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Sowing the seeds of sustainability: a deep dive into farmers' recycling practices of pesticide packaging waste in China

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Despite growing agricultural modernization, a majority of pesticide packaging waste (PPW) remains inadequately recycled in China, posing threats to agricultural sustainability and food safety. Drawing from the nationally representative CRRS dataset encompassing 10 provinces and 2,131 households, this study addresses critical research gaps in PPW management by integrating novel dimensions of farmers' cognition, infrastructure accessibility, and regional heterogeneity, using both multinomial logit (MNL) and propensity score matching (PSM) methods. Our findings show that farmers' awareness of PPW's harm on soil and the environment positively influences recycling behavior, while cognitive obstacles negatively impact recycling likelihood. Farmer perspectives on food security demonstrate a dual role, indicating a potential knowledge gap regarding the harmful consequences of burying or burning PPW. The results also highlight that the presence of fixed collection points significantly enhances farmers' recycling practices. The study suggests a need for interventions, such as promoting fixed collection points and targeted educational programs, to enhance awareness and dispel misconceptions. A comprehensive policy approach, integrating infrastructure development, education, and community engagement, is crucial for fostering sustainable PPW management, ensuring an environmentally responsible and agriculturally sustainable future.

KEYWORDS

pesticide packaging waste disposal, recycling practices, farmer's decision making, cognition, environmental policy

1 Introduction

Pesticide packaging waste (PPW) refers to the packaging materials used in the production, distribution, and application processes of pesticide products, such as bottles, bags, boxes, and similar items. China is the world's largest consumer of pesticides, utilizing a substantial volume annually, resulting in a significant generation of pesticide packaging waste. It is estimated that China produces approximately 2.9 billion to 3.5 billion units of packaging waste from pesticide application in agricultural production each year. Among these, discarded bottles range from 1.3 billion to 1.6 billion units, discarded bags from 1.6 billion to 1.9 billion units, equivalent to a weight of around 100,000–110,000 tons (Ren et al., 2021). However, a majority of the PPW remains inadequately recycled or disposed of, being carelessly discarded in fields, ditches, and waterways, buried *in situ* or burnt in open air, which accumulates over time, resulting in soil, water and air pollution, affecting agricultural landscapes, disrupting ecosystems, and posing a significant threat to the safety and quality of agricultural products (Patarasiriwong et al., 2013; Damalas et al., 2008; Ansari et al., 2024; Kaur et al., 2024). In developed countries, packages are often collected by professional organizations (Briassoulis et al., 2014), whereas the smallholder context in China makes the collection of this waste much more difficult (Jin et al., 2018). Hence, there is an urgent need to strengthen supervision and management of the recycling and disposal of PPW to prevent its pollution.

Regarding this situation, in recent years, China has successively introduced regulations aimed at strengthening the control of agricultural non-point source pollution and promoting green agricultural development. However, these legal provisions lack strong operability and thus cannot fully meet the practical needs of PPW management. Therefore, as major users of pesticides, studying the behaviors of farmers in recycling PPW is of great practical importance.

Previous studies have extensively examined various factors influencing farmers' disposal behavior of pesticide packaging waste (PPW). Xu et al. (2021) identified recycling price, local government regulations, and economic compensation as key factors promoting ex situ disposal of PPW. Huang and Elahi (2022) and King et al. (2023) highlighted that the main reason farmers did not recycle agricultural plastics was insufficient available facilities in rural areas. Generally, farmers prefer subsidy incentives over penalties, although subsidies are less effective for higher-income farmers (Huang and Elahi, 2022). In such cases, social norms may play a crucial role in promoting recycling behavior (Li et al., 2022; Sorkun, 2018; Zhang Y.H. et al., 2023).

Additionally, farmers' cognition, such as knowledge about how to recycle agricultural plastics (King et al., 2023), environmental cognition (Xu et al., 2021), ecological attitude (Abadi, 2023; Song et al., 2024) and perceived value (Li et al., 2020), has been shown to have a significant and positive impact on their intention and behavior of plastic residue management. Neighborhood effects and social learning have been found to improve farmers' environmental awareness and appropriate disposal behaviors (Cishahayo et al., 2022; Qiao et al., 2023; Chen et al., 2024). Membership in cooperatives or associations further enhances farmers' adherence to government policies regarding PPW disposal (Al Zadjali et al., 2013; Li and Huo, 2023). Policy interventions, such as mortgage return policies (Hu et al., 2022) and government's actions toward increasing farmers' environmental awareness (Wąs et al., 2021), have also been found to significantly enhance recycling rates.

As can be seen, the existing studies have significantly advanced our understanding of PPW management by elucidating the roles of economic incentives, environmental awareness, and policy interventions in shaping disposal behaviors. Nonetheless, a few notable limitations persist. Firstly, seldom research investigates the impact of fixed collection point on farmers' behavior, with only Li et al. (2022) undertaking a comprehensive investigation in Zhejiang province. However, they neglected farmers' alternative disposal methods such as burning or burial *in situ*. Secondly, the nuanced influence of farmers' cognition on broader aspects, such as food security and recycling challenges, has not been adequately examined. Little attention has been directed toward understanding whether farmers who possess heightened awareness of challenges and demonstrate a higher concern for food security are more inclined to adopt and implement more sustainable PPW disposal practices. This study aims to bridge this research gap by incorporating these dimensions into our empirical models. Thirdly, the diverse preferences for PPW disposal across regions and the decision-making processes among farmers are insufficiently understood. Decision-making processes among farmers involve navigating through a spectrum of choices, encompassing recycling to fixed points or markets, burning, burial *in situ*, collection and burial, and indiscriminate dumping. In particular, burning and burial in situ emerge as prevalent disposal practices in rural China, which deserves careful consideration. To address this research gap, our study employs a multinomial logit (MNL) model to comprehensively examine the impact of various features on farmers' choices among these disposal categories. Fourthly, existing studies often rely on small-scale or region-specific datasets, limiting their representativeness (King et al., 2023). To overcome this limitation, we employ the 2020 China Rural Revitalization Survey (CRRS) nationally representative dataset for empirical analysis, aiming to provide a basis for the formulation of policies related to promoting the construction of fixed collection points.

This study is organized as follows: the research hypothesis, data and methods are explained in section 2; empirical results are presented in section 3; discussion is provided in section 4 and conclusion is summarized in section 5.

