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Research on the Impact of Agricultural Infrastructure Construction on the High-Quality Agricultural Development Efficiency

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Abstract

Agriculture, as the fundamental pillar industry of the national economy, plays a pivotal role in China's national strategy for the new era. High-quality agricultural development is a core component of this strategy, and enhancing agricultural infrastructure construction is a crucial approach to achieve it. Based on panel data from 30 provinces in China spanning from 2011 to 2023, this paper employs the super-efficiency SBM-DEA model to measure the high-quality agricultural development efficiency. It empirically examines the impact and mechanism of agricultural infrastructure construction on this efficiency. The results indicate that agricultural infrastructure construction significantly enhances the efficiency of high-quality agricultural development. This conclusion remains valid after a series of robustness and endogeneity tests. Agricultural infrastructure construction can improve the high-quality agricultural development efficiency through two mechanisms: enhancing new agricultural productivity and extending the agricultural industry chain. The impact exhibits regional heterogeneity, being more pronounced in the Eastern China, Western China, Northeast China, and Southeast region of the Hu Huanyong Line. Based on these findings, policy recommendations are proposed: further improving agricultural infrastructure construction, continuously fostering new agricultural productivity, promoting the extension of the agricultural industry chain, and leveraging the positive role of agricultural infrastructure construction in Northwest region of the Hu Huanyong Line.

Keywords

Agricultural infrastructure construction; High-quality agricultural development efficiency; Super-efficiency SBM-DEA model; New agricultural productivity; Extension of the agricultural industry chain.

1. Introduction

The No. 1 central document of 2025 points out that "we must fully, accurately, and comprehensively implement the new development concept, and adhere to giving priority to agricultural and rural development" and "do everything possible to promote agricultural benefit increase" [1], making the promotion of high-quality agricultural development and the improvement of its efficiency have become key goals of the "Three Rural" work at the current stage. The No. 1 central document of 2026 further states that it is necessary to "strengthen rural infrastructure construction", "improve the level of rural water supply guarantee, enhance the power supply guarantee and comprehensive carrying capacity of rural power grids, and promote the renovation of old rural roads, the widening of excessively narrow roads, and the improvement of substandard road sections" [2], making the strengthening of agricultural infrastructure construction have become an important way to promote rural construction and achieve high-quality agricultural development. Currently, China's agricultural development has

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entered a critical stage of transitioning towards quality and efficiency. It is timely to enhance agricultural infrastructure construction to better promote the improvement of high-quality agricultural development efficiency. However, the quality of China's agricultural development faces the contradiction between rural development needs and backward infrastructure, which restricts the improvement of high-quality agricultural development efficiency in China [3]. In view of this, exploring the impact effect and mechanism of agricultural infrastructure construction on high-quality agricultural development efficiency and boosting the benefits of high-quality agricultural development in China from the perspective of strengthening infrastructure construction have important practical significance.

High-quality agricultural development refers to promoting the sustainable development of agriculture and the rural economy by enhancing total factor productivity (TFP) in agriculture, advancing agricultural modernization, promoting agricultural industrial upgrading, and improving the quality and market competitiveness of agricultural products, under the premise of ensuring national food security, increasing farmers' income, and improving the rural ecological environment [4]. Agricultural infrastructure provides fundamental services for the agricultural production process, is essential throughout the entire agricultural production process, and plays a significant role in agricultural production development, both materially and socially. It is the social precursor capital for agricultural development and serves as the prerequisite and foundation for developing modern agriculture and strengthening the agricultural foundation [5]. The academic community has conducted extensive research on both, which can be briefly summarized as follows: First, research on measuring the level of high-quality agricultural development efficiency. Ding Baogen et al. [6] believe that high-quality agricultural development seeks the coordination and unification of economic efficiency, environmental efficiency, and social efficiency. They used the Data Envelopment Analysis-Banker-Charnes-Cooper (DEA-BCC) model to measure the high-quality agricultural development efficiency in 11 provinces of the Yangtze River Economic Belt. Yang Ziyi et al. [7] and Wang Yale et al. [8] used the DEA-BCC model and the Slacks-Based Measure-Data Envelopment Analysis (SBM-DEA) model to measure China's agricultural production efficiency and agricultural ecological efficiency, respectively. Zha Huachao et al. [9] used the Super-Efficiency Slacks-Based Measure-Data Envelopment Analysis (SE-SBM-DEA) model and found that the high-quality rural industrial development efficiency in China exhibits characteristics of effective decision-making units. Second, research on agricultural infrastructure construction issues. Regarding the role of agricultural infrastructure construction, Fan Xiangcheng [10] believes that well-developed agricultural infrastructure helps reduce agricultural production costs, improve agricultural output rates, resource utilization rates, and labor productivity. In terms of measuring the level of agricultural infrastructure construction, Wang Dawei et al. [11] selected several indicators such as effective irrigation area, rural road mileage, total agricultural machinery power, and rural electricity consumption for measurement; Wang Hao et al. [12] used the perpetual inventory method to measure the level of agricultural infrastructure construction. Third, research on the relationship between agricultural infrastructure construction and high-quality agricultural development efficiency. Ma Chenglong et al. [13] believe that agricultural infrastructure construction positively promotes the green total factor productivity (TFP) of food in the local and surrounding areas. Zhu Jing et al. [14] found that agricultural infrastructure construction can reduce food production costs and enhance product competitiveness by increasing the total factor productivity of food. Chu Mingqin [15] found through empirical analysis that the improvement of rural transportation infrastructure can significantly drive the enhancement of agricultural efficiency. Xiao Xiangxiong et al. [16] believe that the construction of farmland water conservancy infrastructure can comprehensively enhance agricultural production capacity and efficiency, promoting high-quality agricultural development.

