Biopesticide Extension and Rice Farmers' Adoption Behavior: A Survey From Rural China

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Biopesticide Extension and Rice Farmers' Adoption Behavior: A Survey from Rural China

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Abstract: Although the beneficial effects of the agricultural extension of farmers' biopesticide adoption have been largely demonstrated, the questions of what approaches can better extend biopesticides and how to improve the inefficiencies of biopesticide extension still need to be explored. In a survey of 1148 rice farmers in Hubei Province, China, the technology supply and demand theory was used to explain the low efficiency of biopesticide extension. The endogenous switching probit model was used to estimate the impact of biopesticide technology publicity, training, demonstration and subsidies on farmers' adoption. The results show that biopesticide extension can promote rice farmers' adoption probability by 10.3% ~ 11.7%. Among these methods, technology demonstration is currently the best way to extend biopesticides. Moreover, inadequate supply and demand of biopesticides are important for explaining the inefficiency of biopesticide extension in China. Extending biopesticides is better for farmers with smaller scales, younger ages, and lower education and for those who are cooperative members. Therefore, we should not only actively conduct biopesticide demonstration but also more importantly induce farmers' biopesticide demand and secure the market supply of biopesticide products. These findings will provide useful guidance for biopesticide extension and pesticide reduction in China and other developing countries.

Keywords: Biopesticide; Agricultural extension; Pesticide reduction; Technology supply and demand; China; ESP model

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1. Introduction

Biopesticides are considered necessary elements to replace chemical pesticides and realize the sustainable development of agriculture (Constantine et al., 2020). They have excellent technical attributes, such as low toxicity, low residue, and environmental friendliness (Srinivasan et al., 2019). While chemical pesticides have helped increase agricultural productivity and eliminate human hunger, they also pose a serious threat in terms of polluting the environment and damaging human health (Gould et al., 2018; Huang et al., 2020). As the world's largest producer and consumer of pesticides, China has been paying increasing attention to the issue of green agricultural development in recent years. In particular, the extension of biopesticides to build a green pest management system is one of the key objectives (Guo et al., 2019). The Chinese government began to vigorously promote biopesticide in 2006. However, as of 2020, the market share of biopesticides in China is only approximately 10%, far below the 20% to 60% level in other developed countries in the world[①]. Determining how to quickly and effectively promote biopesticide application is a pressing issue.

Although agricultural extension is considered by most scholars to be a useful way to promote the adoption of biopesticides (Toepfer et al., 2020; Wuepper et al., 2021), its effectiveness has not been satisfactory thus far. On the one hand, users need to master the strict operational standards of biopesticide use, such as application time, dosage, climate, and crop disease (Guo et al., 2019). If users do not follow implementation standards, it is difficult to achieve the desired effect of pest management (Bagheri et al., 2021). Agricultural extension can deliver biopesticide technology information to farmers, compensating for the misuse of pesticides caused by information

[①] Pesticide product market statistics results from the China Pesticide Information Network: http://www.chinapesticide.org.cn/.

asymmetry (Yang et al., 2014; Huang et al., 2021). Some previous studies have also shown that technical training and demonstration are beneficial to farmers' biopesticide adoption (Feder et al., 2004; Grovermann et al., 2017). On the other hand, some scholars have pointed out that agricultural extension does not necessarily promote farmers' biopesticide adoption (Sun et al., 2019; Gao et al., 2020). Biopesticide extension has long-term social benefits, which do not match the short-term private gains of farmers. As a result, Chinese farmers show a deviation of "think it is good, but do not adopt it" (Guo and Wang, 2016). In addition, some empirical studies have even found that technology publicity, training, and subsidies do not significantly promote farmers' biopesticide adoption probability in China (Geng et al., 2017). Therefore, what is a good way to extend biopesticides? How can the effectiveness of biopesticide extension be optimized?

From the theory of technology supply and demand, it is known that the best method of agricultural extension (supply) is to target farmers' technical demand for biopesticides (Yuan and Niehof, 2011). However, China's current agricultural technology extension model is still typically government-led, relying heavily on national policy objectives and financial support (Hu et al., 2009; Sun et al., 2019). This mandatory agricultural extension can lead to a mismatch between the supply of biopesticide technology and the real needs of farmers. For example, some studies have found that farmers do not have easy access to the applicable biopesticide products they need because of the slow pace of biopesticide product development and the small variety of products available (Guo et al., 2019). The product attributes of many biopesticides on the market, such as high procurement costs, slow insecticidal effects, and a narrow insecticide spectrum, are not preferred by farmers (Constantine et al., 2020). Obviously, it is difficult to promote the adoption of biopesticides by farmers through government agricultural extension when the supply of products in the biopesticide market is insufficient or when farmers themselves do not need biopesticides.

Therefore, based on a survey of 1148 rice farmers in Hubei Province, China, an endogenous switching probit model was used to empirically analyze the heterogeneous effects of different biopesticide extension methods on farmers' adoption behavior. The regulating effects of technology supply and demand were estimated in groups. The main contributions of this study are as follows. First, previous studies have focused only on the effects of a single agricultural extension approach, such as technical training or subsidies for biopesticide extension (Feder et al., 2004; Grovermann et al., 2017; Toepfer et al., 2020). In this study, we compare and analyze the heterogeneity of the effects of four forms of agricultural extension, namely, technical publicity, training, demonstration, and subsidies for biopesticide extension. This comparison and analysis will provide a reference for evaluating which approach is better for extending biopesticides. Second, the current studies by scholars exploring the impact of agricultural extension on biopesticide adoption behavior only involve the supply of technology while ignoring farmers' real demand for biopesticides (Yuan and Niehof, 2011; Sun et al., 2019). After considering the "technology supply and demand" condition in the model, we found that the lack of biopesticide supply and demand is an important reason for the inefficiency of biopesticide promotion in China. The above research findings will provide useful experience for biopesticide extension and pesticide reduction in China and other developing countries.

