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RESEARCH ARTICLE

Research on the impact of agricultural green production on farmers' technical efficiency: evidence from China

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Abstract
Agricultural green production (AGP) and efficiency improvement of smallholders' management are the objective requirements for the development of China's modernized agriculture and the understanding of the rural vitalization strategy. Based on field survey data of 582 rice farmers in Shaanxi Province, this study used the Logit model to analyze the determinants of smallholders' adoption of agricultural green production technology (AGPT) and used the propensity score matching (PSM) method to measure the effect of AGPT on the technical efficiency (TE) of rice production and the heterogeneity of this influence among smallholders. Results showed that the AGPT adoption rate and the mean of rice production TE were 15.1% and 0.312, both had a lot of room for improvement. Furthermore, it was found that household's characteristics, family characteristics, agricultural management characteristics, social characteristics, and cognitive characteristics significantly affect smallholders' AGPT adoption, and the AGPT adoption significantly increased the TE of rice production by 18.8 to 24.5%. Besides, farmers with older age, less education, more specialized planting, more fragmented land, and more off-farm employment adopting AGPT could significantly improve the TE; the increase proportion was 29.8%, 29.5%, 21.3%, 27.2%, and 16.8%. The study also showed that the AGPT could not significantly increase the rice output value of smallholders. In addition, considering the endogeneity problem caused by sample selection bias, the study re-estimated using the endogenous transformation regression (ESR) model which showed that the promotion of AGPT to TE was still robust. The study puts forward policy recommendations on how to further promote the adoption of AGPT and improve the TE by farmers.

Keywords Agricultural green production technology · Smallholders · Technical efficiency · Propensity score matching

Introduction

China's per capita arable land area is less than half of the world average (Kenneth Keng 2006). For a long time, the excessive use of pesticides and fertilizers in China's grain production had caused many public problems such as non-point agricultural pollution and hidden food safety problems (Han and Zhao 2009; Ju et al. 2004; Li et al. 2008; Lu et al. 2015; Wang et al. 1996). Therefore, promoting the green development of agricultural and rural areas is an inevitable choice for realizing agricultural modernization and leading rural revitalization (Yu 2018). The realization of green development of agriculture not only requires transforming the mode of agricultural production, but also depends on farmers' active adoption of agricultural green production technology (AGPT) (Li et al. 2020). At present, the smallholders are still the main subjects of agricultural production in China (Han 2018; Huang and Ding 2016), using AGPT to transform the production mode of smallholders is the micro-foundation and objective requirement to realize the green development of agriculture in China.

At present, scholars' research on farmers' adoption of AGPT mainly focuses on the following aspects: the first is the willingness, behavior, and influencing factors of farmers to participate in green production (Li et al. 2019; Wang et al. 2016; Wu et al. 2017; Yang 2018; Yu et al. 2017; Zhang et al. 2019). The study found that factors such as aging, social networks, technological cognition, informal institutions, and environmental regulations affect farmers' willingness and behavior to participate in green production. The second is to study the driving effect of new agricultural business entities on

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green production. Sun and Liu (2019) found that land trusteeship can not only drive farmers with green production willingness to engage in green production, but also promote production by introducing green production factors to farmers without green production willingness. Cai and Du (2016) found that family farms tend to participate in green production, and the individual characteristics of farmers, family management characteristics, and farm characteristics have a significant impact on participation in green production. The third is to study the economic and ecological benefits brought about by green production. Geng et al. (2018) studied the economic and environmental impacts of farmers adopting green prevention and control technologies in the main kiwifruit-producing areas. The results showed that green prevention and control technologies have significant economic and environmental effects. It can increase the output of farmers and reduce the use of pesticides.

The development of agricultural modernization relies on the improvement of technical efficiency (TE) (Adom and Adams 2020; Kalirajan et al. 1996; Nkamleu 2004; Ogundari 2014). Whether adoption of AGPT improves TE, and how the adoption of AGPT by smallholders affect TE? The TE of China's green agricultural production is still at a relatively low level, although the average annual technical change rate of each province is positive. The five-year average annual technical change rate is relatively small (Liu et al. 2020). Xiao et al. (2020) found that China's agricultural green production efficiency is generally on the rise. Technological progress has cumulative positive effects on the improvement of agricultural green production efficiency whereas TE has cumulative negative effects. Moreover, Xiong and Xu (2019) based on the panel data of Sichuan Province concluded that the TE had a trend of decline and then rise between 2006 and 2016 after the implementation of environmentally friendly agriculture. Yet, the result of studying the impact of AGPT on TE from a micro perspective is positive. Zhang and Gao (2018) studied the factors influencing the adoption of new agricultural technologies by small farmers and large grain growers and the differences in TE. Research shows that adopting new technologies can improve TE, and large grain growers not only facilitate the adoption of new technologies but also improve TE. The results of Ge and Zhou (2012) showed that rice farmers' use of soil testing and formula fertilization technology is beneficial to the improvement of rice planting technology efficiency.

So, whether AGPT influences TE is far from settled. It can be supplemented in the following three aspects. First in terms of research methods, previous studies (Ge and Zhou 2012; Geng et al. 2018) had used traditional measurement methods to analyze the impact of AGPT on TE and production efficiency. In fact, the adoption of AGPT by farmers is not random, using traditional methods will cause biased results due to model setting bias. The initial conditions of the farmers using AGPT and those without AGPT are not exactly the same, so there is a problem of selection bias. Propensity score matching (PSM) can compress the information of the multi-dimensional vector into one dimension, and matches according to the propensity score. It can make the treated group individuals and the control group individuals as similar as possible under the established observable characteristic variables, thus alleviating the problem of selection bias in treatment effects (Rosenbaum and Rubin 1983; Wooldridge 2002). Second in terms of object, although the land large-scale management such as agricultural cooperative and agricultural productive services is currently encouraged in China, land fragmentation and decentralized small-scale farming operations are the current status of operations (Fan and Chan-Kang 2005; Wang et al. 2020; Xie and Lu 2017). Furthermore, reduction of chemical fertilizers and pesticides conflicts with the growing experience of farmers over the year (Sun et al. 2019), Therefore, clarifying the impact of AGPT that reduces the use of fertilizers and pesticides on TE is indispensable for reversing farmers' perceptions of AGPT and promoting the AGPT adoption. Third is in terms of content; although the influence of AGPT on TE had been studied in the literature, the differences in the influence effect among heterogeneous agricultural production groups had been ignored. The study aims at analyzing the heterogeneous impact of AGPT adoption on TE in order to draw more refined conclusions.

The paper proceeds as follows. "Methodology and data" section presents the theoretical analysis and six hypotheses are proposed, specifies the model, data source, variable definition, and statistical analysis. "Results and discussion" section describes the empirical analysis including robustness test and discusses the main results. "Conclusions and policy implications" section gives the conclusions and policy implications.

Methodology and data

Theoretical analysis

Impact of AGPT adoption on TE

The concept of TE was first proposed by Farrell (1957) and gave the definition of TE from the perspective of input; he believed that TE refers to the ratio of the ideal minimum possible input to the actual input of a production unit under the same output. Leibenstein (1966) believed that TE refers to the ratio of the actual output of a production unit to the ideal maximum possible output under the same input. In other words, TE improvement exists in two aspects: reducing production factor inputs or increasing crop output.