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Overall, there is still limited research in academia on measuring the high-quality agricultural development efficiency using the super-efficiency SBM-DEA model, and studies exploring the relationship between agricultural infrastructure construction high-quality agricultural development efficiency are even rarer. Therefore, this study aims to investigate the impact mechanism of agricultural infrastructure construction on the high-quality agricultural development efficiency. Furthermore, based on panel data from 30 provinces in China spanning from 2011 to 2023, it empirically examines the impact effect and transmission mechanism of agricultural infrastructure construction on the high-quality agricultural development efficiency, striving to provide decision-making references for accelerating the improvement of the quality and efficiency of comprehensive agricultural production capacity.

2. Theoretical Analysis and Research Hypothesis

2.1. The direct impact of agricultural infrastructure construction on high-quality agricultural development efficiency

Pareto efficiency is the core resource allocation theory of neoclassical economics, which posits that under given conditions of production factor inputs and technology, optimal economic efficiency is achieved when resource allocation cannot be further improved through readjusting factor distribution or increasing overall output value without reducing the welfare of others. Therefore, the core of high-quality agricultural development lies in achieving more agricultural output value with fewer factor inputs. Agricultural infrastructure construction, as a fundamental condition necessary for the entire agricultural production process, provides direct support in three dimensions: production efficiency, cost control, and risk resistance. Firstly, agricultural infrastructure construction enables modern agricultural production to break through spatial and temporal constraints, optimize resource allocation, and enhance comprehensive agricultural production capacity, thereby improving agricultural production efficiency. Secondly, agricultural infrastructure construction can reduce transportation costs and market transaction costs, achieving cost control while enhancing the circulation capacity of agricultural products, thereby improving the efficiency and market competitiveness of agricultural production and operation [17]. Lastly, agricultural production is vulnerable to natural and market risks. Agricultural infrastructure construction can effectively enhance agricultural resilience and disaster resistance by establishing a risk buffer mechanism, thereby improving the stability of agricultural production [18].

Based on this, we propose the research hypothesis H1: Agricultural infrastructure construction has a direct promoting effect on the high-quality agricultural development efficiency.

2.2. The indirect impact of agricultural infrastructure construction on high-quality agricultural development efficiency

The "Plan for Accelerating the Construction of a Strong Agricultural Nation (2024-2035)" issued by the CPC Central Committee and the State Council points out that "we should promote the construction of a strong agricultural nation by developing new agricultural productivity"; one of the important goals of building a strong agricultural nation is that "the modern rural industrial system is basically sound, and the industrial chain, supply chain, and value chain are extended and expanded" [19]. It can be seen that developing new agricultural productivity and extending the agricultural industrial chain are two important ways to promote high-quality agricultural development. Based on this, this study selects new agricultural productivity and extension of agricultural industry chain as mediating variables to clarify the internal mechanism path through which agricultural infrastructure construction affects high-quality agricultural development efficiency.

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2.2.1. New agricultural productivity

Agricultural infrastructure construction can promote the cultivation and growth of new agricultural productivity from the dual dimensions of basic support provided by traditional agricultural infrastructure and digital and intelligent empowerment from new agricultural infrastructure. New agricultural productivity, in turn, rely on comprehensive innovations in new laborers, labor materials, and labor objects to drive the improvement of high-quality agricultural development efficiency.

Agricultural infrastructure construction can enhance the new agricultural productivity. On the one hand, the improvement and updating of traditional agricultural infrastructure serve as the foundation for the development of new agricultural productivity. Farmland water conservancy infrastructure has improved the natural constraints on agricultural production, while rural transportation infrastructure has reduced the flow costs of production factors. The improvement and updating of these traditional infrastructures provide the necessary basic support for the formation and development of new agricultural productivity. On the other hand, new agricultural infrastructure further promotes the development of new agricultural productivity. By digitizing traditional agricultural infrastructure, the digital transformation and intelligent upgrading of agricultural production are accelerated, which facilitates real-time monitoring of agricultural production environmental data, improves the precision and efficiency of agricultural operations, and aids agricultural producers in making scientific decisions, thereby promoting the development of new agricultural productivity [20].

