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The Impact of Environmental Regulation on Pesticide Use in China

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Abstract: Reducing pesticide use is of great significance for ensuring the quality and safety of agricultural products, as well as alleviating agricultural non-point source pollution. Exploring the mechanisms by which environmental regulation drives pesticide reduction under different scenarios can help improve policy effectiveness and promote the sustainable development of agriculture. Utilizing panel data from 30 Chinese provinces spanning the period of 2010 to 2023, this study empirically analyzed the impact of environmental regulation on pesticide use through a fixed-effect model and further explored the moderating role of agricultural economic scale in this process. Moreover, a heterogeneity analysis was conducted based on regional and environmental regulation dimensions, respectively. The findings reveal that, overall, there exists an inverted U-shaped relationship between environmental regulation and pesticide use, where it initially increases and then decreases. Agricultural economic scale, serving as a moderating variable, amplifies the promotional effect of environmental regulation on pesticide reduction and accelerates the attainment of the inflection point of the inverted U-shaped curve. Regional heterogeneity analyses reveal an inverted U-shaped relationship between environmental regulation and pesticide use in the eastern and central regions, while this relationship is not significant in the western region. Notably, market-based environmental regulation exhibits a more pronounced impact compared to command-and-control environmental regulation.

Keywords: environmental regulation; pesticide use; pesticide reduction; agricultural economic scale; China

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1. Introduction

Pesticides, as the core tool for crop protection globally, play an irreplaceable role in agricultural production [1]. However, in recent years, the food safety risks posed by pesticide residues in Chinese agricultural products have become increasingly prominent, potentially stemming from the overuse of pesticides [2]. According to the Food and Agriculture Organization (FAO) database estimates in 2022, China accounts for approximately 6% of the total global pesticide consumption. In the context of China, food security strategies have historically prioritized high yields as a central goal. This policy orientation conflicts directly with conventional agricultural practices dependent on chemical inputs, thereby generating tensions with ecological conservation efforts. While agricultural industrialization during the post-reform era has substantially enhanced production efficiency, the quantity-driven developmental paradigms continue to perpetuate elevated pesticide use,

creating a significant challenge for the sustainable development of agriculture. Simultaneously, swift urbanization has triggered a significant outflow of rural labor, compelling remaining farmers to compensate for increasingly scarce manual labor by increasing pesticide use [3]. Moreover, due to the pronounced externality of agricultural production, farmers often excessively apply agrochemicals to minimize the risk of crop failure and maximize profits [4]. Insufficient government regulation further exacerbates this issue, contributing to "regulatory failure" in agricultural practices. Additionally, the land transfer policy has given rise to new agricultural management entities, such as agribusinesses, which, while positively promoting technological advancements, may adopt risk-averse business strategies that could intensify pesticide misuse in large-scale operations [5]. In this scenario, the labor depletion caused by urbanization, coupled with the resource overconsumption spurred by agricultural intensification, creates dual pressure. Managing agricultural surface pollution has thus become crucial to resolving the dilemma between stabilizing production and preserving ecology, representing a core issue that demands immediate attention and effective solutions.

The excessive use of agrochemicals not only damages the ecological environment and increases human health risks but also directly threatens the quality and safety of agricultural products [6,7]. The history of development of many countries shows that the government is the core force in promoting the reduction and sustainable development of agrochemicals [8]. Direct intervention in the production behavior of micro subjects through policies, regulations, and other environmental regulatory tools has become one of the most effective methods in solving the externalities of environmental pollution and enhancing ecological efficiency [9]. In light of this, the Chinese government has launched a series of strategies to promote pesticide reduction. From the perspective of sustainable development, pesticide reduction practices need to balance the dual goals of economic development and ecological protection, and high-quality environmental management is necessary [10,11]. Specifically, environmental sustainability requires that the cumulative pollution of soil and water ecosystems by pesticides must be curbed to avoid the loss of ecosystem service value due to the sharp decline in biodiversity [12]. Agricultural economic sustainability requires the promotion of green technologies such as the precision application of pesticides and biological control to break the vicious cycle of "reduce pesticide—reduce yield—reduce income" and gradually reduce the dependence of agricultural production on chemical inputs [13]. Despite the fact that the existing regulatory system covers the whole chain of pesticide production, sales, and applications, there are still shortcomings in policy implementation [14,15]. First, the governance system is characterized by fragmentation, and the lack of cross-sectoral synergistic mechanisms leads to insufficient policy synergy. Second, farming groups are driven by economic benefits and traditional farming inertia, and the endogenous motivation to participate in green transformation is insufficient. Third, the insufficient integration of green technologies (e.g., precision application and biocontrol) makes it difficult to break the "chemical dependency cycle". To address these challenges, it is necessary to reorganize the environmental regulatory framework so that economic incentives and ecological management can form a synergistic mechanism.

