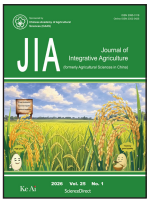
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RESEARCH ARTICLE

Does the adoption of direct-seeded rice affect pesticide use? Evidence from China

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Highlights

- The adoption of direct-seeded rice (DSR) increases pesticide expenditure by 401.72 CNY ha^{-1} in China's Yangtze River Basin.
- DSR adoption demonstrates the most substantial positive impact on insecticide expenditure, and the least positive impact on herbicide expenditure.
- DSR adoption exhibits a stronger positive impact on pesticide expenditure among farmers under 60 years of age, with minimum 6 years of education, and managing rice sown areas below 2 ha.

Abstract

In China, farmers have increasingly adopted direct-seeded rice (DSR). While various impacts of DSR have been studied, limited evidence exists regarding the effect of DSR adoption on pesticide use. This study examines the impact of DSR adoption on pesticide use utilizing data from a 2018 survey of 982 rice farmers in China's Yangtze River Basin. The endogenous treatment-regression and switching regression models are employed to address self-selection bias. The results indicate that, after accounting for self-selection, DSR adopters spend 401.72 CNY ha^{-1} more on pesticides compared to non-adopters. Although DSR adoption significantly increases the use of insecticides, fungicides and herbicides, its impact is most pronounced for insecticide expenditure and least pronounced for herbicide expenditure. The findings remain robust when altering the dependent variable, truncating the research sample, and modifying the estimation method. Heterogeneous analysis reveals that DSR adoption has a stronger positive impact on pesticide expenditure among farmers below 60 years of age, with at least 6 years of education, and managing rice sown areas less than 2 ha. Based on these findings, this study recommends enhancing complementary techniques for DSR, improving the dissemination of DSR cultivation technologies, and strengthening socialized services. This research provides a comprehensive assessment of DSR's advantages and disadvantages, particularly regarding pesticide use, offering important policy implications for pesticide reduction.

Keywords: direct-seeded rice, pesticide use, self-selection issue, labor-saving technology, China

1. Introduction

Following China's reform and opening-up policy in 1978, a significant migration of young rural laborers to urban non-agricultural sectors has occurred (Zhao 2002). This transition has led to scarcity, aging, and relative shortage in the agricultural labor force, accompanied by a substantial increase in agricultural labor costs (Qian *et al.* 2016). In 2021, the daily wages for hired labor in grain crops, cotton, apples, and vegetables production in China reached 139.71, 132.35, 128.29, and 123.99 Chinese Yuan per day (CNY d^{-1}), respectively, representing increases of 6.5, 5.8, 7.2, and 6.2 times compared to the 2000 levels, respectively (NDRCC 2022). During this period, the agricultural production price index increased by approximately 190% (NBSC 2022b). In response to these rising labor costs, Chinese farmers have

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increasingly adopted labor-saving agricultural technologies as an adaptation strategy, with direct-seeded rice (DSR) emerging as a notable innovation (Sha *et al.* 2019; Zhang and Hu 2022).

DSR involves sowing rice seeds directly into fields rather than transplanting them (Tao *et al.* 2016). Compared to transplanted rice, DSR has demonstrated reduced labor requirements, making it an economically viable alternative for farmers facing labor shortages and increasing labor costs (Wang J *et al.* 2020). Farmers in China and numerous developing countries have widely adopted DSR (Cabangon *et al.* 2002; Farooq *et al.* 2011; Weerakoon *et al.* 2011; Mishra *et al.* 2017; Zhang and Hu 2022). Understanding the benefits and costs of DSR has become increasingly important, with recent studies examining various aspects. Regarding yield and cost effects, findings remain inconsistent (Xu *et al.* 2019). Tao *et al.* (2016) reported that wet DSR grain yield exceeded transplanted rice (TPR) by 10.8% in China. Mishra *et al.* (2017) documented that DSR adoption increased rice yield by 3.74–6.79% while reducing total production costs by 3.71–7.51% in India. Sha *et al.* (2019) demonstrated a 3.1% increase in rice yield and 66% increase in net income for Chinese farmers adopting DSR over TPR. Ishfaq *et al.* (2020) similarly found higher DSR productivity compared to TPR in Pakistan. However, Cabangon *et al.* (2002) showed higher TPR yields compared to dry DSR in Malaysia. Wang J *et al.* (2020) also reported lower rice yields among DSR adopters compared to TPR adopters in China. Studies comparing water use and productivity between DSR and TPR revealed that dry DSR utilized less irrigation water while achieving higher water productivity in Malaysia (Cabangon *et al.* 2002). Tao *et al.* (2016) found wet and dry DSR water productivity exceeded TPR by 13.4 and 11.6%, respectively. Ishfaq *et al.* (2020) confirmed lower water consumption in DSR compared to TPR in Pakistan. Environmental impacts of DSR have also garnered attention. While Tao *et al.* (2016) reported 60.4–76.2% lower global warming potential for DSR compared to TPR, other studies identified concerns including soil erosion, increased nutrient runoff losses, and higher cumulative methane emissions (Zhang *et al.* 2018; Li *et al.* 2019; Zhou *et al.* 2019).

