the sample size is small, leading to the problem of weak tool variable. System GMM estimation generates the effective estimation value by using information hidden in the initial conditions. Its basic principle is that whilst using the conventional method, the lag first-order difference of the variable is used as tool variable in the equation to increase the effectiveness of the tool variable. Compared with the difference GMM estimation, the estimation efficiency of the system GMM estimation is higher. The constructed equation is as follows:

$$\ln y_i = \alpha_i + \beta_{1i} \ln X_i + \beta_{2i} \ln y_i\left(-1\right) + \mu_i \quad (10)$$

3.2.3.2 Tool variable least square method (iv-2sls)

Apart from using system GMM for endogenous analysis, the instrumental variable least square method (iv-2sls) is also selected to further test endogeneity to overcome the endogenous problem of the model.

First stage regression:

$$\ln x_1 = \beta_0 + \beta_{1i} \ln x_{2i} + \beta_{2i} \ln z_i + v_i \quad (11)$$

where Z_i represents the control variable and v_i represents the random disturbance term.

Second stage regression:

$$\ln y_i = \gamma_0 + \gamma_1 \ln \hat{x}_1 + \gamma_{2i} \ln x_{2i} + u_i \quad (12)$$

where μ_i represents the random disturbance term and i represents the sample.

3.3 Data sources

Given the limited availability of relevant data, the sample period of this study is set as 2010–2020. The sample areas used are 16 prefectures and cities in Anhui Province. Data used in this study are from the Anhui Statistical Yearbook and China Urban Statistical Yearbook. For missing data in some years, the interpolation method is used to compensate, and the relevant data are price-reduced.

4 Results and discussion

4.1 Analysis of estimation results of benchmark equation

Estimation results of the benchmark equation (Table 2) show that the estimation coefficients of the core independent variable agricultural science and technology innovation resource allocation are positive in the robust least square method, generalized least square method, random panel model and fixed panel model, as well as pass the 1% significance test. This verifies the research hypothesis that a well-allocated level of agricultural science and technology innovation resources plays a positive role in promoting the comprehensive index of rural development.

4.2 Robustness analysis

Robustness analysis results from spatial effects and non-linear relationships show that the estimated parameters of agricultural science and technology innovation resource allocation as core independent variable in the spatial econometric and PTR models remain positive. Through the 1% significance test, they are consistent with the estimated results of the benchmark equation, showing good robustness. The significant positive impact of agricultural science and technology innovation resource allocation on the comprehensive index of rural development remains valid.

In the analysis of the spatial econometric model, Moran's index (Moran's I) is used to analyse the spatial correlation degree of rural development comprehensive index in various regions of Anhui Province. Results of the spatial autocorrelation test (Table 3) show that all Moran's indexes are positive and pass the significance test. Therefore, the original hypothesis is rejected, and the comprehensive index of rural development in various regions of Anhui Province has strong spatial autocorrelation (SAR). Its spatial distribution is not random but generally shows significant spatial correlation, with strong spatial dependence. The spatial metrology model can be used for further fitting.

According to the estimation results of the SAR model (Table 4), estimation results of the Hausman test indicate that the fixed effect model should be selected, and the spatial autocorrelation coefficients of the fixed and random effects model should be selected (ρ); all are positive. Moreover, the significance test shows that the comprehensive index of rural development in various regions of Anhui Province has a significant and positive spatial spillover effect. Additionally, rural development in this region will drive the improvement of the comprehensive index of rural development in adjacent regions.

In the estimation results of SEM (Table 4), none of the spatial error coefficients of the fixed and random effect models (λ) passed the significance test. This result indicates that the spatial dependence of

TABLE 2 Estimate results of benchmark equation.

Variable	OLS	XTGS	FE	RE
lnx1	1.1465***	0.6314***	0.7306***	0.7661***
lnx2	−0.0097	0.1039	0.0967	0.0869
lnx3	0.4028***	−0.2993***	−0.2729***	−0.2459**
lnx4	0.0835*	0.0514*	0.0680**	0.0719**
lnx5	−0.2439***	0.0549	0.0964***	0.0794**
lnx6	1.2009***	−0.6479	0.2040	0.2469
c	11.2414***	11.4661***	8.8395***	8.9802***
F	121.65***	—	46.09***	—
Wald	—	5513.12***	—	319.59***
R^2	0.8058		0.6423	0.6416
Hausman	—	—	11.44*	

***, **, and * are significant at 1, 5 and 10%, respectively.

TABLE 3 Moran's I test of rural development composite index.

