

## Impact of Innovative Agricultural Green Technology Application on Agricultural Green Total Factor Pro- ductivity

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**Abstract.** This study examines the impact of innovative agricultural green technology (AGTI) on agricultural green total factor productivity (GTFP) and the regulatory role of environmental regulation (ER). Using panel data from 30 Chinese provinces (2011-2022) and a two-way fixed effect model, it finds that AGTI significantly boosts GTFP, highlighting its positive role in sustainable agriculture. This suggests that adopting new green technologies can enhance agricultural efficiency and reduce environmental impact, crucial for long-term sector sustainability. However, further analysis shows that ER negatively affects the relationship between AGTI and GTFP. Strict regulations may add costs or constraints to new technology implementation, hindering productivity improvements. To ensure reliability, endogeneity was addressed using instrumental variables, and robustness was tested by varying model specifications and considering different industrial structures and regional heterogeneity. The core conclusions remained robust across models and samples. The study offers a new perspective on the economic effects of agricultural green technology and provides insights for policy-makers. It emphasizes balancing ER intensity with AGTI promotion. A well-calibrated regulatory approach is needed to avoid over-restricting green technology adoption, which could limit agricultural productivity and sustainability gains.

**AMS subject classifications:** 90C08, 90B50

**Key words:** Innovative agricultural green technology, Green total factor productivity of agriculture, Green agriculture, Heterogeneity.

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## 1 Introduction

With the increasingly severe global climate change and environmental problems, green development has become a global consensus. As a basic industry for human survival and development, the transformation to green agriculture is of vital significance to the realization of sustainable development. Existing literature on green total factor productivity in agriculture mainly focuses on the digital economy [1], ER [2], regional differences and heterogeneity [3], technological progress and innovation, to discuss the digital economy, land circulation [4], agricultural insurance [5], agricultural planting structure [6] the influence of other factors on GTFP, but there are few literatures exploring the influence of AGTI on GTFP from the perspective of agriculture. Sun and Zhong [7] more attention to the impact of digital inclusive finance and digital economy on GTFP. Such as Zhou [8] the research pointed out that digital technology has significantly improved the agricultural total factor productivity by optimizing the allocation of production factors and promoting industrial upgrading. There are also some scholars, such as Luo [9] from the perspective of ER, it reveals the positive and non-linear relationship between ER and GTFPy and propose to optimize this influence through technological innovation and policy adjustment. In addition, most of the existing studies discuss the green total factor productivity of agriculture from the perspective of regional differences and heterogeneity, but ignore the differences in internal agricultural endowment and external agricultural natural environment in different regions.

This study using the provincial panel data from 2011-2022, such as using SBM (Slacks-Based Measure) super efficiency model and GML (Global-Malmquist-Luenberger) index method tools of 30 provincial GTFP, the AGTI effect of GTFP and regional heterogeneity, and discusses the regulation effect of ER, in order to promote AGTI and agricultural green coordinated development of total factor productivity, enhance the level of GTFP to provide theoretical support.

## 2 Theoretical analysis and research hypothesis

### 2.1 Influence of the application of AGTI on GTFP

The application of AGTI has become a key force in promoting the green transformation of agriculture. These technologies have played a significant role in promoting the green total factor productivity of agricultural production by improving the efficiency of resource utilization, reducing the use of chemical inputs and enhancing the stability of the agricultural ecosystem. Innovative agricultural green technologies, such as precision agriculture, biotechnology, and water-saving irrigation systems, have improved the utilization efficiency of land, water resources and energy by optimizing agricultural production processes. This increase in efficiency is directly reflected in the growth of green total factor productivity in agriculture, as it covers the entire transition process from factors of production to output. These techniques, by reducing the overuse of fertilizers and

pesticides, reduce the negative environmental impact of agricultural production, while also improving crop yield and quality. This environmentally friendly production mode helps to realize the sustainable development of agriculture, and then improve the green total factor productivity of agriculture. Based on the above content, hypothesis H1 is proposed.

H1: The application of AGTI promotes the improvement of GTFP.