The adoption of DSR represents a technological shift in farming practices that significantly alters rice cultivation patterns compared to TPR due to its distinct characteristics. This transition from TPR to DSR affects not only rice yield and productivity but also influences farmers' cultivation practices throughout the growing season, particularly regarding agrochemical usage. In China, pesticides constitute a primary agrochemical extensively utilized in rice production, with their overuse leading to substantial negative environmental, ecological, and health impacts (Zhang *et al.* 2015). Between 1990 and 2020, China's total pesticide consumption increased substantially from 0.73 million tonnes to 1.24 million tonnes (NBSC 2022a). Despite a decrease in total pesticide use since 2015, the intensity of pesticide application remains elevated (NDRCC 2022). Research has established that excessive pesticide use has resulted in severe ecological imbalances, environmental deterioration, and health risks (Chatzimichael *et al.* 2022). Previous research has examined the factors influencing pesticide use in China through various perspectives. First, farmers' individual characteristics, including labor endowment, farm size, risk preference, and nonfarm experience, significantly influence pesticide application decisions (Liu and Huang 2013; Gong *et al.* 2016; Hou *et al.* 2020). Second, studies have demonstrated the significant impact of agricultural extension services, training programs, biotechnology, and digital technology on pesticide utilization (Pan *et al.* 2021; Sun *et al.* 2021; Ma and Zheng 2022). Third, pesticide use correlates strongly with economic factors, particularly market prices. Higher pesticide prices reduce usage (Liu and Huang 2013), while increased agricultural product prices encourage pesticide application (Bayramoglu and Chakir 2016). Fourth, institutional factors significantly influence pesticide use, with empirical evidence supporting the impact of fiscal, exchange rate, and agricultural environmental policies (Kuhfuss and Subervie 2018). Additionally, environmental factors have been shown to affect pesticide application patterns (Guo *et al.* 2021).

DSR exhibits marked differences from TPR regarding rice growth patterns, pest occurrence, and weed proliferation (Wang Q *et al.* 2020). Given the increasing adoption rate of DSR, how does its implementation affect pesticide use in rice production? A significant knowledge gap exists regarding the impact of DSR adoption on pesticide usage. Notably, grain crops constitute nearly 70% of the total crop sown area, with rice representing approximately one-quarter of the grain crop area (NBSC 2022a). However, pesticide application per unit area in rice cultivation exceeds that of other grain crops such as wheat, maize, and soybeans by 2–3 times (NDRCC 2022). Consequently, rice has become a priority crop in China's Action Plan for Zero Growth in Pesticide Use initiated in 2015 (Lin *et al.* 2022a). Therefore, examining the relationship between DSR adoption and pesticide use is crucial within the context of China's pesticide reduction initiatives.

To fill this gap, this study aims to analyze the effect of DSR adoption on pesticide use among Chinese farmers in rice production. The analysis utilizes data from a survey of 982 rice farmers in the Yangtze River Basin conducted in 2018. The Yangtze River Basin was selected as the study area due to its status as China's largest rice-growing region and one of the areas where DSR has achieved widespread adoption (Li *et al.* 2019; NBSC 2022a). This research contributes to existing literature in three significant ways. First, it provides a comprehensive assessment of DSR's advantages and disadvantages, focusing on pesticide use implications, which yields important policy recommendations for pesticide reduction. Second, it addresses potential self-selection bias in empirical analysis through the endogenous treatment-regression (ETR) model. The self-selective nature of DSR adoption by farmers necessitates addressing this issue to avoid biased estimates. Third, it investigates the channels and heterogeneity of DSR adoption's impact on pesticide use. The study separately examines the effects on insecticide, fungicide, and herbicide use to identify impact channels. Furthermore, it analyzes impact heterogeneity across different farmer ages, education levels, and rice sowing areas.

The subsequent sections are organized as follows. Section 2 presents the theoretical analysis of DSR adoption's potential impact on pesticide use, the ETR model for empirical analysis, survey and data collection methodology, and variables and descriptive analysis. Section 3 discusses the empirical results and their implications. The final section presents conclusions and policy recommendations.

2. Data and methods

2.1. Theoretical analysis

Pesticides are essential agrochemicals utilized to control crop insects, diseases, and weeds, thereby minimizing crop yield losses. These agrochemicals can be classified into insecticides, fungicides, and herbicides. During crop cultivation, farmers determine pesticide application levels based on the severity of crop pest infestations, diseases, and weed presence. Specifically, the application of insecticides, fungicides, and herbicides correlates directly with the severity of insect, disease, and weed infestations, respectively. Thus, to analyze the impact of DSR adoption on pesticide use systematically, it is crucial to examine how DSR adoption specifically influences insect, disease, and weed infestations.

Firstly, the frequency and severity of insect infestation in DSR cultivation exceed those in TPR cultivation, compelling farmers to increase insecticide application. Previous studies indicate that DSR exhibits higher planting density compared to TPR, creating a more pronounced damper microenvironment under increased canopy closure. This environment facilitates the infestation of rice insects, including the striped rice borer, yellow rice borer, and rice planthopper (Farooq *et al.* 2011; Liu *et al.* 2022). Additionally, DSR adoption frequently incorporates zero- and minimum-tillage cultivation (Cabangon *et al.* 2002; Farooq *et al.* 2011). This practice preserves the habitat of rice insects, thereby intensifying the infestation of migratory insects, such as rice weevil larvae (Chen and Lu 2013).

Secondly, the distinct sowing period, planting density, and planting method of DSR likely exacerbate rice disease infestations, necessitating increased fungicide usage. The aforementioned higher planting density and resultant damper microenvironment under increased canopy closure have been linked to more severe rice diseases, including blast, sheath blight, and false smut (Farooq *et al.* 2011; Liu *et al.* 2022). Research confirms that several rice diseases in DSR cultivation, such as stripe blight, leaf blight, dry tip nematode, and malignant seedling disease, manifest more severely than in TPR cultivation (Chen and Lu 2013). Limited ventilation between rice plants due to higher planting density promotes the development of diseases like rice blight (Li *et al.* 2011). Furthermore, DSR cultivation requires additional nitrogen fertilizers compared to TPR, increasing rice tiller formation and promoting rice sheath blight and mildew infestations (Zhang and Hu 2022).

Thirdly, DSR cultivation demonstrates significantly higher weed infestation levels compared to TPR cultivation (Wu *et al.* 2024), necessitating increased herbicide application. Because level cultivated farmlands, shallow water, and high soil moisture promote weed reproduction (Cabangon *et al.* 2002; Farooq *et al.* 2011). Additionally, DSR and weed seeds typically germinate simultaneously, resulting in minimal coverage of standing DSR seedlings. In zero- and minimum-tillage cultivation, weed infestation in DSR cultivation intensifies, characterized by diverse species and complex population combinations (Wang Q *et al.* 2000; Zhang *et al.* 2000; Li *et al.* 2011). Moreover, the rapid proliferation and diversification of invasive weed rice in DSR ecosystems significantly elevates the weed hazard index (Wu *et al.* 2024).