The AGPT discussed in the current study include soil testing and formula fertilization technology, green pesticides, biological pesticides, and insecticidal lamps; they may reduce the input of production factors and increase crop output to improve TE. In the traditional farming process, farmers usually apply chemical fertilizers in excessive amount (Huang et al. 2008), and the reasons for this excessive application are lack of soil productivity and chemical fertilizer application knowledge which ultimately result in loss of TE. Compared with traditional chemical fertilizer application, soil testing formula fertilization technology directing farmers to accurately apply fertilizers to avoid overuse. It can effectively reduce fertilizer consumption and input costs meanwhile improve fertilizer utilization and production (Dong et al. 2020). Ordinary pesticides as the chemical agents, can not only kill non-target organisms, but also cause residues of agricultural products and non-point source pollution (Bakker et al. 2021). Green pesticide has low dosage and rapid effect, it not only acts on certain harmful organisms but also has less toxic and can degrade rapidly (Liu et al. 2005). Biological pesticides as non-chemically synthesized natural chemical substances and organisms can reduce drug resistance and effectively prevent pests while increasing yield (Nwilene et al. 2008), therefore, it can be a safe alternative to chemical pesticides (Shabana et al. 2017). In addition, existing studies had shown that insecticidal lamps can not only save the cost and labor input by reducing the pesticides application amount and times, but also shorten the time and degree of peak harm (Li et al. 2010) and increased the yield of rice (Chen et al. 2015; Hu 2014). Soil testing and formula fertilization technology reduces fertilizer use without adversely affecting crop yield; green pesticide has low dosage and rapid effect, and insecticidal lamps save the cost and labor input. The technical advantages of AGPT improving the TE by reducing capital input and labor input from the perspective of agricultural production input. The positive effects of soil testing and formula fertilization technology, green pesticide, and insecticidal lamps on crop yields also improve TE from the perspective of increasing crop output.

Common factors affecting the AGPT adoption and TE

Diffusion of innovation theory pointed out that individual innovation is an important influencing factor in the new technology-accepted process (Rogers 1995). Innovation refers to the degree that individuals or other organizational units in the social system earlier accept a new idea than the others. Therefore, farmers abandon the original fertilizer and pesticide application behavior then choose AGPT in production process can be regarded as green production innovation. The diffusion of innovation theory believes that the individual's social and economic characteristics, personality and values, communication behaviors, and manner are closely linked to their innovation (Rogers 1995). The main characteristics of individual's cognition and family socioeconomic of the farmer will affect their learning behavior, information receiving ability, and innovation, thereby affecting their adoption behavior. However, existing studies had shown that the above characteristics had an impact on the farmer's TE, such as age (Abdulai and Eberlin 2001; Saiyut et al. 2018), years of education (Saha et al. 1994), operation scale (Ahmad and Bravoureta 1995; Ferreira and Féres 2020; Townsend et al. 1998), land fragmentation (Chen et al. 2009; Rahman and Rahman 2009; Sherlund et al. 2002; Tan 2005), and off-farm employment (Danso-Abbeam et al. 2020; Zhao et al. 2020). Therefore, it is difficult to confirm whether the difference in TE between farmers is due to AGPT adoption or their own factor endowments. So, reliable conclusions should be based on the fact that the farmers have the same or very close factor endowments except for differences in AGPT adoption. Thus, it is necessary to control the factor endowments before and after the AGPT adoption by farmers to avoid biased estimates when studying the impact of AGPT on TE.

Heterogeneity impact of AGPT adoption on TE

Although aged farmers have been engaged in agricultural production for a long time and have rich planting experience, due to their adherence to traditional planting experience and the decline of labor capacity, they have less contact with surroundings, lack of information sources, and generally have low TE (Li and Sicular 2013; Liu et al. 2019). Soil testing and formula fertilization can effectively reduce excessive fertilizer input, reverse the long-standing farming habit of over-application of chemical fertilizers, and save cost of inputs. In addition, AGPT such as insecticidal lamps operation is simple and efficient that can reduce fertilizing and spraying drug times, alleviating the efficiency loss caused by insufficient labor.

The farmers' level of education can partly reflect their learning ability. Undereducated farmers have poor understanding and acceptance for new technologies and factors in agricultural production is unevenly allocated. Therefore, their management level is poor and have insufficient motivation to improve production efficiency (Asadullah and Rahman 2009; Kalaitzandonakes and Dunn 1995; Lockheed et al. 1980). Soil testing and formula fertilization technology has professionals to guide farmers, which can improve their fertilizer input and application level. Insecticidal lamp as a physical pest control method is simple to use and saves the investment of pesticides. Therefore, after adopting AGPT, undereducated farmers can optimize the allocation of factors and improve the management effect more obviously, and the improvement of TE may be more significant.

The high planting proportion is suitable for scale operation, which can effectively improve the efficiency of operation and management (Xu et al. 2019). Farmers with high planting proportion are more dependent on production and have a stronger desire to reduce planting risks, so they have a greater need for technological improvement. Specialized farmers are easier to get the advantages of technology because they are more sophisticated in the farmland management and application of AGPT; therefore, the effect of improving TE may be better.

Land fragmentation requires more production materials and management costs (Wadud and White 2000). The insecticidal lamp only requires simple operation, which can effectively reduce the pesticide input and at the same time avoid the labor cost of applying pesticides in multiple places. Farmers with more fragmented land may still have poor soil fertility. Soil testing and formula fertilization can precise improvement of soil quality, which can improve soil fertility and reduce excess chemical fertilizer input.

Part-time farmers spend relatively less time in agriculture and the management is relatively extensive. In addition, the arable land lacks intensive cultivation, thus needs a higher room for improvement in TE (Abdulai and Huffman 2000). Techniques such as soil testing and formula fertilization and insecticidal lamp have low requirements on labor input and can save costs and increase income. Biological and green pesticides have better defense effect on pests and diseases than chemical pesticides.

Based on the above analysis, the study puts forward the hypothesis:

H1-1. The adoption of AGPT has a positive impact on TE.
H2-1. Aging farmers adopting AGPT can improve the TE more significantly.
H2-2. Undereducated farmers adopting AGPT can improve the TE more significantly.
H2-3. Higher proportion of rice planting farmers adopting AGPT can improve the TE more significantly.
H2-4. Farmers with high degree of land fragmentation adopting AGPT can improve the TE more significantly.
H2-5. Part-time farmers adopting AGPT can improve the TE more significantly.

Analytical techniques

In the first step, there is a need to select control variables that simultaneously affect farmers' AGPT adoption and TE, the specific variables were household head's characteristics, family characteristics, management characteristics, and social and cognitive characteristics.

In the second step, using logit model to calculate the score value of individual i's tendency to participate in AGPT. The model is as follows:

$$PS_i = \text{Prob}(T_i = 1|D_i) = E(T_i = 0|D_i) \qquad (1)$$

i represents the farmers, $T_i = 1$ represents the farmers who adopt AGPT, $T_i = 0$ represents the farmers who don't adopt AGPT, and $D_i$represents vector of control variables.

