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Adoption of Multiple Sustainable Manure Treatment Technologies by Pig Farmers in Rural China: A Case Study of Poyang Lake Region

Jingyuan Cai [1], Liguo Zhang [2,*], Jing Tang [2] and Dan Pan [2,3,*]

1 School of Accounting Shanghai National Accounting Institute, Shanghai 201702, China; daisy_cai@outlook.com
2 School of Economics, Jiangxi University of Finance and Economics, Nanchang 330013, China; tjing_0318@163.com
3 Jiangxi Provincial Condition Research Center, Nanchang 330077, China
* Correspondence: njlgzhang@163.com (L.Z.); pandan@jxufe.edu.cn (D.P.); Tel.: +86-791-8381-6042

Received: 26 June 2019; Accepted: 13 November 2019; Published: 16 November 2019

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Abstract: The adoption of sustainable manure treatment technologies (SMTTs) in livestock production helps to reduce agricultural contamination. As such, understanding what determines farmers' adoption of SMTTs is an essential prerequisite for the administrative handling of livestock pollution. Applying a multivariate probit model on a cross-sectional data set of 686 pig farmers in Poyang Lake Region in China, this study discovered that two key factors influencing farmers' decisions to adopt multiple SMTTs are off-farm labor and environmental awareness. In other words, households with a higher share of off-farm labor are less likely to adopt SMTTs. Farmers with higher environmental awareness are more likely to adopt SMTTs. The results also revealed that because of the inappropriateness of government subsidy and insufficient technical training, the impact of Chinese government subsidy on the adoption of biogas technology is negligible, but the subsidy on composting greatly helps to promote the adoption of composting technology. We also found a substitution effect and complementary effects between different SMTTs. These findings can improve policymakers' understanding of farmers' joint adoption decisions. It also helps policymakers to optimize subsidy strategies to encourage farmers' adoption of SMTTs in rural China.

Keywords: pig production; manure management; multivariate probit model; Poyang Lake region

1. Introduction

With the increasingly rapid industrialization and urbanization progress, as well as the growing demand for livestock products, livestock production in China has developed rapidly in recent years [1]. The gross output value of livestock production in 2018 in China is RMB 28,697 billion ($4159 billion), which is 137 times more than the value in 1978. Currently, China is the world's largest producer of livestock products [2]. The continued increase in livestock production has generated a large amount of manure. It is estimated that the Chinese livestock industry produces approximately 3.8 billion tons of manure each year [3]. Theoretically, if treated appropriately, this amount of manure can produce 3.68 million tons of organic fertilizers with a total value of RMB 262 billion ($38 billion) annually [3].

To stimulate sustainable manure management, a series of policies, including subsidy policies, rules, and regulations, are enforced in China [4,5]. For example, the Chinese government has provided financial subsidies to induce farmers to apply biogas technology for manure treatment since 2000. It is reported that the total biogas subsidy for manure treatment has reached nearly RMB 500 billion ($72.5 billion) in 2018 [6]. In 2014, The Ministry of Agriculture and the Ministry of Finance started the "Sustainable Manure Treatment" program, and by 2018, the Chinese government had invested RMB 430 billion ($62.3 billion) to promote this program. In addition, some regulations, such as "Prevention and Treatment on Pollution from Livestock Cultivation", stated that farms must treat manure in a sustainable way. In some provinces, farmers will pay a pollution fee if they do not treat manure in a sustainable way; the level of pollution fees ranged from 30 RMB/head/year to 120 RMB/head/year in pig production [7].

Despite these massive initiatives to encourage farmers to treat manure in a sustainable way, farmers' adoption rate of sustainable manure treatment technologies (SMTTs) remains low [7]. It is reported that 40% of manure in China is not effectively treated and utilized and over 20% of manure is being directly discarded into rivers or lands without appropriate processing [3]. Unsustainable treated manure will cause great harm to the air, land, water systems, and human health [8]. As such, strategic management of livestock manure is an important approach to reduce GHG emissions and to protect the environment [3]. Understanding the main influencing factors that impede or facilitate farmers' adoption of SMTTs is an essential prerequisite toward the sustainability of livestock production in the rural areas of both the developed and developing countries.

Most existing studies have treated farmers' adoption of SMTTs as separate decisions, focusing on the adoption of only one or two isolated types of SMTTs independently, such as returning to the field [2,9], producing biogas [10,11], composting [12], sale [7], and arbitrary discard [13]. Limited attention has been given to the adoption of multiple types of SMTTs. However, as the benefits, costs, and constraints associated with different manure treatment technologies are in great variety, farmers may adopt a bundle of manure treatment technologies rather than a single technology to maximize their expected utility [14]. For example, Zheng et al. [15] found that farmers often simultaneously adopt a bundle of SMTTs, and different SMTTs may be closely related, either as complements or as substitutes. Pan et al. [7] also highlighted that the impact of SMTTs on manure pollution reduction depends on whether they are adopted independently or as a package. Hence, analyses without considering interdependence among different SMTTs may get biased estimates of the impact of various factors on the decision of SMTTs adopting.

Therefore, this study aims to fill this gap by employing a multivariate probit model (MVP) to jointly analyze the driving forces that facilitate or impede the probability of farmers' simultaneous adoption of multiple SMTTs. Our study is based on first-hand collected data of 686 pig farmers in the Poyang Lake Region (PLR) of China, a region located in one of the largest freshwater lakes in China and the biggest ecological wetland in Asia.

Pig farmers are selected for this study because pig manure management is the main challenge of sustainable manure management in China. Pigs are the main slaughtered livestock in China. For example, the number of slaughtered pigs was 694 million in China in 2018, accounting for 55% of the world's total slaughtered pigs [16]. Pig manure accounts for more than 60% of all manure from livestock production in China. As such, understanding the adoption of SMTTs by pig farmers is important for livestock manure management.

The remaining part of the paper proceeds as follows: Section 2 provides detailed information on the data and statistical model. Section 3 reports the estimation results of the multivariate probit model. The final section gives conclusions.

2. Materials and Methods

2.1. Study Site

This paper selected the Poyang Lake Region (PLR) in Jiangxi Province as the study site (see Figure 1). Located in Poyang Lake, one of the largest freshwater lakes in China and the biggest ecological wetland in Asia, PLR plays an important role in safeguarding the ecological environment and protecting biodiversity [17]. However, in recent years, pollution from livestock production has caused accelerated environmental deterioration in this region, such as eutrophication, water quality decline, and biodiversity losses [18]. Advancing farmers' adoption of SMTTs in this region is a significant way towards environmental sustainability.