Time	Spatial autocorrelation	Expectation value	standard deviation	Normal statistics	Probability
2010	0.077	−0.067	0.048	2.983	0.003
2011	0.033	−0.067	0.049	2.042	0.041
2012	0.035	−0.067	0.049	2.072	0.038
2013	0.032	−0.067	0.049	2.010	0.044
2014	0.040	−0.067	0.050	2.148	0.032
2015	0.054	−0.067	0.051	2.363	0.018
2016	0.047	−0.067	0.051	2.223	0.026
2017	0.048	−0.067	0.051	2.248	0.025
2018	0.056	−0.067	0.051	2.399	0.016
2019	0.055	−0.067	0.051	2.394	0.017
2020	0.051	−0.067	0.051	2.315	0.021

TABLE 4 Estimation results of spatial and threshold models.

Variable	SAR		SEM		PTR
	FE	RE	FE	RE	
lnx1	0.7218***	0.7592***	0.7209***	0.7540***	—
lnx2	0.0727	0.0550	0.1029	0.0924	0.2508***
lnx3	−0.2330**	−0.2033**	−0.2571**	−0.2340**	0.0323
lnx4	0.0638**	0.0665**	0.0701**	0.0735**	0.0911**
lnx5	0.0739**	0.0602*	0.0914**	0.0778**	−0.1762***
lnx6	−0.2371	−0.2316	0.1439	0.1831	1.5873***
c	—	7.2778	—	9.1567***	9.8482***
lnx1 < −1.216	—	—	—	—	0.7108***
−1.216 ≤ lnx1 < −0.614	—	—	—	—	1.1726***
lnx1 ≥ −0.614	—	—	—	—	0.5313***
ρ	0.2845**	0.2994***	—	—	—
λ	—	—	0.1306	0.1239	—
R^2	0.6514	0.6510	0.6421	0.6413	0.7720
F	—	—	—	—	66.89***
Hausman	11.17*		−4.88		

***, **, and, * are significant at 1, 5 and 10%, respectively.

rural development in various regions of Anhui Province is not evident, which may be caused by the special regional environment of the province. The Huaihe River and Yangtze River divide Anhui Province into three regions: north of the Huaihe River, between the Yangtze River and Huaihe River and south of the Yangtze River. The three regions have significant differences in dialects and customs. Moreover, there are certain obstacles to the economic and social exchange between different regions.

Estimated coefficients of the agricultural science and technology innovation resource allocation variables in the four spatial econometric models are all positive and have passed the 1% significance test. This result shows that the improvement of the agricultural science and technology innovation resource allocation level can promote the development of local villages and spatial spillover of the comprehensive index of rural development. Thus, the spillover effect of the neighboring areas on the development of local villages is promoted.

In the analysis of the panel threshold model, the panel threshold regression equation is constructed with the allocation of agricultural science and technology innovation resources as explanatory and threshold variables. Moreover, the nonlinear relationship between the allocation of agricultural science and technology innovation resources and comprehensive index of rural development is investigated. The threshold effect test results (Table 5) show that the F-statistic values of the single and double thresholds pass the significance test of at least 5%. This result indicates a double threshold effect between the allocation of agricultural science and technology innovation resources and comprehensive index of rural development. Therefore, the double threshold effect model is selected for parameter estimation.

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TABLE 5 Threshold effect test.

Null hypothesis	Alternative hypothesis	*F* statistics	Probability value	Threshold of significance level		
				1%	5%	10%
Linear model	Single threshold model	9.457**	0.028	11.196	7.796	5.881
Single threshold model	Double threshold model	86.957***	0.000	14.691	9.178	6.829
Double threshold model	Three-threshold model	−33.986	0.818	3.427	0.073	−1.877

F value and relevant critical value are obtained by repeated sampling for 500 times using bootstrap method; ***, **, and * represent significant levels at 1, 5 and 10%, respectively.

Parameter estimation results of the panel threshold model (see Table 4) show that the nonlinear relationship between the allocation of agricultural science and technology innovation resources and comprehensive index of rural development is a piecewise function separated by the allocation efficiency of agricultural science and technology innovation resources. Estimation coefficients of the core independent variable agricultural science and technology innovation resource allocation in the three intervals divided by the two threshold values are all positive pass the 1% significance test. This outcome indicates that the nonlinear impact of agricultural science and technology innovation resource allocation on the rural development comprehensive index has a positive impact in different threshold intervals. Furthermore, the estimation coefficient of the threshold variable shows evident fluctuation in different threshold value intervals. When the allocation of agricultural science and technology innovation resources is in the second interval, its impact on the comprehensive index of rural development is greater than that in the first and third intervals. Overall, its impact on the comprehensive index of rural development shows an inverted U-shaped track characteristic with the change of the threshold interval. That is, when the allocation of agricultural science and technology innovation resources reaches a certain condition, its promotion effect on the comprehensive index of rural development is the best.