## 2.2 The regulatory role of ER

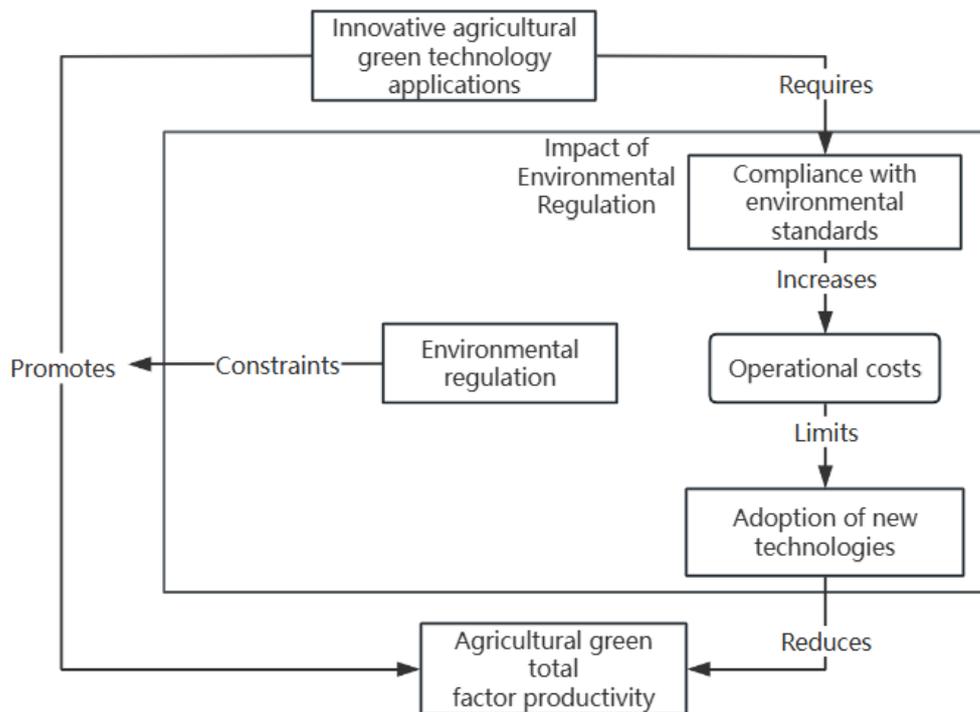


Figure 1: AGTI, ER, and GTFP three relationship diagram

The application of AGTI may increase environmental costs such as higher costs for adopting environmentally friendly production methods through ER, such as reducing the use of fertilizers and pesticides and adopting more environmentally friendly production methods, which may cause more additional input in agricultural production without changes in output levels, thus reducing productivity in the short term; if ER are too strict and agricultural technological progress fail to keep up in time, it may also decrease in production efficiency; the impact of ER may not be limited to the region, but also affect the adjacent areas through spatial spillover effects. If the ER in the neighboring areas is relatively loose, it may attract the transfer of polluting industries, thus having a negative

impact on the green and total factor productivity of agriculture in the region, as shown in Figure1, accordingly, hypothesis H2 is proposed.

H2: In the application process of AGTI, ER restricts the improvement of GTFP, indicating that it has a regulatory effect. This chart presents a model of the relationship between AGTI, ER, and GTFP. It highlights that AGTI can directly promote GTFP, but at the same time is limited by ER.

AGTI is positioned as a central factor that directly contributes to GTFP. This suggests that implementing innovative green technologies in agriculture can improve the efficiency of resource use, thereby increasing overall productivity in a sustainable way. However, the effect of AGTI on GTFP was moderated by ER.

ER has dual effects on AGTI: on the one hand, it restricts AGTI, and on the other hand, it affects AGTI. On the one hand, ER imposes restrictions on AGTI by requiring compliance with environmental standards, which may limit the adoption of new technologies by increasing operating costs. This is defined as ER increasing operational costs, which in turn limits the adoption of new technologies. On the other hand, ER also influences AGTI by requiring compliance with environmental standards, which can drive AGTI adoption. This is because ER sets standards that encourage the use of green technologies to meet regulatory requirements. This regulatory push can lead to the development and implementation of more sustainable practices, which can indirectly improve GTFP. The chart also shows that the adoption of new technologies, while limited by ER, can reduce operating costs in the long run. This suggests that although initial compliance with ER may increase costs, it can lead to more efficient and cost-effective agricultural practices, thereby reducing costs and promoting the adoption of AGTI.