In the third step, the implementation of PSM is needed. There are differences between different matching methods in weighing deviation and effect (Caliendo and Kopeining 2008). In order to strengthen the robustness of the conclusions, the study uses six methods to match: (1): Nearest neighbor matching, find n samples that are closest to the PS_i value to matching, in this study, n is set to 4. (2): Radius matching, limit the distance of PS_i values between matching samples, the study sets the caliper range to 0.03. (3): Kernel matching, the study uses the default commands provided by Stata 15.0. (4): Local linear regression matching, the study uses the default commands provided by Stata 15.0. (5): Spline matching, the study uses the default commands provided by Stata 15.0, spline matching cannot directly get the standard error of the estimated value, so the standard error of this matching method is obtained by repeated sampling of bootstrap 500 times. (6): Mahalanobis matching, in this study, n is set to 4, the ai is set to 4.

The fourth step is to obtain average treatment effect on treated (ATT). The specific formula is:

$$\begin{aligned} \text{ATT} &= E(y_{1i}|T_i = 1) - E(y_{0i}|T_i = 1) \\ &= E(y_{1i} - y_{0i}|T_i = 1) \end{aligned} \qquad (2)$$

y_{1i} represents farmers' TE after adopt AGPT, y_{0i} represents the TE if the treated group farmers did not adopt AGPT after matching, $E(y_{1i}| T_i = 1)$ can be observed directly, but $E(y_{0i}| T_i = 1)$ cannot be observed directly, so need to use PSM to construct corresponding indicators instead.

Data collection

Shaanxi is selected as a study area due to the agricultural non-point source pollution in Shaanxi Province is becoming more and more serious. The annual consumption of chemical fertilizers in the province reaches 2.417 million tons (discounted pure), and the average utilization rate of chemical fertilizers is only about 30%. The average application rate is as high as 840Kg/ha, exceeding the safety upper limit of 225Kg/ha in developed countries and the national average of 480 Kg/ha. The annual pesticide usage amounts to 13,000 tons, and 46,666 ha of farmland suffers from varying degrees of pesticide pollution. Excessive chemical fertilizers, pesticides, and mulch are left in the soil and water bodies, causing obvious or latent pollution of the soil environment of rivers and large areas of farmland, which has become a serious problem affecting the sustainable development of modern agriculture and food safety in Shaanxi Province[1]. Therefore, it is necessary to

[1] The data comes from the "Sustainable Development Plan of Agriculture and Animal Husbandry in Shaanxi Province (2014-2020)" released by Department of Agriculture and Rural Affairs of Shaanxi Province. URL: http://nyt.shaanxi.gov.cn/www/ghjh1188/20161209/574026.html

guide farmers in the Shaanxi province to adopt AGPT to realize the green development of agriculture.

The data of this study are derived from two household surveys of rice farmers conducted by the research group in Ankang City and Hanzhong City, Shaanxi Province. The survey obtained the relevant situation of rice production in 2016. There are three reasons for choosing these two cities as study areas: first of all, Ankang and Hanzhong are the main rice-producing areas in Shaanxi Province, with a perennial planting area of more than 90,000 hm2. Second, the two cities are not only the key zones of ecological function but also the source of water conservation in the middle route of the South-to-North Water Diversion project. In recent decades, the problem of agricultural non-point source pollution has become increasingly prominent, Meng et al. (2017) found that the annual output of nitrogen and phosphorus non-point source pollutants in Hanzhong and Ankang were both very high and analyzed by the eutrophication of representative-monitored cross-section in the Danjiangkou Reservoir. Moreover, Hanzhong has the highest annual total phosphorus output among administrative cities, exceeding 11,700 ton. Subsequently, it is necessary to promote AGPT in these two cities. Third, the two cities successively promoted AGPT such as soil testing and formula fertilization in 2006 to 2008, while some farmers have already adopted the corresponding technologies. Therefore, choosing Ankang and Hanzhong as the research areas is typical and representative.

The survey questionnaire mainly included the agricultural production status, the basic characteristics of the family, the adoption of AGPT, the use of chemical fertilizers and pesticides, and the perception of their damage. This survey follows the principle of combining stratified sampling with random sampling technique and comprehensive consideration of factors such as economic development, agricultural production, and landforms. Hanbin District, Hanyin County, and Pingli County were selected in Ankang City, and Chenggu County and Mian County were selected in Hanzhong City. Later, 4–6 unincorporated villages in each County (District) were selected, and 20 to 35 farmers were randomly selected in each village to conduct one-to-one household surveys. A total of 670 questionnaires were distributed in this survey. After excluding invalid questionnaires, missing variables, logical error questionnaires, a total of 632 valid questionnaires were obtained, including 310 from Ankang City (49.05%) and 322 from Hanzhong City (50.95%). The effective rate of samples was 94.33%. This study analyzes the TE of rice production after excluding 32 non-rice growers and the final sample size was 600; whereas, the number of rice smallholders is 582[2].

[2] Based on divided farmers according to 0.67 hectares of cultivated land standard in the third national agricultural census, in this study, smallholders are classified according to the standard of rice cultivation area less than or equal to 0.67 hectares; At the same time, scholars often use 0.67 hectares as the standard to study smallholders, such as Han (2018).

Variable definition

Explained variable

The explained variable in this study is the TE of rice production. The TE is measured by the classic input-oriented BCC model. The output index of TE is the annual total output of rice production, the input index is the material cost input of rice production (including costs of chemical fertilizers, farmyard manure, pesticides, use and lease of agricultural machinery, seedling, and irrigation), labor input for rice production (including own labor input and hired labor input), and land area input for rice production (Planting area). The specific form of the BCC model of n DUM (decision making unit) is:

$$\begin{cases} \min[\theta - \varepsilon(e^t s^- + e^t s^+)] \\ \sum_{i=1}^{n} \lambda_t y_{ir} - s^+ = y_{0r} \\ \sum_{i=1}^{n} \lambda_i x_{ij} + s^- = \theta x_{0j} \\ \sum_{i=1}^{n} \lambda_i = 1, i = 1, 2, \cdots, n \\ \lambda_i \geq 0, s^+ \geq 0, s^- \geq 0 \end{cases} \tag{3}$$

x_{ij} 、 y_{ir} respectively represents the jth input and rth output of the ith farmer, θ between 0 and 1. λ_i represents the weight, s^- 、 s^+ represents input redundancy and output redundancy of farmers.

Independent variable

This study takes the AGPT adoption as the independent variable and it includes whether to use soil testing formula for fertilization, green pesticides, biological pesticides, and insecticidal lamps. If farmers adopt any of these AGPT, they will assign the value of 1 to “whether to adopt green production technology,” otherwise the value will be 0.

There are two reasons for defining the adoption of green production technology in the study. On the one hand, the four technologies included in AGPT are all related to the reduction of chemical fertilizers and pesticides. Any one of these technologies can reduce the amount of pesticides or chemical fertilizers to a certain extent, thereby reducing agricultural non-point source pollution and promoting green agricultural development. On the other hand, the adoption rate of a single green production technology in the surveyed areas is very low. Therefore, as long as one of these technologies is adopted, it is regarded as adopting green production technology.

Control variables

The PSM control variables not only affect both AGPT and TE at the same time but also can distinguish farmers who adopt AGPT and those who do not. The study selects the characteristics of the head of household (age, education level, health condition), household characteristics (housing construction area, non-agricultural labor income, proportion of agricultural income), management characteristics (rice cultivation area, maximum land area), social characteristics (social network, whether to participate in chemical fertilizer and pesticide training), and cognitive characteristics (chemical fertilizer standard dosage cognition, pesticide residue hazard cognition, chemical fertilizer environmental hazard awareness) as the control variables.