2 Hypotheses, data and methods

2.1 Research hypotheses and variable selection

Based on an in-depth analysis of cognition-behavior theory, this study constructs an analytical framework for the impact of cognition on farmers' PPW disposal behaviors. Studies have shown that environmental cognition is a strong predictor of environmental behavior. Cognitive variables, usually include those factors about knowledge of the environment or environmental policy (He et al., 2022; Xue et al., 2021). This entails not only knowledge of rural environmental policies, but may also have pertained to the knowledge of the benefits of a specific environmental governance measure. For example, Song et al. (2024) defined ecological cognition as farmers' understanding and perception of PPW governance, including four dimensions: time and energy cognition, management effect cognition, pollution prevention responsibility, and public health protection responsibility. The impact of cognition on undesirable waste disposal behaviors has also been studied, highlighting how perceived risk and expected harm to individuals and the public can influence environmental behavior. For instance, Xu et al. (2021) found that farmers' awareness of the risks of pesticide use on farmland significantly influenced their ex situ disposal of waste plastic bottles. Similarly, Zhou et al. (2020) concluded that Chinese farmers' soil pollution risk perception (including the perception that pesticides may contaminate the soil) have positive effects on their pro-environment behavior. Based on the above analysis, we then hypothesize:

> *H1:* Households that perceive harms on soil, crop production or environment from PPW are more likely to perform sustainable PPW disposal behaviors.
>
> *H2:* Households that perceive obstacles from recycling PPW—such as no subsidy/punishment or peer effect—are more likely to perform unsustainable PPW disposal behaviors.

The concern for food security may also significantly influence households' likelihood of engaging in sustainable disposal behaviors of PPW. Nguyen et al. (2022) argued that households that perceive personal benefits from sorting food waste into the green bin are more likely to perform sustainable waste disposal behaviors. Similarly, households prioritizing food security, caring about pesticide residue and producing "safe" vegetables for their own consumption may perceive higher personal benefits. This heightened awareness of personal benefits can lead to greater awareness of the environmental impacts of agricultural practices, including the disposal of PPW. Therefore, we propose

> *H3:* Households that pay more attention on food security are more likely to perform sustainable PPW disposal behaviors.

The availability of fixed collection points for PPW could significantly influence the likelihood of households engaging in sustainable disposal behaviors. This hypothesis is supported by empirical evidence from various studies. Fixed collection points provide a convenient and accessible location for households to dispose of their PPW, thereby reducing the barriers and transaction costs associated with waste disposal, making it more feasible for households to participate in recycling programs (Li et al., 2022). Additionally, fixed collection points may also serve as a signal of community supervision and the establishment of social norms around sustainable waste management. Social norms and network have been identified crucial factors influencing farmers' eco-friendly behavior (Qin et al., 2024; Lin et al., 2025; Yan et al., 2025). Therefore, we propose

> *H4:* Households with access to fixed collection points are more likely to perform sustainable PPW disposal behaviors.

In addition to the key independent variables, household socio-demographic variables (including age, gender, education, land area and etc.) and village factors (terrain, income) were also introduced as control variables (Zhao et al., 2023; Zhang S.B. et al., 2023; Xu et al., 2021), representing the factors related to household living and the factors involving rural residential environment, respectively.

2.2 Data source

Data used in this study comes from the China Rural Revitalization Survey (CRRS), which was initiated and completed by the Rural Development Institute of the Chinese Academy of Social Sciences in August–September 2020.

To ensure the representativeness of the sample, stratified sampling was applied in this large-scale survey. In the first phase, 10 representative provinces were selected from the eastern, central, and western regions based on economic development levels, geographic location, and agricultural production conditions. These provinces include Guangdong, Zhejiang, Shandong, Anhui, Henan, Heilongjiang, Guizhou, Sichuan, Shaanxi, and Ningxia (see Figure 1). Secondly, within each province, all counties/cities were divided into five groups according to their per capita GDP. Considering the principle of uniform geographic distribution, one county was randomly selected from each group, resulting in a total of five counties per province. Thirdly, following a similar approach to county selection, three townships were randomly chosen in each county to represent high, medium, and low levels of economic development. Within each township, two villages were randomly selected to represent high and

FIGURE 1
Location of the study sites. Source: Standard Map of China (http://bzdt.ch.mnr.gov.cn/).

low economic development levels. Finally, based on the household rosters provided by the village committees, 12–14 households were selected from each village using systematic sampling. This approach yielded a comprehensive dataset encompassing 50 counties/cities, 156 townships, 300 villages and over 3,800 households (Du, 2021). These households were surveyed on topics including family population, labor employment, land management, agricultural and non-agricultural operations, income, and consumption.

Within this study, emphasis was placed on 2,757 households who were actively engaged in agricultural production and generating PPW. Additionally, households opting for the “7 = other” category in PPW disposal practices and those with substantial missing values were systematically excluded, resulting in a refined sample size of 2,131 households across 294 villages. The sample distribution across provinces is presented in Table 1.

2.3 Model specification

Decision-making mechanisms have long been studied. Common theoretical framework for the farmers' decision-making mechanism is random utility theory or theory of planned behavior (TPB). However, TPB emphasizes behavioral intentions shaped by attitudes, subjective norms, and perceived behavioral control (Ajzen, 1991), it fails to account for the probabilistic nature of choices among unordered alternatives. To capture the determinants of disposal preferences, farmers' choices of PPW disposal options were evaluated using a random utility theory-based model. The random utility is warranted for the study as the alternatives have no natural ordering and the relationship between the unobservable or the latent variable and the observed outcome is probabilistic (Diriye et al., 2022). The random utility theory assumes that a person facing a choice over a list of options chooses an alternative that pays the maximum utility (Hensher et al., 2005). Based on this assumption, respondents are likely to choose the instrument option, which gives the perceived maximum utility compared to other alternatives in the choice list.

The decision-maker is also assumed not to have complete information, so some portion of uncertainty must be also taken into account. Therefore, to reflect this uncertainty, the utility is modeled as a random variable, that is, the utility that the decision-maker n associates with the alternative i in the choice set C_n is given by Gora et al. (2020) and Coolen and Jansen (2012):

$$U_{in} = V_{in} + \varepsilon_{in}$$

where V_{in} is the deterministic part of the utility U_{in}, and ε_{in} is a random term representing uncertainty. The decision-maker chooses the alternative with the highest utility. Therefore, the probability that decision-maker n chooses the alternative i from the choice set C_n can be given as:

$$P(i|k) = P\left[U_{in} \geq U_{jn} \forall j \in C_n\right] = P\left[U_{in} = \max_{j \in m} U_{jn}\right]$$

Where:

U_{in} and U_{jn} represent the utility if decision-maker n chooses the alternative i and j, respectively. If the utility of alternative i exceeds j, i will be chose.

m signifies the choice set of PPW disposal, including 0 = dumping (set as baseline choice), 1 = burial *in situ*, 2 = collecting and landfilling, 3 = burning, 4 = recycling to fixed collection points, and 5 = recycling to agricultural markets.

