Pol. J. Environ. Stud. Vol. 33, No. 3 (2024), 2065-2075
DOI: *10.15244/pjoes/174829* ONLINE PUBLICATION DATE: 2024-01-24

Original Research

The Impact of Adopting Green Control Technologies on Farmers' Income: Based on Research Data from Tea Farmers in 16 Provinces of China

Feng Gao#, Jianghong Xu#, Dongxu Li#, Fuqiao Chen*

Tea Research Institute, Chinese Academy of Agricultural Sciences, Hangzhou, China

Received: 19 September 2023
Accepted: 4 November 2023

Abstract

The adoption of green control technologies in agriculture is an important approach to ensure the quality and safety of agricultural products, address agricultural pollution from its source, and promote increased productivity and income in agriculture, thereby driving high-quality agricultural development. This paper is based on production and operation data from 2,155 tea farmers in 16 major tea-producing provinces in China. Using an endogenous transformation model from the perspective of the value chain, it empirically analyzes the impact of adopting green control technologies on tea farmers' income and draws three conclusions. First, the adoption of green control technologies significantly promotes income growth for tea farmers. Second, the awareness of tea farmers regarding pesticide residue limits and the exchange of pest control techniques among tea farmers significantly enhance the adoption of green control technologies. Third, the income effects of adopting green control technologies differ across different stages of the value chain, with the income growth in the cultivation stage being lower than that in the processing and marketing stages. Finally, based on the analysis and relevant research by scholars, four targeted suggestions are proposed: (1) Increase efforts to promote the adoption of green control technologies and enhance farmers' willingness to adopt them. (2) Promote education and training on green control technologies for tea farmers. (3) Ensure fair distribution of benefits along the agricultural value chain. (4) Strengthen the promotion of green control technologies at the market and consumer end.

Keywords: green control technologies, technology adoption, endogenous transformation model, value chain; income growth

#The authors contributed equally to this work and should be considered co-first authors.
*e-mail: cfq@tricaas.com

Introduction

The 2022 Central Rural Work Conference of China proposed strengthening the comprehensive management of agricultural non-point source pollution and promoting rural ecological revitalization. Green control technology, based on the principles of "public plant protection" and "green plant protection," is a technical concept formed under the guidance of the plant protection policy of "prevention first, comprehensive control" [1]. The promotion and application of green control technologies in agriculture are vital for ensuring the quality and safety of agricultural products, addressing agricultural pollution at its source, and driving high-quality agricultural development.

The tea industry is a pillar industry for poverty alleviation and rural revitalization in China, playing a significant role in achieving common prosperity [2]. At the same time, as a healthy beverage, tea has a wide consumer base in China, and the issue of pesticide residues has long been a concern. Throughout the process of tea plantation management, the widespread application of green prevention and control technologies ensures a higher quality of tea leaves, fostering consumer confidence and, consequently, elevating their willingness to pay. Ultimately, this dynamic enhances the prosperity of tea growers by increasing their income. Furthermore, it helps implement the Party's strategy of consolidating and expanding the achievements of poverty alleviation and effectively linking them with rural revitalization, thus advancing the important goals of common prosperity and sustainable economic and social development.

Changes in income are a primary concern for farmers during the process of technology adoption. Can the adoption of green control technologies lead to income growth? What heterogeneity effects will the adoption of green control technologies have on different value-added segments of the tea value chain? Answering these questions is crucial for promoting the further adoption of green control technologies and holds significant practical and academic value.

Therefore, this paper utilizes fixed observation points from the National Tea Industry Technology System of China, selecting data from 2,155 tea farmers in 70 major tea-producing cities across 16 tea-producing provinces in 2016. Through the use of an endogenous transformation model, it explores the impact of the adoption of green control technologies on tea farmers' income.

Literature Review

In recent years, scholars have paid great attention to the impact of agricultural technology adoption on farmers' income. For instance, Rejesus et al., using propensity score matching, found that the adoption of water-saving irrigation technology effectively improved irrigation water efficiency and subsequently increased farmers' income [3]. Liu et al., employing a three-stage least squares and mediation effect model, revealed that the adoption of agricultural machinery services significantly reduced land transfer-out and increased land transfer-in, thus helping farmers increase their income [4]. Himmelstein et al., through empirical analysis of the income of farmers with different initial endowments, identified scientific fertilization technology as an important means to promote grain yield increase and farmers' income [5]. Chivenge et al., based on survey data from family farms engaged in planting in sub-Saharan Africa, demonstrated the positive income effect of site-specific nutrient management technology, which significantly enhanced agricultural income [6]. Hu et al., in their study on the rice-crayfish co-cultivation model in China, found that ecological agricultural practices had a significant impact on increasing agricultural income [7].