Based on these analyses, this study proposes the following two hypotheses:

H1: The adoption of DSR increases pesticide use in rice cultivation.

H2: The adoption of DSR increases the use of insecticides, fungicides and herbicides.

Farmers generally adopt DSR instead of TPR to reduce labor inputs in rice cultivation (Sha *et al.* 2019; Zhang and Hu 2022). The impact of DSR adoption on pesticide use may vary according to different labor endowments and human capital conditions. Given the substantial disparity between agricultural and non-agricultural labor compensation, numerous rural laborers in China have migrated to urban areas for non-agricultural work (Li *et al.* 2023). Notably, younger and better-educated farmers can earn higher wages through non-agricultural employment. When DSR leads to increased infestation of rice insects, diseases, and weeds, younger and better-educated farmers are more likely to employ chemical control methods through pesticides rather than manual control. Conversely, older and less educated farmers may prefer to manage rice pests through labor inputs due to their lower opportunity costs. This indicates that younger and better-educated farmers tend to substitute labor inputs with pesticides for pest control. Based on this context, this study proposes the third hypothesis:

H3: The adoption of DSR exerts a larger positive impact on pesticide use for the younger and better educated farmers.

Rice cultivation area in China varies considerably among farmers, with both large-scale and smallholder farmers operating simultaneously. Smallholder farmers typically derive their primary income from non-agricultural work rather than rice cultivation, particularly in the context of rural-urban labor migration. Consequently, when smallholder farmers encounter increased pest infestations in DSR cultivation, they may prefer pesticide application over manual labor inputs for control. Therefore, the fourth hypothesis is proposed:

H4: The adoption of DSR exerts a larger positive impact on pesticide use for the smallholder farmers than the large-scale one.

2.2. Empirical model

In empirically examining the impact of DSR adoption on pesticide use in rice production, addressing the self-selection issue of DSR adoption is crucial. While DSR is accessible to all farmers, adoption is selective. Farmers' decisions to adopt DSR may be influenced by both observed and unobserved heterogeneity, which could also affect pesticide use in rice production. For example, labor-deficient farmers may be more inclined to adopt DSR to minimize labor inputs while

simultaneously using more pesticides due to insufficient labor for pest control. Consequently, ordinary least squares (OLS) estimation may yield biased results regarding the impact of DSR adoption on pesticide use. Although the propensity score matching (PSM) method has been employed to address self-selection, it cannot account for unobserved heterogeneity (Maddala 1983). This study therefore employs the ETR model, which effectively addresses self-selection arising from both observed and unobserved heterogeneity. The ETR model consists of treatment and outcome equations that require joint estimation (Lin *et al.* 2022a, b).

The treatment equation models a farmer's decision to adopt DSR based on the expected net return from DSR adoption. Let DSR_i^* denote the difference in expected net benefit between adopting DSR and not adopting it for the *i*-th farmer. The farmer would adopt DSR if $DSR_i^*>0$. The dummy variable DSR_i is defined as one when the farmer adopts DSR, and zero otherwise. The treatment equation can be expressed as follows:

$$DSR_i^*=\boldsymbol{Z}_i\boldsymbol{\alpha}_i+v_i,\ DSR_i=1 \text{ when } DSR_i^*>0 \quad (1)$$

where $\boldsymbol{Z}_i$ indicates a set of exogenous explanatory variables for farmers' adoption of DSR, $\boldsymbol{\alpha}_i$ indicates a set of coefficients, and v_i indicates a random disturbance. Both DSR_i^* and DSR_i are defined as above.

The outcome equation models the impact of farmers' adoption of DSR and other factors on pesticide use. It is specified as follows:

$$Y_i=\beta_i DSR_i+\boldsymbol{X}_i\boldsymbol{\gamma}_i+u_i \quad (2)$$

where Y_i indicates pesticide use in rice cultivation, $\boldsymbol{X}_i$ indicates a set of exogenous explanatory variables influencing pesticide use, β_i and $\boldsymbol{\gamma}_i$ indicate the coefficients, and u_i is a random disturbance.

The ETR model assumes that the random disturbances u_i and v_i follow a bivariate normal distribution with a mean of zero and a covariance matrix as:

$$\sum=\begin{bmatrix}\sigma_u^2 & \rho_{uv}\sigma_u\\ \rho_{uv}\sigma_u & \sigma_v^2\end{bmatrix} \quad (3)$$

where σ_u^2 denotes the variance of u_i, σ_v^2 represents the variance of v_i, σ_u indicates the standard deviation of u_i, and ρ_{uv} represents the correlation coefficient between u_i and v_i. A statistically significant correlation coefficient ρ_{uv} indicates the presence of self-selection in farmers' DSR adoption (Maddala 1983; Wooldridge 2010; Lin *et al.* 2022b). Specifically, a positive ρ_{uv} indicates a positive self-selection bias, suggesting that farmers with above-average pesticide use have a higher probability of adopting DSR.

The estimation of the ETR model requires one or more instrumental variables to be included in $\boldsymbol{Z}_i$ but not in $\boldsymbol{X}_i$. Valid instrumental variables must demonstrate strong correlation with the endogenous treatment variable (DSR adoption), while showing no direct correlation with the outcome variable (pesticide use) except through its relationship with the endogenous treatment variable.

2.3. Survey and data collection

The data for this study were collected through a random survey of rice farmers from three main rice-producing provinces — Hubei, Jiangsu and Jiangxi — located in the lower and middle reaches of the Yangtze River Basin in China, where DSR adoption has increased significantly (Sha *et al.* 2019; Liu *et al.* 2022; Zhang and Hu 2022). The farmers were randomly selected in 2018. These provinces were chosen as study sites because the lower and middle reaches of the Yangtze River Basin produced approximately 50% of China's rice, with these three provinces accounting for nearly 60% of the region's rice production in 2018 (NBSC 2019). Additionally, the proportion of DSR sown area in total sown area in Hubei, Jiangsu and Jiangxi provinces has reached approximately 40, 30 and 50% in recent years, respectively.