Current research on environmental regulation primarily centers around the following areas. First, the majority of existing studies adopt the industrial economy as their analytical focus, emphasizing the direct mechanisms through which environmental regulation influences environmental quality [9,16,17]. Empirical analyses show that environmental regulation can significantly improve environmental quality by restraining industrial emissions and promoting technological innovation and other paths [18,19]. On the one hand, the field of technological innovation focuses on the empirical testing of Porter's hypothesis, which argues that reasonable environmental regulation can promote corporate innovation

and enhance competitiveness [20–22]. On the other hand, studies on economic development effects reveal an inverted U-shaped relationship between environmental regulation intensity and the quality of economic growth by constructing a dynamic analytical framework [23,24]. Second, related studies have also been gradually extended to the agricultural field in recent years, mainly focusing on whether environmental regulation is conducive to promoting eco-efficiency [9], the green production behaviors of farmers [25,26], and intelligent technology adoption decisions [27]. In addition, cross-disciplinary studies have shown that environmental regulation has a significant shaping effect on social behavior. In terms of corporate behavior, studies have focused on changes in corporate behavior under different environmental regulatory conditions, including green investment, green consumption, and green finance [28,29]. In the field of agriculture, there is already evidence that environmental regulation can sway farmers' engagement in environmental management [26,30,31]. These regulations effectively motivate farmers to adopt green agricultural practices and augment their inclination towards sustainable behaviors [32].

However, there is a lack of research in the literature that examines the impact of environmental regulation on pesticide use. Existing studies on the overuse of agrochemicals have focused on micro-level drivers—farmers' socio-demographic characteristics (e.g., gender, age, and risk aversion) [33–35] and household resource endowment (e.g., land size and labor allocation) [36–38]—and external factors such as the market environment and social norms [39]. Notably, the critical role of national regulatory systems in guiding the transformation of agrochemical use has not been adequately studied, especially when analyzed from the perspective of Environmental Kuznets Curve (EKC) dynamics. Despite the fact that EKC studies in the industrial sector have revealed an inverted U-shaped relationship between economic growth and pollution emissions [40], research in the agricultural sector is still weak. We argue that a combination of market-based regulatory tools and command-and-control policies may accelerate the pollution inflection point, transforming the traditional upward trajectory into a policy-driven "inverted U-shaped emission reduction curve". Concretely, early agricultural development under weak regulation relied on chemical agricultural inputs to maximize yields. At the intermediate levels of development, stringent environmental regulation drives efficiency gains and the adoption of integrated pest management. At the advanced level, the substitution of low-toxicity and bio-pesticides is achieved through stronger enforcement and the promotion of green technologies. Furthermore, the actual effectiveness of environmental regulation on pesticide reduction may be influenced by the moderating effect of agricultural economic scale. In regions with advanced economic levels, large-scale production fosters a reduction in the marginal costs associated with green technologies, thereby promoting the adoption of precision application technologies or biopesticides. Furthermore, the expansion of the economic scale bolsters the regulatory resources available to local governments. This augmentation enables authorities to address the longstanding challenge of monitoring "small and scattered" farming operations, thereby fostering advancements in environmental protection.

While existing evidence suggests that environmental regulation can effectively encourage the adoption of green practices, there is a scarcity of empirical studies that validate the EKC hypothesis within the context of pesticide-intensive agricultural systems. Moreover, the precise mechanisms through which environmental regulation influences pesticide reduction remain inadequately understood, especially concerning its interplay with varying levels of economic development. Such knowledge gaps underscore the need for further research to clarify these dynamics and inform more effective policy design. Therefore, this study attempts to discuss the following research questions: How does environmental regulation affect the intensity of pesticide use in Chinese agriculture? How does agricultural economic scale moderate this relationship? What are the regional and typological