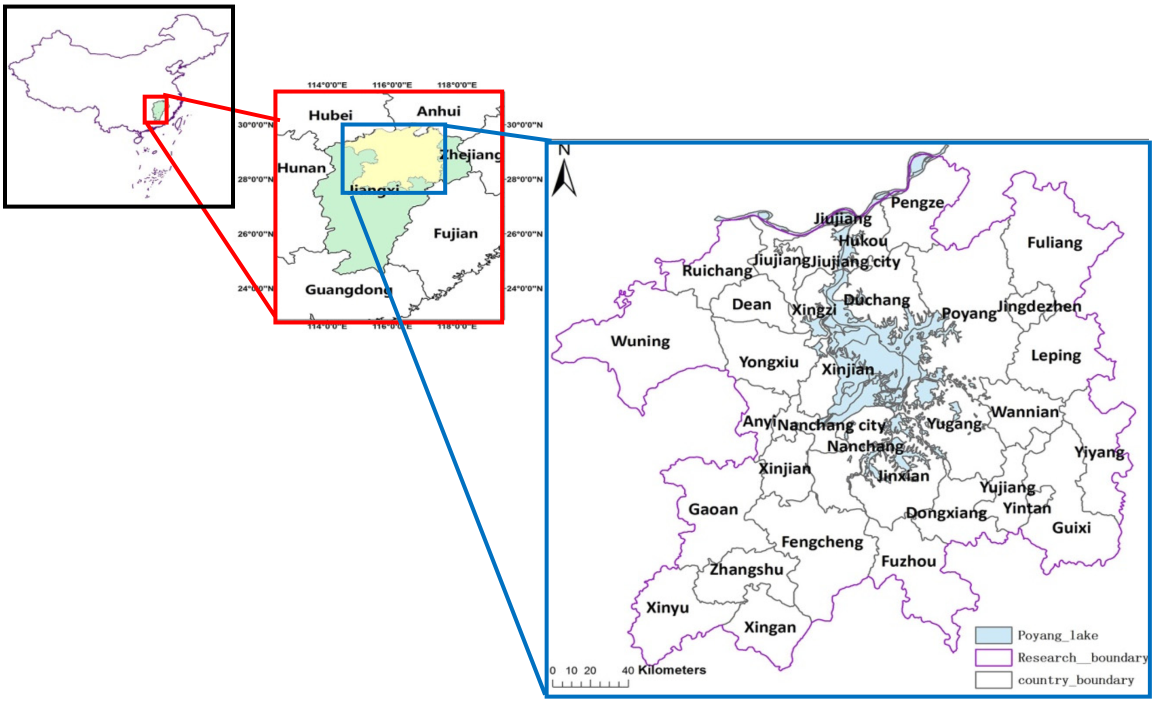

Figure 1. The Location of the Poyang Lake region.

2.2. Sampling Techniques

The data used in this study were collected by the authors in PLR from June to July 2018. We used a stratified random sampling method to choose samples. First, 12 counties were chosen from PLR based on pork production. Second, four villages in each county were chosen based on pork production. Finally, we randomly selected fifteen to twenty pig farmers in each village. Hence, 686 pig farmers in 48 villages from 12 counties were investigated.

We used a structured questionnaire to get first-hand data through face to face interviews. The questionnaire consisted of five sections. The first section focused on pig farmers' socioeconomic information, including age, education, pig breeding years, risk attitude, farm size, and off-farm labor. The second section related to information regarding pig breeding situation, including pig breeding size, pig breeding income, and others. The third section collected information on farmers' environmental awareness of manure. Farmers were investigated regarding their perception of the impacts of manure on the environment and human health and their willingness to treat manure. During the interview, farmers were required to give detailed information concerning their pig manure treatment approaches. The final section related to information regarding government support policies about pig manure treatment, such as biogas subsidy and technical training.

2.3. Dependent Variables

The adoption of manure treatment technologies in rural China is the dependent variable in our analysis. Five manure treatment approaches are mainly adopted in pig production in China, namely returning to the field, arbitrary discard, composting, producing biogas, and sale [5]. Table 1 shows the definition and impacts of different manure treatment technologies. The latter three technologies—*Composting*, *Biogas*, and *sale*—are defined as SMTTs because the environmental damage of these technologies is relatively low. The first two technologies, *Returning* and *Discard*, are not SMTTs because they are less environmentally friendly.

Table 1. Definition and impacts of different manure treatment technologies.

Types of Manure Treatment Approaches	Definition	Impacts	SMTTs or Not
Returning to the field (*Returning*)	Manure is directly returned to the field as fertilizer without any treatment	Must consider how much manure the land can absorb and will cause damage to the environment.	No
Arbitrary discard (*Discard*)	Manure is arbitrarily dumped into land or river	Impose serious environmental damage	No
Composting technology (*Composting*)	Manure is composted to generate organic fertilizer.	Reducing the use of chemical fertilizer and the damage of manure	Yes
Producing biogas technology (*Biogas*)	Manure is collected and stored in biogas digesters to produce biogas.	Alleviating energy shortage in rural China	Yes
Sale technology (*Sale*)	Manure is sold to planting farmers or agricultural factories to produce organic fertilizer	Reducing the use of chemical fertilizer and the damage of manure	Yes

2.4. Independent Variables

Based on previous literature on the adoption of sustainable agricultural technologies, especially manure treatment technologies, we categorize the factors influencing farmers' adoption of SMTTs into five categories: Individual characteristics, household characteristics, pig breeding characteristics, environmental awareness, and government support policies. Detailed descriptions of the explanatory variables and their expected effects on the adoption of manure treatment technologies are discussed below.

Individual characteristics. (1) *Gender*. Compared with younger farmers, older farmers might be more shortsighted and less physical and mental efficacy, resulting in a lower likelihood of adopting SMTTs [19]. (2) *Education*. We expect that education can increase the possibility of adopting SMTTs. Education can increase the farmers' ability to access new information about SMTTs [20]. In addition, farmers with higher education are more likely to recognize the benefits and constraints of new technologies [21]. (3) *Leader*. Being a village leader usually implies a wide interpersonal network [22]. Farmers who are village leaders can obtain more information about the benefits of new technologies and thus are more likely to adopt SMTTs. (4) *Breeding experience*. Breeding experience captures farmers' manure management knowledge gained through past experience. Farmers may continue their manure management behavior in the future based on their breeding experience [23]. Because SMTTs have not been widespread in the past in rural China, we expect that farmers with more breeding experience are less likely to adopt SMTTs. (5) *Risk attitude*. The adoption of SMTTs might be risky and challenging for pig farmers because it requires obvious changes in pig production and high financial input [24]. Therefore, we expect that farmers who are accepting of risk are more likely to adopt SMTTs, especially those technologies that require high financial investment, such as *Biogas* and *Composting*.