Using a random sampling approach, one county was selected from each province: Zhongxiang in Central Hubei, Sheyang in the coastal areas in Central Jiangsu, and Yiyang in Northeastern Jiangxi. Four rice-producing townships were randomly selected from each county: Shipai, Shuanghe, Yangzi and Zhangji in Zhongxiang, Hubei; Haihe, Qianqiu, Xingqiao and Xintan in Sheyang, Jiangsu; and Gangkou, Gexi, Qinghu and Zhongfan in Yiyang, Jiangxi. From each township, four villages were randomly selected, and from each village, 20–25 rice farmers were randomly chosen, resulting in a total sample of 982 rice farmers.

This study focuses on middle-season rice (i.e., single-cropping late rice) and double-cropping late rice. All data regarding rice cultivation were collected at the plot level. The collected information encompasses four main categories: detailed information about pesticide use, information about DSR adoption, data on individual and household characteristics, and information regarding rice-planting characteristics.

2.4. Variables and descriptive analysis

The dependent variable in this study examines farmers' pesticide use in rice cultivation. The measurement variables for pesticide use primarily include pesticide expenditure per unit area and pesticide use per unit area (i.e., pesticide use intensity in terms of either commodity or active ingredient). However, different types of pesticides vary significantly in their toxicity and effectiveness against target insects, diseases, and weeds. Consequently, the quantities of different pesticides used cannot be directly compared or aggregated. Therefore, utilizing pesticide expenditure provides a more appropriate measure of pesticide use. Generally, higher-priced pesticides demonstrate greater effectiveness, thus pesticide expenditure levels across farmers better reflect their effective inputs in controlling rice pests. Pesticide expenditure has been widely adopted in previous literature for similar purposes (Huang *et al.* 2003; Jaraitė and Kažukauskas 2012; Feng *et al.* 2021). Specifically, pesticide expenditure (i.e., the average cost of pesticides per unit area) and the expenditures on insecticides, fungicides, and herbicides are calculated as dependent variables in the outcome equation. For robustness checks, pesticide use intensity serves as an alternative measure.

The independent variable of interest is the dummy variable of DSR adoption. The dummy variable equals one if a farmer adopts DSR, and zero otherwise.

Several control variables are incorporated in the empirical model. These include a dummy variable for male farmers,

age of farmers, years of schooling education of farmers, a dummy variable for village leaders, farmers' knowledge score about pesticide use, proportion of farm laborers, household assets, a dummy variable for large-scale planting of rice cultivation, average pesticide price, a dummy variable for access to extension services, a dummy variable for adoption of hybrid varieties, a dummy variable for double-cropping late rice, a dummy variable for using automatic sprayers, and dummy variables for sampled counties.

To address the self-selection issue of farmers' DSR adoption, instrumental variables are required. A valid instrumental variable must correlate with farmers' DSR adoption while not directly correlating with pesticide use except through its relationship with DSR adoption. Previous studies have frequently employed community- or village-based instrumental variables based on peer effects among farmers (Zhu *et al.* 2021; Lin *et al.* 2022b; Ma and Zheng 2022). While rice cultivation modes may converge among farmers within the same village, potentially compromising village-level instrumental variables, this does not preclude designing instrumental variables based on peer effects. In this study, the proportion of DSR adopters among sampled farmers in all other sampled villages within the same county serves as an instrumental variable. The instrumental variable (IV_i) for the *i*-th farmer is calculated as:

IV_i=(No. of DSR adopters in the county–No. of DSR adopters in the village)/(No. of farmers in the county–No. of farmers in the village)×100% (4)

This instrumental variable demonstrates strong correlation with the *i*-th farmer's DSR adoption. The proportion in eq. (4) reflects DSR popularity in the farmer's county, where higher popularity typically increases the probability of DSR adoption. However, since rice sowing occurs within a brief timeframe, a higher proportion of DSR adopters in other villages may reduce the *i*-th farmer's access to DSR given limited seed availability. Additionally, this variable satisfies the exclusion restriction, as it reasonably lacks direct correlation with the *i*-th farmer's pesticide use except through DSR adoption. While cultivation mode convergence may occur among farmers within the same village, the instrumental variable effectively addresses this concern.

Note that the details of variable definition are summarized in Appendix A.

Table 1 presents the descriptive statistics and mean differences of the main variables between DSR adopters and non-adopters. Several variables show statistically significant differences between groups. Pesticide expenditure and pesticide use intensity among DSR adopters exceed those of non-adopters by 273.84 CNY ha^{-1} and 3.11 kg ha^{-1}, respectively. Similar significant differences appear in fungicide and herbicide expenditures. Regarding other variables, DSR adopters demonstrate significantly higher probability of large-scale rice cultivation and lower probability of adopting hybrid varieties and double-cropping late rice. These significant differences suggest that farmers' DSR adoption likely results from self-selection.