2. Materials and Methods

2.1 Biopesticide extension in China

The extension of biopesticides in China developed rapidly in 1980~1990. At that time, *Abamectin*, *Wellbutrin* and *Bt* pesticide products were developed and registered in large quantities. However, since the beginning of the 21st century, considering food security and agricultural production efficiency, chemical pesticides have received more attention from society, thus slowing the development of biopesticides. However, the negative effects of the long-term use of chemical pesticides have been highlighted. In recent years, the extension and application of biopesticides in agriculture has been re-emphasized in China since the concept of "public plant protection and green plant protection" was introduced in 2006 (Guo et al., 2019). The National Ministry of Agriculture and Rural Affairs issued the "Action Plan for Zero Growth in Pesticide Use by 2020" in 2015 and the "National Strategic Plan for Revitalizing Agriculture by Quality (2018-2022)" in 2019. Both of plans show that "green control technologies such as biopesticides should be used to replace chemical pesticides" to achieve pesticide reduction. Thus, effectively promoting biopesticides has become an important goal for China. Data predictions show that China’s market share of biopesticides will increase from the current 10% to 30% in the next decade. China will become the fastest growing country in the Asia-Pacific market demand for biopesticides (Zaki et al., 2020).

2.2 Hypothesis

Agricultural extension is the activity of popularizing the application of high-tech agricultural technologies in agricultural production through publicity, demonstration, training and subsidies (Guo et al., 2019). It is both a key force supporting the development of modern agriculture and an important policy tool for the government to support agriculture (Hu et al., 2009). Reasonable technical publicity can deliver information on biopesticide technology to farmers and correct unsafe application practices by farmers (Guo and Wang, 2016). Technical training can increase farmers’ knowledge of and skills with biopesticides, enhance their understanding of the ease and usefulness of the technology, and effectively solve the technical difficulties encountered by farmers in practice (Khan and Damalas, 2015). Technology demonstrations can provide reference suggestions to farmers in the region for their use decisions. It can effectively eliminate the "worries" of farmers, accelerate radiation and drive neighboring farmers to use biopesticides (Geng et al., 2017). Technology subsidies can effectively reduce the acquisition cost of biopesticides and weaken the uncertain impact of technology and market risks on farmers' income (Gould et al., 2018).

However, the theory of technology supply and demand indicates that the real demand of farmers for biopesticides is also the key to determining the success of agricultural extension (Yuan and Niehof, 2011). Previous studies exploring biopesticide adoption behavior from the perspective of agricultural extension note that it can only guarantee and promote the effective supply of biopesticides, ignoring the real demand for biopesticides from farmers. Biopesticide extension should be based on meeting the different technical demands of farmers as the starting point, clarifying the main position of farmers as technology demanders and users, and solving the difficulties encountered in the process of agricultural production and operation as the main goal. For example, the use of biopesticides can protect the ecological environment, increase the profitability of agricultural products, ensure food safety and reduce human health damage (Paul et al., 2020; Constantine et al., 2020). That is, farmers will be motivated to adopt biopesticides when and only when doing so meets their needs and utility goals (Benoît et al., 2020). In this context, the extension of biopesticides and securing market supply will successfully promote the adoption behavior of rice farmers.

Based on the above analysis, the following research hypothesis can be obtained: Biopesticide supply and demand will regulate the impact of biopesticide extension on the adoption behavior of rice farmers. Biopesticide extension is more effective when the conditions of "both supply and demand" are met. The framework of this study is shown in Fig. 1.

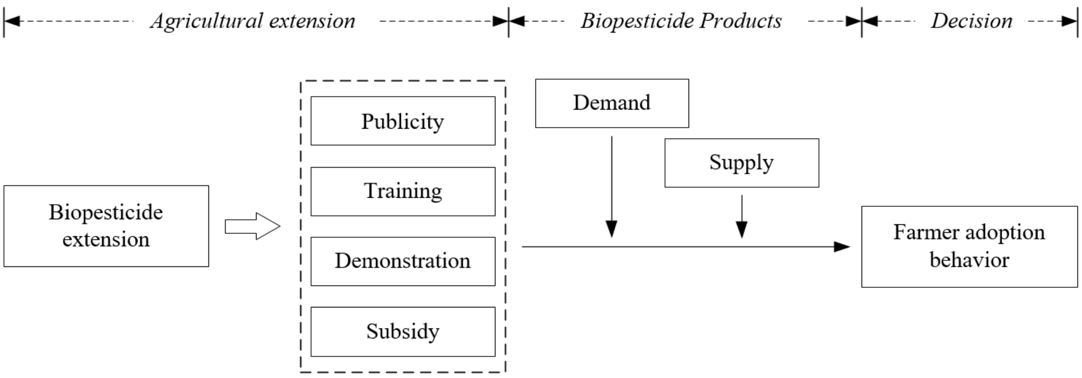

Figure 1 Framework of this study

2.3 Data

The research data are from a household survey of rice growers conducted by the research group of Xiangyang, Huanggang, Jingmen and Yichang of Hubei Province, China, from September 2019 to September 2020. The document "Implementation Opinions of the Ministry of Agriculture and Rural Affairs on Supporting the Green Development of Agriculture and Rural Areas in the Yangtze River Economic Belt"[2] was issued in November 2018 and stressed that the Chinese government would strongly support the provinces (cities) in the Yangtze River Economic Belt to implement negative growth in pesticide use. In addition, a number of green pest control demonstration bases should be built to guide farmers to use biopesticides. Hubei Province is an important part of the Yangtze River Economic Belt and one of the main grain production areas in China. Research on its pesticide reduction activity will provide a certain practical reference value for all of central China. More importantly, the Hubei Province Agricultural Management

[2] Details of the policy text can be obtained from the following website: http://www.moa.gov.cn/gk/zcfg/qnhnzc/201809/t20180921_6157725.htm

Department made it clear that the "pesticide reduction technology of grain crops" was urgently incorporated into the agricultural technology extension service system[3]. Among these technologies, "biological pest management" is an important technology extension object. Therefore, selecting Hubei Province as the sample area for the study of rice farmers' biopesticide adoption behavior not only has a certain scientific representativeness but also has practical significance for guiding farmers to use more biopesticides.