Household characteristics. (1) *Farm size*. *Returning* and *Composting* need sufficient farmland to absorb the generated manure [3]. Therefore, with the increase in farm size, the possibility of adopting *Returning* and *Composting* is higher, and the possibility of adopting *Discard*, *Biogas*, and *Sale* is lower. (2) *Share of off-farm labor*. The impact of the share of off-farm labor on adopting SMTTs is inconclusive. On one hand, with the increase of the share of off-farm labor, farmers would spend less time on livestock breeding and are less likely to adopt labor-intensive manure treatment technologies, such as *Composting* and *Biogas* [25]. On the other hand, a higher share of off-farm labor may allow farmers to have enough money to pay the high and long-term investment costs of SMTTs [26]. (3) *Household income*. We expect that households with higher income are more likely to adopt SMTTs, especially technologies that require high financial investment, such as *Biogas* and *Composting*. This is because adopting SMTTs requires high investment, while the economic returns are expected in the medium to long term [27].

Pig breeding characteristics. (1) *Pig breeding scale*. We hypothesize that pig breeding scale will increase the likelihood of adopting SMTTs. Increasing pig breeding scale leads to more generated manure and thus requires significant effort to address manure pollution [28]. Meanwhile, governmental manure treatment regulation is stricter with the increase of pig breeding scale. For instance, the "Prevention and Treatment on Pollution from Livestock Cultivation" enforced in 2014 stated that larger-scale pig breeding farmers (market pig inventory of more than 500) must adopt SMTTs to treat manure, otherwise they will face a pollution fine. In addition, farmers with larger pig breeding scale often have enough capital to invest in SMTTs [29]. (2) *Share of pig breeding income*. A higher share of pig breeding income implies that more importance is attached to pig breeding. In addition, compared with households with a lower share of pig breeding income, the benefits of adopting SMTTs in the long term are greater for households with a higher share of pig breeding income [1]. Thus, we expect that the share of pig breeding income has a positive impact on the adopting of SMTTs.

Environmental awareness. The theory of planned behavior has proven that awareness is a harbinger to a decision to take action [30]. Environmental awareness has been empirically confirmed to be a decisive influencing factor in the farmers' decision to adopt sustainable agricultural technologies [31]. We use three variables to proxy environmental awareness: Environmental impact awareness of manure, human health impact awareness of manure, and manure treatment willingness. We hypothesize that higher environmental awareness will induce farmers to adopt SMTTs.

Government support policies. Adopting SMTTs is, in fact, a public goods game. From the perspective of farmers, profit can be earned by neglecting to treat manure pollution, while public goods—the environment—could be lost because of untreated manure. Therefore, the Chinese government has provided different kinds of financial supports for the adoption of SMTTs [32]. There are mainly two kinds of subsidies for SMTTs. One is the biogas subsidy, which aims at inducing farmers to generate biogas from manure and the other is the composting subsidy, which encourages farmers to treat manure as composting fertilizers [7]. We proxy government support policies using the following three indicators: Biogas subsidy, composting subsidy, and technical training. We expect that government support policies will increase farmers' possibility of adopting SMTTs.

2.5. Statistical Method

A commonly used method in previous literature on the adoption of agricultural technologies is a univariate econometric method, such as probit or logit model [33]. However, as stated in the introduction, farmers will adopt a package of manure treatment technologies rather than a single technology to maximize their expected utility [14]. Farmers' adoption of different manure treatment technologies may be interdependent, either as complements (positive correlation) or as substitutes (negative correlation). Using univariate probit or logit models in such cases will result in biased and inefficient conclusions since univariate models ignore potential interdependence that exists between different manure treatment technologies [34–36].

Against this background, we apply a multivariate probit (MVP) modeling approach that can account for the correlation in the error terms of different manure treatment technologies adoption equations. MVP can estimate multiple technologies adoption models simultaneously while allowing unobserved and unmeasured factors (error terms) to be correlated [37]. Our MVP model comprises five binary choice equations, namely treatment technology of returning to the field, arbitrary discard, composting, producing biogas, and sale. As a result, we have five dependent binary variables Y_{ij}^* for a farmer. The MVP model is specified as:

$$Y_{ij}^* = \beta_j X_i + \mu_{ij},\ j = 1,2,3,4,5 \tag{1}$$

$$Y_{ij} = \begin{cases} 1 & \text{if } Y_{ij}^* > 0 \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

where j represents the choices of five manure treatment technologies; Y^*_{ij} denotes the latent variable captured the level of expected utility derived from the choice of technology j; this latent variable is assumed to be a linear combination of observed characteristics, X_i, including pig farmers' individual characteristics, household characteristics, pig breeding characteristics, environmental awareness and government support policies, and unobserved characteristics captured by the stochastic error term, μ_{ij}, β_j are vectors of coefficients to be estimated. Given the latent nature of Y^*_{ij}, estimation is based on observable binary variables Y_{ij}, which is a binary observable variable showing whether or not farmers adopt the technology.

In the MVP model, the error terms $\mu_{ij}(j = 1,2,3,4,5)$ are assumed to jointly follow a multivariate normal distribution (MVN) with conditional mean 0 and a variance-covariance matrix Ψ, namely $\mu_{ij} \approx \mathrm{MVN}(0,\Psi)$. The variance-covariance matrix Ψ has value 1 on the leading diagonal, and correlations $\rho_{ij} = \rho_{ji}$ as off-diagonal elements. The symmetric variance-covariance matrix is given as follows:

$$\Psi = \begin{bmatrix} 1 & \rho_{12} & \rho_{13} & \rho_{14} & \rho_{15} \\ \rho_{12} & 1 & \rho_{23} & \rho_{24} & \rho_{25} \\ \rho_{13} & \rho_{23} & 1 & \rho_{34} & \rho_{35} \\ \rho_{14} & \rho_{24} & \rho_{34} & 1 & \rho_{45} \\ \rho_{15} & \rho_{25} & \rho_{35} & \rho_{45} & 1 \end{bmatrix} \tag{3}$$

where ρ(rho) refers to the pairwise correlation coefficient of the error terms corresponding to any two manure treatment technologies adoption equations to be estimated. ρ provides information on the correlation relationship between different manure treatment technologies. If ρ is significantly positive, then there is a complementary relationship between different manure treatment technologies. If ρ is significantly negative, then there is a substituted relationship between different manure treatment technologies.