Fig. 1 depicts the relationship between DSR adoption and pesticide expenditure among the sampled farmers across regions. The data indicate that farmers in Jiangsu allocate substantially more resources to pesticide use in

Table 1 Descriptive statistics and mean differences of the main variables

Variables	Mean (Std. Dev.)[1)]			Mean differences
	All farmers	DSR adopters	DSR non-adopters	
Pesticide expenditure (CNY ha^{-1})	1,209.76 (843.33)	1,267.49 (857.26)	993.64 (752.45)	273.84***
Insecticide expenditure (CNY ha^{-1})	639.55 (566.49)	651.25 (563.08)	595.76 (578.34)	55.49
Fungicide expenditure (CNY ha^{-1})	359.01 (489.03)	388.77 (502.27)	247.61 (418.59)	141.16***
Herbicide expenditure (CNY ha^{-1})	211.20 (272.04)	227.47 (276.77)	150.28 (244.74)	77.19***
Pesticide use intensity (kg ha^{-1})	9.45 (7.72)	10.10 (8.12)	7.00 (5.30)	3.11***
DSR adoption (1=yes, 0=no)	0.79 (0.41)			
Male (1=yes, 0=no)	0.94 (0.23)	0.94 (0.23)	0.95 (0.22)	–0.00
Age (year)	56.00 (8.11)	55.82 (8.23)	56.67 (7.65)	–0.85
Education (year)	6.99 (3.46)	7.00 (3.46)	6.94 (3.46)	0.07
Village leader (1=yes, 0=no)	0.18 (0.39)	0.18 (0.39)	0.19 (0.39)	–0.01
Knowledge scores	2.35 (1.07)	2.36 (1.08)	2.29 (1.03)	0.06
Proportion of farm laborers (%)	71.75 (20.97)	71.40 (21.64)	73.06 (18.24)	–1.66
Household assets (1,000 CNY)	397.59 (506.60)	397.91 (499.14)	396.39 (534.87)	1.52
Large-scale cultivation (1=yes, 0=no)	0.28 (0.45)	0.30 (0.46)	0.21 (.41)	0.10***
Pesticide price (CNY kg^{-1})	178.03 (156.79)	174.46 (147.34)	191.37 (187.80)	–16.91
Extension services (1=yes, 0=no)	0.22 (0.41)	0.22 (0.42)	0.19 (0.40)	0.03
Hybrid varieties (1=yes, 0=no)	0.63 (0.48)	0.58 (0.49)	0.83 (0.38)	–0.25***
Double-cropping late rice (1=yes, 0=no)	0.08 (0.27)	0.06 (0.25)	0.14 (0.34)	–0.07***
Automatic sprayer (1=yes, 0=no)	0.83 (0.38)	0.83 (0.37)	0.82 (0.38)	0.01
Instrumental variable (%)	79.23 (9.54)	79.92 (9.74)	76.66 (8.29)	3.25***
Observations	982	775	207	

[1)] DSR denotes the direct-seeded rice.
***, P<0.01. T-test was employed to assess the difference between the means. Variable definitions are presented in Appendix A.

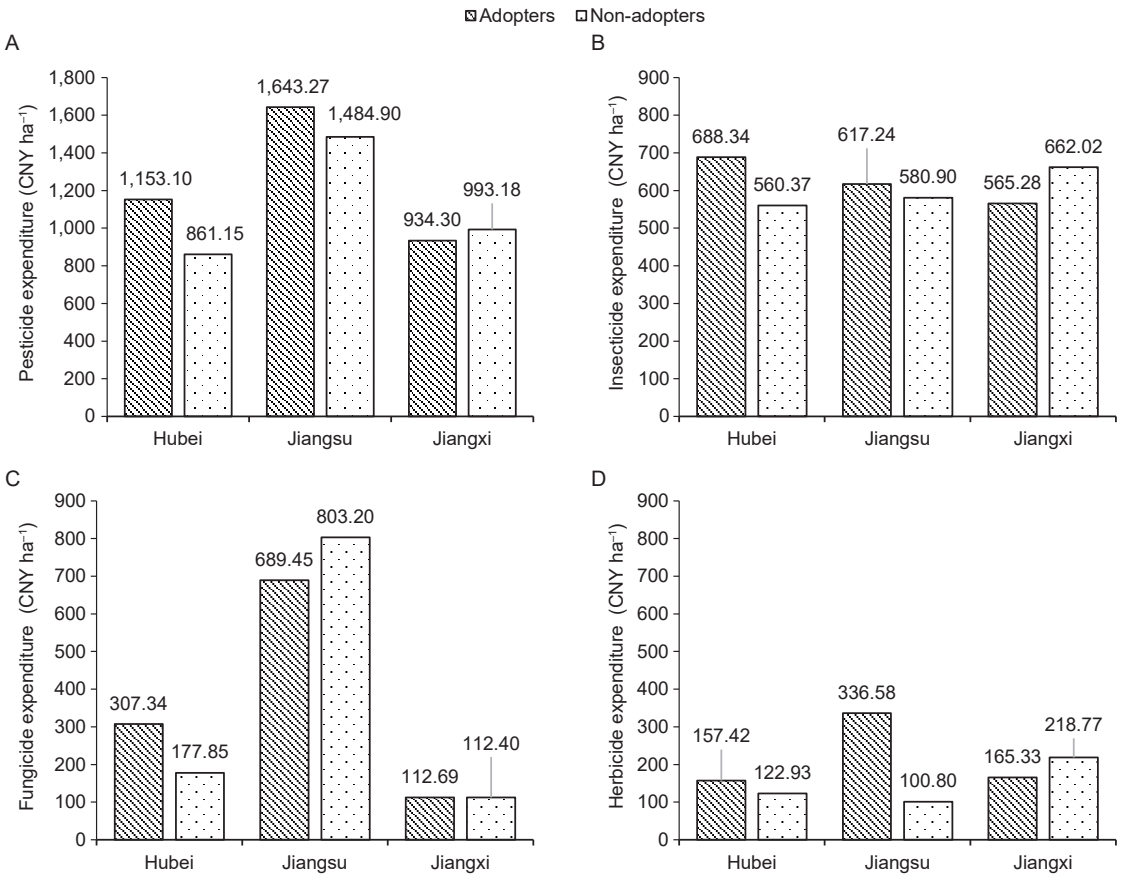


Fig. 1 Differences in average pesticide expenditure between adopters and non-adopters of direct-seeded rice. A, difference in total pesticide expenditure between adopters and non-adopters. B, difference in insecticide expenditure between adopters and non-adopters. C, difference in fungicide expenditure between adopters and non-adopters. D, difference in herbicide expenditure between adopters and non-adopters.