Farmers of different ages, education levels, and health condition have different quantity and quality of labors devoted to agricultural production, and their awareness of fertilization and pesticides application in the planting process is also different, so there will be differences in deciding whether to adopt AGPT. Agricultural production decision-making is often a family behavior, so family characteristics will naturally affect the adoption of green production technology by farmers. The housing construction area of a family can characterize family assets and reflect the family's ability to pay for funds to a certain extent. Therefore, this variable will affect whether to adopt green production technology. The non-agricultural labor income and proportion of agricultural income affect the number of labor and capital that farmers invest in agricultural production, and have a certain impact on whether to adopt green production technology. The maximum cultivated area mainly reflects the characteristics of farmers' land element endowments. These land elements affect farmers' production scale and production conditions, which in turn affect the overall input and output levels of farmers (Gourlay et al. 2019), and affect farmers' adoption of green production technologies. The number of people frequently contacted in the mobile phone contacts reflects the size of the social network of farmers to a certain extent, and is related to the information sources of farmers and the scope of social interaction. Farmers often communicate with each other and obtain technical information through social networks, thereby revising their expectations of agricultural production benefits and making decisions on adoption (Bandiera and Rasul 2006; Maertens and Barrett 2013). Whether farmers participate in fertilizer and pesticide training will affect their awareness of the use of fertilizers and pesticides, and in turn affect their green production behavior. Farmers who have a good grasp of the standard amount of chemical fertilizers have a relatively objective understanding of the amount of chemical fertilizers, and will not rely too much on chemical fertilizers to increase yield, and are more willing to try green production technologies. The higher the farmers' awareness of the negative impacts of agricultural residues and environmental pollution caused by the excessive use of fertilizers and pesticides, the more they will realize the importance of protecting the environment and food security, and will largely prefer green production technologies.

Statistical analysis

Table 1 shows definition and descriptive statistics of variables used in this study. From the individual characteristics of the sample, the average value of farmer's rice production TE is 0.312; the level is generally low and thus has more room for improvements. The average value of AGPT adoption is only 0.151. The average age of the heads of households is about 58 years, and the years of education are mainly concentrated in elementary schools (49.66%) and junior high schools (40.55%); most of the heads of households are in good health. 61.51% of farmers' household agricultural income is concentrated in [0.20%]; the average rice cultivation area was 0.175 ha; 75.60% of farmers concentrated rice cultivation area in [0.067, 0.200] ha, and the average maximum cultivated area was 0.084 ha, with a high degree of land fragmentation. The average number of people frequently contacted by farmers was about 14, and 4.47% of the sample farmers had participated in the training of chemical fertilizer and pesticide. More than half of the farmers knew the standard dosage of fertilizer (51.03%), and most of them believed that excessive input of chemical fertilizer would lead to residues of agricultural products (91.41%). More than half of the farmers believed that excessive input of chemical fertilizer would cause environmental pollution (52.06%), and farmers had a certain degree of awareness of the damage caused by excessive application of chemical fertilizer and pesticide.

Results and discussion

Comparison of characteristics of sample farmers

Table 2 shows *t* test results of difference in the mean between treated group and control group. TE of treated group is significantly higher than control group at a significant level of 5%. Except for age, non-agricultural labor income and proportion of agricultural income, other control variables have significant differences between the two groups. According to the statistical results, there is a significant difference in factor endowments between treated group and control group. Treated group may have higher TE due to their better endowment combinations, probably the difference in TE does not necessarily stem from the direct impact of AGPT. Therefore, it is necessary to use the PSM to measure the net effect of adopting AGPT on TE.

Table 1 Variable definition and descriptive statistics

Variables	Variable definition	Mean	S.D.
Explained variable			
TE of rice production	TE of 2016 Rice production	0.312	0.196
Independent variable			
Whether adopt AGPT	Assign a value of 1 if adopt any one of the techniques of soil testing formula fertilization, green pesticide, biological pesticide, and insecticidal lamp, otherwise assign a value of 0	0.151	0.359
Control variable			
Age	Age of household head (years)	57.918	9.960
Education level	Years of education of household head (years)	6.450	3.492
Health condition	Householder head self-assessment the health condition, 1 = very healthy; 2 = good health; 3 = average physique; 4 = poor physique; 5 = sick all the year round	2.155	1.106
Housing construction area	Housing construction area (square meters)	234.320	104.332
Non-agricultural labor income	Family non-agricultural labor income in 2016 (ten thousand yuan)	3.644	3.343
Proportion of agricultural income	The proportion of agricultural income in total household income, 0 = 0, 1 = 10%, 2 = 20%, 3 = 30%, 4 = 40%, 5 = 50%, 6 = 60%, 7 = 70%, 8 = 80%, 9 = 90%, 10 = 100%	3.007	3.142
Rice cultivation area	Rice cultivation area in 2016 (hectare)	0.175	0.125
Maximum cultivated area	The area of the largest piece of arable land among all the arable land operated by farmers in 2016 (hectare)	0.084	0.062
Social network	The number of people frequently contacted in the mobile phone contacts (person)	13.840	22.188
Whether participate in chemical fertilizer and pesticide training	Whether participated in the training of chemical fertilizer and pesticide in the past three years, 1 = Yes; 0 = No	0.045	0.207
Cognition of fertilizer standard dosage	Knowing the standard application dosage of fertilizer, 1 = Yes; 0 = No	0.510	0.500
Cognition of pesticide residue hazards	Excessive input of pesticides will leave pesticides in agricultural products and endanger human health, 1 = Yes; 0 = No	0.914	0.280
Cognition of chemical fertilizer environmental hazards	Excessive input of chemical fertilizers pollutes the atmosphere, 1 = Yes; 0 = No	0.521	0.500

Estimation of influencing factors on AGPT adoption

In order to achieve sample matching, the study analyzed the factors affecting farmers' AGPT adoption, and the estimated results are shown in Table 3. The study conducted a collinearity test among the independent variables; the maximum VIF value is 1.24 indicating that there is no collinearity problem.

ROC (receiver operating characteristic curve) can test whether the variables in the Logit model can effectively distinguish dummy variables. Table 3 shows that the AUC (area under the receiver operating characteristic curve) of the model is 0.791, close to 0.800, proving that the selected variables can well distinguish whether farmers adopt AGPT or not. In terms of individual characteristics of household heads, farmers with higher age, higher education level, and poorer health condition are more inclined to adopt AGPT. In terms of the characteristics of households, farmers with bigger housing construction area, less of non-agricultural labor income, and lower proportion of agricultural income are more intended towards the adoption of AGPT. In terms of management characteristics, the larger maximum cultivated area is the more favorable for farmers to adopt AGPT. In terms of social characteristics, the larger the social network, the greater the possibility of farmers adopting AGPT. As far as cognitive characteristics, farmers who have a better grasp of the standard dosage of fertilizer and know that excessive fertilizer input will pollute the environment are more inclined to adopt AGPT.

Common support domain hypothesis and PSM matching result

Figure 1 shows the density function graph before and after matching. The propensity scores in the treated group and the control group have a large overlap range, and most observations are within the common value range, indicating that the matching is basically in line with the common support domain hypothesis. Only treated group lose 2 samples during matching, indicating that the overall matching effect is good.