3. Results and Discussion

3.1. Descriptive Statistics of the Survey

The statistical description and expected signs of independent variables are presented in Table 2. The average age of the surveyed samples is 48 years and most farmers have six years of education, which is in consistent with the fact that most farmers in China being middle-aged with poor education [38]. One-quarter of the surveyed respondents are village leaders. Most farmers are risk averse and have seven years of pig breeding experience. On average, farmers have 1.78 mu (0.11 ha) farmland areas and the share of off-farm labor is almost 50%, which is in accordance with most farmers in China being small-scale and highly engaged in off-farm activities [39]. The average household income is nearly RMB 48,000 ($ 6952), which is close to the average household income in Jiangxi province in 2017. The environmental awareness of pig production was relatively low, with most surveyed respondents believing that manure has a little negative effect on the environment and has nearly no negative effect on human health. Nevertheless, most pig farmers (78%) are willing to treat manure in a sustainable way. Most farmers have received biogas subsidies and composting subsidies from the government, but only 12% of samples have participated in technical training on manure treatment.

In sum, our surveyed samples are in consistent with the Chinese agricultural population in age, education, farm size, share of off-farm income, and household income.

Table 2. Variable definitions and expected signs.

Variables	Definition	Mean	Std. Dev.	Expected Sign				
				Discard	Returning	Biogas	Sale	Composting
Individual characteristics								
Age	Age of household head (years)	48.29	11.27	+	+	-	+/-	-
Education	Education of household head (years)	7.35	2.89	-	-	+	+	+
Leader	1 = household head is village leader; 0 = otherwise	0.16	0.36	-	-	+	+	+
Breeding experience	Years breeding pigs	7.26	0.87	+	+	-	+/-	-
Risk attitude	1 = risk-accepting; 2 = risk-neutral; 3 = risk-aversion	2.31	0.69	+	+	-	+/-	-
Household characteristics								
Farm size	Cultivated land area per capita (mu/person)	1.78	8.43	-	+	-	-	+
Share of off-farm labor	Share of off-farm labor in the total labor (%)	0.47	0.29	+	-	-	+	-
Household income	Household income (thousand RMB)	48.98	58.25	+/-	-	+	+/-	+
Pig breeding characteristics								
Pig breeding scale	Number of pigs owned by the household	235.6	1214.46	-	-	+	+	+
Share of pig breeding income	Share of pig breeding income (%)	0.52	0.44	-	-	+	+	+
Environmental awareness								
Environmental impact awareness of manure	1 = nearly no negative impact; 2 = little negative impact; 3 = less serious negative impact; 4 = serious negative impact	2.08	1.56	-	-	+	+/-	+
Human health impact awareness of manure	1 = nearly no negative impact; 2 = little negative impact; 3 = less serious negative impact; 4 = serious negative impact	1.42	0.92	-	-	+	+/-	+
Manure treatment willingness	1 = willing to treat manure in a sustainable way; 0 = otherwise	0.78	0.45	-	-	+	+/-	+

Table 2. *Cont.*

Variables	Definition	Mean	Std. Dev.	Expected Sign				
				Discard	Returning	Biogas	Sale	Composting
Government support policies								
Biogas subsidy	The logarithm of the amount of biogas subsidy farmers received	4.36	2.35	-	-	+	+/-	+
Composting subsidy	The logarithm of the amount of composting subsidy farmers received	2.01	1.87					
Technical training	1 = if the farmer has participated in technical training about manure treatment; 0 = otherwise	0.12	0.28	-	-	+	+/-	+

Data source: Author's survey, 2018; Note: "+" indicates the effect of this variable is positive; "-" indicates the effect of this variable is negative; "+/-" indicates the effect of this variable is not sure.

3.2. Statistical Analyses of Variables

3.2.1. Statistical Analyses of Dependent Variables

Figure 2 shows the proportion of farmers adopting different manure treatment technologies in pig production in our survey. It implies that *Returning* is the main manure treatment technology in that 62% of the pig farmers in our sample adopt it. Other treatments, *Biogas*, *Discard*, *Composting*, and *Sale* are used by 26%, 18%, 14%, and 11% of pig farmers, respectively. These figures indicate that SMTTs is not widely adopted in rural China, as only 58% of pig farmers have adopted *Biogas*, *Composting*, and *Sale*. As a result, there is still great potential to enhance the adoption of SMTTs. In addition, our results show that 63% of pig farmers have adopted at least two manure treatment technologies, which indicates that farmers adopt a bundle of technologies rather than a single one.

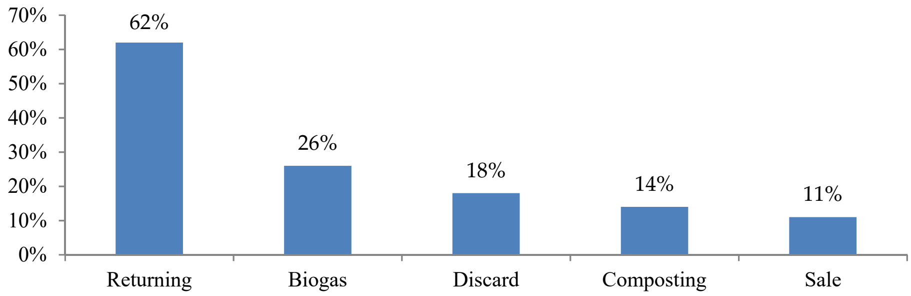

Figure 2. The proportion of pig farmers adopting different manure treatment technologies in rural China. Data source: Author's survey, 2018; Note: Farmers may adopt multiple manure treatment technologies, so the total proportion exceeds 100%.

Our survey results are consistent with previous studies. For example, Huang et al. [13] reported that 9.76% of pig farmers sold their manure to markets. Chadwick et al. [3] showed that 66% of farmers recycled manure into farmland and almost 20% of farmers discarded manure into rivers or lakes. Wei et al. [40] found that almost 15% of farmers adopted composting technology and nearly 28% of farmers adopted biogas technology to treat pig manure.

3.2.2. Statistical Analyses of Independent Variables

Table 3 shows the statistical analyses of the relationship of different independent variables and the adoption rates of SMTTs. The results are in line with our expectation stated in Section 2.4. For example, farmers that are younger, higher-educated, have more breeding experience, and risk-accepting are more likely to adopt SMTTs. Households with more farmland, lower share of off-farm labor, more household income, larger pig breeding scale, and higher share of pig breeding income have a higher possibility to adopt SMTTs. Farmers with higher environmental awareness and government subsidy are also more likely to adopt SMTTs.

However, this simple statistical analysis has no causal interpretation of the impact of independent variables on the adoption of SMTTs. Therefore, in the next section, we will use the MVP model that can control for other factors to empirically examine the effect of independent variables on SMTT' adoption.

Table 3. Statistical analyses of independent variables.