With the introduction of top-level designs and policy concepts regarding ecological civilization construction in China, research related to green control technologies has been increasing. Qing et al., based on data from rice farmers in Sichuan Province, showed that the adoption of green control technologies significantly improved rice farmers' economic benefits [8]. Li et al., utilizing factor analysis and analyzing data from vegetable farmers in Shouguang, Shandong Province, found that the adoption of green control technologies had a certain impact on farmers' income [9]. Li et al., using structural equation model to analyze fruit farmers in Shaanxi Province, concluded that increasing government subsidies for green control technologies would promote their adoption by fruit farmers and, consequently, increase their income [10]. In the context of the tea industry, Lou et al., through micro-level data analysis of tea farmers in the Dabie Mountain area, found that the adoption of green control technologies significantly increased agricultural income for farmers in mountainous areas [11]. Xie et al., based on survey data from tea growers in Fujian Province, revealed that the adoption of green production technologies increased the expected income of tea farmers [12]. Hu et al., in their study on the welfare level of tea farmers in the main tea-producing areas of Sichuan Province, found that the adoption of green control technologies significantly improved tea farmers' profits per mu of tea, disposable household income, and living consumption expenditure [13]. However, there is still some controversy in the academic community regarding whether the adoption of green control technologies promotes farmers' income. Huang et al., in their investigation and research on rice farmers in Hubei, Jiangxi, and Zhejiang provinces, concluded that the improvement in cost-benefit resulting from the adoption of green control technologies was not significant [14]. Malacrinò et al., in their study on 24 long bean farms in Cambodia, found no significant improvement in farmers' income from the adoption of green control technologies [15].

Although there have been relevant studies as mentioned above, several issues remain to be addressed. First, most studies are based on small-scale regional data [16-18], with limited coverage and sample size. While some scholars have delved into research on the relationship between green prevention and control technologies and changes in tea farmers' income [19-21], the studies' scope is primarily confined to a single province or region. These studies often encompass a limited number of households, which introduces certain constraints. Second, there is a lack of differentiation in income sources for tea farmers. Many tea farmers engage in multiple income-generating activities [22], not just tea production. Failure to distinguish income sources as explanatory variables can lead to overestimation or underestimation of income effects. Third, inappropriate selection of instrumental variables. Although instrumental variables have been used to address endogeneity issues, the use of regional averages as instrumental variables may introduce noise and potential omitted variable bias [24], as these aggregated data cannot guarantee complete exogeneity. Fourth, there has been limited research on the impact of green control technologies on tea farmers' income from the perspective of value chains or division of labor.

This study aims to address these issues. Firstly, it employs a large sample of data that covers nearly 90% of tea-producing regions nationwide, which enhances the representativeness and generalizability of the findings. Secondly, it separates tea income from overall agricultural income, enabling a more accurate assessment of the net effects of adopting green control technologies. Thirdly, it further disaggregates tea income into income from fresh tea and income from processed tea, allowing for an evaluation of the impacts of green control technologies on different value chain segments of the tea industry. Finally, it uses farmers' awareness of pesticide residue limits for tea and their participation in pest and disease control technology exchange with other tea farmers as instrumental variables, satisfying the exogeneity and relevance conditions and passing relevant tests, thereby enhancing the reliability of the estimated results.

Theoretical Framework and Model Construction

Theoretical Framework

Chen Zongmao [25] pointed out that the large-scale use of chemical pesticides in tea gardens since the 20th century has led to five major changes in pest populations nationwide, with a significant reduction in beneficial biological populations in some areas and an increasing cost of pest control. Furthermore, the issue of pesticide residues in tea leaves has severely hindered the export of Chinese tea. The adoption of green control technology not only promotes the restoration of ecological levels in tea gardens but also enables higher premiums through improved raw material quality, thereby increasing tea farmers' income. Therefore, this paper proposes the following hypotheses 1:

H1: Compared to tea farmers who have not adopted green control technology, tea farmers who have adopted green control technology show a significant increase in their tea leaves income.

The agricultural value chain can be roughly categorized into six value-added stages (as shown in Fig. 1), presenting an upward-opening U-shaped structure [26]. The production stage, represented by cultivation, is at the bottom of the value chain, with relatively lower growth rates in the value-added process of agricultural products. On the other hand, the processing and marketing stages hold advantageous positions in value addition. Tea farmers' income mainly consists of sales revenue from fresh tea leaves and processed tea. The sales of fresh tea leaves correspond to the production stage in the agricultural value chain and represent the lowest part of the overall value distribution. On the contrary, the sales of processed tea correspond to the processing stage, which is situated in a higher value-added position. Therefore, this paper proposes the hypothesis 2:

H2: The adoption of green control technology has differential effects on the income of different segments of the tea value chain, with a greater increase in income observed in the processed tea segment compared to the fresh tea leaves segment.

Model Construction

Drawing inspiration from several researches on tea farmers. [27-29], we begin by constructing a linear equation for the income of tea farmers derived from total tea sale (including fresh tea and processed tea):

$$Y_i = \beta L_i + \eta controls_i + \mu_i \tag{1}$$

Where Y_i represents the income of tea farmers. L_i is a dummy variable indicating whether tea farmer

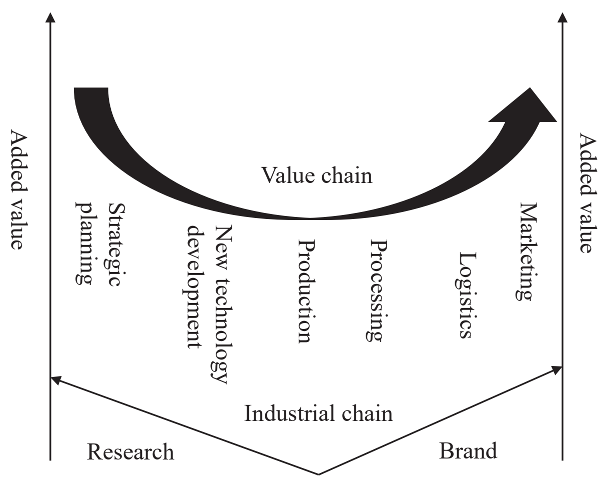

Fig. 1. Agricultural value chain.