Balance test

The balance of control variables before and after matching (Table 4) shows that Pseudo-R^2 decreased from 0.176 before matching to 0.002~0.033. LR chi^2 decreased from 87.050 before matching to 0.490~8.090. The joint significance test of control variables changed from highly significant to insignificant after matching. The mean bias of the control variables

Table 2 *T* test of difference in the mean between treated group and control group

Variables	Treated group		Control group		Mean difference	*t* value
	Mean	S.D.	Mean	S.D.		
Explained variable						
TE of rice production	0.361	0.206	0.304	0.193	0.057**	2.540
Control variable						
Age	58.886	9.439	57.745	10.049	1.141	0.990
Education level	7.625	3.337	6.241	3.481	1.384***	3.460
Health condition	1.795	1.156	2.219	1.085	-0.424***	-3.340
Housing construction area	258.648	106.443	229.986	103.462	28.662**	2.380
Non-agricultural labor income	3.124	3.432	3.736	3.322	-0.612	-1.580
Proportion of agricultural income	2.739	2.839	3.055	3.193	-0.316	-0.870
Rice cultivation area	2.938	2.044	2.563	1.841	0.375*	1.730
Maximum cultivated area	1.531	1.257	1.211	0.843	0.320***	3.020
Social network	23.080	34.011	12.194	18.923	10.886***	4.300
Whether participate in chemical fertilizer and pesticide training	0.080	0.272	0.038	0.193	0.042*	1.720
Cognition of fertilizer standard dosage	0.705	0.459	0.476	0.500	0.229***	4.000
Cognition of pesticide residue hazards	0.977	0.150	0.903	0.296	0.074**	2.300
Cognition of chemical fertilizer environmental hazards	0.705	0.459	0.488	0.500	0.217***	3.790

***, **, and * represent significance at 1%, 5%, and 10% level

dropped from 29.0% before matching to 2.4~9.4%. The median bias reduced from 29.9% before matching to 2.0~7.4%. After matching, farmers in the control group and the treated group have no significant differences in control variables except for whether they adopt AGPT.

Figure 2 shows the % bias across matching variables before and after matching. Before matching, the % bias across matching variables all exceed 10%. After matching, all variables are less than 10% except the social network, indicating that the overall matching effect is good.

Table 3 Estimated results of farmers' adoption of AGPT based on the Logit model

Variables	Coefficient	Standard error
Age	0.049***	0.014
Education level	0.123***	0.041
Health condition	− 0.386***	0.130
Housing construction area	0.003**	0.001
Non-agricultural labor income	− 0.113**	0.044
Proportion of agricultural income	− 0.096**	0.049
Rice cultivation area	0.076	0.068
Maximum cultivated area	0.279**	0.114
Social network	0.009*	0.005
Whether participate in chemical fertilizer and pesticide training	0.725	0.503
Cognition of fertilizer standard dosage	0.806***	0.272
Cognition of pesticide residue hazards	1.093	0.759
Cognition of chemical fertilizer environmental hazards	0.891***	0.278
Loglikelihood	− 203.958	
Pseudo-R^2	0.175	
LR chi^2	86.540***	
AUC	0.791	

***, **, and * represent significance at 1%, 5%, and 10% level

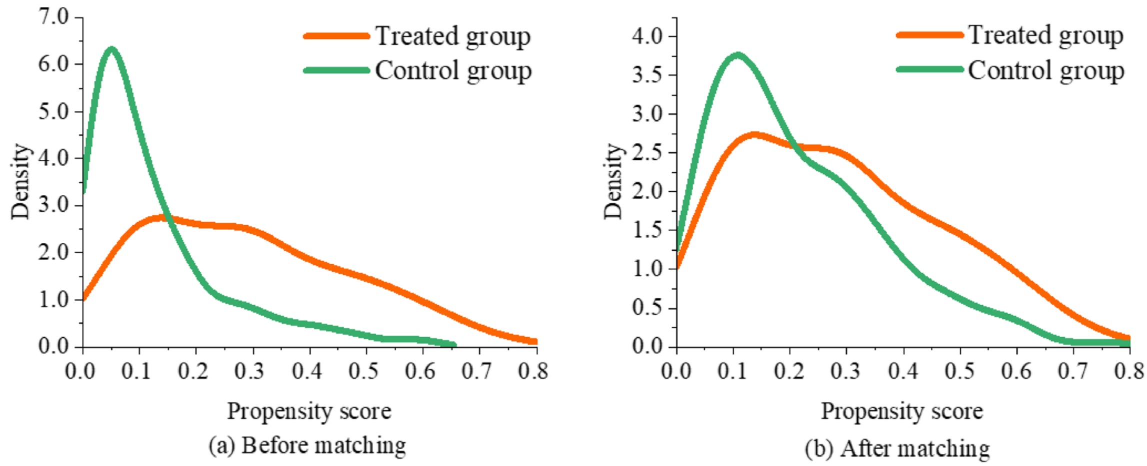

Fig. 1 Density function before and after matching

Estimation of impact effect

Table 5 shows the ATT based on the six matching methods. The results of the six matching methods are basically the same, the estimated results have well robustness. From the results, if farmers who are using AGPT do not adopt AGPT, their TE is 0.290~0.305. After adopting AGPT, the TE of rice production has been improved to 0.361~0.363. The TE of rice production has been significantly improved 0.057~0.071; the increase ratio is 18.8~24.5%; this is consistent with the H1.

The effect of adopting AGPT on land productivity

It is preliminarily concluded from the above results that adopting AGPT can promote the improvement of TE, but it can be seen from the statistical analysis that the proportion of farmers adopting AGPT is not high, and the question is why? For a new technology, agricultural performance will directly affect the adoption decision of farmers. Besides TE, the index that measures agricultural production performance still has labor productivity, land productivity, and so on. TE is a comprehensive evaluation of the whole process of agricultural production considering both inputs and output. However, the improvement of TE is not intuitive to farmers, while the change of land yield per hectares or output value per hectares is more obvious to farmers. Therefore, it is necessary to include relatively intuitive indicators into the scope of study to provide further basis for policy publicity.

Referring to the above methods, this study further explores the impact of AGPT adoption on land productivity. Land productivity is expressed in terms of per hectares output value of rice. The average land productivity of the sample farmers was 22,378.470 RMB·hectare^{-1}; the average land productivity of farmers in the treated group was 22,921.530 RMB·hectare^{-1}; the farmers in the control group were 22,281.525 RMB·hectare^{-1}; and the mean difference was 640.005 RMB·hectare^{-1}. The *t* test value of mean difference is not significant (1.43), that is before matching, there was no significant difference in land productivity between the two groups.