Referring to the list of "Green Control Technology Demonstration Counties" published by the National Ministry of Agriculture and Rural Affairs[4], our research group randomly selected six counties (districts) from the main rice planting areas in Hubei Province, including the cities of Xiangyang, Huanggang, Jingmen and Yichang (Fig. 2). Combined with the regional distribution of rice production, we selected 6 counties from the above 4 cities (Nanzhang, Wuxue, Qichun, Yingshan, Zhongxiang, Yiling). Then, according to the principle of random stratified sampling, 2~3 townships were selected from each county, 4~6 villages were selected from each township, and 10~20 rice growers were selected from each village. Finally, 1148 valid questionnaires of rice farmers in 15 towns and 80 villages were obtained. The questionnaires were completed in face-to-face interviews, with household heads or main agricultural production decision-making members as the respondents. The content design of the questionnaire mainly included detailed data on farmer characteristics, pest control, agricultural production cost, and so on.

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[3] Implementation Plan for the Main Extension Technology of Pesticide Reduction, Damage Control and Efficiency Increase of Grain Crops in 2020. http://nyt.hubei.gov.cn/bmdt/yw/zbzh/202004/t20200429_2251651.shtml

[4] This list is available at: https://www.natesc.org.cn/

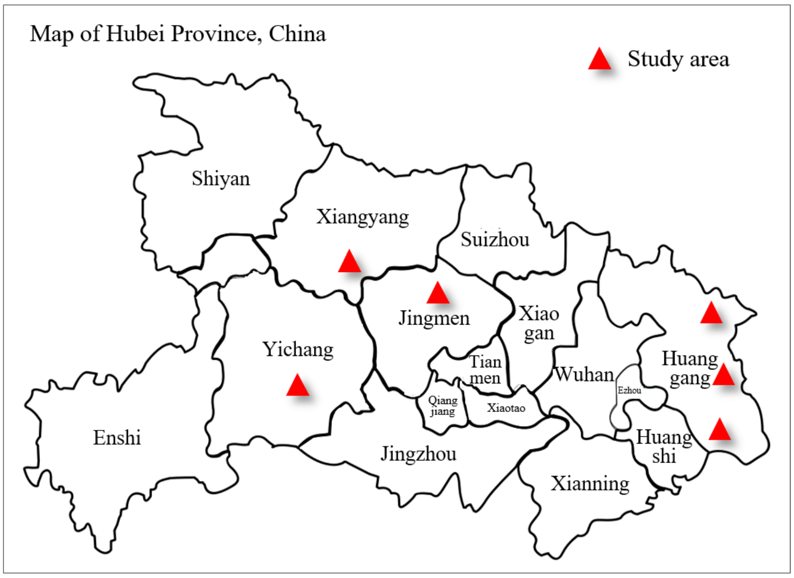

Figure 2 Distribution of study area

2.4 Model

To estimate the effect of technology extension on the adoption of biopesticides by rice farmers, the following econometric model is constructed:

$$biopesticide_i = \alpha + \beta_1 extension_i + \beta_2 control_i + \varepsilon_i \qquad (1)$$

where $biopesticide_i$ denotes the biopesticide adoption status of the ith rice farmer, $extension_i$ indicates biopesticide extension, and $control_i$ are other control variables affecting rice farmers' biopesticide adoption. α is the intercept term, ε is the random error term, and β are the coefficients to be estimated. If farmers participate in biopesticide extension and adopt biopesticides completely randomly independent of each other, the marginal effect β_1 obtained using OLS estimation can characterize the true effect of biopesticide extension on farmers' adoption behavior.

However, there are three possible difficulties for estimation. First, the adoption status of the same sample farmer before and after participating in biopesticide extension cannot be observed simultaneously. Second, both farmers' participation in agricultural extension and adoption of biopesticides may be influenced by common factors in this model, leading to sample selectivity bias (Gao et al., 2020). For example, younger and larger-scale farmers may have more opportunities to participate in agricultural extension, but age and scale are also important factors influencing biopesticide adoption. Third, the model may have endogeneity problems due to intercausality, measurement bias, or model setting bias.

Accordingly, this study further draws on the endogenous switching probit (ESP) model proposed by Lokshin and Sajaia (2011). First, the ESP model uses maximum information likelihood estimation (MILE) to construct a "counterfactual situation" opposite to the real situation of rice farmers so that the probability of biopesticide adoption by the same farmer in both participating and nonparticipating agricultural extensions can be predicted simultaneously. Second, the problem of sample selectivity bias due to observable and unobservable factors is controlled in the model by a two-stage estimation approach. Third, instrumental variables are introduced to address the potential endogeneity of the model.

First, an experimental group (participating in biopesticide extension) and a control group (not participating in biopesticide extension) were set up with reference to the quasi-natural experimental method. The treatment variable $extension_i$=1 indicates that the sample farmers were in the experimental group, while $extension_i$=0 indicates that the sample farmers were in the control group. The selection equation for rice farmers (whether to participate in biopesticide extension) was constructed using the probit model:

$$extension_i^* = \lambda_i V_i + \kappa_i I_i + \varepsilon_i, \begin{cases} extension_i = 1 \ \ if \ \ extension_i^* > 0 \\ extension_i = 0 \ \ otherwise \end{cases} \quad (2)$$

where $extension_i^*$ represents the latent variable of rice farmers' participation in biopesticide extension, and the value depends on the observable variable $extension_i$. V_i are other factors affecting farmers' participation in biopesticide extension. I_i is the instrumental variable. λ and κ are coefficients to be estimated. Here, we will draw on Huang et al.'s (2020) study and select "town distance" as the instrumental variable. The more distant the town is, the more difficult it is for rice farmers to access agricultural extension services, and the town distance is a geographic factor that satisfies the exogeneity condition of the model.

Second, the model outcome equation (whether to adopt biopesticides or not) was constructed:

$$biopesticide_{1i}^{*} = \mu_{1i} X_{1i} + \delta_{1i}, \begin{cases} biopesticide_{1i} = 1 \quad if\ biopesticide_{1i}^{*} > 0 \\ biopesticide_{1i} = 0 \quad otherwise \end{cases} \quad for\ extension_i = 1 \qquad (3)$$

$$biopesticide_{0i}^{*} = \mu_{0i} X_{0i} + \delta_{0i}, \begin{cases} biopesticide_{0i} = 1 \quad if\ biopesticide_{0i}^{*} > 0 \\ biopesticide_{0i} = 0 \quad otherwise \end{cases} \quad for\ extension_i = 0 \qquad (4)$$

where $biopesticide_i^{*}$ denotes the latent variable of rice farmers' biopesticide adoption, which depends on the observable variable $biopesticide_i$. u is the coefficient to be estimated. δ is a random interference term. Eq. (3) and (4) are fitted to estimate the predicted relationships between the independent and dependent variables in the experimental and control groups, respectively.