In summary, the chart shows the complex interactions between AGTI, ER, and GTFP. AGTI directly promotes GTFP, but this relationship is influenced by ER, which both limits and influences AGTI. The model suggests that while ER may initially limit the adoption of new technologies due to increased costs, it also encourages the adoption of AGTI by setting environmental standards. This regulatory framework could ultimately lead to more sustainable and efficient agricultural practices, increasing GTFP.

### 3 Variable selection and model setting

#### 3.1 Data source

The original data used in this paper are mainly derived from the statistical data of 30 provincial administrative regions in China from 2011 to 2022, including China Statistical Yearbook, China Agricultural Statistical Yearbook, China Rural Statistical Yearbook and the State Intellectual Property Office. Due to the limitations of raw data acquisition and the differences in agricultural development, Tibet and Hong Kong, Macao and Taiwan are not included in the research framework of this paper.

## 3.2 Variable selection

### 3.2.1 Interpreted variables

Table 1: Input-Output Indicators for GTFP Measurement

<b>Input Indicators:</b>		
<b>Name</b>	<b>Description</b>	<b>Unit</b>
Agricultural labor input	Workers in primary industry	Thousand people
Agricultural land input	Total sown area of crops and aquaculture area	Thousand hectares
Agricultural fertilizer input	Chemical fertilizer use (pure equivalent)	Ten thousand tons
Agricultural machinery input	Total power of agricultural machinery	Ten thousand kilowatts
Agricultural diesel input	Agricultural diesel consumption	Ten thousand tons
Agricultural plastic film input	Agricultural plastic film use	Ten thousand tons
Pesticide input	Pesticide use	Ten thousand tons
Agricultural water input	Effective irrigation area	Thousand hectares
<b>Output Indicators:</b>		
Desired output	Total output value of agriculture, forestry, animal husbandry and fishery	Billion yuan
Undesired output	Agricultural carbon emissions	Ten thousand tons

GTFP is a comprehensive evaluation index, which covers the development of agricultural economy, the improvement of ecological environment and the improvement of efficiency. This study started as the benchmark year from 2011, using the non-angular non-radial SBM hyperefficiency model and GML index method [10], the GTFP was measured in 30 Chinese provinces (including municipalities directly under the Central Government and autonomous regions) between 2011 and 2022, as shown in Table 1.

### 3.2.2 Core explanatory variables

AGTI is the key to promoting the development of green agriculture. It is a technology system to promote the development of green agriculture through the application of precision agriculture technology, the improvement of resource utilization efficiency, and the utilization of agricultural waste. This paper adopts the IPC classification number of green agriculture and forestry from the Green Technology Patent Classification System released by the State Intellectual Property Office of China in 2023. By searching and summarizing relevant patents, we express the stock of AGTI, as shown in Table 2.

Table 2: Classification of Agricultural Green Technology Patents

Technical Branch	International Patent Classification (IPC)
Alternate irrigation technique	A01 C23/04, A01 G25/00, A01 G27/00, A01 G29/00, E02 B13/00
Insecticide alternative	A01 M1/00, A01 M3/00, A01 M5/00, A01 M7/00, A01 M9/00, A01 M11/00, A01 M13/00, A01 M15/00, A01M17/00, A01 M19/00, A01N25/32, A01 N63/00, A01 N65/00
Soil improvement	(C05 G3/00 NOT C05 G3/02), (C05 G3/00 NOT C05 G3/60), C09 K17/00

### 3.2.3 Adjustment variables: ER

The intensity of ER is considered to be an important factor affecting the green total factor productivity of agriculture. ER can promote technological innovation, improve agricultural production efficiency, and reduce environmental pollution in agriculture. The words related to environmental protection used by the government in its work report reflect the importance it attaches to ecological protection. This study references Chen and Chen [11], using the frequency of environmental protection vocabulary in the work report of provincial governments to indicate the intensity of ER.

### 3.2.4 Control Variables

Based on existing research results, the following control variables are identified: (1) the agricultural disaster rate, which is measured by the proportion of the affected area in the crop sown area; (2) the agricultural industrial structure, using the ratio of the added value of the primary industry to the regional GDP; (3) the agricultural development level and the proportion of the total output value of the rural population; (4) the proportion of the provincial budget; (5) the agricultural planting structure, using the proportion of the grain sown area in the sown area of crops to represent the agricultural planting structure, see Table 3.

