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Effects of Organic Fertilizer Substitution on the Technical Efficiency among Farmers: Evidence from Bohai Rim Region in China

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Abstract: Using organic fertilizer to replace chemical fertilizer is an effective way to promote sustainable agricultural development. Based on survey data of 514 farmers from five provinces and cities in the Bohai Rim region of China, collected in 2019, organic fertilizer substitution's effects on farmers' technical efficiency were analyzed. The PSM method is used to solve the problem of farmers' self-selection. Considering the causal relationship between the substitution behavior of organic fertilizer and farmers' technical efficiency, the IV-Tobit model, 2SLS, and ML estimation methods are used to solve the endogenous problem. The study found that: (1) quality and safety awareness, part-time employment level, participation in insurance, and training significantly promote using organic fertilizers to replace chemical fertilizers; (2) the technical efficiency of farmers who use organic fertilizer to substitute the chemical fertilizers is 0.625, 9.46% higher than their counterparts; and (3) the promotion effect of organic fertilizer substitution on technical efficiency has heterogeneity, which has a significant role among small-scale farmer households with fewer and low-educated family laborers. Regarding the policy implications, it is necessary to strengthen agricultural subsidies by improving the accuracy of policy formulation and implementation, fully considering the heterogeneity of farmers for implementation.

Keywords: substitution of organic fertilizer for chemical fertilizer; technical efficiency; farmers' income; Matthew effect; green development

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1. Introduction

Substituting organic fertilizers for chemical fertilizers is an effective measure to curb the degradation of the agricultural ecological environment, stabilize agricultural production, and promote sustainable agricultural development [1,2]. Excessive application of chemical fertilizers is widespread in China's agricultural production [3]. However, the negative effects caused by the irrational application of chemical fertilizers have gradually emerged. As a result, the agricultural non-point source pollution problem brought about by the excessive input of chemical inputs has gradually evolved into an environmental problem [4–6]. Chemical fertilizers have played an essential role in the development of agricultural production in China; compared with 2000, the average unit area output of China's three major staple grains in 2020 increased by 31.2%, and the increase in vegetable production was incredible. However, with the continuous improvement of dependence on chemical fertilizers, problems such as unreasonable fertilization intensity and fertilization structure in agricultural production have become increasingly prominent. As a result, the amount of chemical fertilizer application per unit area in China's agricultural production has increased from 273.2 kg/hm^2 in 2001 to 313.50 kg/hm^2 in 2020, reaching the highest value in history in 2014. This rate is above the global average. Due to rapid economic and social development, urban and rural residents' consumption levels and social structures have undergone tremendous changes. As a result, the requirements for the quality and

safety of agricultural products have been continuously improved, especially since food consumption is no longer limited to the level of food and clothing. The rapid demand for green agricultural products has become an inevitable trend. The changes in demand for agricultural products will inevitably force the transformation of agricultural production to new themes, such as sustainable and organic. In view of the above problems, the Chinese government has established the reduction of chemical fertilizers as a phased task of agricultural production. In 2015, the government put forward the goal of "zero growth of chemical fertilizers by 2020". Since 2016, Central Document No. 1 has continuously established the reduction of agricultural fertilizers as an important work goal. In 2017, the government has further promoted green agricultural development, including the use of organic fertilizers instead of chemical fertilizers. The target of this work goal is to change the current unreasonable fertilization structure and fertilization methods, and to achieve partial substitution of chemical fertilizers through the use of new agricultural production technologies. It helps to achieve the ultimate goal of chemical fertilizer reduction and agricultural green development.

Farmers are the micro-subjects of agricultural production and the behavioral decision-making units that respond to the push towards the reduction of chemical fertilizers and the green development of agriculture [7]. Thus, exploring the relationship between the production behavior of farmers and their technical efficiency is a necessary way to promote and coordinate the dual goals of green agricultural development and ensure farmers' income increases. Technical efficiency is the gap between farmers' production and technological frontiers and is a visual embodiment of farmers' production and management capabilities. The excessive application of chemical fertilizers will inevitably reduce its marginal output [8]. Applying organic fertilizers instead of chemical fertilizers can reduce excessive fertilizer inputs to reduce costs and improve the marginal output of organic fertilizers. In addition, organic fertilizers can improve the soil environment and quality and further optimize the marginal output of other production factors [9]. Therefore, using organic fertilizers instead of chemical fertilizers may have significant advantages for improving farmers' technical efficiency and may also make significant contributions to the green development of agriculture.

Vegetables are the largest cash crops in China, and their sown area reached 21.485 million hectares in 2020, making them the second largest crop after food crops. For vegetables, fertilizer input is related to environmental impact. At the same time, product quality and safety are closely related, so this study selected vegetable farmers as the research object. This study is based on the survey data of 514 vegetable growers in the five main vegetable-producing areas of the Huang-Huai-Hai and Bohai Rim: Shandong province, Hebei province, Liaoning province, the city of Beijing, and the city of Tianjin. This study provides a policy basis for further promoting the replacement of chemical fertilizers with organic fertilizers and promoting the green development of agriculture.

2. Literature Review

The use of organic fertilizers by farmers is a sustainable production behavior. This study first explores the literature from the perspective of farmers' green production behavior and then reviews the relevant research on substituting chemical fertilizers with farmers' organic fertilizers.

Research on green agricultural production behavior is generally carried out from the perspective of willingness and behavior. From the perspective of willingness to adopt, farmers have different performances across various green production technologies, production factors, or production methods. The difficulty and cost of these production technologies, factors, or methods are essential factors affecting farmers' willingness [10,11]. From the perspective of adoption behavior, the proportion of farmers in China adopting green production behavior is low [12,13]. Some scholars considered the correlation between different agricultural production technologies; they regarded green agricultural production behavior as a combination of agricultural production technologies, and came to similar

conclusions [14,15]. The influencing factors of adoption behavior are more complex and diverse than those of farmers' willingness to adopt. They include farmer endowments [16], social networks [17,18], land characteristics [19,20], government subsidies [21,22], and other factors.

Many studies have focused on the effects of green production behavior on farmers. Some scholars believe that green production behavior has positive effects. For example, some studies have found that adopting integrated bio-textile technologies can reduce environmental costs and total costs, thereby increasing total returns [23]. Adopting arable land protection technology can increase the rice yield of farmers [24]. The adoption of green production technology can significantly improve agricultural production efficiency [25]. Some scholars also believe that green production behavior has no significant effect. The use of conservation tillage techniques has not effectively increased the yield of wheat and maize in the Yellow River Basin, which may be related to the scale of farmers' operations and the proportion of farmers' adoption in the surrounding areas. Some scholars believe that the effect of green production behavior will also be affected by several external conditions [26,27].