Although V_{in} is the observable component of the utility function, it is not observed directly (Diriye et al., 2022). What is observable though are the choices farmers make and the characteristics variables of the farmers. Based on our assumptions, a multinomial logit (MNL) model is justified because the farmers employ a comparative evaluation to choose among a dependent variable that has multiple outcomes that are not naturally ranked or ordered in terms of their relative importance. Let Y be an outcome variable with possible value of m ($m = 0, 1, \ldots, 5$) and the baseline category is $Y = 0$. Let the independent variable $X = (X_1, X_2, \ldots, X_k)$, the probability of a farmer preferring to choose option i versus the baseline category can be given as:

$$\ln = \left(\frac{P(Y = i|X)}{P(Y = 0|X)}\right) = \beta_{i0} + \sum \beta_{ik} X_{ik}$$

Where the coefficients ($\beta_{i0}, \ldots, \beta_{ik}$) can be estimated using MNL model to determine the effect of the explanatory variables on the probability choices.

TABLE 1 Distribution of sample size by province.

Region	Province	Number of villages	Number of households
East	Guangdong	28	140
	Zhejiang	30	159
	Shandong	27	192
Central	Anhui	29	174
	Henan	30	244
West	Sichuan	29	252
	Guizhou	30	243
	Shaanxi	30	248
	Ningxia	30	209
Northeast	Heilongjiang	31	270
Total		294	2,131

3 Results

3.1 Descriptive statistics

Table 2 shows the basic characteristics of the sample. Only 40.5% of the sample villages in CRRS dataset had established recycling points for PPW. Regarding the PPW disposal practices, the most common practice was recycling to a fixed collection point, adopted by 49.2% of farmers. Three other prevailing practices include *in situ* burial (15.8%), burning (14.9%), and indiscriminate dump (12.9%). A smaller proportion of farmers (5.2%) opted for collection and landfilling, and merely 2.3% recycled their PPW at agricultural material markets. Among these, the practices of recycling PPW to designated fixed

TABLE 2 Descriptive statistics of the variables.

Variable	Definition	Value	Obs.	Mean	SD	Min	Max
Dependent variables	Bury in situ (Y1)	1 = yes, 0 = no	2,131	0.158	0.365	0	1
	Collect and bury (Y2)	1 = yes, 0 = no	2,131	0.052	0.222	0	1
	Burn (Y3)	1 = yes, 0 = no	2,131	0.149	0.356	0	1
	Collect to fixed point (Y4)	1 = yes, 0 = no	2,131	0.492	0.500	0	1
	Collect to market (Y5)	1 = yes, 0 = no	2,131	0.023	0.150	0	1
	Dump (Y0, baseline)	1 = yes, 0 = no	2,131	0.129	0.335	0	1
	Recycle (Y)(Y4 = 1 or Y5 = 1)	1 = yes, 0 = no	2,131	0.515	0.500	0	1
Farmer's cognition	Cognition on harm of PPW (HARM)	1. Damage the soil? 1 = yes, 0 = no	2,131	0.417	0.493	0	1
		2. Affect crop yields? 1 = yes, 0 = no	2,131	0.224	0.417	0	1
		3. Pollute the environment? 1 = yes, 0 = no	2,131	0.731	0.444	0	1
	Cognition on food security (FS)	1. Do you care about food safety? 1 = Very concerned, 5 = very unconcerned	2,129	1.774	0.927	1	5
		2. Most concerned about chemical residues such as pesticides? 1 = yes, 0 = no	2,103	0.759	0.428	0	1
		3. Will you produce some "safe" vegetables for your own consumption? 1 = yes, 0 = no	2,128	0.741	0.438	0	1
		4. Heard of organic food, green food, pollution-free food? 1 = yes, 0 = no	2,131	0.445	0.497	0	1
	Cognition on obstacles of PPW recycling (OBST)	1. No subsidy? 1 = yes, 0 = no	2,131	0.257	0.437	0	1
		2. No penalty? 1 = yes, 0 = no	2,131	0.319	0.466	0	1
		3. Indifferent attitude? 1 = yes, 0 = no	2,131	0.051	0.220	0	1
		4. Neighbor does not do it? 1 = yes, 0 = no	2,131	0.140	0.347	0	1
Household characteristics	HH age (AGE)	Age of household head	2,126	55.48	10.64	22	89
	HH gender (SEX)	1 = male, 0 = female	2,128	0.953	0.212	0	1
	HH education level (EDU)	1 = not in school, 2 = primary, 3 = middle, 4 = high, 5 = junior high, 6 = vocational, 7 = college diploma, 8 = bachelor, 9 = master	2,130	2.736	0.989	1	8
	If HH is CPC (CPC)	1 = yes, 0 = no	2,131	0.217	0.412	0	1
	If HH is a village cadre (CADRE)	1 = yes, 0 = no	2,131	0.187	0.390	0	1
	Family size (NUM)	Family size	2,131	4.146	1.547	1	10
	Non-farm employment (NF)	Number of non-farm employment	2,131	0.876	1.016	0	6
	Land area (LAND)	Total farmland area	2,112	28.22	82.50	0	2,200
	Fragmentation (PLOT)	Land plots	2,079	7.103	9.183	0	214
	Fruit income (FI)	Fruit income/total income	2,120	0.042	0.153	0	1
	If join a cooperative (COOP)	1 = yes, 0 = no	2,118	0.243	0.429	0	1
Village characteristics	Infrastructure (Point)	If there is a fixed PPW collection point in village: 1 = yes, 0 = no	2,120	0.405	0.491	0	1
	Terrain (TERR)	1 = plain, 2 = hill, 3 = mountainous	2,120	1.908	0.881	1	3
	Per capita income (INC)	Yuan	2,096	14,455	17,188	3,400	264,480

Source: own calculations based on CRRS dataset.

points or agricultural material markets represent sustainable waste management approaches. Notably, these practices were adopted by over half of the participants in the sample, accounting for 51.5%. This significant proportion underscores the potential effectiveness of recycling initiatives in mitigating environmental impacts in rural agricultural settings.