Table 6 shows the ATT based on the six matching methods. The change of land productivity is not statistically significant, indicating that the change of land productivity before and after adoption is not obvious. In other words, the adoption of green production technology cannot make farmers feel the increase in output value intuitively. To a certain extent, it explains the reasons for the low level of AGPT adoption and the slow promotion of AGPT in the survey area. Therefore, simply judging whether to adopt AGPT from the perspective of whether it can increase output or output value

Table 4 Result of balance test

Matching method	Pseudo-R^2	LR chi^2	p > chi^2	Mean bias (%)	Median bias (%)
After matching	0.176	87.050	0.000	29.000	29.900
Nearest neighbor matching	0.013	3.200	0.997	5.100	3.500
Radius matching	0.007	1.790	1.000	4.800	4.200
Kernel matching	0.002	0.490	1.000	2.400	2.000
Local linear regression matching	0.031	7.470	0.876	6.900	4.600
Spline match	0.031	7.470	0.876	6.900	4.600
Mahalanobis matching	0.033	8.090	0.837	9.400	7.400

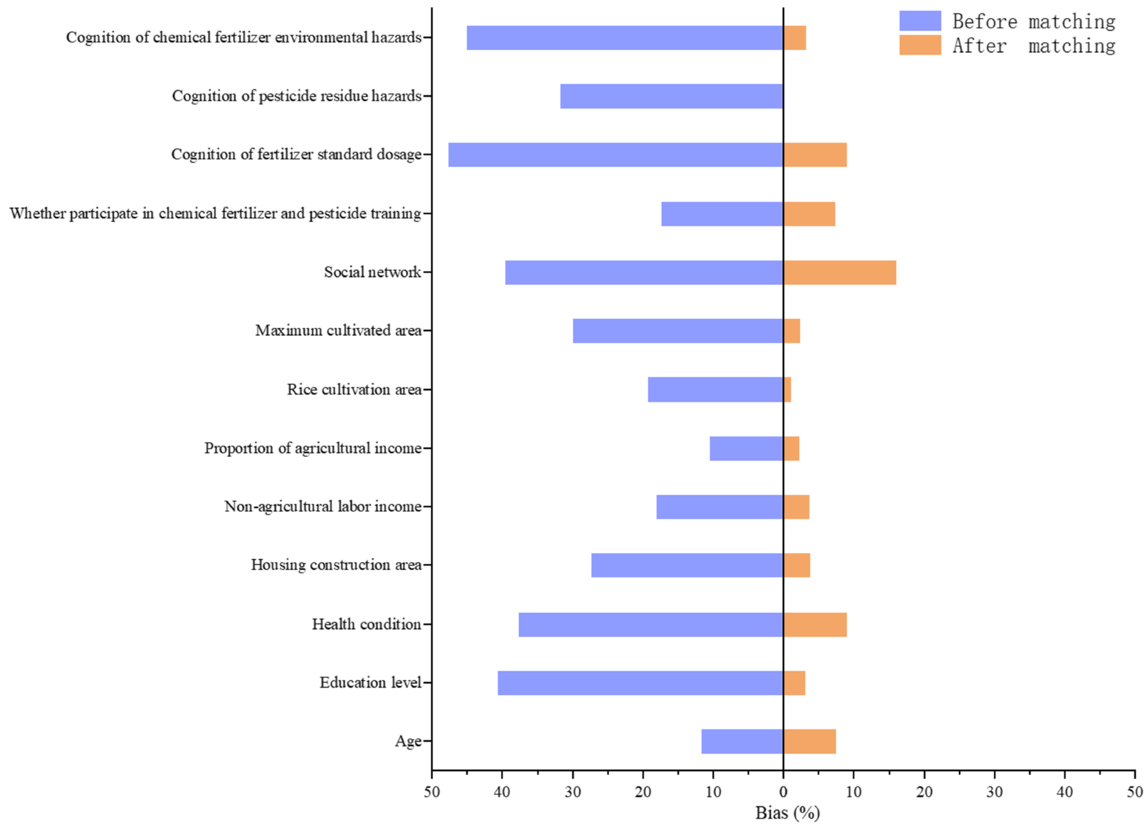

Fig. 2 Standardized % bias across matching variables

may cause farmers to fall into the misunderstanding that the adoption of AGPT will not work on agricultural production.

Heterogeneity analysis

In order to further explore the impact of AGPT adopted by farmers with different characteristics on the TE, the study adopted two methods of nearest neighbor matching and radius matching for heterogeneity analysis to ensure the robustness of the conclusion. The results are shown in Table 7.

The study used the internationally recognized 60-year-old as the standard for dividing the elderly population. Farmers aged less than or equal to 60 years old were taken as young and middle-aged group, while farmers aged over 60 years old were taken as aging group. The overall sample was divided into two groups for analysis. Before adopted AGPT, the average TE in the aging group was 0.299 (mean value of the control group of nearest neighbor matching and radius matching: [(0.308 + 0.290)/2]), After adopted AGPT, the average TE increased to 0.388 (mean value of the treated group of nearest neighbor matching and radius matching: [(0.388 +

Table 5 The effect of adopting AGPT on TE

Matching method	Treated group	Control group	ATT	Standard error	*T* value	Increase ratio (%)
Nearest neighbor matching	0.361	0.292	0.069**	0.027	2.550	23.6
Radius matching	0.363	0.305	0.058**	0.027	2.170	19.0
Kernel matching	0.361	0.303	0.058**	0.026	2.190	19.1
Local linear regression matching	0.361	0.304	0.057*	0.034	1.670	18.8
Spline match	0.361	0.304	0.057**	0.024	2.400	18.8
Mahalanobis matching	0.361	0.290	0.071***	0.025	2.820	24.5

***, **, and * represent significance at 1%, 5%, and 10% level; the increase ratio calculation method is each matching method' ATT value/control group value

Table 6 The effect of adopting AGPT on land productivity

Matching method	Treated group	Control group	ATT	Standard error	*T* value
Nearest neighbor matching	1528.102	1506.501	21.601	34.929	0.620
Radius matching	1529.919	1498.535	31.383	31.841	0.990
Kernel matching	1528.102	1502.665	25.438	31.457	0.810
Local linear regression matching	1528.102	1505.886	22.216	44.170	0.500
Spline match	1528.102	1512.911	15.192	32.467	0.470
Mahalanobis matching	1528.102	1509.992	18.111	28.749	0.630

Table 7 PSM estimation results of heterogeneous farmers

Category name	Treated group	Control group	ATT	Standard error
Aging				
Nearest neighbor matching				
< = 60	0.338	0.310	0.028	0.036
> 60	0.388	0.308	0.079*	0.043
Radius matching				
< = 60	0.337	0.307	0.030	0.036
> 60	0.387	0.290	0.097**	0.044
Education level				
Nearest neighbor matching				
Primary school and below	0.369	0.286	0.083*	0.045
Above primary school	0.357	0.308	0.049	0.035
Radius matching				
Primary school and below	0.376	0.290	0.086*	0.050
Above primary school	0.358	0.325	0.033	0.036
Rice planting proportion				
Nearest neighbor matching				
<50%	0.308	0.250	0.057	0.073
> = 50%	0.379	0.308	0.070**	0.030
Radius matching				
<50%	0.364	0.256	0.108	0.095
> = 50%	0.373	0.311	0.063**	0.030
Cultivated land number				
Nearest neighbor matching				
< = 5	0.337	0.301	0.036	0.040
> 5	0.409	0.319	0.090*	0.048
Radius matching				
< = 5	0.338	0.290	0.048	0.036
> 5	0.414	0.329	0.086*	0.051
Proportion of agricultural income				
Nearest neighbor matching				
< = 20%	0.364	0.353	0.012	0.084
> 20%	0.361	0.311	0.049*	0.030
Radius matching				
< = 20%	0.364	0.358	0.006	0.091
> 20%	0.362	0.308	0.055*	0.029

** and * represent significance at 5% and 10% level.

0.387)/2]), the TE was significantly increased by 0.089 (29.8%[3]), which confirmed the H2-1.