Finally, a counterfactual scenario is constructed using MILE to obtain the average treatment effect of the impact of biopesticide extension on farmer adoption. For the sample farmers in the experimental group (who already participated in agricultural extension), the difference in the probability of biopesticide adoption between the two scenarios, assuming they were in the nonparticipation scenario, is referred to as "the average treatment effect of the treated (ATT)".

$$ATT = \frac{1}{n}\sum_{i=1}^{n} \left\{ \Pr\left(biopesticide_{1i} = 1 \,\middle|\, extension_i = 1, X_i\right) - \Pr\left(biopesticide_{0i} = 1 \,\middle|\, extension_i = 1, X_i\right) \right\} \qquad (5)$$

Similarly, for sample farmers in the control group (not participating in biopesticide extension), the difference in the probability of biopesticide adoption between them, assuming they were in the participation scenario, is referred to as "the average treatment effect on the untreated (ATU)".

$$ATU = \frac{1}{m}\sum_{i=1}^{m}\left\{\Pr(biopesticide_{1i}=1 \mid extension_i=0, X_i) - \Pr(biopesticide_{0i}=1 \mid extension_i=0, X_i)\right\} \tag{6}$$

In Eqs. (5) and (6), n and m are the sample sizes of the experimental and control groups, respectively. The ATT and ATU values obtained from these calculations can be used as a basis for determining the average treatment effect of biopesticide extension on farmer adoption. In addition, this study will examine the regulatory effect of the "technology supply and demand" of biopesticides using group estimation to verify the heterogeneous impact.

2.5 Variable definition

(1) Dependent variable: Biopesticide adoption ($biopesticide_i$). The questionnaire item "Did you use biopesticides in rice cultivation in that year?" was used to measure farmers' biopesticide adoption status. If farmers had used biopesticides, $biopesticide_i$=1; otherwise, $biopesticide_i$=0. It was found that the main varieties of biopesticides that are commonly used are those made from *Bacillus thuringiensis*, *Avermectin*, *Wellbutrin* and *Bitter ginseng alkaloids*.

(2) Independent variable: biopesticide extension ($extension_i$). The questionnaire item "Have you participated in technical extension activities related to biopesticides?" was used to characterize agricultural extension. Similarly, the participation of rice farmers in agricultural extension was defined as $extension_i$=1; otherwise, $extension_i$=0. It should be noted that agricultural extension in this study mainly refers to biopesticide-related technology publicity, training, demonstration and subsidy activities conducted by government agricultural extension organizations (Geng et al., 2017; Wuepper et al., 2021).

(3) Regulated variables: Biopesticide supply and demand. The supply of biopesticides in this study refers to the availability of suitable biopesticide products on the market for farmers. Demand

refers to whether farmers truly want to use biopesticides. The effective supply and demand of biopesticides is formed only when farmers want to use and can purchase biopesticides (Yuan J, Niehof, 2011).

(4) Other variables: To ensure the rationality of the model setting, other important factors affecting farmers' biopesticide adoption were controlled as much as possible and mainly include factors such as rice farmers' personal characteristics, family characteristics, production characteristics, market characteristics, and farmers' cognition (Constantine et al., 2020; Paul et al., 2020; Huang et al., 2021). The variable definitions are detailed in Table 1.

Table 1 Definition, description and statistics of variables in the model

Variables	Definition and description	Biopesticide extension (N=928)		No biopesticide extension (N=220)		T-test
		Average	S.D.	Average	S.D.	
Biopesticide adoption	Do rice farmer use biopesticide? Yes = 1, no = 0	0.586	0.132	0.373	0.176	0.213**
Biopesticide extension	Do rice farmer participate in biopesticide extension (publicity, training, demonstration or subsidy)? Yes = 1, no = 0	-	-	-	-	-
Supply	Can rice farmers easily buy the biopesticide products in the market they want? Yes = 1, no = 0	0.225	0.106	0.219	0.120	0.106
Demand	Do rice farmers want to use biopesticide? Yes = 1, no = 0	0.317	0.158	0.286	0.115	0.031*
Age	The age of interviewee (year)	48.272	9.201	52.329	7.865	-4.057***
Education	The education years of interviewee (year)	9.263	2.357	8.256	3.051	1.007
Risk attitude	Risk attitude of interviewees: Risk aversion = 1, neutrality = 2, risk preference = 3	1.768	1.029	1.806	0.986	-0.038
Family income	Total family income of the interviewee in the previous year (10000 yuan)	13.882	5.120	10.257	4.281	3.625*
Production purpose	The main purpose of rice production: Self consumption = 1, market sales = 2	0.256	0.097	0.678	0.205	-0.422**
Scale	The scale of rice production (hm^2)	0.558	0.351	0.344	0.285	0.214***
Co-organization	Do rice farmers join the rice production cooperation organization? Yes = 1, no = 0	0.256	0.335	0.317	0.158	-0.061
Residue test	Are pesticide residue tests required when selling rice? Yes = 1, no = 0	0.152	0.105	0.167	0.121	-0.015
Brands	Whether the rice is certified by local, organic, green or ecological brands? Yes = 1, no = 0	0.109	0.056	0.098	0.047	0.011
Selling price	Average market price of rice sold (yuan/kg)	2.067	0.247	1.989	0.316	0.078
Pest cost	Average cost input of pest management per unit area (10000yuan/hm^2)	0.066	0.005	0.070	0.006	-0.004
Environment cognition	Importance of environmental protection: 1-5 points, very unimportant=1 and very important=5	3.625	1.002	3.577	0.991	0.048
Food safety cognition	Importance of food safety: 1-5 points, very unimportant=1 and very important=5	4.256	0.648	4.572	0.719	-0.316
Town distance	The distance from residential house to market town (km)	2.597	0.858	3.168	1.067	-0.571*

Notes: Regional variables and rice varieties are controlled in the form of dummy variables, which are not listed in this table. T-test is the test result of using Stata software to execute "ttest" code to obtain the average value difference between groups. *,**, and*** indicate significant at the 10%, 5%, and 1% significance levels, respectively.