Variables	Category	Adopting Rates				
		Discard	Returning	Biogas	Sale	Composting
Age	≤30	12.28%	38.6%	49.12%	14.04%	19.3%
	30–40	14.29%	57.82%	25.85%	12.24%	16.33%
	40–50	14.55%	63.33%	23.03%	11.52%	13.64%
	≥50	16.36%	68.64%	18.18%	11.36%	12.27%
Education (year)	≤6	21.96%	65.49%	15.29%	9.81%	12.16%
	6–9	13.75%	61.89%	27.22%	10.03%	13.18%
	9–12	9.17%	63.89%	27.78%	16.67%	13.89%
	≥12	4.76%	38.1%	57.14%	28.57%	26.19%
Leader	Yes	10.12%	31.36%	36.56%	20.32%	25.21%
	No	20.68%	58.43%	19.89%	9.95%	20.78%
Breeding experience (year)	≤5	15.74%	51.8%	27.21%	11.48%	11.48%
	5–10	13.85%	64.23%	28.85%	11.54%	14.62%
	≥10	16.93%	75.66%	15.87	7.94%	11.11%
Risk attitude	Risk-accepting	10.62%	48.67%	28.33%	27.43%	13.33%
	Risk-neutral	20.45%	61.1%	25.19%	8.73%	11.47%
	Risk-aversion	9.17%	70.05%	19.47%	5.83%	9.73%
Farm size (mu)	≤1	15.48%	57.12%	24.91%	11.92%	10.32%
	1–2	17.76%	58.88%	25.23%	9.35%	20.56%
	≥2	11.76%	62.35%	24.71%	3.53%	16.47%
Share of off-farm labor	≤20%	3.61%	81.93%	12.05%	8.43%	9.64%
	20%–50%	13.69%	61.73%	26.54%	9.51%	15.36%
	50%–80%	21.26%	61.02%	25.59%	6.32%	11.42%
	≥80%	16.95%	40.68%	30.51%	38.98%	3.39%
Household income	Low	25.67%	67.89%	17.32%	8.15%	13.24%
	High	13.12%	43.21%	36.34%	18.91%	17.81%
Pig breeding scale	≤50	15.31%	72.56%	16.12%	4.17%	12.92%
	50–500	17.33%	42.08%	40.59%	22.28%	9.93%
	≥500	8.16%	36.73%	46.94%	28.57%	24.49%
Share of pig breeding income	≤20%	16.67%	54.84%	29.03%	3.76%	20.43%
	20%–50%	15.19%	58.86%	34.18%	6.96%	17.09%
	50%–80%	12.84%	58.78%	20.95%	18.92%	4.73%
	≥80%	16.03%	62.98%	30.15%	12.98%	8.46%
Environmental impact awareness of manure	Nearly no negative impact	22.87%	73.93%	9.97%	9.25%	14.08%
	Little negative impact	20.11%	58.05%	27.01%	15.52%	17.24%
	Less serious negative impact	18.11%	50.39%	38.58%	9.45%	7.09%
	Serious negative impact	13.39%	45.54%	51.79%	6.25%	6.25%
Human health impact awareness of manure	Nearly no negative impact	20.82%	68.45%	17.81%	12.66%	14.59%
	Little negative impact	23.16%	59.32%	31.07%	5.65%	12.43%
	Less serious negative impact	18.31%	50.71%	33.83%	15.49%	4.23%
	Serious negative impact	15.11%	20.32%	40.21%	2.56%	2.75%
Manure treatment willingness	Yes	16.58%	82.76%	15.17%	3.45%	0.69%
	No	10.34%	57.14%	27.26%	12.32%	15.27%
Biogas subsidy	Low	19.12%	65.32%	16.75%	10.18%	13.21%
	High	18.76%	59.89%	67.85%	11.21%	14.36%
Composting subsidy	Low	17.63%	64.35%	25.35%	10.22%	11.82%
	High	18.25%	60.04%	26.12%	12.03%	32.45%
Technical training	Yes	16.41%	62.38%	24.33%	10.61%	12.59%
	No	2.13%	57.45%	34.04%	10.64%	14.89%

Data source: Author's survey, 2018.

3.3. Interdependence of SMTTs

Table 4 shows the estimates of the binary correlations between the error terms of the five adoption equations. It shows SMTTs are interdependent with each other. The likelihood ratio test ($\chi^2(10) = 86.24$; Prob > $\chi^2 = 0.000$) of the independence of different manure treatment technologies' adoption rejected the null hypothesis of zero correlation between the error terms, suggesting that the adoption of different manure treatment technologies is not mutually independent. Therefore, the MVP is more appropriate than the single-equation probit or logit models. Significant coefficients between different manure treatment technologies also support the assumption that different manure treatment technologies are not adopted independently of each other. Specifically, we find five relations of substitutability and one relation of complementarity. In particular, there is a substitute relationship between *Discard* and *Biogas*, *Returning* and *Biogas*, *Returning* and *Composting*, *Biogas* and *Sale*, and *Biogas* and *Composting*, while there is a complementary relationship between *Returning* and *Discard*.

Table 4. Correlation coefficient estimates for multivariate probit model (MVP) regression equations.

Approaches	Discard	Returning	Biogas	Sale	Composting
Discard	—	—	—	—	—
Returning	0.397 ***(0.125)	—	—	—	—
Biogas	−0.214 **(0.103)	−0.354 ***(0.102)	—	—	—
Sale	−0.132(0.104)	−0.295(0.179)	−0.197 ***(0.049)	—	—
Composting	−0.198(0.232)	−0.326 ***(0.084)	−0.479 ***(0.121)	0.127(0.078)	—

Note: (1) Likelihood ratio test of $\rho_{21} = \rho_{31} = \rho_{41} = \rho_{51} = \rho_{32} = \rho_{42} = \rho_{52} = \rho_{43} = \rho_{53} = \rho_{54} = 0$; $\chi^2(10) = 86.24$; Prob > $\chi^2 = 0.000$. (2) ***, ** denote statistical significance at the one percent and five percent levels, respectively.

3.4. MVP Estimation Results

The estimation results of the determinants of farmers' adoption of SMTTs are presented in Table 5. We find that most of the estimated coefficients for individual characteristics, government support policies, and environmental awareness are in line with our expectations.

3.4.1. Individual Characteristics

As expected, age has a significant positive impact on *Discard* and *Returning*, indicating that older farmers are more likely to choose unsustainable manure treatment technologies than younger farmers are. Education plays a negative role in the adoption of *Discard* and *Returning*, while a significant positive impact of education is found on *Biogas* and *Sale*. These results indicate that education can promote the adoption of SMTTs, which is in accordance with the conclusion of previous studies [15]. However, the correlation between education and *Composting* is not significant, which contradicts our expectation. A possible reason is that just as Table 4 shows, *Composting* and *Biogas* are substitutes, farmers can substitute *Composting* by choosing *Biogas*, resulting in a positive effect on *Biogas* while no effect on *Composting*.