In terms of farmers' awareness regarding the harmful effects of PPW disposal practices, a significant majority (73.1%) recognized its potential to pollute the environment. However, only a fraction of the sampled households (41.7%) demonstrated awareness of the potential harm to soil quality caused by PPW. Moreover, a mere 22.4% of the households were informed about the potential reduction in crop production resulting from unsustainable PPW disposal practices. This indicates a notable disparity in the comprehensive understanding of the detrimental effects of improper PPW disposal and may lead to different disposal behaviors.

In assessing the perceptions of food security, farmers were asked to rate their level of concern regarding food safety on a 5-point Likert scale, where 1 indicated strong concern and 5 indicated strong unconcern. The results revealed an average scale score of 1.77, indicating that the majority of farmers exhibited a heightened awareness and concern for food security. Notably, a significant 76% expressed heightened concern specifically about chemical residues, such as those from pesticides. Moreover, approximately 74% indicated that they usually cultivate some "safe" vegetables with reduced or no pesticide usage for their own consumption. Additionally, 44.5% of households reported awareness of terms such as organic food, green food, and pollution-free food. These figures highlight the farmers' proactive efforts in cultivating and consuming produce with a focus on minimizing chemical residues and embracing alternative, sustainable food options. In relation to farmers' understanding of the challenges associated with PPW recycling, the primary obstacles can be categorized as follows: the absence of penalties (31.9%), lack of subsidies (25.7%), non-participation by neighbors (14%), and general indifference attitude among the populace (5.1%).

When it comes to the socio-economic factors, a predominant proportion of the household heads was males (95%), aged around 55, and possessed a middle school education level. Approximately 21.7% of the heads were affiliated with the Chinese Communist Party (CPC) and 18.7% held positions as village cadres. Shifting the focus to household characteristics, the average household population of the sample was 4.15, with 0.88 individuals engaged in non-farm sectors. Notably, nearly a quarter of the households joined the cooperatives. The average land area per household was 28 mu (approximately 1.87 hectares), spread across an average of seven plots. Income derived from fruit planting accounted for 4.2% of the overall household income. With regards to village terrain, households were distributed across plain areas (44%), hilly areas (21%), and mountainous areas (35%). The village-level per capita income exhibited a range from CNY 3,400–264,480, with an average of CNY 14,455.

3.2 Estimation of the MNL model

Table 3 presents the MNL model results using Stata 17 software, where each column shows a different model compared to the baseline model with the dependent variable of "Y0: dump anywhere." The estimated value of the likelihood ratio (chi-square = 554.90, $p = 0.0000$) suggests that the predictive power of the model is reasonable. The collinearity test results of each variable showed that the maximum value of variance inflation factor (VIF) was 1.48 and the mean value was 1.18, both of which were less than 10, indicating that there was no serious multicollinearity between the variables, and regression analysis could be performed.

3.2.1 The effects of the cognition factors

3.2.1.1 Cognition on harm

The environmental awareness of farmers significantly influences their decision-making process in relation to PPW disposal. Those who recognize the adverse impact of PPW on soil quality (HARM_1) are more inclined to engage in sustainable practices including both recycling to fixed points or agricultural materials markets. Farmers who considered the pollution on environment of PPW (HARM_3) tend to adopt practices such as recycling to fixed point, collecting and burying, or burning, as opposed to indiscriminate dumping. This suggests that farmers may be able to tell the harmful effects of dumping anywhere, yet may lack awareness that practices such as collecting and burying or burning are also unsustainable. Consequently, this lack of clarity may introduce confusion into their decision-making process. Therefore, H1 has been partially supported. As sustainable agricultural practices gain increasing importance, addressing this awareness deficit becomes crucial. Efforts to educate farmers on the multifaceted impacts of different PPW disposal practices are essential for bridging the knowledge gap and contributing to the adoption of more sustainable practices in the future.

3.2.1.2 Cognition on obstacle

Farmers' perception on the obstacles related to PPW recycling are significantly and negatively associated with disposal behaviors when compared to the baseline model "Y0 indiscriminate dumping." Specifically, the absence of financial incentives (OBST_1) emerges as the most prominent hindrance to farmers' engagement in recycling practices, showing a negative association with burying *in situ*, as well as recycling to fixed collection points or markets. Furthermore, the absence of regulatory penalties (OBST_2) significantly reduces the likelihood of burying waste in situ in comparison to indiscriminate dumping. Moreover, the lack of peer effects (OBST_4) negatively impacts farmers' participation in recycling, particularly within agricultural material markets. Without the demonstration effect from neighbors, farmers may have limited awareness regarding the possibility of recycling PPW within the agricultural material market. In summary, farmers who recognized various obstacles of PPW recycling demonstrate a preference for indiscriminate PPW disposal over burying in situ or recycling to fixed points or markets. PPW recycling exhibits the attributes of a positive externality. Without economic incentives, penalties or peer effects, farmers, despite their awareness of the potential inappropriateness of their actions, may opt for convenience, such as indiscriminate dumping, over environmentally responsible practices. This result partially supports H2.

3.2.1.3 Cognition on food security

Farmers' considerations regarding food security exert a substantial influence on their PPW disposal choices. Those who exhibit minimal concern for food security (as indicated by FS_1 ranging from 1 = very concerned to 5 = very unconcerned) tend to favor the disposal of PPW through dumping rather than opting for *in situ* burial, burning, or recycling at fixed point. Conversely, farmers who express heightened apprehension regarding chemical residues, particularly pesticides (FS_2), demonstrate a greater inclination toward burning or recycling directed toward the agricultural materials market. Interestingly, farmers who usually cultivate some "safe" vegetables with reduced or no pesticide usage for their own consumption (FS_3) paradoxically turn to the practice of burning PPW. This apparent contradiction raises intriguing questions about the complex dynamics between farmers' cognition and sustainable waste disposal in the agricultural sector. Moreover, farmers familiar with terms such as

TABLE 3 The multinomial logit model for PPW recycling preference.