3. Results

3.1 Descriptive statistics

We counted the participation of the sample rice farmers in biopesticide extension (Fig. 3). The data showed that the participation of rice farmers in biopesticide extension was 80.99%, 62.91%, 43.66%, and 9.86% for the technology publicity, technology demonstration, technology training, and technology subsidy samples, respectively. Rice farmers mainly obtain biopesticide information through technology publicity, such as posters, banners and brochures. Next, there are biopesticide technology demonstrations, which are mostly technology promotion activities in the sample region. The participation rate of farmers in technology training is also not very high. In addition, the research found that farmers currently know little about biopesticide subsidies, and most rice farmers consider the purchase of biopesticides to be "expensive" and "no subsidies". This may be related to China’s subsidy policy, which mainly targets pharmaceutical companies rather than individual farmers (Guo et al., 2019).

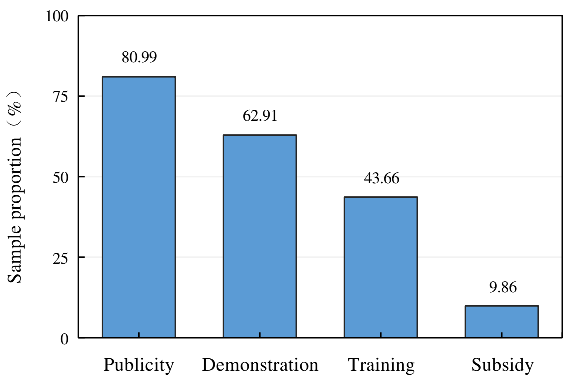

Figure 3 Proportion of biopesticide extension methods of sample rice farmers

Notes: The observed sample number is 1148 from the survey. Biopesticide extension methods include technical publicity, demonstration, training and subsidy.

Then, we determined statistics on the supply and demand of biopesticides among the sample rice farmers (Fig. 4). It was found that only 14.26% of the farmers were in the effective supply and demand category, and 69.56% of the sample still did not have the demand for adopting biopesticides. Worse still, 77.61% of the sample farmers felt that they could not purchase the required biopesticide products. It is worth noting that 16.18% of the sample farmers still could not buy satisfactory biopesticide products despite the demand for their use. Farmers in our research generally responded that biopesticides have few product varieties, slow effects, high prices, a narrow insecticidal spectrum and other attribute disadvantages. Only a small number of biopesticides sold on the market play a "long-acting" role, such as *Avermectin* and *Wellbutrin*, which are the only ones that can meet the real needs of farmers.

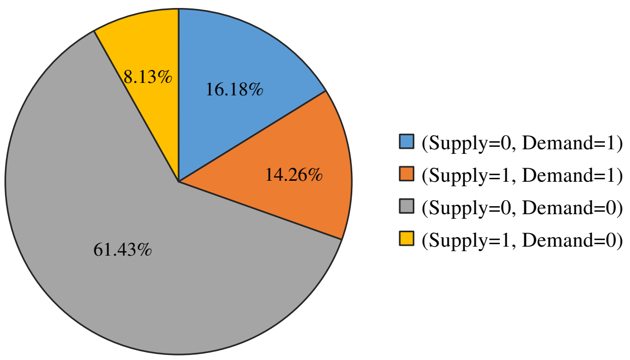

Figure 4 Statistics of biopesticide supply and demand of sample rice farmers

Notes: The observed sample number is 1148 from the survey. The definition and assignment of demand and supply are shown in Table 1.

3.2 Simultaneous estimation results of the selection equation and result equation

Necessary covariance diagnostics were performed for all variables in the model in turn. Then, to identify whether there is an association between the selection equation (whether to participate in biopesticide extension or not) and the outcome equation (whether to adopt biopesticides or not), the two equations were estimated jointly using MILE in Stata14 software, and the results are shown in Table 2. From the correlation coefficients ρ estimated from the selection equation and outcome equation, ρ_{ua} and ρ_{un} passed the significance level test of 10% and 5%, respectively, which shows that the covariance matrix between the equations is indeed correlated. The participation of rice farmers in agricultural extension and the adoption behavior of biopesticides are not completely independent. That is, the use of the ESP model is necessary.

Table 2 Simultaneous estimation results of selection equation and result equation

Variables	Selection equation: Biopesticide extension (Yes or no)		Outcome equation: Biopesticide adoption			
			Biopesticide extension		No biopesticide extension	
	Coef.	S.E.	Coef.	S.E.	Coef.	S.E.
Supply	0.102	0.065	0.051*	0.026	0.049**	0.017
Demand	0.025**	0.011	0.033**	0.012	0.022*	0.013
Age	-0.034***	0.009	-0.017*	0.009	-0.011*	0.006
Education	0.071***	0.025	0.063**	0.025	0.039**	0.015
Risk attitude	0.158	0.108	0.121	0.109	0.076	0.067
Family income	0.034**	0.014	0.029**	0.012	0.016**	0.006
Production purpose	-0.242**	0.104	0.248	0.199	0.219*	0.122
Scale	0.012***	0.002	-0.001	0.002	-0.001	0.001
Co-organization	-0.008	0.110	0.032	0.114	0.020	0.069
Residue test	-0.201	0.216	0.067**	0.028	0.041**	0.029
Brands	0.101	0.171	0.441**	0.168	0.088	0.104
Selling price	-0.006	0.008	-0.003	0.008	0.012**	0.005
Pest cost	-2.766	3.879	-1.701**	0.745	-1.123*	0.625
Environment cognition	-0.068	0.072	0.035	0.073	0.223***	0.044
Food safety cognition	-0.107	0.114	0.190*	0.113	0.177**	0.070
Town distance	0.316**	0.117	-	-	-	-
Constant	0.948	1.100	0.916*	0.493	0.585	0.467
ρ_{ua}	-		-0.308*	0.169	-	-
ρ_{un}	-		-	-	-0.435**	0.156
Log pseudo likelihood	-468.725		-	-	-	-
Wald test	5.830***		-	-	-	-

Notes: Regional and rice variety variables have been controlled. *,**, and*** indicate significant at the 10%, 5%, and 1% significance levels, respectively.