Table 3 shows the descriptive statistical characteristics of the variables studied, including their mean and SD. These variables are classified as explanatory variables, core explanatory variables, supervisory variables, and control variables. The explanatory variable, GTFP, has a mean of 1.472 and a standard deviation of 0.534, indicating a moderate degree of dispersion around the mean. The core explanatory variable, namely AGTI, shows a higher mean of 4.729 and a larger standard deviation of 1.472, indicating significant variability in the adoption of these technologies across regions or units. Regulatory variables include ER and ADR. The mean value of ER is 5.730 and the standard

deviation is 0.955, indicating that the execution is strong and there is some variability. The average ADR was 6.581 and the standard deviation was much larger at 5.872, reflecting considerable variation in the implementation of disaster regulations.

Table 3: Descriptive Statistics of Variables

Variable	Symbol	Mean	SD
<b>Dependent variable</b>			
Green total factor productivity in agriculture	GTFP	1.472	0.534
<b>Independent variables</b>			
Innovative green technologies for agriculture	AGTI	4.729	1.472
Environmental regulations	ER	5.730	0.955
<b>Control variables</b>			
Agricultural disaster rate	ADR	6.581	5.872
Agricultural industrial structure	AIS	9.510	5.145
Agricultural development level	ADL	0.067	0.492
Agricultural public investment	API	0.112	0.035
Agricultural planting structure	APS	0.656	0.150

The control variables include AIS, ADL, API and APS. The average value of AIS is 9.510 and the standard deviation is 5.145, which shows a significant difference in industrial structure. The mean value of ADL was 0.067 and the standard deviation was 0.492, indicating a low level of development and low variability. The mean value of the API is 0.112 and the standard deviation is 0.035, indicating a more consistent level of public investment. The mean value of APS was 0.656 and the standard deviation was 0.150, indicating moderate variability in planting structure.

### 3.3 Model setting

Before empirically testing the influence of AGTI on GTFP, it is necessary to measure and analyze the development level of GTFP. Based on the existing measurement system of GTFP, this chapter will construct an input-output table to measure GTFP from the aspects of capital input, labor input, land input, expected output and non-expected output. The GML index method based on the super-efficiency SBM model estimates the GTFP level of 30 provinces in China during 2011-2022, in order to provide data support for the empirical test of this paper. A benchmark model is constructed to analyze the influence of AGTI on GTFP.

### 3.3.1 Calculation method of GTFP

The super-efficient SBM model can effectively circumvent the issue of multiple efficiency values being simultaneously equal to 1 when measuring total factor productivity [12], thereby facilitating comparisons among different decision-making units. Simultaneously, in combination with the GML index, the dynamic changing trend of GTFP can be further analyzed.

Therefore, the ultra-efficient SBM-GML index model (3.1) was selected to calculate the GTFP of 30 provinces and autonomous regions (except Tibet) in China during 2011-2022. Referring to the research setting of Tone et al [13].

$$\rho = \min \frac{1 + \frac{1}{m} \sum_{i=1}^m \frac{s_i^s}{x_{i0}}}{1 - \frac{1}{s_1 + s_2} \left( \sum_{k=1}^{s_1} \frac{s_k^y}{y_{k0}} + \sum_{l=1}^{s_2} \frac{s_l^z}{z_{l0}} \right)} \quad (3.1)$$

$$\text{s.t.} \begin{cases} x_{i0} \geq \sum_{j=1}^n \lambda_j x_j - s_j^x, & \forall i; \\ y_{k0} \leq \sum_{j=1}^n \lambda_j y_j - s_k^y, & \forall k; \\ z_{l0} \geq \sum_{j=1}^n \lambda_j z_j - s_l^z, & \forall l; \\ 1 - \frac{1}{s_1 + s_2} \left( \sum_{k=1}^{s_1} \frac{s_k^y}{y_{k0}} + \sum_{l=1}^{s_2} \frac{s_l^z}{z_{l0}} \right) > 0; \\ s_i^x \geq 0, s_k^y \geq 0, s_l^z \geq 0, \lambda_j \geq 0, & \forall i, j, k, l. \end{cases}$$