Research on adopting organic fertilizers is also prevalent, and many scholars regard organic fertilizers as a green factor of production and include them in their research frameworks [28,29]. Since organic fertilizer is an input-based production technology, it can improve soil structure, environmental quality, and fertility [30]. The stability of land rights has been the focus of such studies. Most scholars believe that stable land property rights can promote the adoption of organic fertilizers [31]. On the other hand, some scholars believe that the stability of land rights will not affect farmers' use of organic fertilizers [32]. In addition, adopting organic fertilizer as a green production technology is also affected by a series of factors, including farmer characteristics, land endowments, and policy subsidies. Therefore, organic fertilizer as a production technology will not exist independently and be widely adopted. Many scholars have studied such problems by considering the interaction effect of organic fertilizer with other production factors or production technologies [33,34].

Studies on the effect of replacing chemical fertilizers with organic fertilizers are more specific, and the conclusions are more consistent. Replacing chemical fertilizers with organic fertilizers can significantly improve soil quality, which is beneficial to crop drought, pest presence, and lodging resistance. In addition, the yield per mu of the fertilized plots was higher than that of the unfertilized plots [35,36]. In recent years, the number of studies exploring the application effect of organic fertilizers from the economic perspective has gradually increased. Based on microdata studies in Hubei and Hunan, some studies found that using organic fertilizers can significantly reduce agricultural non-point source pollution and domestic waste [37]. Some studies suggest that when compared with chemical fertilizers, organic fertilizers can improve production efficiency more significantly [38]. Some studies found that using organic fertilizers can increase farmer incomes by 2661~2959 ETB in Ethiopia (ETB refers to the currency code of Ethiopian Birr.) [39].

In summary, professors and scholars in China and abroad have conducted many analyses of farmers' green production behavior, organic fertilizer adoption behavior, and corresponding effects from different perspectives. As a result, multidisciplinary research has dramatically enriched the academic perspective of substituting chemical fertilizer with organic fertilizer. However, there are still the following aspects to be deepened and improved. First, the relevant research on the use of organic fertilizers is still primarily found in the field of natural sciences. However, this study aims to conduct its analysis from the economic perspective to assess the impact of organic fertilizer substitution on farmers' production. Second, studies on the effect of organic fertilizer substitution of chemical fertilizers primarily focus on the impact on farmers' income and yield. In contrast, this study focuses on the impact of organic fertilizer substitution on the technical efficiency among farmers. Third, studies are primarily based on micro-survey data, but there is a non-random behavior of farmers using organic fertilizers. Therefore, the problem of "self-selection" often occurs.

3. Theoretical Mechanisms and Research Methods

3.1. Influence Mechanism of Organic Fertilizer Substitution of Chemical Fertilizer on the Farmers' Technical Efficiency

Technical efficiency is the output efficiency brought about by technological progress or the improvement of management capabilities. It reflects the maximum output capacity of farmers at a given input level or the ability to achieve the optimal allocation of input factors when achieving a specific output. Therefore, from the perspective of input and output, this study analyzes the changes brought about by substituting organic fertilizers for chemical fertilizers on the input and output of farmers' production and then clarifies the impact mechanism on farmers' technical efficiency (Figure 1).

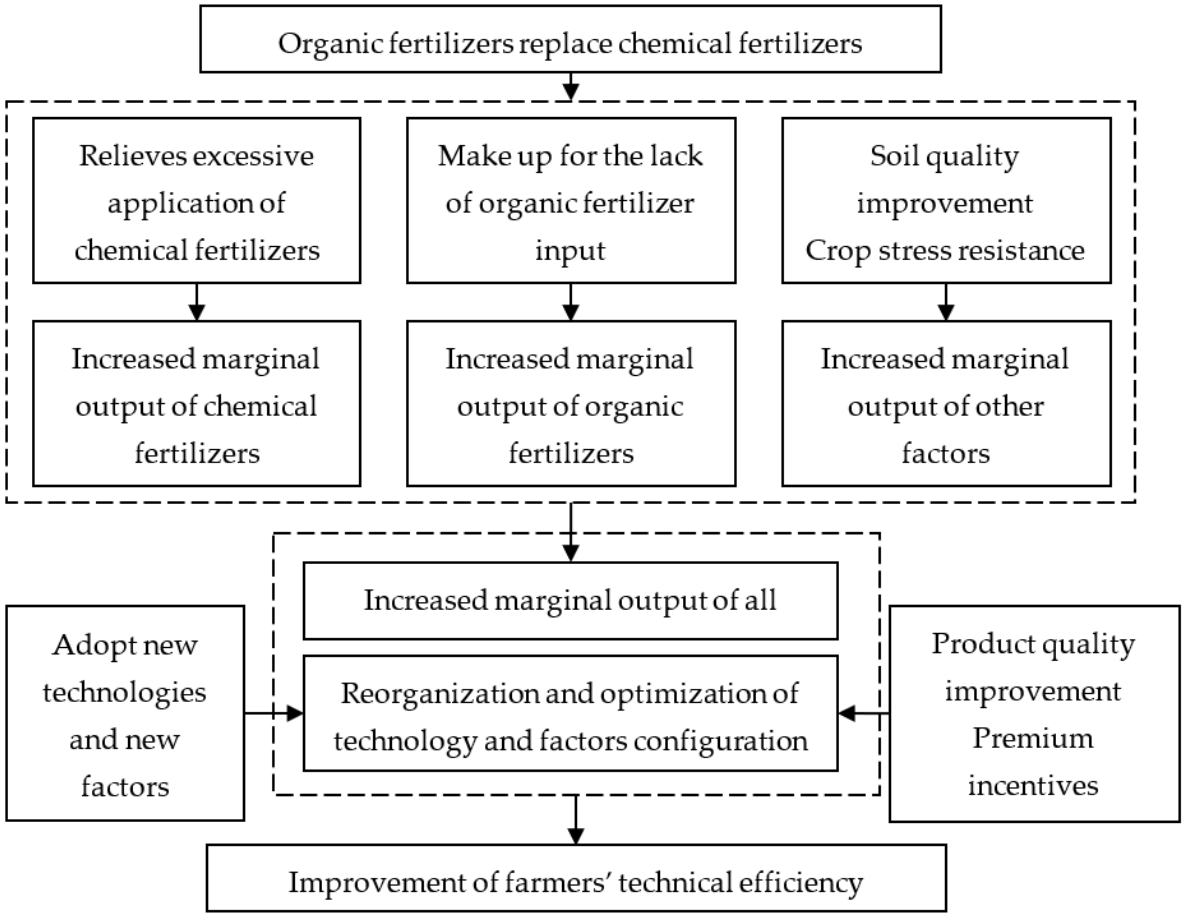


Figure 1. Influence mechanism of organic fertilizer substitution of chemical fertilizer on the farmers' technical efficiency.