rice production compared to their counterparts in Hubei and Jiangxi. Analysis of pesticide expenditure components reveals no comparable insecticide expenditure levels among farmers across these provinces. However, farmers in Jiangsu demonstrate higher fungicide and herbicide expenditures relative to those in Hubei and Jiangxi. Additionally, the data show elevated pesticide expenditure among DSR adopters in Hubei and Jiangsu compared to non-adopters. Conversely, pesticide expenditure among DSR adopters in Jiangxi is marginally lower than non-adopters. Specifically, insecticide expenditure is higher among DSR adopters across all three provinces compared to non-adopters. While DSR adopters in Hubei and Jiangxi allocate more resources to fungicide use than non-adopters, DSR adopters spend less on fungicide use than non-adopters. Herbicide expenditure is higher among DSR adopters in Hubei and Jiangsu but comparatively lower among adopters in Jiangxi. These observations demonstrate regional variations in pesticide expenditure, necessitating the control of regional effects when analyzing the impact of DSR adoption on pesticide expenditure.

3. Results and discussion

Table 2 presents the estimated impacts of DSR adoption and other independent variables on pesticide expenditure using the ETR model, with OLS regression results for comparison. The χ^2 statistic of Wald test of independent equations equals 5.46 and is significant at the 5% level, confirming the presence of DSR adoption self-selection. The correlation coefficient ρ shows significant negative values, suggesting that farmers using fewer pesticides than average are more likely to adopt DSR. This indicates that OLS regression would underestimate the impact of DSR adoption on pesticide expenditure. Therefore, the ETR model proves more appropriate and necessary for addressing the self-selection issue.

Multiple tests confirm the validity of the instrumental variable employed in this study (Table 2). The first-stage F statistic estimated using the two-stage least squares method equals 821.80, substantially exceeding its critical value of 10.00; additionally, the minimum eigenvalue statistic of a Wald test at the 5% level with an actual rejection rate of no more than 10% equals 377.57, significantly surpassing its critical value of 16.38. These statistics demonstrate that the instrumental variable. Given that the number of instrumental variable and endogenous variables is equal, statistical testing of the exclusion restriction of instrumental variable is not feasible. Following an established alternative approach (Fang and Zhao 2011; Lin *et al.* 2022a, b), this study regresses pesticide expenditure on both DSR adoption and instrumental

Table 2 Effects of direct-seeded rice (DSR) adoption and other factors on pesticide expenditure

Variables	ETR model[1)]		OLS regression[2)] (pesticide expenditure)
	DSR adoption	Pesticide expenditure	
DSR adoption		401.72*** (100.44)	165.04* (38.81)
Male	0.06 (0.34)	–305.87*** (68.78)	–294.40** (37.63)
Age	0.01 (0.02)	–0.32 (1.14)	–1.32 (0.47)
Education	0.04 (0.06)	7.75 (5.27)	7.94 (4.26)
Village leader	0.02 (0.04)	–60.29 (121.70)	–66.71 (121.52)
Knowledge scores	–0.00 (0.00)	38.33*** (12.34)	38.79 (15.63)
Proportion of farm laborers	–0.00 (0.01)	–1.29 (1.12)	–1.41 (1.14)
ln(Household assets)	–0.10** (0.05)	–4.54 (26.56)	–7.54 (25.91)
Large-scale cultivation	–0.00 (0.00)	–94.81** (45.38)	–82.49 (53.69)
Pesticide price	0.44*** (0.14)	1.55*** (0.24)	1.56** (0.25)
Extension services	–0.16 (0.12)	11.64 (44.48)	9.60 (51.57)
Hybrid varieties	–0.34*** (0.12)	25.95 (46.52)	7.80 (42.75)
Double-cropping late rice	–0.57*** (0.07)	295.24*** (65.51)	225.73 (79.89)
Automatic sprayer	–0.50*** (0.11)	–31.29 (115.04)	–66.91 (118.81)
Instrumental variable	–0.49*** (0.06)		
County effect	Yes	Yes	Yes
Constant	46.18*** (6.84)	1,374.97*** (116.62)	1,687.01** (200.65)
Independent equations (χ^2)	5.46**		
ρ	–0.25** (0.10)		
First-stage F statistic	821.80***		
Minimum eigenvalue statistic	377.57 [16.38]		
Observations	982		982

[1)] ETR model denotes the endogenous treatment-regression model.
[2)] OLS regression denotes the ordinary least squares regression.
*, P<0.10; **, P<0.05; ***, P<0.01. Figures in parentheses are county-clustered standard errors. The figure in square bracket is the critical value of a Wald test at the 5% significance level with an actual rejection rate not exceeding 10% (Stock and Yogo 2005). The null hypothesis of weak instrumental variable can be rejected when the minimum eigenvalue statistic exceeds the critical value of 16.38.

variable. As shown in Appendix B, while the instrumental variable is significant at the 10% level when pesticide expenditure is regressed solely on the instrumental variable, it becomes statistically insignificant when pesticide expenditure is regressed on both DSR adoption and instrumental variable. This indicates that the instrumental variable affects pesticide expenditure exclusively through DSR adoption, thus satisfying the exclusion restriction.

3.1. Determinants of DSR adoption

The treatment equation results in Table 2 indicate that household assets, pesticide price, hybrid variety adoption, double-cropping late rice, and automatic sprayer usage significantly influence farmers' DSR adoption decisions. The logarithmic household assets coefficient shows negative significance at the 5% level, suggesting that farmers with greater household assets demonstrate lower likelihood of DSR adoption. The pesticide price coefficient exhibits positive significance, indicating that increased pesticide prices correlate with higher DSR adoption likelihood. The hybrid varieties coefficient shows negative significance at the 1% level, suggesting reduced DSR adoption likelihood among hybrid rice cultivators. Farmers cultivating double-cropping late rice show lower inclination toward DSR adoption compared to those growing middle-season rice or single-cropping late rice. Furthermore, the data suggest a potential negative correlation between automatic sprayer utilization and DSR adoption.