(1) Factors influencing the participation of rice farmers in biopesticide extension

From the estimation results of the selection equation, the probability of rice farmers' participation in biopesticide extension was significantly influenced mainly by demand, interviewee age, education, family income, production purpose, scale, and town distance. Specifically, there is no doubt that the supply of agricultural extension services is a prerequisite for farmers' participation. The age of the respondents negatively influenced the probability of rice farmers participating in biopesticide extension, which shows that the older the rice farmers are, the less likely they are to receive biopesticide extension and that they are in a disadvantaged position in the agricultural extension system (Sun et al., 2019). Similarly, the effects of education and family income are positive, which suggests that rice farmers with more education and higher incomes are more likely to have access to biopesticide extension services, as these farmers are often labeled "elite" in rural areas. The influence of production purposes is negative because subsistence rice farmers are generally smallholders, and the supply of agricultural extension they participate in cannot be effectively guaranteed (Huang et al., 2021). The impact of the rice scale is positive, indicating that rice farmers with larger scales are more likely to participate in biopesticide extension. Large-scale farmers are the "main force" of agricultural production in China and are also the main beneficiaries of agricultural extension. The influence of town distance is positive because agricultural extension service organizations are mainly clustered in townships, making it more convenient for rice farmers to access extension services the closer they are to the town.

(2) Factors influencing the adoption of biopesticides by rice farmers

From the estimation of the outcome equation, the adoption of biopesticide by rice farmers was significantly influenced by supply, demand, age, education, family income, production purpose, residue test, brands, selling price, pest cost, environmental cognition, and food safety cognition variables. What is obvious is that technology supply and demand are indeed key factors influencing farmers' biopesticide adoption. Specifically, farmer age negatively influenced the adoption of biopesticides by rice farmers, indicating that the older the rice farmers were, the lower the probability of adopting biopesticides. It is difficult to change the "habits" of older farmers in the short term due to their previous production experience (Huang et al., 2020; Bagheri et al., 2021). The direction of influence of education and household income is positive, indicating that highly educated and affluent rice farmers are more likely to adopt biopesticides (Yang et al., 2014). The direction of influence of production purposes is positive because subsistence rice farmers pay more attention to the quality and safety of rice and prefer to use biopesticides with a low toxicity and low residue (Paul et al., 2020). The positive impact of residue tests and brands indicates that both residue tests and brand systems for agricultural products will help increase the probability of active adoption of biopesticides, as the market demand for high-quality agricultural products will push rice farmers to use greener and safer production methods (Li and Guo, 2019). A higher selling price of rice and lower pest costs were also key factors promoting biopesticide adoption among farmers. In addition, the influence of environmental cognition and food safety cognition is also positive. Because biopesticides do not cause serious environmental pollution, they are typically green pesticides (Benoît et al., 2020). They also allow the production of safer and quality assured rice grains and avoid the agricultural poisoning caused by the overuse of chemical pesticides (Chen et al., 2013).

3.3 Average treatment effect estimation

The average treatment effect of biopesticide extension on the adoption behavior of rice farmers was further measured using Eqs. (5) and (6). The results are shown in Table 3. For the sample farmers who had participated in agricultural extension, their mean probability of adopting biopesticides was 0.552. In contrast, in their counterfactual scenario, the mean probability of adopting biopesticides was 0.435 assuming that they had not participated in agricultural extension. This result shows that for participating biopesticide extension sample farmers, the mean treatment effect ATT of agricultural extension on biopesticide adoption by rice farmers was 0.117. Similarly, for the sample farmers who did not participate in biopesticide extension, the mean treatment effect ATU of agricultural extension on biopesticide adoption among rice farmers was 0.103, which shows that the average treatment effect of biopesticide extension on rice farmers' adoption is 0.103~0.117, which means that agricultural technology can promote a 10.3% ~ 11.7% increase in the probability of farmers' biopesticide adoption.

Table 3 Average treatment effects of biopesticide extension on rice farmer's adoption behavior

Samples	Biopesticide adoption probability		Average treatment effects			
	Biopesticide extension	No biopesticide extension	ATT	*T*-valu	ATU	*T*-value
Biopesticide extension	0.552	0.435 [a]	0.117**	2.276	-	-
No biopesticide extension	0.570 [a]	0.467	-	-	0.103**	2.191
Only publicity	0.553	0.477 [a]	0.076	1.575	-	-
No publicity	0.547 [a]	0.388	-	-	0.159	1.403
Only training	0.502	0.347 [a]	0.155**	2.225	-	-
No training	0.547 [a]	0.399	-	-	0.148*	1.803
Only demonstration	0.566	0.381 [a]	0.185**	2.120	-	-
No demonstration	0.528 [a]	0.357	-	-	0.171***	2.991
Only subsidy	0.571	0.491 [a]	0.080	1.530	-	-
No subsidy	0.549 [a]	0.497	-	-	0.052	1.506

Notes: [a] means that this is the "counterfactual" estimation result obtained by MILE. Biopesticide extension in this table refers to any one or more of technical publicity, training, demonstration and subsidy. The number of observations is 1148. *,**, and*** indicate significant at the 10%, 5%, and 1% significance levels, respectively.

In addition, the ESP model was used to estimate the effects of four biopesticide extension methods, namely, technology publicity, training, demonstration, and subsidy, on adoption by rice farmers, and the results are shown in Table 3. From the values of ATT and ATU, technology publicity can promote a 7.6% ~ 15.9% increase in the probability of biopesticide adoption by rice farmers. Similarly, the enhancement effect from technology training is 14.8% ~ 15.5%; the enhancement effect from technology demonstration is 17.1% ~ 18.5%; and the enhancement effect from technology subsidies is 5.2% ~ 8.0%. Overall, biopesticide technology demonstration was the most effective way to extend biopesticides, followed by technology training. However, the effect of biopesticide technology publicity and subsidies needs to be improved because their coefficients were small and did not pass the significance test.