First, the marginal output of fertilizer inputs can increase. Excessive input of chemical fertilizer is common. This has adverse effects on the agricultural production environment and causes waste of resources, increases unnecessary costs, and reduces the marginal output of chemical fertilizer. However, organic fertilizer input in agricultural production is still insufficient [40]. Therefore, if organic fertilizer is used to replace some chemical fertilizers, the marginal output of both organic and chemical fertilizers will be significantly improved. Therefore, substituting organic fertilizers for chemical fertilizers will significantly increase the marginal output of fertilizers as an input factor, thereby improving farmers' technical efficiency.

Second, the marginal output of other inputs can increase. Numerous studies have shown that using organic fertilizers can effectively improve soil quality while improving the resilience of crops to stress [41]. This improvement in soil quality and crop resilience means that producing the same agricultural products on the same land requires less input

from machinery, labor, and other factors. From another point of view, this is the increase in the marginal output of other factors such as machinery and labor. Therefore, replacing chemical fertilizers with organic fertilizers can improve the quality of some input factors in agricultural production to improve the marginal output of other factors, thereby promoting the improvement of farmers' technical efficiency.

Third, the optimization of the technology portfolio is caused by substituting production technology, elements, and complementarity. Farmers' adopting new production technology is a systematic behavior [42]. When farmers adopt new technology, they may use some other technologies simultaneously to achieve technological complementarity or abandon part of the technology to carry out technological substitution to maximize their interests. These behaviors will promote the further optimization of their technology portfolio. At the same time, production factors have complementary or substitution effects. As a green and environmentally friendly agricultural production technology, the adoption of organic fertilizer will inevitably lead to the reorganization and optimization of farmers' production technology and factor allocation.

Fourth, the quality of agricultural products is improved, and premium incentives are encouraged. According to existing studies, using organic fertilizer can effectively improve the quality of agricultural products, thus leading to a price premium compared to ordinary agricultural products. The higher the quality of agricultural products, the higher the premium level obtained [43]. For small farmers, the adoption of new technologies or new inputs will lead to higher costs and risks, and this premium will provide incentives for farmers to adopt the new technology or input. New technologies further optimize resource allocation, encourage farmers to upgrade their technology, and optimize resource allocation, forming a virtuous circle that continuously improves their technical efficiency.

In summary, farmers using organic fertilizers in place of chemical fertilizers can improve their technical efficiency by strengthening the marginal output of production factors and promoting the restructuring and optimization of production technology and factor allocation. At the same time, it also provides long-term incentives for this promotion through price premiums. Based on the above analysis, the hypothesis proposed by this study is that farmers' using organic fertilizer to substitute chemical fertilizers can improve technical efficiency.

3.2. Model and Data

3.2.1. Technical Efficiency Measurement Based on Stochastic Frontier Model

There are a variety of indicators to measure agricultural productivity, including but not limited to productivity, technological efficiency, and total factor productivity. Among them, single-factor productivity, such as land and labor productivity, measures agricultural production efficiency through the ratio of individual factors to agricultural output. Total factor productivity is the part of output growth that deducts the increase in factor inputs. In actual research, the growth of total factor productivity can be deconstructed into the rate of technological progress, return on the scale, improvement of technological efficiency, and improvement of allocation efficiency. Among them, technical efficiency refers to the degree to which farmers master and utilize a particular technology, which is the ratio of actual output to the boundary production function; allocation efficiency is the adjustment of input and output relative to the price after the production technology is selected [44]. In this study, organic fertilizer substitution was considered a production technology and its effects were analyzed; as such, technical efficiency was selected as the core explanatory variable. In the current study, the measurement of technical efficiency is primarily conducted using Stochastic Frontier Analysis (SFA) and Data Envelopment Analysis (DEA).

On the one hand, the advantage of the DEA method is that there is no need to set the specific function form to avoid the structural deviation caused by the mis-setting of production functions, such as traditional accounting methods and SFA methods. On the other hand, undesired outputs can be integrated into a unified input and output production system [45]. However, the DEA method also has shortcomings. Although it can measure

the efficiency problem of multi-input and multi-output, it ignores the influence of random error [46]. In other words, in the actual analysis, the resulting bias may be caused by the existence of random error., It is difficult to test the overall significance of the regression results using the DEA method, thus it is impossible to directly analyze the influencing factors of efficiency [47,48]. The SFA method is superior to DEA in that it considers the impact of random error on the results, which determines the production function form In advance. As a result, it can improve the accuracy of calculation technology efficiency and analyze the correlation between efficiency and influencing factors. Therefore, based on the C-D production function, the SFA method is used to measure the technical efficiency value of farmers. Its general form is as follows:

$$y_i = F(x_i, \beta) \exp(v_i - \mu_i) \tag{1}$$

Logarithm on both sides:

$$\ln y_i = \beta_0 + \sum_{j=1}^{k} \ln(x_{ki}) + (v_i - \mu_i), i = 1, 2, 3 \cdots n; j = 1, 2, 3 \cdots k \tag{2}$$

In Formula (2), y_i, the output variable, is the total output value of the ith farmer. Current estimates of the technical efficiency of agricultural production generally express output variables in terms of the quantity or value of output [49]. Determining the output variable needs to consider the organic fertilizer substitution because fertilizer can improve the quality of agricultural products by improving soil quality and affect the price of agricultural products. If the total output is determined as the output variable, it cannot reflect the impact of organic fertilizer substitution on the quality and price of agricultural products. Therefore, the total output value is determined as an output variable, which can more accurately reflect the output level of farmers. x_{ki} is the input variable, that is, the input of the ith farmer to the kth factor. Regarding the determination of input variables, four categories have been widely used: land, fertilizer, labor, and mechanical [50]. Since the data used in this study come from the survey of vegetable farmers, for whom agricultural film input, pesticide input, and seedling input are also essential input factors, the input variables in this study are set to 7 categories: seedling input, mechanical input, fertilizer input, pesticide input, agricultural film input, labor input, and land input. The measurement method and sample situation of each input variable are shown in Table 1. $v_i - \mu_i$ represents the mixed error term, while μ_i represents a random error term that follows a normal distribution and the farmer's productivity loss rate. k represents the number of input factors and n represents the sample size.

Table 1. Calculation basis for the technical efficiency of farmers' production.