New agricultural productivity contribute to enhancing high-quality agricultural development efficiency Firstly, the new-type laborers within these forces can reduce costs and increase efficiency in agricultural production through the application of agricultural technology, rational management, and proficient operation, providing human capital impetus for the improvement of high-quality agricultural development efficiency. Secondly, the new-type labor materials in agricultural new productivity can achieve digitalization, precision, automation, and green upgrading across the entire agricultural production chain, enhancing the efficiency of agricultural product production and ensuring green development through ecological efficiency. Lastly, the new-type labor objects in agricultural new productive forces contribute to improving the quality and output of agricultural production. For instance, expanding the value dimension and market space of agricultural products through functional agricultural products and activating the diverse values of agricultural production with agricultural ecological resources help break the time, space, and industry constraints of traditional agricultural development, thereby providing a value foundation for enhancing high-quality agricultural development efficiency[21].

Based on this, we propose research hypothesis H2: Agricultural infrastructure construction can indirectly promote high-quality agricultural development efficiency through new agricultural productive forces.

2.2.2. Extension of the agricultural industry chain

Agricultural infrastructure construction promotes the realization of agricultural informatization and digitalization through increasing investment and connectivity in traditional agricultural infrastructure, thereby facilitating the extension of the entire agricultural industry chain. Extension of the agricultural industry chain empowers high-quality agricultural development efficiency improvement through four dimensions: promoting the transformation and upgrading of rural industrial structure, enhancing the added value of agricultural products, driving employment for farmers, and promoting agricultural technological innovation.

Agricultural infrastructure construction can promote the extension of the agricultural industry chain. In terms of traditional agricultural infrastructure, by increasing investment in the

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construction of traditional infrastructure such as agricultural transportation, water conservancy, and communication, as well as improving the planning ability and connectivity of infrastructure construction, it can promote the professional and intensive development of agriculture, thereby deepening the division of labor in the industry chain and promoting the extension of the agricultural industry chain. In terms of new agricultural infrastructure, through the construction of new agricultural infrastructure such as electricity and digital networks, it can make up for the information technology shortcomings in the agricultural industry chain, promote the digital application scenarios construction of the entire industry chain of agricultural production, processing, warehousing logistics, operation, and sales, achieve upstream and downstream information exchange, and thus avoid the risk of "broken chain" such as the disconnection between production and marketing, helping the efficient extension of the agricultural industry chain [22].

Extension of the agricultural industry chain can enhance high-quality agricultural development efficiency. It promotes the diversification and upgrading of rural industrial structures, increases the path options for rural economic development, and drives the improvement of high-quality agricultural development efficiency through sustainable development. Extension of the agricultural industry chain can enhance the added value of agricultural products and promote high-quality agricultural development through diversified processing methods, technological innovation, and the construction of brand marketing systems. Extension of the agricultural industry chain has created a large number of job opportunities in areas such as agricultural product processing and circulation, as well as the integrated development of agriculture with other industries, thereby broadening employment channels for farmers and promoting employment, which is conducive to achieving high-quality agricultural development [23]. Finally, Extension of the agricultural industry chain also helps to create an inclusive innovation environment, promote agricultural technological innovation in production, processing, and digital technology, achieve economies of scale in regional innovation, and subsequently enhance high-quality agricultural development efficiency[24].

Based on this, we propose research hypothesis H3: Agricultural infrastructure construction can indirectly promote high-quality agricultural development efficiency through extension of the agricultural industry chain.

3. Research Design

3.1. Construction of benchmark model

A two-way fixed effects model is constructed to examine the direct impact of agricultural infrastructure construction on high-quality agricultural development efficiency. The benchmark regression model is constructed as follows:

$$\ln Y_{it} = C_0 + \alpha_0 \ln X_{it} + \sum_{\kappa=1}^{n} \beta_\kappa control_{\kappa it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{1}$$

In equation (1), $\ln Y_{it}$ represents the logarithm of the high-quality agricultural development efficiency of the ith provincial administrative region in year t; C_0 denotes a constant term; $\ln X_{it}$ stands for the logarithm of agricultural infrastructure construction; $control_{\kappa it}$ denotes the set of control variables, and κ denotes the number of control variables; μ_i represents individual fixed effects, λ_t represents time fixed effects, ε_{it} represents a random disturbance term, α_0 and β_K are the coefficients to be estimated in the model.

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3.2. Mediation effect model

To examine the channel mechanism through which agricultural infrastructure construction affects the high-quality agricultural development efficiency, drawing on the approach of Wen Zhonglin et al. [25], two additional testing models need to be constructed based on Equation (1). The results of model construction are as follows:

$$\ln Midd_{it} = C_{11} + \alpha_{11}\ln X_{it} + \sum_{\kappa=1}^{n}\beta_{1k}control_{\kappa it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{2}$$

$$\ln Y_{it} = C_{12} + \theta_1 \ln Midd_{it} + \alpha_{12}\ln X_{it} + \sum_{\kappa=1}^{n}\beta_{2k}control_{\kappa it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{3}$$

In equations (2) and (3), $Midd_{it}$ represents the mediating variable, encompassing new agricultural productivity and extension of the agricultural industry chain. The meanings of other symbols remain the same as before.