3.2. Impacts of DSR adoption and other factors on pesticide use

Table 2 also presents the estimated results of the outcome equation. The coefficient of DSR adoption equals 401.72, significant at the 1% level, indicating that DSR adoption is associated with an increase of 401.72 CNY ha^{-1} in pesticide expenditure. As previously discussed, the positive impact of DSR adoption on pesticide use in rice production can be attributed to DSR limitations, including higher planting density (Farooq *et al.* 2011; Liu *et al.* 2022), environments conducive to rice insect and weed reproduction (Cabangon *et al.* 2002; Farooq *et al.* 2011), and increased fertilizer requirements (Zhang and Hu 2022). The OLS regression results indicate that while the coefficient of DSR adoption remains statistically significant, it is substantially smaller. Failing to account for the self-selection issue of DSR adoption could result in underestimating its positive impact on pesticide use in rice production. This aligns with the significantly negative correlation coefficient ρ, validating the appropriateness and necessity of the ETR model.

In addition to DSR adoption, several factors influence pesticide use in rice production (Table 2). Male farmers' pesticide expenditure in rice production is 305.87 CNY ha^{-1} lower than female farmers'. Notably, farmers with higher knowledge scores demonstrate increased pesticide usage. Large-scale farmers with rice sown area of 2 ha or more spend 94.81 CNY ha^{-1} less on pesticides compared to small-scale farmers with areas below 2 ha, supporting recent

research showing an inverse relationship between farm size and pesticide use (Gao *et al.* 2021). Pesticide price positively affects expenditure, with each 1 CNY kg^{-1} increase leading to a 1.55 CNY ha^{-1} rise in pesticide expenditure. Furthermore, cultivation of double-cropping late rice increases pesticide expenditure by 295.24 CNY ha^{-1} compared to middle-season rice or single-cropping late rice cultivation.

3.3. Channel analysis

To examine the mechanism through which DSR adoption affects pesticide expenditure, this study analyzes its impacts on insecticide, fungicide, and herbicide expenditures separately. Table 3 presents these results. While DSR adoption shows significant positive impacts across all three pesticide types, the magnitude varies considerably. DSR adoption increases insecticide expenditure by 198.14 CNY ha^{-1}. The positive impacts on fungicide and herbicide expenditures are comparatively lower, with increases of 120.08 and 76.40 CNY ha^{-1}, respectively.

3.4. Robustness checks

This study implements three distinct robustness checks. First, pesticide use intensity serves as an alternative measure to pesticide expenditure. As shown in the first and second columns of Table 4, the estimated coefficient of pesticide use intensity is significantly positive at 2.75, demonstrating that DSR adoption increases pesticide use intensity by 2.75 kg ha^{-1}. Second, the research sample is truncated at the 1 and 99% percentiles regarding pesticide expenditure. Given that micro-level survey data may contain extreme values affecting econometric estimation accuracy, data truncation may be necessary (Dong and Wang 2023; Anderson *et al.* 2024). The third and fourth columns of Table 4 indicate that DSR adoption significantly increases pesticide expenditure by 358.10 CNY ha^{-1} for the truncated sample. Third, the endogenous switching regression (ESR) model serves as an alternative to the ETR model. The ESR model represents another effective econometric method widely employed to address potential self-selection issues (Huang *et al.* 2015; Zhu *et al.* 2021). The key difference lies in the ESR model's two outcome equations: one for the treated group (DSR adopters) and the other for the untreated group (DSR non-adopters). Table 5 results demonstrate that DSR adoption increases pesticide expenditure among both adopters and non-adopters. DSR adopters spend 523.25 CNY ha^{-1} more on pesticides than they would without DSR adoption, representing a 70.31% increase. Similarly, if non-adopters implemented DSR, their pesticide expenditure would increase by 308.51 CNY ha^{-1} or 31.04%.

3.5. Heterogeneity analysis

The heterogeneity analysis provides deeper insights into how pesticide use responds to DSR adoption. For this analysis,

Table 3 Results of channel analysis using the endogenous treatment-regression (ETR) model

Variables	Insecticide expenditure	Fungicide expenditure	Herbicide expenditure
Outcome equation			
DSR adoption[1)]	198.14*** (43.97)	120.08** (52.93)	76.40** (38.14)
Control variables	Yes	Yes	Yes
County effect	Yes	Yes	Yes
Constant	261.06** (115.38)	672.61*** (192.56)	450.66*** (127.64)
Treatment equation			
Instrumental variable	–0.49*** (0.06)	–0.48*** (0.06)	–0.49*** (0.06)
Control variables	Yes	Yes	Yes
County effect	Yes	Yes	Yes
Constant	46.22*** (6.87)	45.88*** (6.87)	46.44*** (6.96)
Independent equations (χ^2)	2.88*	11.54***	5.16**
ρ	–0.15* (0.09)	–0.14*** (0.04)	–0.15** (0.07)
Observations	982	982	982

[1)] DSR represents the direct-seeded rice.
*, P<0.10; **, P<0.05; ***,P<0.01. Figures in parentheses are county-clustered standard errors. Control variables are identical to those presented in Table 2.

Table 4 Results of robustness checks for truncated data using the endogenous treatment-regression (ETR) model

Variables	Replacing the dependent variable		Truncated at the 1 and 95% percentiles	
	DSR adoption	Pesticide use intensity	DSR adoption	Pesticide expenditure
DSR adoption[1)]		2.75*** (0.68)		358.10*** (122.25)
Control variables	Yes	Yes	Yes	Yes
Instrumental variable	–0.49*** (0.06)		–0.49*** (0.06)	
County effect	Yes	Yes	Yes	Yes
Constant	–46.08*** (6.93)	17.08*** (1.74)	46.16*** (7.00)	1,489.33*** (104.94)
Independent equations (χ^2)	3.34*		3.51*	
ρ	–0.16* (0.08)		–0.25* (0.13)	
Observations	982		964	

[1)] DSR represents the direct-seeded rice.
*, P<0.10; ***, P<0.01. Figures in parentheses are county-clustered standard errors. Control variables are identical to those presented in Table 2.

the sampled farmers were categorized into different groups based on age, education, and rice sown area. The results indicate that DSR adoption's impact on pesticide use varies across these factors (Table 6). Specifically, DSR adoption increases pesticide expenditure by 267.53 CNY ha^{-1} for farmers aged 60 years and above, while increasing it by 507.39 CNY ha^{-1} for farmers under 60 years old. Notable differences also emerge in the impact across education levels. For farmers with 6 or more years of education, DSR adoption increases pesticide expenditure by 479.70 CNY ha^{-1}. In contrast, it increases expenditure by only 249.44 CNY ha^{-1} for farmers with fewer than 6 years of education. Regarding farm size, DSR adoption increases pesticide expenditure by 331.26 CNY ha^{-1} for farmers with rice sown area of 2 ha or larger, while increasing it by 402.78 CNY ha^{-1} for those with less than 2 ha.