Variable Name	Abbreviation	Variable Definition	Mean	Standard Deviation
Output	ln$Y$	Actual sales (CNY)/logarithm	9.917	0.045
Seedling input	ln$S$	The total input of seeds and seedlings (CNY)/logarithm	5.735	0.131
Mechanical input	ln$M$	The total input of machine tillage, machine sowing, machine harvest (CNY)/logarithm	3.547	0.102
Fertilizer input	ln$F$	The total input of chemical fertilizer, organic fertilizer and biological bacterial fertilizer (CNY)/logarithm	7.601	0.044
Pesticide inputs	ln$P$	The total input of chemical pesticides and biological pesticides (CNY)/logarithm	6.109	0.085
Plastic sheeting input	ln$A$	The total input of mulch film and shed film is (CNY)/logarithm	7.203	0.047
Labor input	ln$L$	The total input of free labor and employed labor (CNY)/logarithm	10.168	0.041
Land input	ln$T$	Actual operating area (mu)/logarithm	0.070	0.021

Further, farmer technical efficiency (TE) can be expressed as:

$$TE_i = \frac{E(y_i|\mu_i, x_i)}{E(y_i|\mu_i = 0, x_i)} \tag{3}$$

In Formula (3), $E(y_i|\mu_i, x_i)$ represents the expected value of the actual output and $E(y_i|\mu_i = 0, x_i)$ represents the expected value of the output on the production front in the absence of technical inefficiency. TE_i indicates farmer technical efficiency; it is the ratio of actual output to output on the frontier, and the value ranges from 0 to 1.

3.2.2. Propensity Score Matching Method

This study used the propensity score matching method (PSM) to empirically analyze the impact of organic fertilizer substitution fertilizer on farmers' technical efficiency. The method is primarily based on the following three considerations. First, although the behavior of organic fertilizer substitution of chemical fertilizer can be observed in each sample, there is a non-randomness of individual selection behavior. Therefore, whether farmers choose organic fertilizer instead of chemical fertilizer is endogenous. Because the existence of unobservable factors will affect the decision of farmers to use organic fertilizer instead of chemical fertilizer, these unobservable factors also affect farmers' technical efficiency. In this case, the ordinary regression method violates the assumption that the expected mean is zero. Second, using organic fertilizers instead of chemical fertilizers may be related to the initial endowments of farmers. In turn, it leads to the problem of "selection bias". The propensity score matching method can test whether the farmers who use organic fertilizers instead of chemical fertilizers are consistent with the technical efficiency when they are assumed to not be used. Third, farmers applying organic fertilizers to substitute chemical fertilizers may have different characteristics when compared with non-users. The tendency score matching method can conduct multi-dimensional matching through counterfactual as-assumptions to improve the estimation efficiency.

This study matched the substitution group (farmers using organic fertilizers instead of chemical fertilizers) and the non-substitution groups (farmers who did not use organic fertilizers instead of chemical fertilizers). The impact of organic fertilizer substitution on farmers' technical efficiency was analyzed under the condition that the same external conditions were controlled. The specific steps are as follows.

In the first step, the Logit model was used to estimate farmers' conditional probability fair value using organic fertilizer instead of chemical fertilizer. The score value expression for the propensity score matching is:

$$PS = \Pr(R = 1|Z_m) = E(R = 0|Z_m) \tag{4}$$

In Formula (4), PS indicates the propensity score value, $R = 1$ indicates farmers who do use of organic fertilizer instead of chemical fertilizer, and $R = 0$ indicates farmers who do not use organic fertilizer instead of chemical fertilizer. Z_m represents a series of observable control variables, primarily including the characteristics of the head of the household, the characteristics of the family, and the characteristics of production and operation.

The second step Is to match the substitution group and the non-substitution group. In this study, three matching methods (nearest neighbor match (1–3 match), kernel match and caliper match (Nearest neighbor matching (1–3 matching)) are to find three farmers who do not use of organic fertilizer instead of chemical fertilizers under the premise of ensuring that the tendency score value is closest; then, we further weighted the average the samples of these three farmers and use it as a matching sample of the farmers who do use organic fertilizer instead of chemical fertilizer. Radius matching was conducted by setting the caliper value to limit the propensity score value. The caliper was set to 0.05 in this study, the nuclear matching was set to the propensity score broadband, and the weighted average of the control group samples in the broadband group was used as the matching sample of the replacement group. The broadband value was set to 0.06 in this study. The

three above mentioned methods were used to separately to ensure the robustness of the matching results.

The third step is performing co-support domain and balance tests. The co-support domain test can determine whether the substitution group and the non-substitution group have a co-support area by the overlap of the value range. The equilibrium test can determine the matching effect by comparing the differences between the substitution group and the non-substitution group in the explanatory variables.

In the fourth step, the mean processing effect (ATT) is calculated. Then, according to the difference in the technical efficiency of farmers in the substitution group and non-substitution group, the actual impact of the use of organic fertilizer instead of chemical fertilizer on farmers' technical efficiency was calculated. The specific expression is:

$$ATT = E(TE_1|R = 1) - E(TE_0|R = 1) = E(TE_1 - TE_0|R = 1) \quad (5)$$

In Formula (5), TE_1 represents the technical efficiency of farmers who use organic fertilizers instead of fertilizers, and TE_0 represents the technical efficiency of farmers where it is assumed they do not. $E(TE_1|R = 1)$ can be observed directly, while $E(TE_0|R = 1)$ cannot be observed; this is a counterfactual result, and this study constructs a corresponding alternative index based on the tendency score matching method.

3.2.3. Tobit Model and IV-Tobit Model

Since the farmer's technical efficiency value ranges from 0 to 1 and is a truncated variable, this study uses the Tobit model for analysis. The specific expressions are as follows:

$$TE_i^* = \beta_0 + \beta_1 OF_i + \gamma_i Z_{ij} + \delta region_i + \varepsilon_i, \varepsilon_i \sim \left(0, \sigma^2\right) \quad (6)$$

$$TE_i = \begin{cases} \beta_0 + \beta_1 OF_i + \gamma_i Z_{ij} + \delta region_i + \varepsilon_i, Efficiency_i^* > 0 \\ 0, Efficiency_i^* < 0 \end{cases} \quad (7)$$

In Formulas (6) and (7), TE_i^* indicates the potential farmer's technical efficiency, OF_i indicates whether the farmer uses organic fertilizer instead of fertilizer, Z_{ij} represents the control variable, i indicates the sample size, j represents the number of control variables, and β and γ are the coefficients to be estimated. In the Tobit model, the dependent variable is the technical efficiency of the farmer calculated according to the SFA model. The core explanatory variable is the farmer's organic fertilizer substitution behavior. The factor influencing technical efficiency is a complex system, so a series of control variables need to be added to the model. Previous studies have focused primarily on the personal characteristics and family characteristics of the head of the farmer's household, including age, education level, identity, part-time level, and the number of laborers [51]. This study aims to explore the substitution effects of organic fertilizer, so the farmers' awareness of the quality and safety of agricultural products is also added. Farmers' land resource endowments are also of concern, such as land scale, land fragmentation degree, and topographic conditions [52,53]. In addition, the peculiarities of vegetable production, planting density, production experience, and training participation have also been added. The fragility of agricultural production processes has led to disaster situations and participation insurance. Finally, the regional effect is controlled by considering whether the surveyed area is a central producing county. δ represents the coefficient of the regional dummy variable and ε represents the random perturbation term. The specific variables and sample cases are shown in Table 2.