3.3. Variable description

3.3.1. Dependent variable

The dependent variable is high-quality agricultural development efficiency. Referring to the studies by Ding Baogen et al. [6] and Wang Yale et al. [8], the super-efficiency SBM-DEA model is adopted for measurement, and the constructed measurement index system is shown in Table 1.

Table 1. Indicator System for Measuring High-quality Agricultural Development Efficiency

Measurement Objective	Dimensional Metric	specific indicators	measurement method	unit
High-quality agricultural development efficiency	Input	Data element	Percentage of rural broadband access users	%
		Land element	Per capita cultivated land area	hectare/10,000 people
		Labor element	Proportion of employees in the primary industry	%
		Fixed asset element	Completed amount of fixed assets investment per laborer in rural households	yuan/person
		Mechanical power element	Total power usage of agricultural machinery per unit	kilowatt/hectare
		Chemical agricultural resources element	The usage amount of chemical fertilizers, pesticides, and agricultural plastic films per mu	ton/hectare
		Energy element	Energy consumption in agriculture, forestry, animal husbandry, and fisheries	10,000 tons standard coal/1000 hectares
	Expected output	Innovation	Agricultural labor output rate	yuan/person
			Agricultural land output rate	ton/hectare

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	Coordination	Crop diversification	%
		Proportion of rural non-agricultural workers	%
	Green	Carbon sequestration in agricultural production	10,000 tons/1,000 hectares
		Multiple cropping index of cultivated land	%
	Open	Dependency on imports of agricultural products	%
		Dependency on agricultural product exports	%
	Share	Per capita income of rural residents	yuan
		Engel coefficient of rural households	%
Undesirable output	Carbon emissions from rural industries	Carbon emissions from agricultural resource inputs	10,000 tons/1,000 hectares
		Carbon emissions from agricultural energy use	
		Carbon emissions from agricultural tillage	
	Agricultural non-point source pollution	Fertilizer loss	
		Pesticide residue	
		Residual plastic film	

Table 1 shows that this paper measures inputs from seven aspects: data, land, labor, fixed assets, mechanical power, chemical agricultural resources, and energy. It selects ten basic indicators to measure expected outputs from the dimensions of innovation, coordination, green development, openness, and sharing. Additionally, six basic indicators are chosen to measure undesired outputs from the dimensions of rural industrial carbon emissions and agricultural non-point source pollution. Among them, agricultural labor output rate, agricultural land output rate, and crop diversification are calculated using the formulas "total output value of agriculture, forestry, animal husbandry, and fishery / employees in the primary industry", "added value of agriculture, forestry, animal husbandry, and fishery / total cultivated land area", and "1 - grain sown area / total sown area of crops", respectively.

3.3.2. Core explanatory variables

The core explanatory variable is agricultural infrastructure construction. Referring to the research conducted by Wang Hao et al. [12] and Cai Baozhong et al. [26], an indicator system is constructed from three dimensions: agricultural water conservancy facilities, agricultural power facilities, and agricultural transportation facilities. The entropy method is used to measure and obtain the indicators. The specific indicator system is shown in Table 2.

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Table 2. Measurement index system for agricultural infrastructure construction

Measurement Objective	Dimensional Metric	Measurement Method	Indicator Attribute
Agricultural infrastructure construction	Agricultural water conservancy facilities	Effective irrigation area / cultivated land area	positive
	Agricultural transportation facilities	Rural road mileage / cultivated land area	positive
	Agricultural power facilities	Rural electricity consumption / cultivated land area	positive

3.3.3. Control variables

The relevant research by Zhang Liguo et al. points out that agriculture is an economic activity completed through collaboration between humans and nature, and its production level is influenced by both the natural environment and the level of socio-economic development [27]. Based on this, in order to avoid omitted variable bias and improve the accuracy of model estimation, this paper selects the following control variables from two dimensions: the natural environment and the socio-economic environment. In terms of the socio-economic environment dimension, four control variables are selected: per capita GDP, urbanization level, degree of industrialization, and level of rural financial development. Among them, per capita GDP is measured by regional per capita GDP, urbanization level is represented by the ratio of urban population to total population, degree of industrialization is measured by the ratio of industrial added value to regional GDP, and the level of rural financial development is measured by the ratio of the balance of RMB agricultural credit in each region to the total rural population. In terms of the natural environment dimension, two control variables are selected: agricultural production environment and total water resources per capita. Among them, agricultural production environment is represented by the proportion of crop disaster area to total crop sown area in each region, and total water resources per capita are represented by the ratio of total regional water resources to total regional population.

3.3.4. Mediating variable

(1) New agricultural productivity. Referring to the research results of Ouyang Ningxiang et al. [28], an indicator system is constructed from three dimensions: new laborers, new labor materials, and new labor objects, and is measured using the entropy method. The measurement indicator system is shown in Table 3.