4. Conclusion

In response to rising agricultural labor costs in China, rice farmers have increasingly adopted DSR. While previous research has examined various benefits and costs of DSR, the relationship between DSR adoption and pesticide use remains understudied. This research addresses this gap by analyzing the impact of DSR adoption on pesticide use, particularly relevant given China's concerns about pesticide overuse and ongoing pesticide-reduction initiatives. The study utilizes data from a 2018 survey of 982 rice farmers in the Yangtze River Basin, employing ETR and ESR models to address self-selection in DSR adoption.

The analysis reveals that approximately 80% of sampled farmers have adopted DSR, leading to a significant increase in pesticide use in rice production. After accounting for self-selection, DSR adopters spent 401.72 CNY ha^{-1} more on pesticides compared to non-adopters. Channel analysis reveals that DSR adoption significantly affects the use of insecticides, fungicides, and herbicides, with the largest impact on insecticide use and the smallest on herbicide expenditure. These findings remain robust across alternative dependent variables, truncated research samples, and different estimation methods. The impact varies across farmer factors, with stronger effects observed among farmers under 60 years old, those with at least 6 years of education, and those cultivating less than 2 ha. Additional factors influencing pesticide expenditure include farmers' gender, knowledge level, rice sown area, pesticide price, and planting season.

These findings suggest several policy implications. First, complementary techniques for DSR require enhancement. The increased pesticide use associated with DSR adoption relates to characteristics, such as higher planting density,

Table 5 Average treatment effects of direct-seeded rice (DSR) adoption on pesticide expenditure using the endogenous switching regression (ESR) model

Groups	Pesticide expenditure (CNY ha^{-1})		Treatment effects (CNY ha^{-1})[1)]	Change (%)
	To adopt	Not to adopt		
DSR adopters	1,267.51 (390.92)	744.25 (372.22)	ATT: 523.25***	70.31
DSR non-adopters	1,302.48 (376.40)	993.97 (443.03)	ATU: 308.51***	31.04

[1)] ATT represents the average treatment effects on the treated; ATU represents the average treatment effects on the untreated.
***, P<0.01. Figures in parentheses are standard deviations. The estimation results of the ESR model are presented in Appendix C.

Table 6 Results of heterogeneity analysis using the endogenous treatment-regression (ETR) model

Variables	Pesticide expenditure					
	Age≥60 years old	Age<60 years old	Education≥6 years	Education<6 years	Rice sown area≥2 ha	Rice sown area<2 ha
Outcome equation						
DSR adoption[1)]	267.53**	507.39***	479.70***	249.44***	331.26***	402.78***
	(122.91)	(108.68)	(56.34)	(73.97)	(57.02)	(103.47)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
County effect	Yes	Yes	Yes	Yes	Yes	Yes
Constant	1,703.46***	1,239.62***	1,078.43***	1,824.28***	1,583.38***	1,214.17***
	(193.90)	(238.74)	(211.14)	(699.99)	(414.16)	(141.20)
Treatment equation						
Instrumental variable	–0.56***	–0.47***	–0.45***	–0.62***	–0.40***	–0.54***
	(0.15)	(0.03)	(0.06)	(0.12)	(0.01)	(0.09)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
County effect	Yes	Yes	Yes	Yes	Yes	Yes
Constant	48.93***	45.03***	43.60***	56.90***	37.09***	51.33***
	(14.50)	(3.44)	(7.43)	(11.49)	(3.20)	(9.71)
Wald test of independent equations (χ^2)	3.76*	7.53***	15.47***	3.11*	2.10	7.96***
ρ	–0.19*	–0.29***	–0.34***	–0.09*	–0.22	–0.26***
	(0.10)	(0.10)	(0.08)	(0.05)	(0.15)	(0.09)
Observations	342	640	665	317	279	703

[1)] DSR represents the direct-seeded rice.
*, P<0.10; **, P<0.05; ***, P<0.01. Figures in parentheses are county-clustered standard errors. Control variables are identical to same as those presented in Table 2.

poor ventilation, and zero- and minimum-tillage cultivation (Caton *et al.* 1999; Wang Q *et al.* 2020; Biswakarma *et al.* 2021). To align with China's pesticide-reduction goals, DSR cultivation techniques should be improved to maintain high yields while minimizing pesticide use. Mechanical direct seeding could address uneven planting density and improve ventilation between rice plants, potentially reducing pest infestations. Traditional tillage practices should be maintained with DSR adoption to disrupt pest reproduction environments. Second, government agricultural extension services should prioritize DSR cultivation technology dissemination. The current limited extension support has left farmers with insufficient understanding of DSR fundamentals, contributing to increased pesticide use. Extension efforts should particularly target smallholder farmers. Third, socialized services for rice cultivation and pest control require strengthening. Younger, better-educated farmers face higher opportunity costs in rice cultivation; therefore, socialized DSR services could address technical challenges while reducing labor requirements. Additionally, specialized pest control services and drone-based pesticide application could improve efficiency and reduce pesticide waste.

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Declaration of competing interest

The authors declare that they have no conflict of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used DeepSeek in order to improve the readability and language of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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