3.4 Regulatory effect estimation: Technology supply and demand

We then wanted to verify the differences in the effectiveness of biopesticide extension under different biopesticide supply and demand scenarios. The samples were divided into two subsamples three times according to biopesticide supply and demand. The impact of biopesticide extension on farmers' adoption behavior in different subsamples was estimated again using the ESP model, and the results are shown in Table 4. First, for the "only demand" samples, the mean treatment effects ATT and ATU of biopesticide extension on adoption by rice farmers were 0.078 and 0.066, indicating that agricultural extension increased the probability of biopesticide adoption by 6.6% ~ 7.8%. Second, for the "only supply" samples, the mean treatment effects ATT and ATU of biopesticide extension on adoption by rice farmers were 0.105 and 0.096, indicating that agricultural extension increased the probability of biopesticide adoption by rice farmers by 9.6% ~ 10.5%. Third, for the "both supply and demand" samples, the mean treatment effects ATT and

ATU of biopesticide extension on rice farmers' adoption were 0.361 and 0.247, indicating that agricultural extension increased the probability of biopesticide adoption by rice farmers by 24.7% ~ 36.1%. Fourth, for the subsamples of "no supply", "no demand" and "no supply or demand", all results estimated in the group failed the significance test.

The above results can be connected to two important findings. On the one hand, the supply and demand of biopesticides significantly regulated the effect of biopesticide extension on the adoption behavior of rice farmers. In the scenario with no effective supply and demand for biopesticides, agricultural extension is very ineffective, which is an important element to explain the poor effectiveness of biopesticide extension in China. The research hypothesis was verified. On the other hand, improving the supply-demand equilibrium of biopesticides can substantially improve the effectiveness of biopesticide extension. The estimated results for the "both supply and demand" sample group are 2.35~5.47 times higher than those for the "only supply" and "only demand" groups. Therefore, increasing the effective supply and demand of biopesticides is the top priority to promote the rapid expansion of biopesticides in China.

Table 4 Grouping estimation of average treatment effect under different supply and demand situation

Group samples	ATT	*T*-value	ATU	*T*-value
Only demand	0.078**	1.995	0.066*	1.791
No demand	0.015	1.028	0.023	1.426
Only supply	0.105*	1.5728	0.096	1.482
No supply	0.071	1.602	0.103	1.379
Both supply and demand	0.361***	4.508	0.247***	2.886
No supply or demand	0.017	0.098	0.014	1.025

Notes: Other result information is omitted here, and only ATT and ATU values are shown. *,**, and***indicate significant at the 10%, 5%, and 1% significance levels, respectively.

The above empirical evidence has found that the effective supply and demand of biopesticides is the key to determining the effectiveness of agricultural extension. However, differences in the roles of different biopesticide extension approaches need to be further explored. The sample farmers were divided into two groups: “both supply and demand” and “no supply or demand”. Then, the ESP model was used to estimate the average treatment effects ATT and ATU for the effects of technology publicity, training, demonstration and subsidies on the probability of farmers’ adoption. What is very clear from the results in Table 5 is the estimated difference between groups. First, in the "both supply and demand" scenario, the effect of any type of biopesticide extension is always significant. This again validates the regulatory effect of "supply and demand". Second, distinguishing the results in Table 3, effective supply and demand led to a substantial increase in the effectiveness of technology publicity, training, demonstration, and subsidies for biopesticide extension. Thus, the research hypothesis was reaffirmed.

Table 5 Average treatment effects of different biopesticide extension methods

Category	Group(1): Both supply and demand				Group(2): No supply or demand			
	ATT	*T*-value	ATU	*T*-value	ATT	*T*-value	ATU	*T*-value
Biopesticide extension	0.361***	4.508	0.247***	2.886	0.017	0.098	0.014	1.025
Publicity	0.325***	3.179	0.301**	2.525	0.125	1.056	0.117	1.635
Training	0.386**	2.598	0.279**	2.460	0.078*	1.971	0.064*	1.960
Demonstration	0.346***	4.207	0.258***	3.297	0.118**	2.325	0.113**	2.657
Subsidy	0.401***	3.005	0.314***	2.984	0.026	1.268	0.015	1.870
N	164				984			

Notes: Biopesticide extension in this table refers to any one or more of technical publicity, training, demonstration and subsidy. *,**, and***indicate significant at the 10%, 5%, and 1% significance levels, respectively.

3.5 Heterogeneous impact on farmers with different characteristics

In addition, we need to account for the impact of sample heterogeneity on the study findings. The sample was grouped in terms of the characteristics of scale, age, education, and co-organization, and the results in Table 6 were obtained after sequential estimation. Obviously, regardless of the characteristics of farmers, "both supply and demand" is still a strong guarantee of the effectiveness of biopesticide extension. Moreover, the results showed that biopesticide extension had a greater impact on smaller-scale, younger, less educated, and cooperative member sample farmers, whose average treatment effects on the probability of biopesticide adoption were 29.6%~30.1%, 20.5%~23.1%, 25.4%~30.4%, and 24.7%~25.5%, respectively.

First, large-scale and family farms have strong independent decision ability, and their access to technical information channels is rich and diverse. In contrast, small-scale farmers are in a disadvantaged position in the agricultural extension system, with a lower level of technical awareness, insufficient knowledge reserves and a single channel of access to technical information (Constantine et al., 2020). Therefore, biopesticide extension activities targeting a large number of smaller-scale farmers can achieve greater marginal utility in the short term. Second, for older farmers, their physical strength and human capital accumulation ability show a substantial decrease. It is difficult for them to understand, digest and absorb the professional technical contents of agricultural extension (Gao et al., 2020). Therefore, the effect of biopesticide extension is greatly reduced. Third, farmers with low education rely more on external technical expertise to conduct agricultural extension for better access to biopesticide information. Therefore, in the real situation in which the Chinese agricultural labor force generally has a low education level, it is necessary to target biopesticide extension, especially for farmers with an elementary school education or below (Paul et al., 2020). Fourth, for relatively scattered smallholder farmers, cooperative organizations will have more standardized agricultural production, supervision and management. Moreover, cooperative organizations can provide members with convenient biopesticide procurement, technical guidance, and marketing services, making biopesticide extension and application more secure.