Table 3. Measurement index system of new agricultural productivity

Measurement Objective	Dimensional Metric	Specific Indicators	Measurement Method	Indicator Attribute
new agricultural productivity	Agricultural laborer	Intensity of education funding	Expenditure on education / Total fiscal expenditure	positive
		Per capita years of education in rural areas	Average years of education = (primary school * 6 + junior high school * 9 + high school * 12 + college * 15 + undergraduate * 16 + graduate * 19) / population aged 6 and above	positive
		Employment concept of rural workers	Migrant labor force/total rural labor force	negative

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Agricultural labor objects	Efforts in environmental protection	Local fiscal expenditure on environmental protection / General budgetary expenditure of local finance	positive
	Number of rural cooperatives	The number of farmers' professional cooperatives per 10,000 people in rural areas	positive
	Situation of agriculture, forestry, animal husbandry, fishery and service industry	The added value of agriculture, forestry, animal husbandry, and fishery services as a proportion of the primary industry	positive
Agricultural labor materials	Digital infrastructure level	Length of optical cable line per square meter	positive
	Agricultural technology level	Directly obtain agricultural technology patent data/added value of agriculture, forestry, animal husbandry, and fishery	positive
	Level of fiscal support for agriculture	Expenditure on agriculture, forestry, and water conservancy in local finance / Total fiscal expenditure	positive

(2) Extension of the agricultural industry chain. Referring to the research results of Li Jieyi et al. [29], we selected five dimensions, namely, the development of the tertiary industry, the development of agricultural product processing industry, the development of rural service industry, rural household investment, and rural resident consumption, to construct an indicator system, and also used the entropy method for measurement. The measurement indicator system is shown in Table 4.

Table 4. Measurement Indicator System for Extension of the agricultural industry chain

Measurement Objective	Specific Indicators	Measurement Method	Indicator Attribute
Extension of the agricultural industry chain	Development of the tertiary industry	The proportion of the added value of the tertiary industry in the gross regional domestic product	positive
	Development of agricultural product processing industry	The proportion of the output value of the agricultural product processing industry in the primary industry	positive
	Development of rural service industry	Rural per capita retail sales of consumer goods	positive
	Rural household investment	Per capita completed amount of fixed assets investment in rural households	positive
	Rural residents' consumption	Rural per capita consumption expenditure	positive

3.4. Sample selection and data sources

Panel data from 30 provinces in China, excluding Xizang, Hong Kong, Macao, and Taiwan, spanning from 2011 to 2023, were selected. The data were sourced from the "China Statistical Yearbook", "China Rural Statistical Yearbook", "Annual Report on China Rural Cooperative Economic Statistics", "Annual Report on China Rural Policy and Reform Statistics", "China Industrial Statistical Yearbook", "China Science and Technology Statistical Yearbook", "China Tertiary Industry Statistical Yearbook", as well as statistical yearbooks of various provinces, and official websites such as the National Bureau of Statistics and the Ministry of Agriculture

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and Rural Affairs. A small amount of missing data were imputed using linear interpolation. Descriptive statistical results of the variables are presented in Table 5.

Table 5. Descriptive statistics of variables

Variable Type	Variable Name	Sample Size	Mean	Standard Deviation	Minimum	Maximum
explained variable	High-quality agricultural development efficiency	390	0.206	0.213	0.065	1.181
explanatory variable	Agricultural infrastructure construction	390	0.085	0.099	0.006	0.905
mediating variable	New agricultural productivity	390	0.165	0.088	0.064	0.680
	Extension of the agricultural industry chain	390	0.198	0.126	0.040	0.775
control variable	Per capita GDP	390	62963.100	31967.400	16413.000	200278.000
	urbanization level	390	0.606	0.119	0.350	0.896
	degree of industrialization	390	0.331	0.079	0.100	0.573
	Agricultural production environment	390	0.135	0.115	0.000	0.695
	Level of rural financial development	390	6.456	4.897	1.089	44.678
	Total water resources per capita	390	2160.280	2 561.270	51.900	17107.400

4. Analysis of Empirical Results

4.1. Analysis of benchmark regression results

Based on the F-test (Fisher-Snedecor F-test) and LR-test (Likelihood Ratio Test), the fixed-effects model is determined to be the best-fitting model, and thus, it is selected as the benchmark regression model. Additionally, time effects and control variables are also relaxed for comparative analysis. The regression results are presented in Table 6.

Table 6. Benchmark regression results

Variable	(1)	(2)	(3)	(4)	(5)	(6)
	High-quality agricultural development efficiency					
Agricultural infrastructure construction	0.450*** (14.338)	0.358*** (5.328)	0.156*** (3.656)	0.219*** (7.739)	0.162*** (3.381)	0.158*** (3.614)
Per capita GDP				0.000*** (5.211)	0.455*** (3.988)	0.265** (2.178)
urbanization level				0.370 (1.596)	-0.646 (-1.441)	-0.670 (-1.224)
degree of industrialization				-0.117 (-1.624)	0.943*** (2.658)	1.001*** (3.059)
Agricultural production environment				-0.085*** (-3.939)	-0.036** (-2.303)	-0.022 (-1.263)

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Level of rural financial development				-0.219*** (-3.945)	0.131 (1.441)	0.012*** (2.764)
Total water resources per capita				0.026* (1.962)	0.003 (0.081)	-0.015 (-0.426)
constant term	-0.558*** (-5.643)	-0.817*** (-4.347)	-1.382*** (-11.443)	-1.736*** (-5.214)	-7.315*** (-5.737)	-4.987*** (-3.388)
regional effect	no control	control	control	no control	control	control
time effect	no control	no control	control	no control	no control	control
sample size	390	390	390	390	390	390
goodness of fit	0.385	0.835	0.879	0.556	0.870	0.880

Note: The robust standard errors are provided in parentheses; *, **, and *** represent significance at the 10%, 5%, and 1% levels, respectively. The same applies hereinafter.