Being a village leader can increase the adoption of *Biogas* and *Sale*. Two possible explanations are as follows. First, village leaders have higher abilities for information acquisition and technology acceptance than ordinary farmers do, which enhances the possibility of adopting SMTTs. Second, village leaders in rural China can often obtain more government subsidies due to their close connection with upper government levels [41]. According to the survey data of our sample, government subsidies for SMTTs allocated to village leaders are four times higher than those allocated to ordinary farmers. This high government subsidy decreases the financial cost of adopting SMTTs for village leaders and thus increases their likelihood of adopting.

The coefficient of breeding experience is not significant in all five models, indicating that breeding experience has no impact on the adoption of SMTTs. Our results also indicate that compared with risk-averse farmers, farmers who are accepting of risk are more likely to adopt *Biogas* and *Composting*, which is consistent with our expectation. However, the adoption behavior of risk-neutral farmers is almost the same as that of risk-averse farmers.

Table 5. Estimates of the multivariate probit model.

Variables	Discard	Returning	Biogas	Sale	Composting
Individual characteristics					
Age	0.030 * (0.016)	0.024 * (0.013)	−0.002 (0.010)	−0.019 (0.017)	−0.002 (0.011)
Education	−0.233 * (0.127)	−0.216 * (0.116)	0.164 * (0.086)	−0.166 * (0.096)	0.024 (0.146)
Leader	−0.234 (0.466)	−0.254 (0.274)	0.303 * (0.167)	0.157 * (0.083)	−0.522 (0.536)
Breeding experience	0.007 (0.021)	0.012 (0.011)	−0.013 (0.012)	0.026 (0.025)	−0.009 (0.016)
Risk attitude (Risk-adverse farmers as reference)					
Risk-accepting farmers	−0.365 (0.331)	−0.231 (0.256)	0.075 *** (0.022)	0.031 (0.114)	0.062 ** (0.031)
Risk-neutral farmers	−0.223 (0.167)	−0.042 (0.193)	−0.087 (0.121)	−0.224 (0.156)	0.153 (0.115)
Household characteristics					
Farm size	−0.021 *** (0.008)	0.050 ** (0.025)	−0.001 (0.007)	−0.469 *** (0.169)	0.012 * (0.007)
Share of off-farm labor	0.089 ** (0.048)	−0.053 ** (0.026)	0.071 (0.079)	0.052 ** (0.026)	−0.067 * (0.038)
Household income	0.000 (0.000)	−0.015 ** (0.008)	0.000 (0.000)	−0.001 (0.001)	0.000 (0.000)
Pig breeding characteristics					
Pig breeding scale	−0.004 *** (0.001)	−0.003 ** (0.001)	0.002 * (0.001)	0.003 *** (0.001)	0.003 ** (0.001)
Share of pig breeding income	0.025 (0.091)	0.022 ** (0.011)	−0.039 (0.038)	0.071 (0.097)	−0.042 (0.059)
Environmental awareness					
Environmental impact awareness of manure (nearly no negative impact as reference)					
Little negative impact	0.254 (0.179)	−0.289 (0.198)	0.197 (0.186)	−0.225 (0.172)	0.153 (0.124)
Less serious negative impact	−0.258 (0.197)	−0.264 * (0.145)	0.642 *** (0.224)	0.226 (0.213)	0.289 (0.204)
Serious negative impact	−0.468 ** (0.233)	−0.215 *** (0.073)	0.641 ** (0.284)	−0.236 (0.184)	0.173 (0.117)
Human health impact awareness of manure(nearly no negative impact as reference)					
Little negative impact	0.079 (0.122)	0.084 (0.075)	0.035 (0.046)	−0.127 (0.095)	−0.321 (0.238)
Less serious negative impact	−0.156 (0.213)	0.187 (0.121)	0.265 * (0.136)	−0.132 (0.204)	−0.641 (0.432)
Serious negative impact	−0.221 ** (0.094)	−0.379 *** (0.123)	0.187 *** (0.052)	0.321 (0.256)	0.542 (0.432)
Manure treatment willingness	−0.459 *** (0.104)	−0.801 *** (0.255)	0.534 ** (0.248)	0.216 ** (0.114)	0.136 ** (0.065)
Government support policies					
Biogas subsidy	−0.042 (0.121)	−0.037 (0.053)	0.024 (0.054)	−0.066 (0.112)	0.077 (0.132)
Composting subsidy	−0.065 (0.127)	−0.023 (0.073)	0.016 (0.087)	0.076 (0.101)	0.025 ** (0.013)
Technical training	−0.128 * (0.070)	−0.096 (0.132)	0.002 (0.253)	0.284 (0.195)	0.119 (0.252)
Constant	−4.139 *** (1.452)	3.345 *** (0.862)	−4.327 *** (0.941)	−1.657 (1.244)	2.146 (1.311)
Log likelihood = −500.82	Wald $\chi^2(95) = 294.33$	Prob > chi^2 = 0.000			

Note: (1) Robust standard errors within brackets. (2) ***, **, * denote statistical significance at the one percent, five percent, and ten percent levels, respectively.

3.4.2. Household Characteristics

Farm size is positively related to the adoption of *Returning* and *Composting* and is negatively related to the adoption of *Discard* and *Sale*. This result may be explained by the fact that farmers with larger farmland areas will have sufficient surrounding areas to consume a large amount of manure, resulting in a higher possibility of the application of *Returning* and *Composting* [42]. This result is in agreement with those obtained by Wu et al. [38] and Ren et al. [43], who stated that scaled farming has created more opportunities for the establishment of eco-agriculture and eco-livestock. The coefficient of farm size on *Biogas* is insignificant, indicating large farm size cannot promote the application of *Biogas*. A possible explanation is that as Table 4 shows, *Composting* and *Biogas* are substitutes; farmers may substitute *Biogas* by choosing *Composting* treatment technology.

Off-farm labor has a significant positive impact on *Discard* and *Sale*, while it has a significant negative impact on *Returning* and *Composting*. These relationships may partly be explained by the fact that *Returning* and *Composting* are labor-intensive technologies demanding a large amount of time and labor input. Households with more off-farm labor will have less labor to adopt *Returning* and *Composting*. This finding was also reported by Kassie et al. [14] and Nigussie et al. [44], who showed that households with a higher share of off-farm labor are less likely to adopt labor-intensive technologies.

Unexpectedly, the impact of household income is significant only in the model of *Returning*, suggesting that household income has no impact on the adoption of SMTTs. This result corroborates the findings of Luo et al. [45], who showed that financial constraint is not the main factor that hinders farmers from adopting sustainable agricultural technologies.