Using the maximum likelihood function to estimate the equation, the log-likelihood function of the sample is as follows:

$$\log L = \sum_{i=1}^{n} \left\{ I_{y_i=0} \ln \left[\varphi \left(-\frac{x_i \beta}{\sigma} \right) \right] + I_{y_i>0} \ln \left[\frac{1}{\sigma} \omega \left(-\frac{y_i - x_i \beta}{\sigma} \right) \right] \right\} \quad (8)$$

In addition, considering that there may be a causal relationship between the use of organic fertilizers instead of chemical fertilizers and their technical efficiency, this study will further use the instrumental variable method. To be specific, in the IV-Tobit model, the farmers' "policy cognition" and "fertilizer cognition" are used as the tool variables, and the two-stage least squares method (2SLS) and the maximum likelihood method (ML) method were used to estimate to solve the endogenous problem.

Table 2. Variable definitions, assignments, and descriptive statistics.

Variable Category		Variable Name	Variable Definitions	Mean	Standard Deviation
Interpreted variables		Technical efficiency	Calculated according to the stochastic frontier model	0.601	0.006
Core explanatory variables		Organic fertilizers replace chemical fertilizers	Whether to use organic fertilizers instead of chemical fertilizers: adopt = 1, unadopt = 0	0.434	0.022
Control variables	Head of household characteristics	Age	Actual age of the head of household (years)	53.953	0.400
		Education	Actual years of schooling at the head of household (years)	8.871	2.806
		Identity	Whether it is a village cadre:yes = 1, no = 0	0.642	0.011
		Awareness of the quality and safety	Whether to conduct quality and safety testing:yes = 1, no = 0	0.652	0.477
	Family characteristics	Part-time level	Ratio of non-farm income to total household income	0.090	0.186
		Laborers	Number of actual household labor force (unit)	2.689	0.045
	Land characteristics	Scale of operation	Planting area (mu)	4.319	0.139
		Degree of fragmentation of the land	The reciprocal of the average area of all plots	0.732	0.026
		Topographic conditions	Whether it is located in a plain area:yes = 1, no = 0	0.948	0.001
	Production characteristics	Planting density	Ratio of the number of seedlings to the area planted/logarithm	7.761	0.023
		Production experience	Vegetable production life (years)	19.462	8.944
		Participation in insurance	Whether to purchase vegetable production insurance:yes = 1, no = 0	0.085	0.278
		Participation in training	Number of training sessions in vegetable production (times)	4.143	8.711
		Disaster situation	Whether or not you have suffered a natural disaster:yes = 1, no = 0	0.746	0.446
Region dummy variables		The main producing county	Whether it is the main producing county:yes = 1, no = 0	0.321	0.021

3.2.4. Data Sources

The data of this study are derived from the stratified random sampling survey among vegetable farmers in the Bohai Rim region of China in July 2019. The surveyed provinces or municipality directly under the Central Government include Shandong Province, Hebei Province, Liaoning Province, Beijing, and Tianjin. The Bohai Rim region is an advantageous vegetable-producing area in China, of which Shandong Province and Hebei Province are the primary sources to ensure the supply of vegetables in the north. In addition, these surveyed areas have diversified vegetable production varieties and technologies, and the industrial development is relatively mature. A total of 15 research areas are selected in the five provinces. Within each research areas, 1–2 villages are randomly selected and within each village, 10–20 farmers are randomly selected for investigation. The research

group conducted the survey through one-on-one interviews between the investigators and the interviewed farmers. The respondents were primarily heads of households. We identified the core explanatory variables in this study by asking householders whether they used organic fertilizers instead of chemical fertilizers in agricultural production. A total of 548 questionnaires were distributed to the respondents, and 514 valid questionnaires were obtained after removing incomplete samples, with an effective rate of 93.8%.

4. Results

4.1. Stochastic Frontier of Technology Efficiency

The stochastic frontier model in the form of the C-D production function in Formula (2) is estimated, and the technical efficiency values of all sample farmers are measured. The estimated results are shown in Table 3. The impact of seedling input, fertilizer input, labor input, pesticide input, and land input on the output value of farmers is significantly positive. After calculation, the average technical efficiency of farmers was 0.6, and 42.2% had higher technical efficiency than this average.

Table 3. Estimates of parameters of the stochastic frontier production function.

Variable Name	Estimated Coefficient	Standard Error
ln$S$	0.066 ***	0.013
ln$M$	0.008	0.016
ln$F$	0.340 ***	0.040
ln$L$	0.105 ***	0.035
ln$P$	0.055 ***	0.019
ln$A$	0.150	0.035
ln$T$	0.433 ***	0.080
σ_u	0.759 ***	0.113
σ_v	0.607 ***	0.428
LR value	9.210 ***	
N	514	

Note: *** represent significance levels of 1%.

4.2. Impacts of Organic Fertilizer Substitution of Chemical Fertilizer on the Technical Efficiency

4.2.1. Logit Model Estimation

To achieve an effective match between farmers who use organic fertilizers instead of chemical fertilizers and farmers who do not, it is first necessary to conduct regression analysis on the conditional probability fair values of farmers using organic fertilizers instead of chemical fertilizers. The maximum likelihood estimation results based on the Logit model are shown in Table 4. The characteristics of the household head, family characteristics, land characteristics, attributes of production, and the region have different degrees of impact on fertilizer substitution. To be specific: (1) characteristics of the household head: age has a significantly negative influence, indicating that the older the age, the lower the ability to accept new production factors and production technologies. (2) Family characteristics: the level of part-time employment shows a significant adverse effect because full-time farmers can obtain higher incomes and provide sufficient financial support for adopting new technologies and new factors. (3) Land characteristics: the scale of operation has a significant negative effect; this is because the more extensive the scale of a farmer's operation, the lower the probability of farmers using organic fertilizers will be, in line with the expansion of scale in order to reduce production costs. (4) Production characteristics: the production experience significantly reduces fertilizer substitution. This may be due to the relatively fixed production mode of small farmers. With the increase in production years, their decisions become more "empiricist" and they are inclined to use traditional production factors and technologies. Participation in insurance can significantly enhance fertilizer substitution. Because participation in insurance can bring stable expected returns to farmers, this factor enhances farmers' ability to resist risks and provide a bottom-up

guarantee for farmers to adopt new technologies and elements. Training can significantly improve the probability of farmers replacing chemical fertilizers with organic fertilizers because training can give farmers a more objective and accurate understanding of the advantages and disadvantages of chemical fertilizers and organic fertilizers. The disaster situation is significantly negatively correlated with the farmer's fertilizer substitution. When encountering natural disasters, the farmer adds more fertilizer input in the short term to increase the yield effect and make up for the loss. (5) Regional characteristics; there are significant differences in the substitution of organic fertilizers by farmers in central vegetable-producing counties and non-primary-producing counties.