differences in the effectiveness of environmental regulation on pesticide use? In China, environmental regulation refers to the systematic supervision and management of pollution in production activities by the government through a variety of tools such as laws and regulations, administrative orders, economic incentives, and technical standards, with the core objectives of mitigating environmental pollution and regulating the behavior of the main body. In this context, precisely identifying the nonlinear impact and regional heterogeneity of environmental regulation on pesticide use intensity can offer a crucial foundation for formulating scientific regulatory policies. These policies aim to strike a balance between ensuring food security and controlling non-point source pollution. This study makes three contributions. First, it elucidates the nonlinear mechanism through which the intensity of environmental regulation affects pesticide reduction, expanding the applicability boundary of the EKC theory in the field of agricultural non-point source pollution control. Second, by introducing agricultural economic scale as a moderating variable, this study reveals how economic development levels influence the effectiveness of environmental regulation in reducing pesticide use. This approach highlights the interplay between economic conditions and policy outcomes, offering insights into the mechanisms underlying governance strategies. Furthermore, this research provides an empirical analysis of regional and typological heterogeneity, delivering specific evidence to inform differentiated governance approaches. These findings advance the theoretical understanding of agri-environmental governance while providing actionable insights for China's green agricultural transition and the sustainable development of agriculture in developing countries.

The organization of the subsequent sections of this study is as follows. Section 2 delineates the theoretical mechanism and research hypotheses. Section 3 elaborates on the data, variable selection, and model design. Section 4 presents the empirical results of this study, while Section 5 discusses these results. Section 6 summarizes the conclusions and offers policy recommendations.

2. Theoretical Framework

According to the externality theory, farmers' improper use of pesticides generates negative externalities, including environmental pollution and chemical residues in the food chain, which ultimately threaten human health and ecosystem sustainability [7]. To correct such market failures and achieve Pareto optimality, government intervention through environmental regulation is essential, as market mechanisms alone fail to internalize these external costs. During the stage of extensive economic growth characterized by low technological efficiency and lax environmental policies, farmers prioritize short-term yield maximization by intensifying pesticide inputs. However, escalating pollution prompts governments to implement stricter regulations—such as pesticide registration systems and restricted-use zones—alongside environmental education campaigns [41]. These measures transmit ecological risk signals to farmers, raising their awareness of the long-term costs of over-application (e.g., soil degradation) and incentivizing greener practices, thereby reducing pesticide intensity [42].

From the rational smallholder perspective, farmers weigh the costs of regulatory non-compliance (e.g., fines) against the benefits of pesticide-driven yield gains. Initially, weak enforcement and low penalty risks may encourage increased pesticide use to maximize profits. However, as regulations intensify—through measures like pollution source controls and administrative penalties—farmers face the rising costs of non-compliance. Concurrently, Porter's hypothesis suggests that stringent environmental regulation can stimulate innovation (e.g., the adoption of precision application technologies or biopesticides), creating a compensation effect that offsets compliance costs and reshapes production decisions [43]. This duality explains the literature's conflicting findings: while the cost

theory emphasizes the short-term economic burden of regulation, the innovation-driven perspective highlights long-term structural optimization. Empirical studies further reveal nonlinear dynamics [44,45], such as the inverted U-shaped relationship between environmental regulation and haze pollution [46], underscoring the need to explore threshold effects in agricultural contexts.

Integrating these insights within the EKC framework, this study posits that the interplay between regulatory costs and innovation incentives creates a nonlinear trajectory for pesticide use. In early stages, weak regulation fails to curb over-application, and compliance costs may even incentivize short-term intensification. Beyond the critical threshold, however, regulatory stringency and enhanced farmer awareness trigger technological and behavioral shifts, aligning private costs with social benefits. Thus, this study proposes the following hypothesis:

H1. *There exists an inverted U-shaped relationship between environmental regulation and pesticide use.*

High-quality agricultural economic development prioritizes ecological sustainability, emphasizing the intrinsic coupling between the agricultural ecological environment and economic progress [47]. Historically, agricultural growth often entailed environmental degradation, exacerbating non-point source pollution and contradicting sustainable development goals. To reconcile this conflict, governments enforce environmental regulations to steer farmers toward green production practices [31], such as reducing pesticide reliance. This shift from quantity-driven to quality-driven agricultural competition necessitates minimizing chemical inputs while enhancing ecological efficiency. Existing studies indicate that economic development influences the level of environmental regulation, thereby impacting ecological efficiency [48]. For example, increased tax revenues enable governments to expand regulatory personnel and enforcement frequency, ensuring policy implementation. Moreover, enhanced economic capacity fosters technological governance, such as digital monitoring platforms that precisely identify non-compliant pesticide use, lowering regulatory costs [15]. Additionally, rising farmer incomes heighten environmental sensitivity, motivating reductions in excessive pesticide application [49].