i has adopted green control technology, with $L_i = 1$ for adoption and $L_i = 0$ for non-adoption. $controls_i$ represents a series of control variables related to tea farmers' tea income. μ_i is the random error term. In this study, we use the endogenous switching regression (ESR) model for estimation, which consists of two parts: the selection equation that measures the factors influencing the adoption of green control technology, and the outcome equation that estimates the income changes of tea farmers in different scenarios by dividing them into the adoption and non-adoption groups. First, we establish the equation for tea farmers' adoption of green control technology and the equation for determining their income.

$$L_i = \alpha Z_i + \epsilon_i \tag{2}$$

$$Y_{1i} = \gamma_1 controls_{1i} + \mu_{1i} \quad if\ L_i=1 \tag{3}$$

$$Y_{0i} = \gamma_0 controls_{0i} + \mu_{0i} \quad if\ L_i=0 \tag{4}$$

Z_i represents several factors that affect tea farmers' technology adoption. According to the setting of the endogenous switching equation, Z_i should include at least one variable that is different from the outcome equation and affects the adoption of green control technology but does not affect tea farmers' income. Therefore, this study selects tea farmers' awareness of the tea pesticide residue limit standard and whether they exchange pest control techniques with other tea farmers as the influencing variables for the adoption of green control technology. After testing, these two variables are significantly correlated with the adoption of green control technology by tea farmers and are not directly related to tea farmers' income. Y_{1i} represents the tea income of tea farmers who have adopted green control technology, while Y_{0i} represents the tea income of tea farmers who have not adopted green control technology. $controls_i$ represents a series of control variables that may affect tea farmers' income. μ_i is the random error term. Based on Equation (1), after introducing the two variables that influence tea farmers' technology adoption, the equation for determining tea farmers' income is adjusted as follows:

$$Y_{1i} = \gamma_1 controls_{1i} + \sigma_{\epsilon 1}\lambda_{1i} + \tau_{1i} \quad if\ L_i=1 \tag{5}$$

$$Y_{0i} = \gamma_0 controls_{0i} + \sigma_{\epsilon 0}\lambda_{0i} + \tau_{0i} \quad if\ L_i=0 \tag{6}$$

λ_i is the inverse Mills ratio calculated based on Equation (2) and is included in the outcome equation to correct for bias caused by self-selection issues. σ_ϵ represents the covariance of the error term, and τ_i is a random error term with a mean of 0. From this, we can obtain the average treatment effect on the treated (ATT) for the adoption of green control technologies and the average treatment effect for the untreated (ATU) under counterfactual conditions:

$$\begin{aligned} ATT &= E(Y_{1i}|L_i = 1) - E(Y_{0i}|L_i = 1) \\ &= (\gamma_1 - \gamma_0)controls_{1i} + (\sigma_{\epsilon 1} - \sigma_{\epsilon 0})\lambda_{1i} \end{aligned} \tag{7}$$

$$\begin{aligned} ATU &= E(Y_{1i}|L_i = 0) - E(Y_{0i}|L_i = 0) \\ &= (\gamma_1 - \gamma_0)controls_{0i} + (\sigma_{\epsilon 1} - \sigma_{\epsilon 0})\lambda_{0i} \end{aligned} \tag{8}$$

Interpretation of Data and Variables

Data Sources

The Chinese mainland (excluding Taiwan) consists of 18 tea-producing provinces, stretching from Shandong in the north to Hainan in the far south, with the majority of tea regions located south of the Qinling Mountains and the Huai River. The data for this study are sourced from the survey conducted by the National Tea Industry Technology System (of China) on the adoption of green control technologies in 2016. The survey covered 16 major tea-producing provinces: Yunnan, Guizhou, Sichuan, Hubei, Fujian, Zhejiang, Anhui, Hunan, Shaanxi, Henan, Jiangxi, Guangxi, Guangdong, Chongqing, Jiangsu, and Shandong. It encompassed 70 tea-producing cities, accounting for 88.89% of the total tea production area nationwide, ensuring the sample's representativeness. After excluding questionnaires with high rates of missing data and obvious outliers, a total of 2,155 valid questionnaires were obtained. Among them, 1,408 households (65.34% of the total sample) adopted green pest control technologies, while 747 households (34.66% of the total sample) did not.

Variable Definition and Descriptive Statistics

Table 1 presents the codes and definitions of the variables, while Table 2 provides the descriptive statistics of each variable. The dependent variable is tea farmers' income, which is distinguished from the overall household income to measure the net effect of adopting green control technologies. To mitigate the influence of outliers, the natural logarithm of tea income is taken. In robustness tests, we replace the dependent variable with per capita tea income. Furthermore, tea income is disaggregated into green tea income and processed tea income, to determine the differential income effects of adopting green control technologies across different value-added stages of the tea value chain.

The key explanatory variable is whether the tea farmer adopt green control technologies, where 1 represents "Yes" and 0 represents "No". In the survey conducted by the National Industry Technology System, the main observed green control technologies used in tea gardens include manual killing, color boards, biological pesticides, and insecticidal lamps. Among the 2155 samples, 1408 tea farmers adopted at least one of these green control technologies, accounting for 65.34% of the total, while 747 tea farmers did not adopt any green control measures, accounting for 34.66%.

Table 1. Variable definitions.