Table 4. Estimation results of the Logit model in which farmers use organic fertilizers instead of chemical fertilizers.

Variable Category	Variable Name	Estimated Coefficient	Robust Standard Error	z Statistics
Head of household characteristics	Age	−0.033	0.016	−2.12 **
	Education	0.074	0.169	0.44
	Identity	−0.693	0.478	−1.45
	Awareness of the quality and safety	2.638	0.314	8.41 ***
Family characteristics	Part-time level	0.385	0.193	2.00 **
	Laborers	−0.084	0.118	−0.71
Land characteristics	Scale of operation	−0.128	0.044	−2.89 ***
	Degree of fragmentation of the land	0.015	0.235	0.06
	Topographic conditions	−0.560	0.573	−0.98
Production characteristics	Planting density	−0.000	0.000	−1.01
	Production experience	−0.054	0.016	−3.49 ***
	Participation in insurance	1.368	0.465	2.94 ***
	Participation in training	0.048	0.193	2.49 ***
Regional characteristics	Disaster situation	−0.705	0.292	−2.41 **
	The main producing county	0.769	0.269	2.86 ***
constant		1.478	1.298	1.14
LR value			169.50 ***	
Pseudo R^2			0.286	

Note: **, *** represent significance levels of 5%, and 1%.

4.2.2. Co-Support Domain and Balance Test

Two primary conditions must be met to ensure the effectiveness of the propensity score matching method. One is the typical support hypothesis. The preference scores of farmers who use organic fertilizers instead of chemical fertilizers and farmers who do not use organic fertilizers instead of chemical fertilizers must have a large common support domain. Plotting the kernel density function plot of the propensity score was used to test the first condition. Taking nuclear matching as an example, it can be seen in Figure 2 that there are apparent differences in the probability distribution of the propensity scores of the two groups of samples before and after the matching. In contrast, the probability distribution of the propensity scores of the two groups of samples after the match is closer, the matching effect is better, and the expected support hypothesis is met.

Another vital assumption when using the propensity score matching method is the equilibrium hypothesis. That is, there are no systematic differences in each matching variable between the two sets of samples after the matching is completed. Because of the different matching methods and the amount of sample loss, three matching methods (nearest neighbor match, radius match, and kernel match) are used in this study to match separately. The balance test results are shown in Table 5. It shows that the mean covariate and the median deviation after matching under the three matching methods significantly

decrease before matching. Furthermore, according to the *p*-value of the likelihood ratio test, it can also be seen that there is no significant difference in the mean difference between the covariates of the two groups of samples after matching, which further ensures the matching effect. That is to say that, by matching, we find some individuals in the control group so that these individuals are similar to the individuals in the treatment group in all other factors except the core explanatory variables, so that the differences in the core explanatory variables can explain the differences in the explanatory variables.

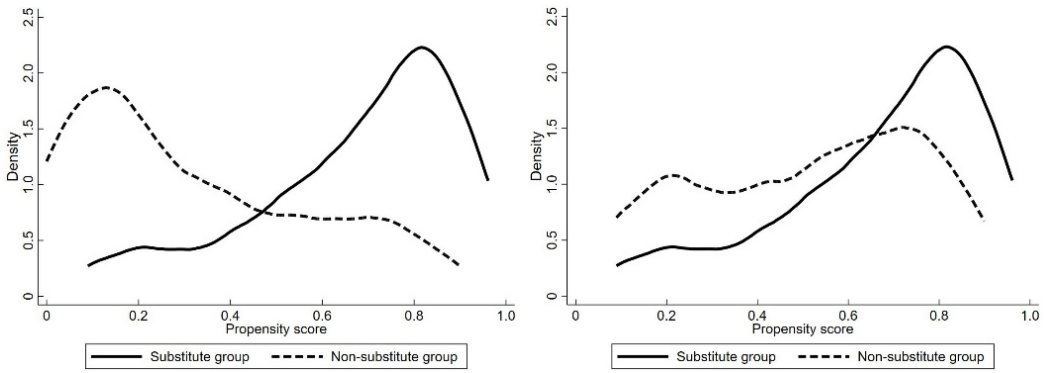


Figure 2. The co-support domains of substitute group and non-substitution group before matching (**left**) and after matching (**right**).

Table 5. Balance test results of explanatory variables before and after matching under different matching methods.

Matching Methods	Pseudo R^2	LR Statistics	*p*-Value	Mean Bias	Med Bias
Before matching	0.287	170.35	0.000	26.7	19.5
Nearest neighbor match	0.020	10.81	0.766	6.2	6.5
Radius match	0.007	4.01	0.998	4.1	4.7
Kernel match	0.007	3.77	0.998	4.1	4.3

4.2.3. The Average Treatment Effect on the Technical Efficiency

Table 6 shows the effects of organic fertilizer substitution on the efficiency of agricultural technology under three matching methods. According to the calculation results, after controlling the differences of various control variables by the tendency score matching method, the measurement results under different methods are very close and consistent. ATT has passed the test at a significant level of 1%. Further, the effects obtained under the different matching methods were averaged at 0.054. According to the counter-facts, the technical efficiency of farmers who use organic fertilizers instead of chemical fertilizers is 0.571 if they do not use them. Their technical efficiency increases by 0.625 after adoption, with a growth rate of 9.46%. Farmers can significantly improve their technical efficiency by replacing chemical fertilizers with organic fertilizers.

Table 6. Based on PSM estimation of the impact of farmer organic fertilizer adoption on technical efficiency.

Matching Methods	Substitute Group	Non-Substitute Group	ATT	Robust Standard Error	t-Value
Nearest neighbor match	0.625	0.574	0.052	0.018	2.85 ***
Radius match	0.625	0.570	0.055	0.017	3.23 ***
Kernel match	0.625	0.570	0.056	0.017	3.28 ***
Mean	0.625	0.571	0.054	—	—

Note: *** represent significance levels of 1%.