	Unsustainable			Sustainable	
	(1) Y1	(2) Y2	(3) Y3	(4) Y4	(5) Y5
	Bury in situ	Collect & bury	Burn	Recycle to point	Recycle to market
HARM_1	0.049	0.357	−0.031	0.446**	0.919**
	(0.206)	(0.281)	(0.218)	(0.178)	(0.414)
HARM_2	−0.21	0.139	0.005	0.168	0.477
	(0.257)	(0.325)	(0.265)	(0.213)	(0.439)
HARM_3	−0.105	0.474*	0.34*	0.665***	0.596
	(0.189)	(0.282)	(0.205)	(0.169)	(0.424)
OBST_1	−0.445**	0.005	−0.31	−0.659***	−1.441***
	(0.204)	(0.271)	(0.211)	(0.175)	(0.495)
OBST_2	−0.417**	−0.251	−0.243	−0.238	−0.642
	(0.2)	(0.282)	(0.206)	(0.171)	(0.398)
OBST_3	0.151	−0.752	0.182	−0.423	−0.377
	(0.376)	(0.661)	(0.385)	(0.345)	(0.819)
OBST_4	0.026	−0.037	−0.099	−0.109	−2.339**
	(0.265)	(0.357)	(0.278)	(0.229)	(1.046)
FS_1	−0.292***	−0.174	−0.165*	−0.167**	−0.066
	(0.095)	(0.135)	(0.097)	(0.078)	(0.202)
FS_2	−0.098	0.169	0.324*	−0.064	0.611*
	(0.181)	(0.248)	(0.188)	(0.157)	(0.37)
FS_3	−0.031	0.172	0.541**	0.062	−0.269
	(0.2)	(0.284)	(0.225)	(0.174)	(0.411)
FS_4	0.413**	0.066	−0.062	0.314*	0.219
	(0.206)	(0.283)	(0.21)	(0.176)	(0.428)
SEX	0.883*	0.664	0.059	0.115	−0.234
	(0.495)	(0.668)	(0.417)	(0.356)	(0.835)
AGE	−0.007	−0.037***	−0.039***	−0.02**	0.008
	(0.009)	(0.013)	(0.01)	(0.008)	(0.02)
EDU	−0.01	−0.114	−0.011	−0.063	0.024
	(0.101)	(0.14)	(0.102)	(0.087)	(0.185)
CPC	−0.057	−0.24	−0.045	−0.007	0.565
	(0.233)	(0.345)	(0.248)	(0.204)	(0.434)
CADRE	0.447*	0.098	0.166	0.302	0.096
	(0.249)	(0.359)	(0.261)	(0.226)	(0.491)
NUM	−0.027	0.084	0.032	0.031	0.075
	(0.065)	(0.089)	(0.067)	(0.056)	(0.133)
NF	−0.068	0.005	−0.161	0.041	0.087
	(0.105)	(0.141)	(0.109)	(0.089)	(0.199)
LN_LAND	−0.14*	−0.175*	−0.122	−0.257***	−0.046
	(0.073)	(0.098)	(0.075)	(0.063)	(0.144)
PLOT	0	0.018	0.019	0.009	0.005
	(0.014)	(0.015)	(0.012)	(0.012)	(0.026)
COOP	0.195	0.065	0.241	0.283	−0.814
	(0.216)	(0.297)	(0.222)	(0.189)	(0.531)

(Continued)

TABLE 3 (Continued)

	Unsustainable			Sustainable	
	(1) Y1	(2) Y2	(3) Y3	(4) Y4	(5) Y5
	Bury in situ	Collect & bury	Burn	Recycle to point	Recycle to market
FI	0.405	−0.948	−0.122	1.529**	2.875***
	(0.716)	(1.362)	(0.802)	(0.607)	(0.852)
POINT	0.016	−0.027	−0.18	0.736***	1.065***
	(0.204)	(0.277)	(0.219)	(0.17)	(0.391)
TERR	0.235**	−0.1	0.563***	−0.102	0.112
	(0.113)	(0.156)	(0.12)	(0.099)	(0.246)
LN_INC	−0.158	−0.013	0.039	0.591***	1.275***
	(0.21)	(0.283)	(0.212)	(0.175)	(0.303)
_cons	1.827	0.768	0.608	−3.283*	−15.81***
	(2.212)	(2.97)	(2.227)	(1.841)	(3.594)
Observation	1,920				
LR chi2 (125)	554.90				
Prob > chi2	0.000				
Pseudo R^2	0.101				

"Y0 Dump" is the baseline model. Standard deviation are in parentheses.
Significance level: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

organic food, green food, and pollution-free food (FS_4) exhibit a propensity for in situ burial or recycling at fixed points for PPW. These findings provide partial supports for H3. It is evident that farmers who pay more attention on food security demonstrate an inclination toward sustainable recycling behaviors. However, the result also reveals a noteworthy preference for burning and in situ burial. This preference may be attributed to the perception among farmers that burning and in situ burial are more sustainable alternatives compared to indiscriminate dumping.

3.2.2 The effects of the fixed collection point

As Table 3 shows, the presence of a fixed collection point within the village emerged as a crucial determinant of sustainable PPW disposal practices, which strongly supports H4. Our findings reveal a noteworthy shift in behavior among farmers who have access to a designated collection point within their villages. Specifically, in comparison to the baseline model "Y0 dumping PPW anywhere," farmers with a fixed collection point in the village exhibit a substantial increase in their inclination toward recycling, with log-odds of 0.736 for recycling to the fixed collection point and 1.065 for the agricultural materials market. This means that in villages where farmers have a designated collection point, their propensity to participate in recycling practices at that fixed location is roughly two-fold higher (odds ratio ≈ 2.087, e^0.736). While the probability of engaging in recycling activities directed toward the market sees a nearly threefold increase (odds ratio ≈ 2.900, e^1.065).

Furthermore, though not statistically significant, the existence of a fixed collection point within the village is associated with a reduced likelihood of opting for unsustainable disposal practices such as collecting and burying or burning, relative to the indiscriminate dumping of PPW. This nuanced shift in disposal preferences underscores the effectiveness of having a centralized collection infrastructure without having to go far.

3.2.3 The effects of the controlled variables

3.2.3.1 Household socio-economic factors

The following socio-economic factors were included in the analyses based on previous research showing associations with PPW behavior (Li et al., 2022; Xu et al., 2021; Jin et al., 2018): gender, age, education level, if the household head was the village cadre/CPC member, income level, household size, ratio of off-farm members, land size, number of land plots, and proportion of fruit income, whether join a cooperative. Some of which were identified to exert a noteworthy influence on the disposal practices of farmers regarding PPW.

Regarding characteristics of household heads, our findings reveal a weak gender disparity, with male household heads exhibiting a higher likelihood of burying PPW *in situ* compared to their female counterparts. Additionally, advancing age among household heads strongly correlates with a decreased probability of adopting disposal practices such as collecting and burying, burning, or recycling to fixed point. Instead, older heads tend to favor the indiscriminate dumping of PPW. Our result also indicates that household heads holding positions as village cadres exhibit a heightened inclination to bury PPW in situ, as opposed to opting for arbitrary disposal. This inclination may again reveal that even village cadres consider bury in situ as a more sustainable practice.