4.3 Endogenous analysis

The benchmark equation of this study has endogenous problems, and the causes of endogenous errors mainly come from three aspects. Firstly, there are simultaneous errors. That is, there is a two-way impact between rural development and the allocation of agricultural science and technology innovation resources. The allocation of agricultural science and technology innovation resources affects the level of rural development. Additionally, rural development will have a negative impact on the allocation of agricultural science and technology innovation resources. A causal relationship also exists between the two. Secondly, there is an error of missing variables. Although a certain number of control variables are considered in the equation, some variables are excluded in the equation because of the constraints of data availability and other reasons. Thirdly, there is a measurement error. This study uses the three-stage DEA method to calculate the efficiency of agricultural science and technology innovation resource allocation. Although this method is an improvement on the traditional DEA model and can relatively more truly calculate the efficiency level of each decision-making unit by eliminating the impact of environmental effects and random interference, there is still a certain degree of measurement error, resulting in a deviation from the actual value. Given the preceding reasons, an endogenous test on the benchmark equation should be conducted to obtain a consistent and asymptotically effective estimation result.

For the choice of tool variables, the efficiency of resource allocation of agricultural science and technology innovation and number of R&D institutions are selected as tool variables. Evidently, the number R&D institutions in various places will directly affect the allocation effect of agricultural science and technology innovation resources and rural revitalization thereafter. Moreover, the change in the number will not be affected by rural revitalization and development, so it has a strong exogenous nature.

Estimation results of sys-gmm and iv-2sls (Table 6) indicate no second-order autocorrelation problem in the estimation results of sys-gmm. The estimation results of iv-2sls passed the unidentifiable and weak instrumental variable tests. Moreover, there is no over-identification problem in both equations, indicating that the tool variables used are reasonable.

Estimation coefficient of the core independent variable agricultural science and technology innovation resource allocation in sys-gmm and iv-2sls remains positive and passed the significance test of 1%, showing very good robustness. The result shows that after removing endogeneity, the impact of agricultural science and technology innovation resource allocation on rural revitalization is consistent with the benchmark equation. Moreover, improving the level of agricultural science and technology innovation resource allocation has a positive effect on rural revitalization. That is, the government should consciously use policy tools to optimize the allocation level of agricultural science and technology innovation resources. Additionally, the government should focus on improving the coupling between the allocation of agricultural scientific and technological innovation resources and rural revitalization through policy formulation.

5 Discussion

The allocation of agricultural technology innovation resources is related to the sustainable development of agriculture and rural areas and is an important support for China's high-quality and comprehensive promotion of rural revitalization. From the current reality, does the allocation of agricultural technology innovation resources have an impact on rural revitalization? If there is an impact, is it linear or nonlinear? Is there spatial dependence and spatial spillover effects? Starting from these issues, this study takes Anhui

TABLE 6 SYS-GMM and IV-2SLS estimation results.

Variable	SYS-GMM		IV-2SLS	
	Estimation coefficient	Standard error	Estimation coefficient	Standard error
lnx1	0.2780***	0.0858	0.8939***	0.1772
lnx2	−0.2112***	0.0329	−0.1409	0.1068
lnx3	0.2618**	0.1351	−0.1689*	0.0914
lnx4	−0.0362	0.0334	0.0942***	0.0261
lnx5	−0.1279***	0.0354	0.0982***	0.0292
lnx6	−0.3619	0.4442	−0.4790*	0.2834
Lny (−1)	0.7896***	0.0696	—	—
c	4.1372***	0.6355	—	—
AR1	−1.97**		—	
AR2	0.32		—	
Sargan	60.10		—	
Hansen	11.89		0.699	
LM	—		18.953***	
Wald F	—		30.440***	

***, **, and * are significant at 1, 5 and 10%, respectively.

Province, China as an example and verifies the above issues by constructing an econometric model.

Our research found that the allocation of agricultural technology innovation resources has a robust positive impact on rural revitalization, which is consistent with the findings of Koohafkan et al. (2012), Balsa-Barreiro et al. (2023), Jiang and He et al. (2024), Wang et al. (2024), and Wang and Wu et al. (2024). The reason why the allocation of agricultural technology innovation resources can have a positive promoting effect on rural revitalization is, on the one hand, that China attaches great importance to the promotion of rural revitalization, and has issued numerous support and protection policies, effectively promoting comprehensive rural revitalization; On the other hand, the improvement of agricultural technological innovation capability and the efficiency of transforming scientific and technological achievements into productivity (Li and Cheng, 2020) enable the allocation of agricultural technological innovation resources to provide stronger support for rural revitalization.