The first three columns in Table 6 show that, without considering control variables and with stepwise control of regional and time effects, the regression coefficients for agricultural infrastructure construction are all positive and significant at the 1% level, indicating that agricultural infrastructure construction has a significant positive effect on high-quality agricultural development efficiency. The goodness of fit of the model also continues to rise from 0.385 to 0.879, indicating that even without the inclusion of control variables, the double fixed-effects fitting in column 3 is still relatively good. The last three columns in Table 6 show that, considering control variables and with stepwise control of regional and time effects, the regression coefficients for agricultural infrastructure construction are still all positive and significant at the 1% level. Among them, the goodness of fit of the model in column 6 is 0.880, indicating the best fitting effect of the model, and the regression coefficient for agricultural infrastructure construction is 0.158, indicating that for every 1% increase in the level of agricultural infrastructure construction during the reporting period, high-quality agricultural development efficiency will increase by 0.158%. Therefore, H1 is preliminarily confirmed.

4.2. Robustness test

To verify the reliability and stability of the benchmark regression results and eliminate potential measurement issues or sample selection biases that may interfere with the conclusions, four robustness checks were conducted: changing the core explanatory variable measurement method, quantile regression, adjusting the sample range, and removing extreme values. The results are presented in Table 7.

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Table 7. Robustness test results

Variable	(1) Transform core explanatory variables	(2) 25th percentile regression	(3) 50th percentile regression	(4) 75th percentile regression	(5) Excluding special samples	(6) Bilateral 1% winsorization
	High-quality agricultural development efficiency					
Agricultural infrastructure construction (perpetual inventory method)	0.220** (0.100)					
Agricultural infrastructure construction		0.132*** (0.001)	0.191*** (0.004)	0.316*** (0.002)	0.193*** (0.064)	0.181*** (0.046)
Agricultural infrastructure construction（one-period lagged）						
constant term	-6.871*** (1.043)				-3.776*** (0.898)	-4.613*** (1.458)
control variable	control	control	control	control	control	control
regional effect	control	control	control	control	control	control
time effect	no control	control	control	control	control	control
sample size	390	387	387	387	338	390
goodness of fit	0.883				0.869	0.896

Based on the research findings of Zhu Jing et al. [14], using 2010 as the base period, the agricultural infrastructure construction, which is the core explanatory variable, was recalculated using the perpetual inventory method. The calculation formula is: , where and represent the agricultural infrastructure construction in the ith province in year t and year t-1, respectively; represents the depreciation rate of agricultural infrastructure construction in the ith province, which is set to 10.2% based on existing research; represents the agricultural fiscal investment in the ith province in year t, measured by the fiscal investment in agriculture, forestry, and water in that year. A regression analysis was conducted again, and the results are shown in column (1) of Table 7. The coefficient of agricultural infrastructure construction remains significantly positive.

In addition, a quantile regression model was employed, incorporating the Markov Chain Monte Carlo method for 1000 simulations, and three quantiles of 0.25, 0.5, and 0.75 were selected for regression. The regression results presented in columns (2), (3), and (4) of Table 7 indicate that the regression coefficients for agricultural infrastructure construction remain significantly positive at the 1% level at the 25%, 50%, and 75% quantiles.

Finally, after excluding the samples from four municipalities and performing a two-tailed 1% winsorization, the results showed that the coefficient for agricultural infrastructure construction was also significantly positive at the 1% level, thus reaffirming the significant positive impact of agricultural infrastructure construction on the high-quality agricultural development efficiency.

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4.3. Endogeneity test

The regression model may also suffer from spurious regression issues due to the reverse causality between the independent and dependent variables. To address this, the instrumental variable method is employed for endogeneity testing. In academia, the lagged value of the core explanatory variable is commonly used as an instrumental variable for testing. Therefore, the lagged value of infrastructure construction is adopted as the instrumental variable for 2SLS (Two-Stage Least Squares) regression. The test results are presented in Table 8.