3.4.3. Pig Breeding Characteristics

In accordance with our expectation, the pig breeding scale has a significant positive impact on *Biogas*, *Sale*, and *Composting*, while it has a negative impact on *Discard* and *Returning*. Similar results were observed in Zheng et al. [41], who found that large-scale farms are more likely to adopt SMTTs. There are three possible explanations for this result. First, with the increase of pig breeding scale, the scale economic benefit of adopting SMTTs is greater, resulting in a higher possibility of adopting SMTTs. Second, large-scale pig breeding farms (market pig inventory of more than 500) are under strict environmental regulation and are required to adopt SMTTs by government. For instance, the technology standard "Discharge Standard of Pollution from Livestock Cultivation", issued by the Chinese State Council, set specific regulations for sustainable manure treatment of scaled farms. Third, large-scale pig breeding farms often lack adequate farmland to absorb relatively greater amounts of generated manure, resulting in a lower possibility of *Discard* and *Returning.*

The coefficient of the share of pig breeding income is significant only in the model of *Returning*, which contradicts our expectation. This inconsistency may be due to that households with a higher share of pig breeding income also have more labor engaged in agriculture, thus resulting in a higher likelihood of adopting *Returning*, which is a labor-intensive technology.

3.4.4. Environmental Awareness

In line with previous studies [46–48], environmental awareness is important for explaining the decision to adopt SMTTs. The estimates related to environmental impact awareness of manure show that compared with farmers who consider manure has no negative impact on the environment, farmers who consider manure has a less serious negative impact on the environment have a higher likelihood of adopting *Biogas* and a lower likelihood of adopting *Returning*, while farmers who consider manure has a serious negative impact on the environment have a higher likelihood of adopting *Biogas* and a lower likelihood of adopting *Returning* and *Discard*. Compared with farmers who consider manure to have no negative impact on human health, farmers who consider manure to have a less serious negative impact on human health have higher possibilities of adopting *Biogas*, while farmers who consider manure to have a serious negative impact on human health have higher possibilities of adopting *Biogas* and a lower likelihood of adopting *Returning* and *Discard*.

In addition, our results suggest that farmers willing to treat manure have higher possibilities of adopting SMTTs, such as *Composting*, *Biogas*, and *Sale*, and are less likely to adopt unsustainable manure treatment technologies, such as *Returning* and *Discard*.

3.4.5. Government Support Policies

The coefficient for biogas subsidy is not significant in any of the five models, indicating that biogas subsidy has no impact on the adoption of SMTTs. This result contradicts with our expectation but it is similar to the previous study of Sun et al. [49], showing that the net effect of biogas subsidy on household biogas development was almost negligible. Three possible explanations are as follows. First, compared with the actual investment in SMTTs, the biogas subsidy is relatively low, resulting in a low incentive for farmers to adopt SMTTs. For example, the current level of biogas subsidy is 500 RMB for each household biogas digester in northeastern and western areas of China, 1200 RMB in central areas of China, and 1000 RMB in eastern areas of China [50]. The average cost of a household biogas digester is approximately 2000 RMB. As a result, approximately 50% of the biogas digester construction cost should be paid by farmers, which hinders the installation of biogas digesters [10]. Second, the biogas subsidy is not targeted effectively. The current biogas subsidy mainly targeted household biogas projects. However, because of the great transformation of the agricultural and rural social environment and other factors, such as scaled livestock breeding, agricultural modernization, and off-farm activities, the impact of biogas subsidy on the development of household biogas projects has been weakened [51]. Third, the economic profit of the household biogas project is very weak, which worsens the impact of biogas subsidy on SMTTs' adoption. It is estimated that the annual economic benefit of a household biogas digester, including profits from biogas power generation and fertilizer sale, is only 1300 RMB when subsidy provided and negative when no subsidy provided [10].

However, our results show that composting subsidy can promote the adoption of *Composting*. This is because composting subsidy in rural China has flexible ways to subsidize composting production, which can reduce the three main costs for the adoption of *Composting*, namely high production cost, high transportation cost, and expensive composted fertilizer price [3]. First, composting subsidy can subsidize composting equipment, such as manure beds, perforated tubes, blowers, forklifts, and heap turners, which helps to decrease the production cost of compost fertilizer [52]. It can also subsidize the transportation of composting fertilizer to lower the high transportation cost. Meanwhile, composting subsidy can provide financial supports to encourage farmers to replace composting fertilizer for inorganic fertilizer. In some programs, the level of subsidy for composting fertilizer is about 180–450 RMB/ton in rural China, which is equal to 20% of the total price of composting fertilizers [7].

The technical training variable is negatively related to the adoption of *Discard*, indicating that trained farmers are less likely to adopt *Discard*. However, unexpectedly, the coefficient for technical training was not significant in the models of *Composting* and *Biogas*, suggesting that technical training has no impact on the adoption of SMTTs. A possible reason is that the central objective of the Chinese livestock technical training system is to maximize livestock production to meet the growing consumption demand for a long time. Livestock technical training systems in China generally only extend yield-increasing technologies and neglect environmental-protection technologies [53]. As a result, almost 80% of the pig farmers in our sample do not have experience attending any technical training programs on the adoption of SMTTs. Therefore, it is not surprising that technical training has not increased the adoption of SMTTs.

3.5. Robustness Check: Addressing the Endogeneity Problem

There may be a potential endogeneity problem in the MVP model because some explanatory variables could be endogenous. For example, manure treatment willingness is one of endogenous variables. First, there may be a reverse effect between manure treatment willingness and adoption of manure treatment technologies. For instance, farmers who have adopted SMTTs will know the benefits and constraints of new technologies better and will thus have higher willingness to treat manure. Second, both manure treatment willingness and adoption of manure treatment technologies may be affected by some omitted variables. For example, some unobservable household characteristics, such as motivation, ability, or breeding skill, may influence the adoption decision of manure treatment technologies, and they also may be correlated to farmers' manure treatment willingness.

To address the endogeneity problem, according to the suggestion by Kassie et al. [54], we conducted the MVP model without the potentially endogenous variable (manure treatment willingness in our case). The results are presented in Table 6. A comparison of the coefficients associated with the variables in Tables 5 and 6 shows that most of the estimated coefficients are almost the same. This finding supports the robustness of our results when considering the endogeneity problem.

Table 6. Estimates of the multivariate probit model excluding potential endogenous variable.