Type	Variable	Variable definition
Tea farmers' income	Tea income	Income from tea (yuan), in order to weaken the influence of extreme values on the estimated results, is expressed logarithmically
Green control technologies	Adoption	1 = Yes; 0 = No
	Cognition	Awareness of the tea pesticide residue limit standard: 1 = Do not know; 2 = Know but not very understood; 3 = Understand; 4 = Very knowledgeable
	Communication	Whether to exchange tea pest control techniques with other tea farmers: 1 = Yes; 0 = No
Individual characteristics of the head of the household	Age	Age of head of household (years old)
	Gender	Gender of the head of household: 1 = Male; 0 = Female
	Education	Whether the head of the household has a high school degree or above: 1 = Yes; 0 = No
	Internet use	Whether the head of the household know how to use Internet: 1 = Yes; 0 = No
Characteristics of family business	Tea plantation area	Total area of tea plantation (mu, 1 mu is approximately equal to 666.67 square meters)
	Cooperative participation	Whether or not to participate in a cooperative: 1 = Yes; 0 = No
	Number of labor force	Household labor force (person)
Regional characteristics	Tea plantation region	1 = Southwest region; 2 = Huanan region; 3 = Jiangnan region; 4 = Jiangbei region

Table 2. Descriptive statistics.

Variable	Observation	Mean	Standard deviation	Minimum	Maximum
Tea income	2,155	10.430	1.147	6.215	15.687
Adoption	2,155	0.653	0.476	0	1
Cognition	2,155	2.379	0.813	1	4
Communication	2,155	0.956	0.204	0	1
Age	2,155	51.189	9.128	24	93
Gender	2,155	0.901	0.299	0	1
Education	2,155	0.273	0.446	0	1
Internet use	2,155	0.637	0.481	0	1
Tea plantation area	2,155	28.584	125.312	0.2	3200
Cooperative participation	2,155	0.660	0.474	0	1
Number of labor force	2,155	2.818	1.025	1	8
Tea plantation region	2,155	2.351	1.018	1	4

This study also incorporates individual characteristics of household heads, household operational characteristics, and regional characteristics as control variables that are related to tea farmers' tea leaves income. From the descriptive statistics, it can be seen that the average age of the sample household heads is 51.19 years, with a predominance of middle-aged and elderly individuals, and over 90% are male. Only 27.3% have a high school education or above, indicating a relatively low level of education overall. About 66% of tea farmers participate in cooperatives, and the average tea garden size is 28.584 mu (approximately 1.9 hectares), with an average of 2.8 laborers per household.

Model Estimation Results and Analysis

Income Effect

This paper employs an ESR model to assess the impact of adopting green control technologies on tea farmers' tea leaves income (as shown in Table 3). The results indicate that the Wald test statistic

Table 3. Estimates of the impact of adopting green control technologies on tea farmers' income.

Variable	Selection equation		Adopt		Not adopt	
	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error
Age	-0.003	0.004	-0.013***	0.004	-0.006	0.004
Gender	0.066	0.095	0.393***	0.101	0.119	0.122
Tea plantation area	0.001***	0.000	0.002***	0.000	0.005***	0.000
Cooperative participation	0.280***	0.061	-0.098	0.068	0.189**	0.078
Number of labor force	0.023	0.029	0.154***	0.030	0.084**	0.036
Education	0.038	0.068	0.289***	0.070	0.114	0.086
Internet use	0.037	0.065	0.157**	0.068	0.178**	0.083
Huanan region	-1.009***	0.091	0.983***	0.115	0.949***	0.127
Jiangnan region	-0.165**	0.072	0.371***	0.070	0.626***	0.100
Jiangbei region	-0.227**	0.105	0.307***	0.107	0.581***	0.135
Cognition	0.361***	0.038				
Communication	0.941***	0.122				
Constant	-1.303***	0.245	10.364***	0.225	9.216***	0.285
$\ln\sigma0$					-0.041	0.028
$\rho0$					-0.126	0.143
$\ln\sigma1$	0.186***	0.029				
$\rho1$	-0.813	0.034				
Log-likelihood	-4221.806					
Wald test	339.88					

* * *, * * and * respectively represent the significance level of 1%, 5% and 10%, the same below.

and $\ln\sigma1$ are significant at the 1% level, suggesting that the adoption of green control technologies by tea farmers is influenced by unobservable factors, indicating the presence of self-selection bias in the sample. This highlights the rationale for using the ESR model to estimate the income effects of green control technologies.

Explanation of the Selection Model Results

From the estimated results of the selection equation (as shown in Table 3), it can be observed that variables such as participation in cooperatives, tea production region, communication with other tea farmers on pest control techniques, and awareness of green control technologies significantly influence the adoption of green control technologies. The positive correlation between participation in cooperatives and the adoption of green control technologies at the 1% significance level indicates that tea farmers who are members of cooperatives are more likely to adopt green control technologies. Compared to other technical training providers, cooperatives provide practical and targeted training programs, which greatly enhance farmers' adoption of green production techniques. The tea production region also affects the adoption of green control technologies by tea farmers, with farmers in South China, Jiangnan, and Jiangbei tea regions showing lower enthusiasm for adopting green control technologies compared to those in the Southwest tea region. The significant positive correlation at the 1% level between communication with other tea farmers on pest control techniques, awareness of green control technologies, and the adoption of green control technologies indicates that these factors play important roles in influencing farmers' adoption decisions. This demonstrates the effectiveness of the selection model results.