4.2.4. Robustness Check

The above analysis verifies that using organic fertilizers instead of chemical fertilizers can significantly improve farmers' technical efficiency. However, farmers with higher technical efficiency may further incentivize themselves to use organic fertilizers instead of chemical fertilizers, which leads to reverse causality. It may, in turn, create "endogenous problems". Therefore, the instrumental variable method is used to solve the problem. Before the instrument variable method was adopted, the OLS and Tobit models were separately used to regress; the regression results are shown in Table 7. It shows that, under the regression of both models, when organic fertilizers replaced chemical fertilizers, there was a significant positive effect on farmers' technical efficiency through the statistical level of 1%.

Table 7. Estimates results based on OLS model and Tobit model.

Variable Name	OLS Model		Tobit Model	
Organic fertilizers replace chemical fertilizers	0.033 ***	0.035 ***	0.033 ***	0.035 ***
	(0.012)	(0.012)	(0.011)	(0.012)
Control variables	Control	Control	Control	Control
Region	—	Control	—	Control
Constant	0.583 ***	0.603 ***	0.584 ***	0.602 ***
	(0.109)	(0.113)	(0.107)	(0.111)
R^2/F value	0.082	0.091	43.82	47.55

Note: (1) *** represent significance levels of 1%. (2) The sound standard error is indicated in parentheses.

Further, the instrument variables of organic fertilizers instead of chemical fertilizers were examined and are shown in Table 8. The Wald tests were significant at a statistical level of 5%, confirming the existence of "endogenous" problems. The two instrument variables of "policy cognition" and "fertilizer cognition" were selected. Specifically, "policy cognition" refers to whether farmers understand the fertilizer reduction policy, and "fertilizer cognition" refers to whether farmers recognize the view that "excessive fertilization of chemical fertilizer will harm the environment and health". The more farmers understand the fertilizer reduction policy, the higher the possibility of replacing chemical fertilizer with organic fertilizer. The higher the awareness of chemical fertilizers among farmers, the greater the willingness to use organic fertilizers instead of chemical fertilizers. From an exogenous point of view, farmers' awareness of relevant policies and fertilizers will not affect their technical efficiency.

Table 8. Estimation results based on the IV-Tobit model.

Variable Name	Instrumental Variables: Policy Awareness		Instrumental Variables: Chemical Fertilizer Cognition	
	2SLS	ML	2SLS	ML
Organic fertilizers replace chemical fertilizers	0.102 ***	0.102 ***	0.040 ***	0.040 ***
	(0.027)	(0.027)	(0.017)	(0.017)
Control variables	Control	Control	Control	Control
Region	Control	Control	Control	Control
Constant	0.501 ***	0.501 ***	0.584 ***	0.584 ***
	(0.115)	(0.115)	(0.108)	(0.108)
AR test for weak instrumental variables	14.84 **		5.48 **	
Wald test for weak instrumental variables	14.24 **		5.58 **	

Note: (1) **, *** represent significance levels of 5%, and 1%. (2) The sound standard error is indicated in parentheses.

Combined with the results of the AR test for weakly instrumental variables, the hypothesis of rejecting weakly instrumental variables can be verified. Results are shown in Table 8 for the use of the IV-Tobit model, 2SLS, and ML methods for estimation,. Regardless of the "policy cognition" or "fertilizer cognition" of the instrument variables, the coefficient of organic fertilizer substitution of chemical fertilizer is significantly positive at the statistical level of 1%. It also shows that using organic fertilizer instead of chemical fertilizer can significantly improve the technical efficiency of farmers, which further verifies the previous conclusions.

4.3. Heterogeneity Analysis

This study further explores the heterogeneity of the influence of organic fertilizer substitution on farmers' technical efficiency from three aspects: household head characteristics, family characteristics, and land characteristics.

4.3.1. Heterogeneity Based on the Characteristics of the Household Head

As shown in Table 9, this study found that farmers under 50 years old have positive ATT and are significant at a statistical level of 5%, while farmers aged 50 and above are not significant. It may because younger farmers are better at using new technologies and new methods, ensuring their technical efficiency is relatively high. Using high school as a cut-off, it can be found that the ATT of low-educated farmers is significantly positive, while the ATT of high-educated farmers is not significant. Highly educated farmers have stronger information processing capabilities, and their technology portfolio has been more reasonable. Using organic fertilizers instead of chemical fertilizers will reduce technical efficiency. However, low-literacy farmers are on the contrary.

Table 9. Heterogeneity analysis based on head of household characteristics.

	Age		**Education**	
	Under 50 Years Old	**50 Years Old and Below**	**Junior High School and Below**	**High School and Above**
ATT	0.0281 **	0.0328	0.0406 ***	−0.0301
	(0.0143)	(0.0281)	(0.0129)	(0.0429)
Sample size	344	170	449	64

Note: (1) **, *** represent significance levels of 5%, and 1%. (2) The sound standard error is indicated in parentheses.

4.3.2. Heterogeneity Analysis Based on the Characteristics of Farmer Families

As shown in Table 10, by dividing farmers into full-time and part-time farmers, it can be found that the ATT of full-time and part-time farmers is positive, while the part-time farmers are not significant. Agricultural production and operation are more critical to full-time farmers than part-time households. Full-time farmers will also invest more time and energy into agricultural production and operation. The use of a new technology or element also has a relatively high effect on improving the efficiency of its technology. Moreover, farmers with a labor force of three and below is significant, while the labor force of more than three farmers is insignificant. The less labor power the family puts into agricultural production and operation, the more it can fully stimulate the potential of labor. For example, using organic fertilizer instead of chemical fertilizer can have a higher marginal labor output, thereby improving its technical efficiency.

4.3.3. Heterogeneity Based on Land Characteristics

As shown in Table 11, the ATT of farmers with more minor operation scales is significantly positive, while farmers with larger planting areas are not significant. This is because small-scale farmers have a relatively small scale of operation, and these smaller areas are more convenient for self-supervision and management. From the perspective

of different degrees of land fragmentation, it can be found that the ATT of farmers with different degrees of land fragmentation is significantly positive. Farmers with a higher degree of land fragmentation have larger ATT values. The possible reason for this is that even if the degree of land fragmentation is low, farmers rarely have the conditions to scale up their operation, and improving production efficiency through an increased scale of operation is challenging. For these small farmers, the higher the degree of fragmentation of the land, the more conducive it is for classified management and intensive farming.

Table 10. Heterogeneity analysis based on family characteristics.

	Part-Time Level		**Number of Laborers**	
	Full-Time Farmer	**Part-Time Farmer**	**3 and Below**	**More Than 3**
ATT	0.0338 **	0.0091	0.0279 ***	0.0225
	(0.0139)	(0.0259)	(0.0139)	(0.0278)
Sample size	358	156	382	132

Note: (1) **, *** represent significance levels of 5%, and 1%. (2) The sound standard error is indicated in parentheses.

Table 11. Heterogeneity analysis based on land characteristics.