This study also found that improving the allocation of agricultural technology innovation resources can not only effectively promote the development of rural revitalization, but also promote spatial spillover of rural development, thereby contributing to the spillover effect of neighboring areas on local rural development. This is consistent with the research findings of Zhao and Guo (2024) and Yao and Zhang (2021). Furthermore, this study found a non-linear relationship between the allocation of agricultural science and technology innovation resources and rural revitalization. Only when the allocation of agricultural science and technology innovation resources meets certain conditions can its promotion effect on rural revitalization be optimal. This is consistent with the research findings of scholars such as Huang et al. (2023), Bian and Wei et al. (2023), Feng et al. (2023), and Wang and Ma et al. (2023). These research findings not only have practical significance for Anhui Province, but also have reference significance for other regions of China and other countries around the world. To further optimize the allocation of agricultural science and technology innovation resources and support the development of agriculture and rural areas, not only should geographical factors be considered in the impact of agricultural science and technology innovation resource allocation on rural revitalization and development, but also conscious guidance and adjustment should be made to achieve coordinated development between the two, in order to maximize the support of agricultural science and technology innovation resource allocation for rural revitalization.

There is room for expansion in the following three aspects of this study. Firstly, based on verifying the positive effect of agricultural technology innovation resource allocation on rural revitalization, further mechanism analysis can be conducted from the perspectives of human capital and urbanization; Secondly, using the spatial Durbin model to further investigate the spatial spillover effect of agricultural technology innovation resource allocation on rural revitalization; The third is to analyze the impact of agricultural technology innovation resource allocation on rural revitalization from the dynamic perspective of rural population migration.

6 Conclusion

6.1 Research conclusion

This study mainly investigates the impact of agricultural technology innovation resource allocation on rural revitalization. Taking Anhui Province as an example, based on theoretical analysis, the relationship between the two was empirically tested by constructing an econometric model, ultimately verifying the research hypothesis. The results indicate that the allocation of agricultural science and technology innovation resources has a steady positive impact on rural revitalization. Improvement of the allocation of agricultural science and technology innovation resources can effectively promote the development of rural revitalization and spatial spillover of rural development, thereby facilitating the promotion of the spillover of neighboring areas to the local rural development. A nonlinear relationship exists between the allocation of agricultural science and technology innovation resources and rural revitalization. The allocation of agricultural science and technology innovation resources can only promote rural revitalization significantly when it reaches a certain condition.

6.2 Research implications

6.2.1 Optimize the layout of agricultural science and technology research bases

The application and construction of national agricultural high-tech industrial demonstration zones, national agricultural science and technology parks and provincial agricultural science and technology parks should be strengthened. Moreover, the construction of various innovation carriers, such as comprehensive agricultural and forestry stations and agricultural technology popularization demonstration bases, must be accelerated. New agricultural science and technology extension service modes should be actively explored and developed. We will accelerate the construction of the factor market for agricultural scientific and technological innovation from the aspects of factors flow obstacles, factor price rigidity and factor price differentiation.

6.2.2 Strengthen the construction of scientific and technological innovation platforms

The construction of innovation platforms, such as the Hefei Comprehensive National Science Center, Hefei Binhu Science City and Hefei Wuhu Beng National Independent Innovation Demonstration Zone, must be further deepened. Additionally, their leading, radiating and driving roles must be maximized. On the one hand, the interaction of agricultural science and technology innovation resources amongst different regions should be promoted. On the other hand, various talent resources must be effectively attracted.

6.2.3 Strengthen the cultivation and introduction of agricultural science and technology innovation subjects

On the one hand, the level of support for agricultural scientific and technological innovation subjects should be continuously consolidated and improved, particularly by focusing on the support and guarantee system for knowledge innovation subjects (e.g., universities and scientific research institutes) and technological innovation subjects (e.g., enterprises) to ensure their continuous consolidation and improvement. On the other hand, we should strengthen the introduction of agricultural science and technology innovation subjects, actively search and introduce innovative subjects with cutting-edge innovation and bring new energy to agricultural science and technology innovation resources in Anhui Province.

6.2.4 Further deepen the industry university research cooperation mechanism

Rural revitalization entities and agricultural science and technology innovation entities (e.g., colleges and universities) must be encouraged to establish a long-term and stable industry university research cooperation mechanism. Additionally, the layout of research directions through industry university research cooperation projects must be further optimized. By focusing on key fields (e.g., biological seed industry, modern agricultural machinery and equipment and intelligent agriculture, deep processing of agricultural products and modern food and agricultural ecological environment protection), we will accelerate the co-construction of R&D platforms and achievement transformation platforms. Lastly, the construction of collaborative innovation systems at all levels must be accelerated.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/supplementary material.

Author contributions

GW: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft. YW: Formal analysis, Investigation, Methodology, Writing – original draft. SY: Conceptualization, Data curation, Formal analysis, Methodology, Software, Writing – original draft.

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Conflict of interest

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

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