Explanation of the Income Determination Equation Results

From the estimated results of the income determination equation (as shown in Table 3), it can be observed that regardless of whether farmers adopt green control technologies, tea leaves income is significantly positively correlated with tea garden area, the number of family laborers, internet access by the household head, and the tea production region. This finding can be explained by several factors. Larger tea garden areas are associated with economies of scale, and having more family laborers allows for increased input in tea production and operation, resulting in higher tea leaves output. Internet access is increasingly important for acquiring production and marketing information, and there is a growing body of literature suggesting that internet skills can help farmers reduce production costs and expand agricultural profits. The Southwest tea region, including provinces such as Yunnan, Guizhou, Sichuan, and Tibet, lags behind other tea regions in terms of economic development, which also affects the tea leaves income of tea farmers in the Southwest region.

Explanation of the Control Variables Results

Among farmers who adopt green control technologies, tea leaves income is also related to the age, gender, and educational level of the household head. Older household heads with lower educational levels may have poorer absorption and understanding of new technologies, which can impact overall tea leaves income. Male household heads, compared to female household heads, tend to allocate more energy to agricultural production activities, which is beneficial for increasing tea production and income.

Among farmers who do not adopt green control technologies, tea leaves income is related to whether they are members of cooperatives. Research by Lei et al. indicates that cooperatives provide support in terms of capital and human capital, enhance individual farmers' bargaining power, expand the market for agricultural products, and promote income growth among farmers [30].

Estimation of the Average Treatment Effect in Two Scenarios

The average treatment effect on the treated (ATT) and the average treatment effect on the untreated (ATU) of the adoption of green control technologies on tea farmers' income were calculated using equations (7) and (8) as mentioned above. The calculations yielded an ATT of 0.399 and an ATU of 1.705. This means that tea farmers who adopted green control technologies experienced an average income increase of 0.399 units, corresponding to a 4% change, while tea farmers who did not adopt green control technologies would have an income increase of 1.705 units, representing a 16.6% change if they were to adopt the technologies.

To provide a more intuitive reflection of the impact of adopting green control technologies on tea farmers' income, the study also plotted the fitted income and counterfactual income probability density distributions for farmers who adopted and those who did not adopt green control technologies. Fig. 2a) shows that for tea farmers who adopted green control technologies, their income probability density distribution curve would shift from the solid line segment to the dashed line segment if they had not adopted the technologies,

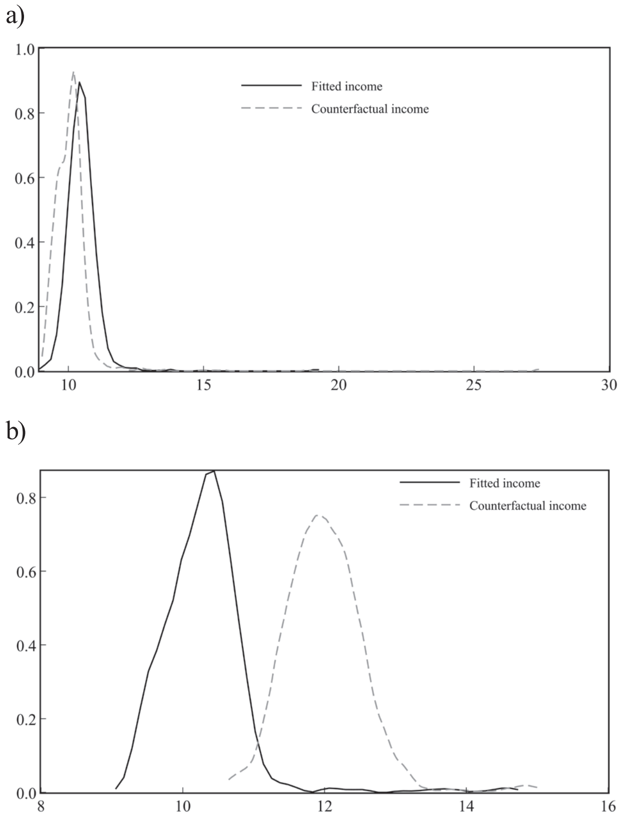

Fig. 2. Probability density of tea farmers' income. a) adopt, b) not adopt.

indicating a significant overall decrease in income. Fig. 2b) shows that for tea farmers who did not adopt green control technologies, their income probability density distribution curve would shift significantly from the solid line segment to the dashed line segment if they were to adopt green control technologies, indicating a substantial income increase associated with the adoption of green control technologies. This confirms the validity of hypothesis 1.

Robustness Test

To ensure the robustness of the results, this paper followed the methodology of Wu et al. [31], Jin et al. [32] and Li et al. [33], conducted tests by replacing the dependent variable and changing the estimation methods. The tests were performed using ordinary least squares (OLS), instrumental variable (IV) estimation, and treatment effects model (TEM). As shown in Table 4, the estimation results from all four methods consistently indicate a significant positive impact of adopting green control technologies on tea farmers' income at a 1% significance level, further validating the conclusion that the adoption of green control technologies promotes tea farmers' income. In the instrumental variable model, cognitive factors and technology exchange were used as instrumental variables, with a Hansen J-value of 0.257, which does not reject the null hypothesis, satisfying

Table 4. Comparison of estimation results by different methods.

Project	ESRM	Treatment effect (TEM)	IV	OLS
Regression coefficient (ATE)		1.22***	1.257***	0.195***
ATT	0.399***			
ATU	1.705***			

Table 5. Impact of the adoption of green control technologies on per capita tea income.