The study divides the sample farmers into two groups according to the education level of primary school and below (years of education less than or equal to 6), and above primary school (years of education more than 6). Before adopted AGPT, the average TE of farmers with primary school education and below was 0.288 (mean value of the control group of nearest neighbor matching and radius matching: [(0.286 + 0.290)/2]). After adopted AGPT, the average TE was 0.373 (mean value of the treated group of nearest neighbor matching and radius matching group: [(0.369 + 0.376)/2]). The TE was significantly increased by 0.085 (29.5%), which confirmed the H2-2.

According to the proportion of rice cultivation area to the total cultivation area, the sample is divided into two groups: rice planting proportion less than 50% and rice planting proportion more than or equal to 50%. Before adopted AGPT, the average TE of farmers with a rice planting proportion of 50% and above was 0.310 (mean value of the control group of nearest neighbor matching and radius matching: [(0.308 + 0.311)/2]). After adopted AGPT, the average TE was 0.376 (mean value of the treated group of nearest neighbor matching and radius matching: [(0.379 + 0.373)/2]). The TE was has been significantly improved by 0.066 (21.3%), which confirmed the H2-3.

According to the characteristics of sample distribution, the farmers are divided into two groups with the number of cultivated lands less than or equal to 5 blocks and more than 5 blocks[4]. Before adopted AGPT, the average TE of farmers with more than 5 blocks cultivated lands was 0.324 (mean value of the control group of nearest neighbor matching and radius matching: [(0.319 + 0.329)/2]). After adopted AGPT, the average TE was 0.412 (mean value of the treated group of nearest neighbor matching and radius matching: [(0.409 + 0.414)/2]). The TE was has been significantly improved by 0.088 (27.2%), which confirmed the H2-4.

The study refers to the classification method of part-time farmer by the Rural Fixed Observation Point Office of the Ministry of Agriculture and Rural Affairs of the People's Republic of China. According to non-agricultural income less than or equal to 20% of total household income and non-agricultural income more than 20% of total household income to divide farmers into two types: pure farmers and part-time farmers. Before adopted AGPT, the average TE of part-time farmers was 0.310 (mean value of the control group of nearest neighbor matching and radius matching: [(0.311 + 0.308)/2]).After adopted AGPT, the average TE was 0.362 (mean value of the treated group of nearest neighbor matching and radius matching: [(0.361 + 0.362)/2]).The TE was has been significantly improved by 0.052 (16.8%), which confirmed the H2-5.

The long-term use of chemical fertilizers and pesticides has adversely affected the quality of cultivated land in China (Liu and Diamond 2005). The sustainable agriculture needs to promote AGPT as soon as possible, though the current adoption and promotion of AGPT in China is not satisfactory. In order to promote the adoption of AGPT by farmers, it is necessary to find out the factors affecting the adoption of AGPT and its effect on TE.

The empirical results of the study show that the use of AGPT has a positive and significant impact on TE, which are consistent with the results found in the studies of Zhang and Gao (2018) and Ge and Zhou (2012). That is, in the process of promoting green production, the improvement of agricultural production technology and the improvement of TE can exist well. In addition, the insignificant impact of the use of AGPT on crop yield per hectare further shows that the promotion of AGPT requires intensive training to guide farmers to correctly understand the relationship between technological change and TE, and highlight the significance of TE in promoting modern agricultural production.

Moreover, the impact of AGPT on TE is obviously heterogeneous among farmers with different characteristics. Aged farmers have more room to improve TE, and their TE has improved significantly after adopting AGPT. Although, the current population aging in the left-behind rural areas is increasing (Hu and Zhong 2012), these groups of farmers can still significantly improve TE by using AGPT. The wave of urbanization in China has promoted farmers with strong labor forces to enter cities for work, leading most farmers became part-time farmers (Li et al. 2014). The use of AGPT by part-time farmers can effectively improve TE, which also provides a new way of improving agricultural production technology for part-time farmers to take good care of agricultural production. China's agricultural land distribution system has also led to the fragmentation of agricultural land (Tan et al. 2006). Farm households with serious land fragmentation use AGPT to improve the TE is more obvious, that is, the improvement of agricultural production technology can overcome some of the shortage of original capital endowments. Additionally, the study also found that the use of AGPT by farmers with low levels of education has a large room for improvement in TE, and the improvement effect is obvious. This finding is of great significance for the current groups of rural farmers in China who generally have a low level of education. Moreover, for farmers with a high proportion of rice, the use of AGPT to improve TE will be more obvious. Studies of differences between groups indicate that in the process of agricultural technology extension, promotion agency should pay attention to the production impact of new technologies among different

[3] The above calculation process is to retain three decimal places, the same below.

[4] The average of cultivated land number is 5.473 blocks, and the median is 5.000 blocks, so according to the characteristics of the sample, used 5 blocks as the dividing point to divide the sample.

Table 8 Endogeneity test and ESR model estimation results

Variables	OLS	IV-2SLS	ESR model		
			Select equation	Adopt AGPT	Not adopt AGPT
Whether adopt AGPT	0.167***	0.476**	—	—	—
	(0.060)	(0.197)			
Age	− 0.002	− 0.004	0.032***	− 0.002	− 0.006**
	(0.002)	(0.002)	(0.007)	(0.007)	(0.002)
Education level	0.011*	0.007	0.063***	0.016	− 0.000[a]
	(0.006)	(0.007)	(0.021)	(0.017)	(0.007)
Health condition	− 0.019	− 0.007	− 0.163**	0.062	− 0.006
	(0.019)	(0.022)	(0.064)	(0.050)	(0.022)
Housing construction area	− 0.000[b]	− 0.000[c]	0.001*	0.000[d]	− 0.001**
	(0.000[e])	(0.000[f])	(0.001)	(0.001)	(0.000[g])
Non-agricultural labor income	0.012*	0.017**	− 0.069***	− 0.001	0.025***
	(0.007)	(0.008)	(0.023)	(0.017)	(0.007)
Proportion of agricultural income	0.015**	0.018**	− 0.056**	0.010	0.023***
	(0.007)	(0.007)	(0.026)	(0.021)	(0.008)
Rice cultivation area	0.147***	0.145***	0.044	0.112***	0.152***
	(0.011)	(0.011)	(0.034)	(0.029)	(0.013)
Maximum cultivated area	0.025	0.013	0.106*	0.051	− 0.021
	(0.022)	(0.020)	(0.063)	(0.044)	(0.027)
Social network	− 0.001	− 0.002	0.007***	− 0.002	− 0.002
	(0.001)	(0.001)	(0.003)	(0.002)	(0.001)
Whether participate in chemical fertilizer and pesticide training	− 0.043	− 0.070	0.437	− 0.320	− 0.039
	(0.097)	(0.083)	(0.279)	(0.200)	(0.114)
Cognition of fertilizer standard dosage	− 0.064	− 0.091**	0.250*	− 0.067	− 0.109**
	(0.041)	(0.044)	(0.141)	(0.117)	(0.046)
Cognition of pesticide residue hazards	0.084	0.065	0.328	− 0.494	0.051
	(0.072)	(0.066)	(0.359)	(0.344)	(0.079)
Cognition of chemical fertilizer environmental hazards	− 0.069*	− 0.096**	0.410***	− 0.111	− 0.120***
	(0.041)	(0.042)	(0.144)	(0.131)	(0.046)
Instrumental variable	—	—	3.336***	—	—
			(0.629)		
Constant	− 1.716***	−1.595***	− 4.548***	− 0.962	−1.425***
	(0.165)	(0.181)	(0.685)	(0.759)	(0.184)
F value of the first stage	—	49.811***	—		
rho1	—	—	− 0.213		
			(0.315)		
rho2	—	—	− 0.891***		
			(0.036)		
Joint independence likelihood ratio test	—	—	21.78***		
Log likelihood	—	—	− 548.744		
Wald chi^2	—	312.70***	40.96***		

***, **, and * represent significance at 1%, 5%, and 10% level. Standard errors are in parentheses, and the IV-2SLS model is robustness standard errors. The estimated result retains three decimal places, after rounding, the reported value of *a*–*g* is 0. After retaining to non-zero decimal places, the estimated value is as follows: $a = -0.00003$, $b = -0.0002$, $c = -0.0003$, $d = 0.0003$, $e = 0.0002$, $f = 0.0002$, $g = 0.0002$

farmers and make sure that farmers can truly accept and learn to apply.