Table 6 Impact of biopesticide extension on farmer's adoption with different characteristics

Group samples	Category	(1): Both supply and demand				(2): No supply or demand			
		ATT	*T*-value	ATU	*T*-value	ATT	*T*-value	ATU	*T*-value
Scale	Average and above	0.301***	3.124	0.296***	2.710	0.117**	2.015	0.151**	2.108
	Below average	0.173***	3.332	0.204***	3.171	0.102*	1.706	0.117*	1.861
Age	Average and above	0.231**	2.127	0.205*	1.746	0.122*	1.831	1.120	1.322
	Below average	0.136**	2.251	0.188**	2.126	0.134	1.060	0.118*	1.771
Education	Average and above	0.254**	1.886	0.304**	2.207	0.142*	1.861	0.155*	1.900
	Below average	0.205	1.571	0.217	1.609	0.172	1.328	0.119	1.526
Co-organization	No Member	0.180*	1.962	0.173	1.555	0.132	1.009	0.098	1.028
	Member	0.255***	3.291	0.247***	3.270	0.176**	2.067	0.190**	2.116

Notes: *,**, and***indicate significant at the 10%, 5%, and 1% significance levels, respectively. The definitions of the above four indicators are detailed in Table 1. the group division boundaries for scale, age and education are mean values.

4. Discussion

Unlike previous scholarly studies arguing for a causal relationship between agricultural extension and farmers' biopesticide adoption (Toepfer et al., 2020), this study further compared and contrasted the impact effects of four specific agricultural extension approaches: technology publicity, training, demonstration, and subsidies. Among them, we found that biopesticide technology demonstration is the most effective extension method. There is still a need to increase the construction of a biopesticide demonstration base so that farmers can see the "seeing is believing" effect for pest management (Guo and Wang, 2016). Of course, the most important finding is that insufficient supply and demand for biopesticide products are the core factors leading to low agricultural extension effectiveness. In our study, we found that 85.74% of the sample farmers affected the effective supply demand for biopesticides due to low demand or insufficient supply, which will be a major problem to be solved in the future extension of biopesticides (Abdollahzadeh et al., 2018). If we can accurately identify the biopesticide needs of farmers and supply targeted biopesticide products as a breakthrough point for biopesticide extension, we will likely achieve better practical effects in a short period of time. The findings of this paper have practical guidance value and can provide some reference for breaking the inefficient dilemma of biopesticide technology extension and optimizing its technology extension strategy.

Of course, this study has only empirically demonstrated agricultural extension by public government agricultural organizations and has not yet addressed the role played by for-profit market agents (e.g., pesticide retailers) in the biopesticide extension system (Constantine et al., 2020; Wuepper et al., 2021; Huang et al., 2021). In addition, we believe that while conducting biopesticide extension, it is equally crucial to cultivate the demand for biopesticide technology among rice farmers. If only the supply side of technology extension is considered, scholars attribute the inefficiency of biopesticide extension to a wrong process, weakness, a bad system, or a lack of financial investment (Sun et al., 2019; Guo et al., 2019). Thus, it will be very difficult for government departments to extend biopesticides for a long time. From the existing studies, the reasons for the lack of demand for biopesticides among farmers in real life mainly includes the high acquisition cost of biopesticides, the lack of product varieties, delayed efficacy, and the imperfect market for green agricultural products (Petrescu-Mag et al., 2019; Constantine et al., 2020). Compensating for these realistic shortcomings and subsequently inducing the demand for biopesticides among rice farmers will be the fundamental way to achieve effective substitution of biopesticides for chemical pesticides and the key to enhancing the efficiency of biopesticide extension from the technical demand side.

5. Conclusion and policy implications

This study uses data from a survey of 1148 rice farmers in Hubei Province, China, to empirically analyze two questions: what is the best way to extend biopesticides, and how can the effectiveness of biopesticide extension be optimized? The main results and findings are as follows.

First, the percentages of technology publicity, demonstration, training and subsidies among the biopesticide extension methods received by the sample farmers were 80.99%, 62.91%, 43.66% and 9.86%, respectively. However, only 14.26% of the farmers had demand for biopesticide products and were able to purchase their required products. A total of 85.74% of the sample farmers experienced ineffective biopesticide supply or demand. Second, biopesticide extension can promote the probability of adoption by rice farmers by 10.3% ~ 11.7%. There were also differences in the effects of technology publicity, training, demonstration, and subsidies. The best effect was biopesticide technology demonstration, followed by technology training. In contrast, the effects of biopesticide publicity and subsidies were not significant. Third, the regulatory effect of technology supply and demand on the impact of biopesticide extension on rice farmers' adoption is significant. The effectiveness of conducting biopesticide extension was substantially improved with the availability of supply and demand, which could explain the inefficiency of biopesticide extension. Fourth, there was heterogeneity in the impact of agricultural extension on biopesticide adoption by farmers with different characteristics. The impact of biopesticide extension was greater for smaller, younger, less educated, and cooperative member sample farmers.

Based on the above conclusions, some policy insights can be drawn. On the one hand, we must objectively understand the heterogeneous effect of the four agricultural extension methods:

biopesticide technology publicity, training, demonstration and subsidies. We must also insist on strengthening technology demonstration work to reduce farmers' worries about using biopesticides. Of course, to consider the equity and efficiency of agricultural extension issues, a wider range of farmers can participate in the promotion of biopesticides. On the other hand, it is important to focus on the excellent attributes of biopesticide products, accurately identify and guide agricultural producers' demand for biopesticides, and then make farmers more active and positive in using biopesticides. At the same time, it is also necessary to increase the product market supply of biopesticides. More importantly, we should focus on smaller, younger, less educated and cooperative member farmers to carry out biopesticide extension to obtain a greater marginal output effect.

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Conflict of Interest Declaration

The authors declare that they have no competing interest.

Author contribution

Yanzhong Huang: Conceptualization, Methodology, Validation, Investigation, Writing - review & editing. **Zhaoliang Li:** Funding acquisition, Project administration, Writing - original draft. **Xiaofeng Luo:** Funding acquisition, Project administration, Resources, Conceptualization. **Di Liu:** Investigation, Data curation, Formal analysis, Visualization.

Data availability

Supporting materials such as research questionnaires, experimental data and sample farmer lists used in this study can be obtained with justification from the first or corresponding author.

Declarations

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