Variable	Selection equation		Adopt		Not adopt	
	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error
Age	-0.003	0.004	-0.010***	0.004	-0.004	0.004
Gender	0.051	0.095	0.329***	0.103	0.028	0.126
Tea plantation area	0.001**	0.000	0.002***	0.000	0.005***	0.000
Cooperative participation	0.281***	0.061	-0.097	0.070	0.181**	0.080
Number of labor force	0.024	0.029	-0.029	0.030	-0.102***	0.037
Education	0.036	0.068	0.270***	0.071	0.168*	0.089
Internet use	0.03	0.065	0.142**	0.069	0.149*	0.085
Huanan region	-1.008***	0.091	0.952***	0.117	0.976***	0.129
Jiangnan region	-0.165**	0.072	0.440***	0.072	0.688***	0.104
Jiangbei region	-0.237**	0.105	0.400***	0.109	0.630***	0.140
Cognition	0.379***	0.038				
Communication	0.920***	0.123				
Constant	-1.309***	0.247	9.316***	0.230	8.194***	0.292
lnσ0					-0.005	0.030
ρ0					-0.177	0.134
lnσ1			0.202***	0.030		
ρ1			-0.799	0.037		
Log-likelihood	-4276.636					
Wald test	268.74					

the exogeneity assumption of instrumental variables. Additionally, the first-stage F-value is significantly greater than 10, satisfying the relevance assumption of instrumental variables, indicating the appropriateness of instrumental variable selection.

This paper also conducted a re-estimation by replacing the dependent variable with per capita tea leaves income. The estimation results show that the adoption of green control technologies is significantly correlated with tea farm size, membership in cooperatives, tea-growing regions, cognitive factors, and technology exchange. For tea farmers who adopted green control technologies, tea leaves income is significantly correlated with age, gender of the head of the household, tea farm size, education level of the head of the household, and internet usage in tea plantation region. For tea farmers who did not adopt green control technologies, tea leaves income is significantly correlated with tea farm size, membership in cooperatives, number of family laborers, education level, internet usage, and tea-growing regions. The estimation results are consistent with the baseline regression results, indicating the robustness of the estimates, as shown in Table 5.

Differences in the Revenue Increase Effect of Technologies Adoption on Different Parts of the Value Chain

To clarify the heterogeneous effects of income improvement on different stages of the value chain, this paper further disaggregated tea farmers' income

Table 6. Impact of green control technologies adoption on tea green and dry tea revenue.

Type of farmer	Tea leaves income			Processed tea income		
	ATT	ATU	Range of change	ATT	ATU	Range of change
Adopt	0.365***		3.752%	0.560***		5.656%
Not Adopt		1.828***	18.797%		2.819***	27.395%

into income from tea leaves sales and income from processed tea sales, and estimated them separately using the ESR model. The estimation results are presented in Table 6.

The average treatment effect on tea leaves income from adopting green control technologies (ATT) is 0.365 units, resulting in a 3.752% income increase for tea leaves sales. The ATT for income from processed tea sales is 0.560 units, leading to a 5.656% income increase. The income improvement effect of green control technologies on tea leaves sales is significantly lower compared to processed tea sales. In the counterfactual scenario, the average treatment effect on tea leaves income (ATU) from adopting green control technologies is 1.828 units for tea leaves sales and 2.819 units for processed tea sales, resulting in income increases of 18.797% and 27.395%, respectively.

Further analysis reveals that the adoption of green technologies has a significant income improvement effect on both tea leaves sales and processed tea sales, but the effect is more pronounced for processed tea. Additionally, the sample statistics show that tea farmers who only sell tea leaves have an average tea garden size of 13.2 mu, significantly smaller than the 49.59 mu for tea farmers who sell processed tea, indicating a characteristic of small-scale operations. This suggests that tea farmers who only sell tea leaves struggle to achieve economies of scale and have weaker bargaining power in tea leaves sales. For tea leaves buyers, it is challenging to identify the adoption of green technologies by small-scale farmers, which further affects the income growth of this group of tea farmers. On the other hand, processed tea is directed towards the end market, and consumers generally have a higher willingness to pay for green and organic agricultural products. For example, Zhou et al. [34] found that consumers' willingness to pay for green agricultural products was higher than for regular agricultural products by using eco-labels of rice as an example. This indicates that the value-added in the production stage of the tea value chain is lower than in the processing and marketing stages, confirming hypothesis 2.

Conclusions

This paper employs the ESR model to empirically analyze the production and operation data of 2,155 tea farmers from 16 major tea-producing provinces in China, aiming to investigate the income improvement effect of adopting green control technologies. The following outcomes can be derived:

(1) The adoption of green control technologies significantly promotes tea farmers' income growth. The analysis using the endogenous switching model reveals a clear income improvement effect of adopting green control technologies for tea farmers, which is also significantly influenced by individual, household, and regional characteristics.

(2) The awareness of tea farmers regarding tea leaf pesticide residue standards and their exchange of pest control techniques with other tea farmers significantly enhance the adoption of green control technologies. The empirical analysis shows that higher levels of awareness of tea leaf pesticide residue standards and more frequent exchange of pest control experiences with other tea farmers lead to a higher likelihood of adopting these technologies.

(3) The income effects of adopting green control technologies vary across different stages of the value chain, with a lower income improvement magnitude observed in the cultivation stage compared to the processing and marketing stages. The empirical analysis reveals that adopting green control technologies has significant income improvement effects for both tea leaves and processed tea sales, but the income improvement magnitude is relatively higher for processed tea.

Drawing from the conclusions mentioned above, this paper presents several recommendations:

(1) Increase the promotion of green control technologies and enhance farmers' willingness to adopt them. The adoption of green control technologies by tea farmers depends on whether they can achieve increased output and profits from these new technologies. Therefore, it is important to understand the local farmers' needs and adoption willingness during the promotion process [35]. Conducting technology demonstrations can effectively guide tea farmers in understanding and adopting green control technologies [36].