Table 8. Endogeneity test results

Variable	(1) First Stage Agricultural infrastructure construction	(2) Second Stage High-quality agricultural development efficiency
Agricultural infrastructure construction (one-period lagged)	0.939*** (0.019)	
Agricultural infrastructure construction		0.247*** (0.035)
constant term	-0.109 (0.154)	-0.765*** (0.261)
Anderson canon. corr. LM statistic	124.411***	
Cragg-Donald Wald F statistic	164.763	
control variable	control	control
regional effect	control	control
time effect	control	control
sample size	360	360
goodness of fit	0.922	0.582

As shown in Table 8, the Anderson Canonical Correlation Lagrange Multiplier Test Statistic (ACCLM) result rejects the null hypothesis of non-identification, indicating that the instrumental variables are just identified, thus eliminating the need for an over-identification test. The Cragg-Donald Wald F Test Statistic (CDW F) result rejects the null hypothesis of the presence of weak instrumental variables, thus validating the choice of instrumental variables. That is, the results obtained from the 2SLS regression also indicate that agricultural infrastructure construction has a significant positive impact on high-quality agricultural development efficiency. Thus, H1 is confirmed.

5. Impact mechanism and heterogeneity analysis

5.1. Mechanism analysis

The construction of agricultural infrastructure has a direct and robust promoting effect on high-quality agricultural development efficiency, but the transmission mechanism of this effect still needs to be verified. To this end, the stepwise regression test and the Sobel-Z test (Sobel-Z Test for Mediation Effect) were used to test the mediating effect. The test results are shown in Table 9.

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Table 9. Mechanism Analysis Results

Variable	(1) New agricultural productivity	(2) High-quality agricultural development efficiency	(3) Extension of the agricultural industry chain	(4) High-quality agricultural development efficiency
New agricultural productivity		0.290*** (0.087)		
Extension of the agricultural industry chain				0.307*** (0.112)
Agricultural infrastructure construction	0.072*** (0.019)	0.279*** (0.033)	0.156*** (0.013)	0.171*** (0.035)
Sobel Z	2.488**		2.659***	
Indirect effect P value	0.013**		0.008***	
Proportion of mediating effect	6.975%		21.796%	
Bootstrap test	6.975%		21.796%	
constant term	-2.373** (0.952)	-1.662 (1.631)	-1.293*** (0.110)	-1.339*** (0.281)
control variable	control	control	control	control
sample size	390	390	390	390
goodness of fit	0.655	0.553	0.895	0.573

Column (1) in Table 9 shows that the regression coefficient of agricultural infrastructure construction on new agricultural productivity is significantly positive at the 1% level. In column (2), both the regression coefficients of new agricultural productivity and agricultural infrastructure construction on high-quality agricultural development efficiency are significantly positive at the 1% level, with a Sobel-Z value of 2.488 and significance at the 5% level. The P value for the indirect effect test is 0.013, also significant at the 5% level, indicating that the mediating effect of new agricultural productivity is valid, and the proportion of the mediating effect is about 6.975%. That is, agricultural infrastructure construction can promote the improvement of high-quality agricultural development efficiency by affecting new agricultural productivity. Therefore, H2 is confirmed.

Column (3) in Table 9 shows that the regression coefficient of agricultural infrastructure construction on the extension of the agricultural industry chain is significantly positive at the 1% level. In column (4), the regression coefficients of both extension of the agricultural industry chain and agricultural infrastructure construction on the high-quality agricultural development efficiency are significantly positive at the 1% level. Additionally, the Sobel-Z value is 2.659 and significant at the 1% level, and the P value of the indirect effect test is 0.008, also significant at the 1% level. This indicates that the mediating effect of extension of the agricultural industry chain is valid, and the proportion of the mediating effect is approximately 21.796%. That is, agricultural infrastructure construction can enhance the high-quality agricultural development

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efficiency by influencing the extension of the agricultural industry chain. Therefore, H3 is confirmed.

5.2. Heterogeneity analysis

To explore the potential heterogeneous impacts of agricultural infrastructure construction, this paper divides the sample into Eastern China, Central China, Western China, and Northeast China, and further divides it into southeast region and northwest region based on the "Heihe-Tengchong Line" for heterogeneity testing. The test results are presented in Table 10.

The first four columns in Table 10 show that the construction of agricultural infrastructure in the eastern, western, and northeastern regions has had a significant positive impact on the high-quality agricultural development efficiency. The impact is greatest in the Western China, moderate in the Eastern China, and minimal in the Northeast China. However, the positive impact in the Central China is not significant. The reason may be that the Western China, with its vast territory and sparse population, has focused on short-board infrastructure construction such as water irrigation and transportation logistics in recent years. This has greatly alleviated resource constraints and circulation bottlenecks that hinder agricultural production, making infrastructure construction an important support for activating characteristic agricultural resources and promoting industrial transformation, thus exerting the strongest promoting effect. In the Eastern China, relying on economic advantages, although the construction of high-standard farmland and smart agricultural facilities has been closely integrated with large-scale operations and the extension of industrial chains in recent years, further releasing the dividends of agricultural infrastructure construction, this marginal effect is diminishing, thus exerting a moderate promoting effect. The Northeast China has a long and relatively cold winter, which to some extent restricts the role of supporting facilities for large-scale agricultural machinery operations and grain storage and logistics systems, limiting crop planting structures and impacting facility agriculture, thus exerting a relatively small promoting effect. In the Central China, the positive impact of infrastructure construction may not be significant due to the lagging transformation of agricultural industrial structure, the high proportion of traditional planting, and the adverse factors such as insufficient maintenance of farmland water conservancy facilities, relatively low proportion of high-standard farmland, and slow promotion of agricultural technology.