In terms of household characteristics, the larger land area a household hold, the greater the transaction cost of waste disposal, thus the less likely they would adopt more sustainable disposal ways such as recycling to fixed point. This is supported by our model results as the coefficients of models (1), (2) and (4) are negative. However, King et al. (2023) found that when the scale is large to a certain extent, the amount of waste generated can obtain an objective income through recycling, it may improve the probability of recycling. Whereas this is difficult to achieve under the current status quo as each household's contracted land is scattered over an average of seven plots.

Significantly, households reliant on a substantial portion of their income from fruit cultivation demonstrate a heightened inclination to actively participate in the recycling of PPW through fixed collection points or market channels. This heightened engagement can be attributed to the observation that pesticide applications are markedly higher in fruit crops compared to grain crops. Consequently, farmers cultivating fruits may exhibit a greater propensity to responsibly manage the substantial volume of PPW. This can manifest either through conscientious disposal at fixed points to prevent environmental pollution or through selling the recyclable materials in the market, thereby not only contributing to environmental sustainability but also deriving economic benefits from their conscientious practices. Regrettably, the engagement of farmers in cooperatives did not effectively contribute to the improvement of their PPW recycling practices. As stated by Jin et al. (2018), cooperatives (or agricultural service companies and large agricultural companies) with contracted farmers possess the potential to serve as vital mediators between pesticide companies and smallholders. By establishing partnerships with these entities, pesticide companies do not need to directly interact with numerous smallholders, thereby mitigating their transaction costs associated with the collection of packaging materials.

3.2.3.2 Village-level factors

When it comes to the village topography, farmers living in hilly or mountainous areas are more likely to burn PPW in open air or bury *in situ* than farmers in plain area. This may be due to the reality that houses and farmland in hilly or mountainous areas are more scattered and the infrastructure is poorer. Therefore, farmers are more inclined to choose more conveniently in situ burial or burning methods to handle PPW materials.

In addition, farmers located in villages with higher per capita income levels demonstrate a greater propensity to engage in the recycling of PPW by channeling it toward fixed collection points or markets. This trend underscores the positive correlation between economic prosperity at the community level and more responsible PPW management practices.

3.3 Robustness tests

3.3.1 Robustness check using logit model

To ensure the reliability of the results drawn from the MNL model, we conducted a robustness check which is shown in Table 4.

We first estimated the MNL model using robust standard errors to account for potential heteroscedasticity and autocorrelation in the residuals (Mullahy, 2015). The results showed that the parameter estimates were highly consistent with those from the benchmark model presented in Table 3. We also replace the MNL model with a binary logit model to further validate the findings. Specifically, we defined a binary variable recycle (where recycle = 1 if $Y = 4$ or $Y = 5$). The results from the logit model in Table 4 revealed that farmers' cognition on PPW harms and their perception of obstacles to PPW recycling significantly influence their recycling behavior. These findings are essentially consistent with the benchmark MNL model, further confirming the robustness of our conclusions.

3.3.2 Robustness check using PSM

The MNL model identifies key factors shaping farmers' decisions regarding the disposal of PPW, including farmers' cognition, fixed collection point, the proportion of income derived from fruit cultivation and per capita income. From these discerned predictors, prioritizing the establishment of fixed points within villages emerges as a viable focal point for public policy intervention, demonstrating its potential efficacy in the short term. Therefore, to offer a more nuanced and robust understanding of the impact of fixed collection points on recycling behavior (take recycle dummy Y as the dependent variable), the study further employs propensity score matching (PSM). PSM provides a methodological advancement that helps mitigate selection biases inherent in observational data by creating a balanced comparison group. In the context of this study, PSM allows us to establish a comparable baseline between farmers with fixed collection points in their villages and those without. This is crucial for isolating and accurately estimating the causal effect of fixed collection points on PPW recycling behavior, thus enhancing the overall validity and reliability of our findings. To ensure the success of the matching process, we conducted rigorous checks on covariate balance between the treatment and control groups after matching, as is shown in Table 5.

In Table 5, the T-values of all covariables were not significant after matching, indicating that the variables between the treatment and the control groups were balanced and comparable after matching. Among them, HARM_1, HARM_2, OBST_2, OBST_4, FS_2, FS_3, FS_4, EDU, LN_LAND, TERR and LN_INC were significantly different before matching. The effectiveness of our PSM approach is also evidenced by the test that that a significant proportion of propensity scores fall within a common range, as illustrated in Figure 2. The convergence of propensity scores, coupled with the outcomes of the balance test, serves to strengthen the internal validity of the analysis, providing confidence in isolating the causal effect of fixed collection points on PPW recycling behavior.

Having achieved covariate balance, we proceeded to estimate the average treatment effect on the treated (ATT), as is shown in Table 6. According to the propensity score values of the samples obtained by multiple linear regression, the samples of the treatment group and the control group were matched by nearest neighbor matching (1:1), and the average treatment effect ATT of the fixed collection points in the village could be calculated. At the same time, nearest neighbor matching (1:4), radius matching (0.01) and kernel matching are also adopted to check the robustness of matching results. The results show that: after one-to-one matching, the recycling probability of treatment group and control group was 66.5 and 45.9%, respectively. The sustainable recycling behavior of farmers with fixed collection points in the village was 20.6% higher than that of farmers in the matched control group, and was significant at the significance level of 1%. After nearest neighbor matching (1:4), radius matching (0.01) and Kernal matching, the recycling behavior of farmers in the treatment group was 18.6, 18.5 and 18.9% higher than that in the control group, respectively, and all were significant at the significance level of 1%. The four matching methods are statistically significant, and the results tend to be consistent, indicating that there is a relatively obvious causal relationship between fixed recycling points and farmers' sustainable recycling behavior.

TABLE 4 Robustness check for the MNL model.