- $\rho$  : Efficiency score (objective function value).
- $m$  : Number of input categories.
- $i, k, l$  : Indices for input, desirable output, and undesirable output categories.  $i=1, 2, \dots, m$  (input type index).  $k=1, 2, \dots, s_1$  (desirable output type index).  $l=1, 2, \dots, s_2$  (undesirable output type index).
- $x, y, z$  : Variable type identifiers.  $x$  represents the input.  $y$  represents the desirable output.  $z$  represents the undesirable output.
- $s_1$  : Number of desirable output categories.
- $s_2$  : Number of undesirable output categories.
- $s_k^y$  : Shortfall in the  $k$ -th desirable output ( below optimal output ).
- $\lambda$  represents the weight vector.
- $x_{i0}$  : Actual value of the  $i$ -th input for the current decision-making unit.
- $y_{k0}$  : Actual value of the  $k$ -th desirable output for the current decision making unit .
- $z_{l0}$  : Actual value of the  $l$ -th undesirable output for the current DMU.

- $s_i^x$  : Slack in the  $i$ -th input (excess input compared to the optimal).
- $s_l^z$  : Excess in the  $l$ -th undesirable output (above optimal pollution).

To comprehensively understand the dynamic changes in GTFP and identify the driving factors behind these changes, we employ the GML index (3.2), a widely recognized method in productivity analysis. This index allows us to decompose productivity changes into technical efficiency ( $EC$ ) and technical progress ( $TC$ ), providing insights into whether improvements stem from better resource utilization or technological advancements. The formula below illustrates how the GML index is calculated, incorporating slack variables ( $S$ ) to account for input redundancy and output insufficiency across different time periods and technology levels. By analyzing these variables, we can assess the efficiency of agricultural resource utilization and the impact of technological innovations on agricultural green development.

$$\begin{aligned}
 GML_t^{t+1} &= \frac{S_C^G(x^t, y^t, z^t)}{S_C^G(x^{t+1}, y^{t+1}, z^{t+1})} \\
 &= \frac{S_C^t(x^t, y^t, z^t)}{S_C^{t+1}(x^{t+1}, y^{t+1}, z^{t+1})} \times \frac{S_C^{t+1}(x^{t+1}, y^{t+1}, z^{t+1}) S_C^G(x^t, y^t, z^t)}{S_C^G(x^{t+1}, y^{t+1}, z^{t+1}) S_C^t(x^t, y^t, z^t)} \\
 &= EC_t^{t+1} \times TC_t^{t+1}
 \end{aligned} \tag{3.2}$$

The equation compares slack variables across different time periods and technology levels to determine the dynamic changes in GTFP. Variables include input ( $x$ ), output ( $y$ ), and non-desirable output ( $z$ ) types, with  $t$  and  $t+1$  denoting different time periods. The GML index helps understand whether productivity improvements stem from better resource use or technological innovations.  $S_C^G$  is based on the global technology frontier (G) and constant returns to scale (C) assumptions, the GTFP efficiency value for period  $t$ .  $S_C^t$  is relaxation variable in year  $t$ .  $S_C^{t+1}(x^{t+1}, y^{t+1}, z^{t+1})$  are represents the slack variables at time  $t+1$ .

### 3.3.2 Benchmark regression model

Theoretical analysis shows that the application of AGTI will have an impact on the total factor productivity of agricultural green, so the following regression model (3.3) is constructed.

$$Gtfp_{it} = \beta_0 + \beta_1 Agti_{it} + \beta_2 X + \mu_i + \theta_t + \varepsilon_{it}, \tag{3.3}$$

where  $Gtfp$  is green total factor productivity in agriculture,  $i$  is the region,  $t$  is the year,  $Agti$  is innovative green technology in agriculture,  $\beta_0$  is a constant term,  $\beta_1$  represents the degree of influence of  $Agti_{it}$  on  $Gtfp_{it}$ ,  $X$  is a control variable,  $\beta_2$  represents the degree of  $X$  influence of on  $Gtfp_{it}$ ,  $\mu_i$  is an unobservable province fixed effect,  $\theta_t$  is a time fixed effect, and  $\varepsilon_{it}$  is a random disturbance term.