(2) Promote education and training on green control technologies for tea farmers. Farmers with higher levels of education and awareness tend to have a stronger willingness to adopt new agricultural technologies [37-39]. Therefore, supporting tea farmers in continuous learning and experience accumulation, improving their cultural and scientific literacy, can help them better perceive the income improvement benefits brought by green control technologies and empower them with a proactive attitude.

(3) Ensure fair distribution of benefits along the agricultural value chain. Actively build mechanisms that connect the interests of enterprises and farmers, with farmers' professional cooperatives as the link, to facilitate the integration of small farmers into larger markets and safeguard their operational profits [40]. Optimize and strengthen the agricultural value chain and allocate the benefits of the value chain's various segments fairly. Explore multiple channels to expand farmers' income opportunities and enable them to gain a sense of achievement and happiness through collaborative and shared development. Encourage farmers to participate in the division of labor within the industry chain, ensuring that more sales profits stay with the farmers.

(4) Increase promotion efforts for green control technologies at the consumer end of the market. Enhance consumer awareness and guide them to consume more green and ecological products. By increasing the premium level of green agricultural products, the intrinsic motivation for tea farmers to adopt green control technologies can be strengthened.

Certainly, this paper still exhibits several limitations. First, there is a multitude of factors influencing the adoption of green prevention and control technologies by tea growers. The presence of these latent influencing variables, which this paper cannot comprehensively control, to some extent diminishes the precision of the results. Second, the paper does not make a distinct differentiation between adoption intention and adoption behavior. In reality, the process from a farmer's willingness to adopt eco-friendly farming to the actual behavior is influenced by various factors, potentially leading to deviations between intention and behavior. Third, new formats and new trends have emerged. Modern communication technologies have propelled rural informatization, and farmers' social networks, influenced by information technology, have extended from real-world interactions to online communications, indicating a digital transformation. Whether the adoption behavior and income effects of green prevention and control technologies among farmers will undergo a transformation in this digital context remains a topic for future research.

Acknowledgments

This research was supported by Earmarked Fund for China Agriculture Research System (CARS-19) and Central Public-interest Scientific Institution Basal Research Fund (1610212022010).

Conflict of Interest

The authors declare no conflict of interest.

References

1. HU L.Y., DU P., CHEN F.Q., JIANG A.Q., JIANG R.H., LU C.Y. An empirical study on the impact factors of adoption of green prevention and control technology by tea-growers. Journal of Tea Science, **37** (3), 308, **2017**.
2. LIANG L., RIDOUTT B. G., WANG L., XIE B., LI M., LI Z. China's tea industry: Net greenhouse gas emissions and mitigation potential. Agriculture, **11** (4), 363, **2021**.
3. REJESUS R.M., PALIS F.G., RODRIGUEZ D.G.P., LAMPAYAN R.M., BOUMAN B.A. Impact of the alternate wetting and drying (AWD) water-saving irrigation technique: Evidence from rice producers in the Philippines. Food Policy, **36** (2), 280, **2011**.
4. LIU Y., HEERINK N., LI F., SHI X. Do agricultural machinery services promote village farmland rental markets? Theory and evidence from a case study in the North China plain. Land Use Policy, **122**, 106388, **2022**.
5. HIMMELSTEIN J., ARES A., GALLAGHER D., MYERS J. A meta-analysis of intercropping in Africa: impacts on crop yield, farmer income, and integrated pest management effects. International Journal of Agricultural Sustainability, **15** (1), 1, **2017**.
6. CHIVENGE P., ZINGORE S., EZUI K.S., NJOROGE S., BUNQUIN M.A., DOBERMANN A., SAITO K. Progress in research on site-specific nutrient management for smallholder farmers in sub-Saharan Africa. Field Crops Research, **281**, 108503, **2022**.
7. HU L., ZHANG J., REN W., GUO L., CHENG Y., LI J., CHEN X. Can the co-cultivation of rice and fish help sustain rice production? Scientific Reports, **6** (1), 28728, **2016**.
8. QING C., ZHOU W., SONG J., DENG X., XU D. Impact of outsourced machinery services on farmers' green production behavior: Evidence from Chinese rice farmers. Journal of Environmental Management, **327**, 116843, **2023**.
9. LI E., XU Y., REN S., LEE J. Spin-offs, innovation spillover and the formation of agricultural clusters: The case of the vegetable cluster in Shouguang City, Shandong Province, China. Land, **11** (2), 279, **2022**.
10. LI M., YAN X., GUO Y., JI H. Impact of risk awareness and agriculture cooperatives' service on farmers' safe production behaviour: Evidences from Shaanxi Province. Journal of Cleaner Production, **312**, 127724, **2021**.
11. LOU S., ZHANG B., ZHANG D. Foresight from the hometown of green tea in China: Tea farmers' adoption of pro-green control technology for tea plant pests. Journal of Cleaner Production, **320**, 128817, **2021**.
12. XIE K., ZHU Y., MA Y., CHEN Y., CHEN S., CHEN Z. Willingness of tea farmers to adopt ecological agriculture techniques based on the UTAUT Extended Model. International Journal of Environmental Research and Public Health, **19** (22), 15351, **2022**.
13. HU H., CAO A., CHEN S., LI H. Effects of risk perception of pests and diseases on tea famers' green control techniques adoption. International Journal of Environmental Research and Public Health, **19** (14), 8465, **2022**.
14. HUANG Y.Z., LUO X.F., TANG L, DU S.X. Cost-saving and income-increasing effect of green control techniques. China Population, Resources and Environment, **30** (10), 174, **2020**.