Variables	Discard	Returning	Biogas	Sale	Composting
Individual characteristics					
Age	0.035 ** (0.015)	0.016 (0.012)	−0.010 (0.008)	−0.021 (0.014)	−0.007 (0.014)
Education	−0.024 * (0.013)	−0.032 ** (0.014)	0.022 * (0.011)	0.02 ** (0.009)	0.023 (0.143)
Leader	−0.215 (0.143)	−0.232 (0.266)	0.132 (0.098)	0.165 ** (0.063)	−0.302 (0.244)
Breeding experience	0.013 (0.017)	0.015 (0.031)	−0.026 (0.018)	0.018 (0.022)	−0.015 (0.022)
Risk attitude (Risk-adverse farmers as reference)					
Risk-loving farmers	−0.147 (0.168)	−0.215 (0.166)	0.075 ** (0.032)	0.055 (0.129)	0.074 *** (0.031)
Risk-neutral farmers	−0.151 (0.116)	−0.044 (0.142)	−0.065 (0.177)	−0.432 (0.268)	0.153 (0.177)
Household characteristics					
Farm size	−0.016 ** (0.008)	0.019 *** (0.007)	−0.013 (0.034)	−0.021 (0.014)	0.017 *** (0.006)
Share of off-farm labor	0.028 * (0.014)	−0.036 *** (0.013)	0.045 (0.036)	0.031 *** (0.0114)	−0.043 ** (0.019)
Household income	0.000 (0.000)	−0.003 (0.003)	0.000 (0.000)	−0.002 (0.001)	0.000 (0.000)
Pig breeding characteristics					
Pig breeding scale	−0.003 ** (0.001)	−0.005 ** (0.002)	0.003 *** (0.001)	0.002 ** (0.001)	0.003 ** (0.001)
Share of pig breeding income	0.032 (0.022)	0.028 ** (0.012)	−0.026 (0.024)	0.065 (0.064)	−0.016 (0.017)
Environmental awareness					
Environmental impact awareness of manure (nearly no negative impact as reference)					
Little negative impact	0.165 (0.124)	−0.209 (0.166)	0.224 (0.168)	−0.255 (0.176)	0.047 (0.142)
Less serious negative impact	−0.244 (0.165)	−0.304 (0.187)	0.568 *** (0.163)	0.322 (0.218)	0.121 (0.134)
Serious negative impact	−0.073 ** (0.035)	−0.693 *** (0.201)	0.987 *** (0.197)	−0.458 (0.292)	0.187 (0.215)
Human health impact awareness of manure(nearly no negative impact as reference)					
Little negative impact	0.215 (0.168)	−0.022 (0.172)	0.033 (0.156)	−0.248 (0.175)	−0.143 (0.121)
Less serious negative impact	−0.212 (0.198)	0.246 (0.153)	0.302 ** (0.142)	−0.215 (0.290)	−0.694 (0.432)
Serious negative impact	−0.147 * (0.083)	−0.303 ** (0.146)	0.169 *** (0.063)	0.206 (0.132)	0.766 (0.642)

Table 6. *Cont.*

Variables	Discard	Returning	Biogas	Sale	Composting
Government support policies					
Biogas subsidy	−0.023 (0.132)	−0.014 (0.036)	0.043 (0.064)	−0.024 (0.098)	0.098 (0.114)
Composting subsidy	−0.068 (0.131)	−0.032 (0.082)	0.025 (0.074)	0.076 (0.113)	0.034 ** (0.014)
Technical training	−0.213 ** (0.087)	−0.068 (0.126)	0.065 (0.076)	0.094 (0.115)	0.321 (0.243)
Constant	−4.319 *** (1.452)	3.345 *** (0.862)	4.327 *** (0.941)	−1.657 *** (0.344)	3.143 ** (1.311)
Log likelihood = −654.38	Wald $\chi^2(95)$ = 323.96		Prob > chi^2 = 0.000		

Note: (1) Robust standard errors within brackets. (2) ***, **, * denote statistical significance at the one percent, five percent, and ten percent levels, respectively.

4. Conclusions

A significant challenge facing the Chinese government is to manage massive amounts of manure in a sustainable way to reduce environmental pollution, alleviate the energy shortage, and decrease inorganic fertilizer use. Understanding farmers' adoption behavior of SMTTs is an essential prerequisite for an efficient policy design of sustainable livestock production. Based on a large household data survey in Poyang Lake Region in rural China, this study investigated the factors that influence farmers' adoption decisions of multiple types of SMTTs in pig production in rural China using a multivariate probit model.

We found that the adoption rates of SMTTs are very low. Only 58% of the pig farmers have adopted SMTTs for *Biogas*, *Composting*, and *Sale*, suggesting a great potential to enhance the adoption rates of SMTTs to safeguard environmental sustainability. Our results also show that many manure treatment technologies are related to each other, some complementary, and others substitutable. Hence, policies aimed at promoting the adoption of SMTTs should consider technology interdependence.

Our results indicate that the adoption of SMTTs requires sufficient labor input. Households with a higher share of off-farm labor are less likely to adopt SMTTs. This suggests that if China wants to achieve broad-based adoption of SMTTs among farmers, policies must fully account for the impact of off-farm activities on labor availability and time devoted to the adoption of SMTTs.

Our results also confirm that the adoption of SMTTs requires adequate knowledge. Farmers with higher environmental awareness are more likely to adopt SMTTs. Hence, improving environmental awareness is a primary channel to promote the adoption of SMTTs. However, the environmental awareness of pig farmers in our sample is relatively low. Most pig farmers identified that manure has "nearly no" or "little" impact on the environment and human health. There is significant potential to increase farmers' environmental awareness and enhance the adoption of SMTTs.

Furthermore, our results show that government support policies, such as biogas subsidy and technical training, have no impact on farmers' adoption of SMTTs. This is mainly due to the inappropriateness and low efficiency of biogas subsidy and insufficient technical training. However, the subsidy encourages the adoption of composting. Therefore, designing scientific biogas subsidy, such as shifting the biogas subsidy from the construction stage to the follow-up management stage, and providing more technical training programs for the sustainable treatment of manure are steps that might improve the adoption of SMTTs.

Author Contributions: Conceptualization, J.C. and D.P.; data curation, J.C. and J.T.; formal analysis, J.C. and L.Z.; funding acquisition, L.Z. and D.P.; investigation, J.T.; methodology, J.T. and D.P.; project administration, J.C., L.Z., and D.P.; software, J.T. and D.P.; writing—original draft, J.C. and D.P.; writing—review and editing, L.Z. and D.P.

Funding: We would like to thank the financial support from the National Youth Talent Support Program, the National Natural Science Foundation of China (No. 71863016; No. 71673123; No. 71663025), the Outstanding Youth of Natural Science Foundation in Jiangxi Province (No. 2018ACB21004), the Science and Technology

Research Foundation of Jiangxi Province (No. GJJ170349), and the Postgraduate Innovation Research Foundation of Jiangxi Province (No. YC2019-S210).

Conflicts of Interest: The authors declare no conflict of interest.

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