## 4 Empirical analysis

### 4.1 Benchmark regression analysis

When evaluating the benchmark effect of the effect of AGTI on the total factor productivity of agricultural green, this study first examined the mixed effects, random effects and fixed effects of the model. The test results show that the fixed-effect model is more accurate in its estimation. Considering the fitting effect of the model, this study decided to adopt a time-temporal fixed-effects model for in-depth analysis, as shown in Table 4. It

Table 4: Benchmark Regression Results

Variables	(1)	(2)	(3)	(4)
AGTI	0.278*** (6.858)	0.276*** (6.675)	0.405*** (6.070)	0.459*** (5.562)
ER		-0.050 (-0.802)	0.038 (0.565)	0.070 (0.901)
AGTI × ER			-0.023** (-2.332)	-0.033** (-2.555)
Constant	-0.049 (-0.295)	-0.224 (-0.624)	-0.412 (-1.209)	-1.031** (-2.167)
Control variables	No	Yes	No	Yes
Fixed effects	Yes	Yes	Yes	Yes
Observations	360	360	360	360
R-squared	0.837	0.836	0.839	0.839

\*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ .

can be seen from the second column of the regression result that when no control variable is introduced, the baseline regression result is 0.278, which is significant at the 1% level, indicating that AGTI has a significant promoting effect on GTFP. In the third column, on the basis of baseline regression, the regulating variable ER is introduced, and the result is -0.050, but the result is not significant. Therefore, the interaction term between AGTI and ER is introduced, and the interaction term coefficient of the fourth column is -0.023, which is significant at the 5% level. In the fifth column, the year and province are fixed, and the control variable is introduced, the regression result is 0.459, which is significant at the 1% level. Moreover, the coefficient is significantly positive in agreement with the expectation, indicating that AGTI has a significant promoting effect on GTFP, so hypothesis H1 is verified. The interaction term coefficient of the control variable is -0.033, which is significantly negative at the 5% level, indicating that, ER plays an obvious regulating

role in the process of the application of innovative agricultural green technology affecting agricultural green total factor productivity. Accordingly, H2 can be verified.

## 4.2 Robustness test

### 4.2.1 The Ordinary Least Squares Model test

To verify the robustness of the results and examine the stability of causal relationships between key variables, we conducted validation tests by modifying the model specifications. As shown in Column OLS of Table 5, OLS model was employed for analysis. The regression coefficient of 0.2784 demonstrates that the impact of AGTI on GTFP remains statistically significant at the 1% level, consistent with the baseline regression outcomes. This confirms the robustness of the original findings, as the positive causality persists under alternative methodological frameworks.

### 4.2.2 Change the explanatory variable

Refer to Liu et al [14], the agricultural green technology invention patent was used to replace the explanatory variable of AGTI for the robustness test. Table 5 column RE.V of the robustness test shows that the agricultural green technology invention patent result is 0.2784, and on the statistical level of 5% significantly promoted the GTFP, AGTI result is 0.2784, significantly in 1% of the statistical level, the promotion effect is stronger than the agricultural green technology invention patent, further, verify the reliability of the benchmark regression results.

Table 5: Endogeneity and Robustness Regression Results

Variable	OLS	Re.v	Lag
AGTI	0.2784*** (6.6748)		
AGTI(new)		0.2784** (2.6493)	
L.AGTI			0.4029*** (14.8866)
cons	-0.2241 (-0.6243)	-0.0494 (-0.1251)	-0.0756 (-0.1318)
Control	Control	Control	Control
Id	Yes	Yes	Yes
Yes	Yes	Yes	Yes
F	40.0399		135.4630
N	360	360	330
R2	0.8364	0.8373	0.7349

### 4.3 Heterogeneity analysis

#### 4.3.1 Heterogeneity of industrial structure

Based on the division criteria for the eastern, central, and western regions of China as outlined on the official website of the National Bureau of Statistics, an analysis was conducted for each region separately [15]. The results, detailed in Table 6, columns Eastern, Central and Western indicate that the adoption of AGTI has a positive impact on GTFP across all three regions. However, the significance levels vary markedly. In the eastern region, the positive effect was substantial at 0.2570, passing the stringent 1% significance level test. The central region exhibited a slightly lower positive effect of 0.1370, which still managed to pass the 10% significance level test. In contrast, the western region did not pass the significance test. This disparity can primarily be attributed to the more developed economy and superior infrastructure in the eastern region, which facilitates the rapid dissemination and application of new technologies, and encourages more active adoption and utilization of these innovations. Conversely, the western region may face constraints in the application and promotion of technologies due to economic limitations and a lack of infrastructure.