	MNL models					Logit
	(1) Y1	(2) Y2	(3) Y3	(4) Y4	(5) Y5	(6) Recycle
	Bury in situ	Collect & bury	Burn	Recycle to point	Recycle to market	Y4 = 1 or Y5 = 1
HARM_1	0.049	0.357	−0.031	0.446**	0.919**	0.453***
	(0.199)	(0.289)	(0.221)	(0.175)	(0.417)	(0.115)
HARM_2	−0.21	0.139	0.005	0.168	0.477	0.215
	(0.248)	(0.327)	(0.268)	(0.205)	(0.422)	(0.135)
HARM_3	−0.105	0.474*	0.34*	0.665***	0.596	0.626***
	(0.189)	(0.277)	(0.204)	(0.166)	(0.429)	(0.117)
OBST_1	−0.445**	0.005	−0.31	−0.659***	−1.441***	−0.458***
	(0.202)	(0.258)	(0.207)	(0.172)	(0.521)	(0.12)
OBST_2	−0.417**	−0.251	−0.243	−0.238	−0.642	−0.019
	(0.199)	(0.27)	(0.204)	(0.166)	(0.42)	(0.114)
OBST_3	0.151	−0.752	0.182	−0.423	−0.377	−0.422*
	(0.373)	(0.657)	(0.369)	(0.365)	(0.843)	(0.237)
OBST_4	0.026	−0.037	−0.099	−0.109	−2.339**	−0.108
	(0.265)	(0.35)	(0.281)	(0.234)	(1.045)	(0.149)
FS_1	−0.292***	−0.174	−0.165	−0.167**	−0.066	−0.013
	(0.095)	(0.121)	(0.1)	(0.079)	(0.201)	(0.056)
FS_2	−0.098	0.169	0.324*	−0.064	0.611*	−0.125
	(0.181)	(0.25)	(0.186)	(0.158)	(0.368)	(0.103)
FS_3	−0.031	0.172	0.541**	0.062	−0.269	−0.103
	(0.202)	(0.285)	(0.226)	(0.174)	(0.412)	(0.119)
FS_4	0.413**	0.066	−0.062	0.314*	0.219	0.164
	(0.209)	(0.278)	(0.21)	(0.177)	(0.415)	(0.124)
SEX	0.883*	0.664	0.059	0.115	−0.234	−0.171
	(0.499)	(0.65)	(0.408)	(0.348)	(0.829)	(0.237)
AGE	−0.007	−0.037***	−0.039***	−0.02**	0.008	0
	(0.01)	(0.014)	(0.01)	(0.009)	(0.021)	(0.005)
EDU	−0.01	−0.114	−0.011	−0.063	0.024	−0.028
	(0.095)	(0.152)	(0.103)	(0.083)	(0.155)	(0.056)
CPC	−0.057	−0.24	−0.045	−0.007	0.565	0.055
	(0.232)	(0.361)	(0.251)	(0.208)	(0.399)	(0.131)
CADRE	0.447*	0.098	0.166	0.302	0.096	0.046
	(0.253)	(0.366)	(0.263)	(0.226)	(0.448)	(0.137)
NUM	−0.027	0.084	0.032	0.031	0.075	0.025
	(0.064)	(0.082)	(0.067)	(0.055)	(0.146)	(0.037)
NF	−0.068	0.005	−0.161	0.041	0.087	0.104*
	(0.107)	(0.139)	(0.107)	(0.09)	(0.198)	(0.058)
LN_LAND	−0.14**	−0.175*	−0.122*	−0.257***	−0.046	−0.113***
	(0.067)	(0.098)	(0.072)	(0.06)	(0.167)	(0.04)
PLOT	0	0.018	0.019	0.009	0.005	−0.002
	(0.015)	(0.014)	(0.013)	(0.013)	(0.023)	(0.006)
COOP	0.195	0.065	0.241	0.283	−0.814	0.08
	(0.215)	(0.293)	(0.227)	(0.188)	(0.535)	(0.121)
FI	0.405	−0.948	−0.122	1.529**	2.875***	1.611***

(Continued)

TABLE 4 (Continued)

	MNL models					Logit
	(1) Y1	(2) Y2	(3) Y3	(4) Y4	(5) Y5	(6) Recycle
	Bury in situ	Collect & bury	Burn	Recycle to point	Recycle to market	Y4 = 1 or Y5 = 1
	(0.747)	(1.281)	(0.867)	(0.648)	(0.826)	(0.354)
POINT	0.016	−0.027	−0.18	0.736***	1.065***	0.788***
	(0.208)	(0.282)	(0.216)	(0.171)	(0.373)	(0.111)
TERR	0.235**	−0.1	0.563***	−0.102	0.112	−0.326***
	(0.116)	(0.148)	(0.119)	(0.1)	(0.233)	(0.065)
LN_INC	−0.158	−0.013	0.039	0.591***	1.275***	0.642***
	(0.194)	(0.323)	(0.226)	(0.172)	(0.282)	(0.12)
_cons	1.827	0.768	0.608	−3.283*	−15.81***	−6.034***
	(2.108)	(3.387)	(2.35)	(1.898)	(3.25)	(1.257)
Observation	1,920					1,959
LR chi2 (125)	483.00					270.00
Prob > chi2	0.000					0.000
Pseudo R^2	0.101					0.1248

"Y0 Dump" is the baseline model. Robust standard errors are in parentheses.
Significance level: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

TABLE 5 PSM balancing test for fixed collection point variable.

Variable	Mean			T test	
	Treat	Control	%bias	t	$p > t$
HARM_1	0.465	0.504	−7.900	−1.560	0.119
HARM_2	0.251	0.250	0.3	0.060	0.954
HARM_3	0.753	0.736	3.8	0.750	0.454
OBST_1	0.259	0.259	0	0.000	1.000
OBST_2	0.299	0.327	−6.000	−1.190	0.234
OBST_3	0.053	0.064	−5.100	−0.960	0.336
OBST_4	0.122	0.117	1.5	0.310	0.757
FS_1	1.781	1.794	−1.500	−0.310	0.759
FS_2	0.414	0.386	5.6	1.130	0.260
FS_3	0.830	0.811	4.5	0.980	0.327
FS_4	0.776	0.783	−1.700	−0.360	0.717
SEX	0.962	0.971	−4.300	−0.980	0.328
AGE	55.435	56.183	−7.100	−1.410	0.158
EDU	2.802	2.748	5.5	1.070	0.284
CPC	0.217	0.203	3.4	0.680	0.498
CADRE	0.174	0.160	3.6	0.740	0.459
NUM	4.105	4.205	−6.500	−1.310	0.191
NF	0.880	0.958	−7.800	−1.550	0.122
LN_LAND	2.367	2.316	3.5	0.680	0.497
PLOT	7.005	7.220	−2.300	−0.450	0.653
COOP	0.231	0.231	0	0.000	1.000
FI	0.042	0.042	0.2	0.040	0.972
TERR	1.560	1.508	6.3	1.380	0.168
LN_INC	9.533	9.500	6.6	1.310	0.189

Source: Stata output.