	Scale of Operation		**Degree of Fragmentation of the Land**	
	Below 4.3 mu	**4.3 mu and Above**	**Below 0.73**	**0.73 and Above**
ATT	0.0362 ***	0.0176	0.0196 **	0.0340 ***
	(0.0153)	(0.0212)	(0.0167)	(0.0204)
Sample size	349	165	335	179

Note: (1) **, *** represent significance levels of 5%, and 1%. (2) The sound standard error is indicated in parentheses.

4.4. Effects on Technical Efficiency and Farmers' Income

The mediating effect model is used in this study to test the transmission mechanism of farmers' technical efficiency in the impact of organic fertilizer substitution on income. In Table 12, Model 1 is the regression equation of organic fertilizer substitution of chemical fertilizer to farmer income. Model 2 is the regression equation of organic fertilizer substitution of chemical fertilizer to farmers' technical efficiency. Model 3 is the regression equation of farmers' technical efficiency (intermediary variable) and organic fertilizer substitution of chemical fertilizer (core explanatory variable) to income.

Table 12. Sobel mediation effect test for farmers' technical efficiency.

Variable Name	**Modle1**	**Modle2**	**Modle3**
Organic fertilizers replace chemical fertilizers	0.142 ** (0.065)	0.041 *** (0.013)	0.086 (0.063)
Technical efficiency	—	—	1.364 *** (0.232)
Control variables	Control	Control	Control
Constant	11.672 *** (0.290)	0.699 *** (0.059)	10.720 *** (0.322)
Sobel test(Z-value)	0.056 *** (0.021)	Proportion of mediating effects	39.707%
Sample size		514	

Note: (1) **, *** represent significance levels of 5%, and 1%. (2) The sound standard error is indicated in parentheses.

According to the Sobel test, the intermediary effect is present. Organic fertilizer substitution of chemical fertilizer has a significant positive effect on farmers' technical efficiency and income. After adding the intermediary variable, the impact of organic

fertilizer substitution of chemical fertilizer on farmers' income is no longer significant. However, the impact of technical efficiency on farmers' income is significantly positive. So, the farmer's technical efficiency plays a complete intermediary or main intermediary effect between organic fertilizer substitution of chemical fertilizer and income. In other words, organic fertilizer substitute of chemical fertilizer primarily promotes the income of farmers by improving their technical efficiency. Therefore, improved technical efficiency is a critical factor in the added benefits of farmers using organic fertilizers instead of chemical fertilizers.

5. Conclusions and Policy implementation

5.1. Conclusions

Based on the survey data of 514 farmers in five provinces and cities around the Bohai Sea in 2019, the influence of organic fertilizer substitution on farmers' technical efficiency was empirically analyzed from the microscopic level. "Policy cognition" and "fertilizer cognition" were instrumental variables in solving the endogenous problem. The heterogeneity analysis was carried out based on the characteristics of farmers. At the same time, the mediating effect of technical efficiency between organic fertilizer substitution of chemical fertilizer and farmer income was tested.

The primary research conclusions are summarized as follows. First, quality and safety awareness, part-time employment level, insurance participation, and training significantly promote the use of organic fertilizers to replace chemical fertilizers. Second, according to the counterfactual analysis, if the farmers who use organic fertilizer substitution do not adopt it, their technical efficiency is 0.571. However, their technical efficiency increases to 0.625 after adoption, a growth rate of 9.46%. Third, the promoting effect of organic fertilizer substitution on technical efficiency has heterogeneity, which is significant among small-scale farmer households with fewer and low-educated family laborers. Fourth, organic fertilizer substitution can indirectly affect farmers' income through the intermediary path of farmers' technical efficiency. Improving technical efficiency is the primary factor for farmers to use organic fertilizer instead of chemical fertilizer to increase income.

5.2. Policy Implemantation

Based on the above research conclusions, the policy recommendations of this study are put forward.

First, the promotion of organic fertilizer as alternative fertilizer technology should be encouraged. Based on the positive effect of organic fertilizer substitution of chemical fertilizer on farmers' technical efficiency, the innovation of related technologies should be promoted from multiple perspectives, including organic fertilizer quality and fertilization technology. To increase the promotion of organic fertilizer instead of chemical fertilizer technology, we consider the improvement effect of organic fertilizers on the quality of agricultural products and farmers' income in addition to publicizing the yield increase and environmental protection effects of organic fertilizers. Based on ensuring the long-lasting effect of organic fertilizer, the enthusiasm of farmers to replace chemical fertilizer with organic fertilizer is improved.

Second, efforts should be made to improve the green certification of agricultural products and the agricultural product market supervision system. On the one hand, improving the quality and safety standards of agricultural products is necessary, forcing farmers to change to a green way of production. On the other hand, it is necessary to consolidate and enhance the position of green agricultural products in the market and increase residents' demand for green agricultural products. In addition, making farmers "profitable" for green production provides incentives to use organic fertilizers.

Third, this study calls to strengthen agricultural subsidies while improving the accuracy of policy formulation and implementation. Policy subsidies can provide stable support for farmers to adopt new technologies and elements and increase farmers' resilience to risks. It includes improving the subsidy standards for farmers to replace chemical fertilizers

with organic fertilizers and optimizing corresponding technical support. Moreover, when formulating and implementing policies, we should fully consider the heterogeneity of farmers. The study demands to classify and accurately implement policies based on the actual needs of different types of farmers and to maintain awareness of the emergence of the "Matthew effect".

5.3. Discussion

The use of organic fertilizers instead of chemical fertilizers can significantly improve the technical efficiency of farmers by optimizing the quality and structure of farmers' factors. However, according to the analysis of farmers' heterogeneity, farmers with a smaller scale of operations and higher degree of land fragmentation have better results. This does not mean that encouraging the increased scale of operation is inefficient, but because the factor allocation structure of small-scale farmers needs to be optimized. We also conclude that the use of organic fertilizer instead of chemical fertilizer can promote farmers' income through efficiency improvement. This increase can provide financial support for their use of relatively higher prices of organic fertilizers. It is noted that low-income farmers may be unable to adopt due to insufficient funds; this may form a vicious circle of "low income—low technology level—low efficiency—low income" and produce a "Matthew effect" in the long run. In addition, this study focuses on the behavior of vegetable farmers because the fertilizer demand in the vegetable production is greater than that of grain crops, so the effect of organic fertilizer substitution may be more prominent. Whether organic fertilizer substitution has the same effect on farmers in other agricultural industries still needs further verification in future studies.

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Institutional Review Board Statement: Ethical review and approval were waived for this study due to REASON (The data in this study is based on surveys of farmers, not through experiments, and only asks farmers to recall their production behavior, so we think it is possible to apply for an exemption from the ethics committee.)

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data that support the findings of this study are available from the corresponding authors upon reasonable request.

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