#### 4.3.2 Regional heterogeneity

Table 6: Heterogeneity Test Results

Variable	Eastern	Central	Western	Major	Non-major
AGTI	0.2570*** (4.1596)	0.1370* (1.9064)	0.0064 (0.1665)	0.0498** (2.2375)	-0.0199 (-0.9736)
cons	-0.5770* (-1.9079)	-0.5770* (2.1796)	1.4102*** (5.1988)	0.8758*** (8.8872)	1.0734*** (11.4434)
Control	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes
F	20.9936	21.4661	27.2335	47.1763	44.9588
R <sup>2</sup>	0.7331	0.7950	0.7828	0.7814	0.7221
N	132	96	132	156	204

Considering the unique industrial characteristics of agriculture, China's 30 provinces are categorized into major grain-producing areas and non-major grain-producing areas, as discussed in Cao [16]. This classification aims to investigate the regional heterogeneity in the application of innovative agricultural green technologies on GTFP. Referring to the results in Table 6, columns Major and Non-major, in the major grain-producing areas, a 1% increase in AGTI leads to a 0.0498 increase in GTFP, which is statistically significant at the 5% level.

In contrast, in the non-major grain-producing areas, there is a decrease of 0.0199. This discrepancy may be attributed to the adoption of green technologies that are well-suited to the local environment and production conditions in the major grain-producing areas, thereby enhancing resource utilization efficiency and crop yields, and thus positively impacting GTFP. However, in the non-major grain-producing areas, the technologies adopted may not be entirely appropriate for the local production conditions, leading to either insignificant technical benefits or even negative effects.

## 5 Conclusions and countermeasures

### 5.1 Conclusions

This paper focuses on studying the influence of AGTI on GTFP. Taking the data of 30 provincial administrative regions from 2011 to 2022 as a sample, the influence effect of the application of AGTI on GTFP is investigated.

The following conclusions are drawn:

(1) Innovative agricultural green technology can significantly promote the green total factor productivity of agriculture.

(2) Through the analysis of the mediation effect was found that, in the application process of innovative agricultural green technology, ER restricts the improvement of GTFP.

(3) The heterogeneity analysis showed that, the application of innovative agricultural green technology in the eastern and central regions and major grain producing areas has a stronger impact on GTFP, in the western region and non-major grain producing areas, the influence effect is weak.

### 5.2 Countermeasures

Based on the above conclusion, in order to further promote the application of innovative agricultural green technology to the development of GTFP, this paper proposes the following policy recommendations.

#### 5.2.1 The government increased investment in technology research and development

The government should set up special funds and financial subsidies to encourage scientific research institutions and enterprises to invest in the innovation and development of green agricultural technology; provide tax reduction and preferential loans and other policies, reduce the research and development costs, increase the attraction of research

and development activities, by strengthening the cooperation with universities and research institutions, promote the transformation and application of scientific research results, establish and improve the agricultural green technology standard system, standardize the technology market, improve the quality of technology products and services, through these measures, effectively promote the innovation and development of agricultural green technology, and improve the sustainability of agricultural production.

### **5.2.2 Implement regionally differentiated technological innovation support policies**

Implement regional differentiated technology innovation support policies to provide higher-level research and development funding and talent introduction programs for the eastern and central regions to maintain its leading position in agricultural technology innovation; and increase investment in infrastructure construction for western and non-grain producing areas [17] improve the scientific research conditions and reduce the threshold and cost of technological innovation; meanwhile, strengthen the technical exchange and cooperation between the eastern and central regions and the western regions to improve the technology absorption capacity and application efficiency through technology transfer and demonstration; for the main grain producing areas, the development and application of water-saving irrigation, precision agriculture should be supported to ensure food security and reduce the environmental load.

### **5.2.3 Establish a cross-regional innovation and collaboration platform**

Establish the cross-regional agricultural technology innovation and collaboration platform, to balance the development differences between different regions and comprehensively increase the green and total factor productivity of agriculture in various regions. This platform serves as a vital bridge to address the significant development disparities that exist across different regions, ensuring that the benefits of technological advancement and innovative practices are evenly distributed. By fostering a spirit of cooperation and shared knowledge, the platform enables regions with varying levels of agricultural development to learn from each other, exchange best practices, and jointly tackle the challenges that hinder progress.

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## **Conflicts of Interest**

The authors declare no conflict of interest.

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