Table 10. Heterogeneity analysis results

Variable	(1)	(2)	(3)	(4)	(5)	(6)
	Eastern China	Central China	Western China	Northeast China	Southeast region of the “Hu Huanyong Line”	Northwest region of the “Hu Huanyong Line”
	High-quality agricultural development efficiency					
Agricultural infrastructure construction	0.162*** (0.056)	0.051 (0.222)	0.346*** (0.125)	0.101** (0.044)	0.154*** (0.047)	0.079 (0.057)
constant term	1.851 (3.861)	4.446 (3.394)	- 8.761*** (1.537)	-4.365** (1.931)	-5.435** (2.149)	-4.734*** (1.679)
control variable	control	control	control	control	control	control
regional effect	control	control	control	control	control	control

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time effect	control	control	control	control	control	control
sample size	127	78	143	39	260	130
goodness of fit	0.925	0.937	0.908	0.973	0.884	0.910

The last two columns of Table 10 show that the estimated coefficients for the Southeast region of the "Hu huanyong Line" are significantly positive, while the estimated coefficients for the Northwest region of the "Hu huanyong Line" are positive but not significant. This indicates that agricultural infrastructure construction can significantly enhance the high-quality agricultural development efficiency in the southeastern provinces of the line. The reason may be that the southeastern provinces of the "Houhuanyong Line" have a dense population, concentrated arable land, and a relatively good economic foundation. Improved agricultural infrastructure can effectively match the needs of agricultural technology application and large-scale production, thus having a significant positive effect on the high-quality agricultural development efficiency. However, the northwestern provinces are vast and sparsely populated, with complex natural conditions. The construction cost of agricultural infrastructure is high, the difficulty of coverage is great, and the utilization efficiency is limited, resulting in the positive effect on the high-quality agricultural development efficiency not being fully manifested.

6. Conclusion and Suggestions

Based on panel data from 30 provinces in China spanning from 2011 to 2023, this paper empirically analyzes the impact effect and channel mechanism of agricultural infrastructure construction on agricultural high-quality development efficiency using a two-way fixed effects model and a mediation effect model. The benchmark regression indicates that agricultural infrastructure construction significantly promotes agricultural high-quality development efficiency, and this conclusion remains valid after multiple robustness tests and endogeneity tests. The mechanism analysis shows that agricultural infrastructure construction indirectly enhances agricultural high-quality development efficiency by promoting the development of new agricultural productivity and extending the agricultural industry chain, and it plays a partial mediating role. The heterogeneity analysis reveals that the impact effect of agricultural infrastructure construction on agricultural high-quality development efficiency is greatest in the Western China, moderate in the Eastern China, and minimal in the Northeast China. However, the positive impact effect in the Central China is not significant. At the same time, it has a significant positive impact on the Southeast region of the “Hu Huanyong Line”, while the positive impact effect on the Northwest region of the “Hu Huanyong Line” is not significant.

Based on this, the following policy suggestions are proposed: First, further improve agricultural infrastructure construction, especially focusing on the management, maintenance, and construction of agricultural infrastructure in the Central China. Continue to improve the construction of irrigation and drainage facilities, field roads, farmland protection and ecological conservation projects, farmland power transmission and distribution, and supporting electromechanical equipment. In particular, the Central China should improve the three-level management and maintenance system of towns, villages, and large farmers, actively raise funds for management and maintenance through various means such as financial subsidies at all levels, village collective self-financing, and agricultural business entities' commitment, and actively expand modes such as professional management and maintenance, self-management by operators, and hiring third-party management and maintenance, to enhance the management, maintenance, and construction of agricultural infrastructure in the Central China.

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Second, continue to cultivate strong new agricultural productivity and focus on promoting the extension of the agricultural industry chain. By leading with technological innovation and focusing on accelerating the deep integration of digital technology and agriculture, actively cultivating agricultural technology enterprises and training new professional farmers, we can continuously cultivate strong new agricultural productivity and fully leverage their promoting effect. By further removing obstacles in the upstream and downstream of the agricultural industry chain, actively promoting the deep processing of agricultural products, and focusing on enhancing the popularity and competitiveness of agricultural products, we can accelerate the extension of the agricultural industry chain and better facilitate the path through which agricultural infrastructure construction promotes high-quality agricultural development efficiency improvement. Third, better leverage the positive role of the "Hu Huanyong Line" in agricultural infrastructure construction in the northwestern provinces. Adopt measures tailored to local conditions and precise strategies, actively improve the quality of agricultural infrastructure construction in the northwestern provinces along the "Hu Huanyong Line" by promoting the construction of high-standard farmland and accelerating the construction of irrigation areas and other water conservancy facilities, as well as adopting separate drainage systems and promoting wind and solar energy, in order to boost the promoting effect on high-quality agricultural development efficiency improvement.

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