15. MALACRINÒ A., SENG K.H., AN C., ONG S., O'ROURKE M. E. Integrated pest management for yard-long bean (Vigna unguiculata subsp. Sesquipedalis) in Cambodia. Crop Protection, **135**, 104811, **2020**.
16. GAO Y., NIU Z., YANG H., YU L. Impact of green control techniques on family farms' welfare. Ecological Economics, **161**, 91, **2019**.
17. YU L., ZHAO D., XUE Z., GAO Y. Research on the use of digital finance and the adoption of green control techniques by family farms in China. Technology in Society, **62**, 101323, **2020**.
18. WU F. Adoption and income effects of new agricultural technology on family farms in China. PLoS One, **17** (4), e0267101, **2022**.
19. SETSOAFIA E.D., MA W., RENWICK A. Effects of sustainable agricultural practices on farm income and food security in northern Ghana. Agricultural and Food Economics, **10** (1), 1, **2022**.
20. CHEN J., ZHOU H. The Role of Contract Farming in Green Smart Agricultural Technology. Sustainability, **15** (13), 10600, **2023**.
21. YANG X., DENG X., ZHANG A. Does conservation tillage adoption improve farmers' agricultural income? A case study of the rice and fish co-cultivation system in Jianghan Plain, China. Journal of Rural Studies, **103**, 103108, **2023**.
22. BLOWFIELD M.E., DOLAN C. Fairtrade facts and fancies: What Kenyan Fairtrade tea tells us about business' role as development agent. Journal of Business ethics, **93**, 143, **2010**.
23. CHEN J., ZHOU H. The Role of Contract Farming in Green Smart Agricultural Technology. Sustainability, **15** (13), 10600, **2023**.
24. GARABEDIAN L.F., CHU P., TOH S., ZASLAVSKY A.M., SOUMERAI S.B. Potential bias of instrumental variable analyses for observational comparative effectiveness research. Annals of internal medicine, **161** (2), 131, **2014**.
25. CHEN Z.M. Development and application of green pest control technology in tea garden. China Tea, **44** (1), 1, **2022**.
26. TRIENEKENS J.H. Agricultural value chains in developing countries a framework for analysis. International food and agribusiness management review, **14** (1030-2016-82778), 51, **2011**.
27. SAIGENJI Y., ZELLER M. Effect of contract farming on productivity and income of small holders: The case of tea production in north-western Vietnam (No. 1005-2016-79177), **2009**.
28. VAN HO B., NANSEKI T., CHOMEI Y. Profit efficiency of tea farmers: case study of safe and conventional farms in Northern Vietnam. Environment, Development and Sustainability, **21**, 1695, **2019**.
29. TANG S., FU H., PAN W., ZHOU J., XU M., HAN K., WU L. Improving tea (Camellia sinensis) quality, economic income, and environmental benefits by optimizing agronomic nitrogen efficiency: A synergistic strategy. European Journal of Agronomy, **142**, 126673, **2023**.
30. LEI L., DAKUAN Q., JIN T., LISHUANG W., YUYING L., XINHONG F. Research on the influence of education and training of farmers' professional cooperatives on the willingness of members to green production – perspectives based on time, method and content elements. Environment, Development and Sustainability, 1, **2022**.
31. WU Q., ZHOU J. Need for cognitive closure, information acquisition and adoption of green prevention and control technology. Ecological Chemistry and Engineering, **28** (1), 129, **2021**.
32. JIN S., HUANG J., WAIBEL H. Location and economic resilience in rubber farming communities in southwest China. China Agricultural Economic Review, **13** (2), 367, **2021**.
33. LI Z., HUANG Y., YANG Y., LAI X. Can TikTok be a good way to extend the adoption of green control techniques? Evidence from rural China. Asian Journal of Technology Innovation, 1, **2022**.
34. ZHOU J., LIU Q., MAO R., YU X. Habit spillovers or induced awareness: Willingness to pay for eco-labels of rice in China. Food Policy, **71**, 62, **2017**.
35. HAN H., ZOU K., YUAN Z. Capital endowments and adoption of agricultural green production technologies in China: A meta-regression analysis review. Science of The Total Environment, 165175, **2023**.
36. FLATHMAN P.E., LANZA G.R. Phytoremediation: current views on an emerging green technology. Journal of Soil Contamination, **7** (4), 415, **1998**.
37. HALL T.J., DENNIS J.H., LOPEZ R.G., MARSHALL M.I. Factors affecting growers' willingness to adopt sustainable floriculture practices. HortScience, **44** (5), 1346, **2009**.
38. CHALAK A., IRANI A., CHAABAN J., BASHOUR I., SEYFERT K., SMOOT K., ABEBE G.K. Farmers' willingness to adopt conservation agriculture: New evidence from Lebanon. Environmental Management, **60**, 693, **2017**.
39. LI B., DING J., WANG J., ZHANG B., ZHANG L. Key factors affecting the adoption willingness, behavior, and willingness-behavior consistency of farmers regarding photovoltaic agriculture in China. Energy Policy, **149**, 112101, **2021**.
40. REARDON T., BARRETT C.B., BERDEGUÉ J.A., SWINNEN J.F. Agrifood industry transformation and small farmers in developing countries. World Development, **37** (11), 1717, **2009**.