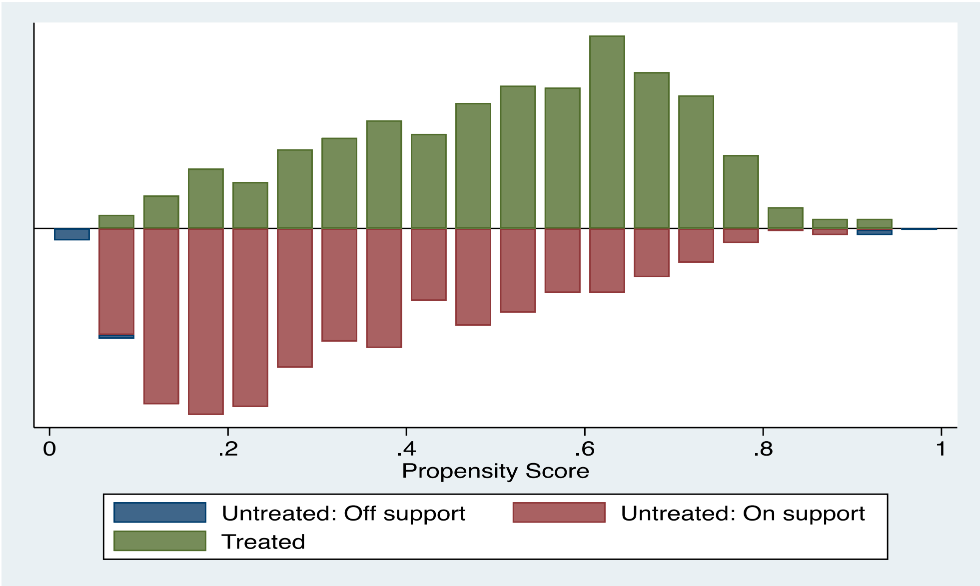

FIGURE 2
Common value range of the propensity scores. Source: Stata output.

TABLE 6 Estimation of treatment effects.

Matching methods		Treat (village has fixed collection point)	Control (village has no fixed collection point)	ATT	S.D	T-value
		(1)	(2)	(1)−(2)		
Nearest neighbor matching (1:1)	Before	0.665	0.411	0.254	0.022	11.38
	After	0.665	0.459	0.206	0.035	5.84
Nearest neighbor matching (1:4)	Before	0.665	0.411	0.254	0.022	11.38
	After	0.665	0.479	0.186	0.029	6.45
Radius matching (0.01)	Before	0.665	0.411	0.254	0.022	11.38
	After	0.664	0.479	0.185	0.027	6.78
Kernal	Before	0.665	0.411	0.254	0.022	11.38
	After	0.665	0.476	0.189	0.027	7.11

Source: Stata output.

4 Discussion

4.1 Policy implications

Policy implications stemming from the main findings are multi-faceted. First and foremost, interventions promoting the establishment of fixed collection points within villages may be a cost-effective and promising strategy to significantly boost PPW recycling rates, which echoes the studies of Huang and Elahi (2022) and King et al. (2023). Presently, a merely 40.5% of the sample villages have embraced the establishment of such collection points. This statistic underscores a substantial untapped potential for influencing recycling behaviors among farmers.

Concurrently, targeted educational programs should be devised to enhance farmers' awareness of the detrimental effects of PPW on soil, water, air, crop production and etc. Specifically, efforts should be directed toward dispelling misconceptions surrounding the potential harm caused by burying or burning PPW, particularly in hilly or mountainous areas. Clarifying these misunderstandings is imperative in fostering a more accurate understanding of the ecological impacts associated with PPW disposal practices.

Addressing these key factors requires a comprehensive policy approach that integrates infrastructure development, educational initiatives, and community engagement. Notably, in January 2024, eight departments of Chinese central government jointly issued the "Notice on Comprehensively Carrying Out the Construction of Healthy Families." This initiative aims to elevate the health literacy levels of residents nationwide and outlines plans to appoint 1–2 family health instructors in each village or community, with the ambitious goal of covering 100% of such areas by the end of 2030. Consequently, fostering collaborative synergy among local governments, village communities, and appointed health instructors presents a strategic opportunity to cultivate sustainable practices in the management of

PPW materials and pave the way for a more environmentally responsible and agriculturally sustainable future.

4.2 Limitations and future research directions

While our study has provided valuable insights into the factors influencing farmers' behaviors regarding PPW management, some limitations should be acknowledged. Firstly, our analysis of fixed collection points only focuses on their presence rather than fully explore their operational characteristics, such as collection frequency, accessibility, and service quality, which could significantly influence recycling behavior. Future research may investigate these aspects to optimize the effectiveness of fixed collection points. Secondly, while our study uses a large-scale national survey dataset to enhance representativeness, the cross-sectional nature of the data limits our ability to establish causality. Future studies may consider using longitudinal datasets to provide a more robust examination of the dynamic relationships between perceptions, behaviors, and policy interventions over time.

5 Conclusion

This study examines the determinants of farmers' behaviors regarding pesticide packaging waste (PPW) management using data from the China Rural Revitalization Survey (CRRS) in 2020. Employing multinomial logit (MNL) and propensity score matching (PSM) methods, our findings show that the presence of a fixed collection point in the village emerges is the most pivotal determinant, significantly enhancing farmers' recycling practices. We also find that farmers' awareness of the harms of PPW on soil and the environment positively promotes recycling. Conversely, cognitive perceptions related to obstacles in PPW recycling exert a noteworthy negative influence, diminishing the likelihood of recycling. In addition, farmers' perspectives on food security appear to play a dual role, enhancing the inclination to burn PPW. This suggests a potential knowledge gap, indicating that farmers (even village cadres) may not fully comprehend the harmful consequences associated with burying PPW *in situ* or burning it in open air. We recommend improving infrastructure and implementing targeted educational programs to address knowledge gaps and promote sustainable PPW management. Future research might focus on longitudinal studies to better understand the long-term impacts of these interventions.

Data availability statement

The data analyzed in this study is subject to the following licenses/restrictions: the raw data supporting the conclusions of this article will be made available by the authors. Requests to access these datasets should be directed to Yuepeng Zhou, zhouyuepeng@xmu.edu.cn.

Author contributions

YZ: Conceptualization, Formal analysis, Funding acquisition, Writing – original draft. FR: Conceptualization, Funding acquisition, Writing – original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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