Smallholders will remain the mainstay of China's agricultural production for a long time (Chen 2018). However, in China, some agricultural policies are inclined to new agricultural business entities such as family farms, large plantation farmers, and agricultural cooperators. Especially in local implementation, green production subsidy projects are often allocated to new agricultural business entities, leading to the negligence of support for green production of smallholders (Zeng et al. 2019; Zhang 2020). Thus, the green production transformation of smallholders should be paid enough attention. At present, although, it is encouraged to promote the transformation of smallholders to green production through new agricultural business entities and productive services (Sun and Liu 2019; Cai and Du 2016). However, due to financial constraints (Khanal and Regmi 2017), the number of farmers who can hire productive services is limited. Therefore, In the process of guiding smallholders to green transition, on the one hand, government subsidies should be increased to favor smallholders to directly promote the transformation of small farmers to green production. On the other hand, through productive services, smallholders can be drawn into the track of green production.

Robustness test

PSM can correct biased estimates caused by model settings, but it cannot solve the problem of selection bias caused by unobservable factors. In order to improve the reliability of the conclusions, the study further use the endogenous switching regression (ESR) models to reanalyze (the results are shown in Table 8). Based on the "peer effects," the proportion of other farmers' AGPT adoption in the same village taken as the instrumental variable of individual farmers' AGPT adoption. The impact of AGPT on TE was estimated using the IV-2SLS model. The F value of the first stage is 49.811, indicating that there is no weak instrumental variable. Using ordinary least square method to estimate the impact of AGPT on TE, the coefficient is 0.167, which is significant at the 1% level. After adding the instrumental variable to re-estimate, the coefficient becomes 0.476, which is significant at the 5% level, indicating that the impact of AGPT on TE will be underestimated without eliminate endogeneity. ERS model estimation results show the correlation coefficient rho2 is negative, significant at the 1% level, indicating the model of the impact of AGPT on TE has the endogenous problem of sample-selection bias. The three equations' joint independence likelihood ratio test is 21.78, which is significant at the 1% level, and the Wald chi^2 value is 40.96, which is significant at the 1% level. Therefore, the ERS model estimation is effective.

Average treatment effect of ESR shows that ATT and ATU (average treatment effect on the untreated) were 0.872 and 0.374 respectively, both of which were significant at 1% level, indicating that the adoption of AGPT has a significant promotion effect on TE, which is consistent with the conclusion drawn by PSM and confirms the reliability of the conclusion.

Conclusion and policy implications

Promoting the green development of agriculture is the realization of agricultural modernization and the trend of sustainable agricultural development in the future. Using AGPT to transform the production behavior of smallholders, as well as to improve the efficiency of agricultural production technology, and promote the organic connection between smallholders and the development of modern agriculture is an inevitable choice to consolidate the foundation of the modern agricultural management system and promote the modernization of China's agriculture. This study is based on the field survey data of 582 rice farmers in Ankang and Hanzhong, Shaanxi province, using logit model to analyze the factors affecting the AGPT adoption by smallholders, studying the effect of AGPT adoption on the TE by PSM model, and to compare the heterogeneity of impact effects among farmers with different characteristics.

The conclusions are drawn as follows:

The smallholders' production TE is low and the adoption rate of AGPT is not high, indicating that there is still room for further improvement in the production efficiency of smallholders, and the promotion of AGPT among smallholders should continue to be increased. Moreover, in terms of influencing factors, the smallholders' individual characteristics, household characteristics, and cognitive characteristics such as age, education level, health condition, housing construction area, non-agricultural labor income, proportion of agricultural income, maximum cultivated area, social network, cognition of fertilizer standard dosage, and cognition of chemical fertilizer environmental hazards were significantly affected farmers' AGPT adoption.

Through the PSM model, we found that the adoption of AGPT is conducive in improving the TE of smallholders' rice production, which will significantly increase by 18.8~24.5%. That is to say, AGPT can promote the TE in the process of alleviating agricultural non-point source pollution and promoting green production. The study also found that the AGPT adoption did not significantly improve the rice output value. Considering that farmers are more sensitive to changes in output than changes in technical efficiency, when promoting AGPT, relevant technical department should introduce to farmers the technical improvements brought about by changes in technical efficiency. Heterogeneity analysis shows age over 60 years old, education level of elementary school and below, rice planting proportion of 50% or above, cultivated land number more than 5 blocks, and proportion of agricultural income over 20% famers adopted AGPT can significantly improve the TE, and the improvement ratios are 29.8%, 29.5%, 21.3%, 27.2%, and 16.8% respectively.

In order to further guide smallholders to participate in green production and promote agricultural green development, this study proposes the following policy recommendations:

First, in view of the fact that the adoption of AGPT only improves the TE of rice production rather than the output value, and the improvement of TE is not easy to be perceived by farmers, so the promotion of AGPT should focus on publicizing the effect in improving the TE thereby increasing farmers' confidence in adopting AGPT. Second, the audience for the promotion of AGPT should be further optimized. In the process of technology promotion, according to the characteristics of farmers' own characteristics and planting characteristics, more flexible classification guidance methods such as "home guidance" and "field teaching" are adopted to improve the mastery of farmers such as aging and low education, so as to ensure the effect of technology implementation and further expand the scope of promotion of AGPT among farmer group. Third, improve the quality distinction between green production and traditional high-fertilizer pesticide agricultural products, preventing the phenomenon of "bad money drives out good money" discourage farmers from participating in green production. Strengthen product promotion and guide farmers through the price mechanism to participate in green production and obtain high-value-added products to increase income.

While this study makes significant advancements in knowledge about the impact of AGTP on TE, it has some limitations. First of all, this study uses rice as an example to explore the impact of AGPT on TE, while did not consider other different crops, but leave it to future research. Besides, this study used cross-sectional data, but if the panel data with time trends will be used in future, the study will be more comprehensive. Finally, if national-level data can be obtained, the study will be much richer and will be helpful for policy makers to suggest policies accordingly with regard to use AGPT for the improvements of TE.

Author contribution Chaoqiong Li: Conceptualization, Formal analysis, Investigation, Software, Methodology, Writing—original draft. Yuxing Shi: Data curation, Formal analysis, Investigation, Software, Methodology. Sufyan Ullah Khan: Data curation, Investigation, Writing—review and editing. Minjuan Zhao: Funding acquisition, Investigation, Project administration, Supervision.

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Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval This is an observational study. We confirmed that no ethical approval is required.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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