Agricultural economic scale thus operates as a dual-force moderator. On one hand, it drives ecological improvements by aligning market dynamics with environmental goals—stricter quality standards transform markets from seller-driven to buyer-driven, incentivizing producers to adopt green technologies (e.g., biopesticides) under regulatory pressure. On the other hand, economic growth amplifies governmental capacity to invest in environmental governance, including subsidies and transfer payments, which elevate farmers' ecological awareness and compliance willingness. These synergies between economic progress and regulatory enforcement suggest that increased agricultural economic scale enhances the pesticide-reducing effects of environmental regulation. Integrating these mechanisms, this study proposes the following hypothesis:

H2. *Agricultural economic scale positively moderates the influence of environmental regulation on pesticide use.*

3. Research Design

3.1. Data Source

This study focuses on 30 provinces in China as the research regions and spans the time frame of 2010 to 2023. The data utilized in this study originate from various sources, including the China Rural Statistical Yearbook, the China Statistical Yearbook, provincial statistical yearbooks, local environmental protection bureaus, Peking University's

Judicial Case Retrieval System, and the official website of the National Bureau of Statistics. Due to the incompleteness of current agricultural data statistics or differences in statistical standards, it proved challenging to encompass all regions within the scope of analysis. Consequently, this study ultimately excludes Tibet, Hong Kong, Macao, and Taiwan, focusing instead on 30 provinces in China as the study sample. These 30 provinces encompass all major agroecological zones and types of agricultural production in China. Moreover, the rationale for selecting the study period is as follows. Since 2010, China has progressively intensified its control over agricultural non-point source pollution. The Central Government's No. 1 Document of 2010 explicitly states to "vigorously promote the specialized control of crop pests and diseases" to facilitate the transformation of the agricultural development mode. In 2015, the Ministry of Agriculture and Rural Affairs of the People's Republic of China issued the "Zero Growth Action Program for Pesticide Use by 2020" [50]. Every subsequent year's Central Document No. 1 clearly emphasizes the promotion of pesticide reduction and efficiency enhancement. In 2022, the Ministry of Agriculture and Rural Affairs of the People's Republic of China issued the "Action Plan for Chemical Pesticide Reduction by 2025" [51], which also explicitly states to "accelerate the reduction in fertilizers and pesticides to increase efficiency and improve the mechanism for the reduction in fertilizer and pesticide." Therefore, the selection of the period from 2010 to 2023 ensured temporal consistency, covered the key stages of policy implementation, and encompassed the cycle of environmental regulation policy.

3.2. Selection of Variables

(1) Dependent variable. The dependent variable in this study is pesticide use (*pesticide*). The amount of pesticide use in each province was divided by the sown area of crops to calculate the intensity of pesticide use per unit of sown area.

(2) Core independent variable. The core independent variable is environmental regulation (*er*). This study defines environmental regulation in agriculture as a collection of institutional tools through which the government directly or indirectly intervenes in the behavior of agricultural producers through mandatory constraints or market incentives to achieve the goals of surface source pollution control. This study measured environmental regulation in terms of command-and-control environmental regulation and market-based environmental regulation [52,53]. Command-and-control environmental regulation refers to the setting of mandatory behavioral standards or prohibitions through legal and administrative means based on the command-and-control mode. This study measured it by using the number of cases of administrative penalties on environmental issues (−) and the number of policies implemented by provinces regarding agricultural pollution prevention and control and environmental protection (+).

Market-based environmental regulation is an institutional mechanism that utilizes economic instruments to guide producers to internalize environmental externalities by adjusting their behavior. The market-based environmental regulation indicator employed in this study is the intensity of the environmental protection tax and was specifically calculated using the ratio of the pollutant discharge fee payment and the remittance amount deposited into the national treasury to the industrial added value (+). In 2018, the environmental protection tax reform transitioned the original pollution discharge fee into a formal tax item, thereby rendering pollution discharge fee payment data an effective proxy variable for environmental protection tax intensity. The study focuses on tax mechanisms within market-based environmental regulation—despite the theoretical inclusion of alternative instruments like emissions trading and ecological subsidies [54]—due to the operational constraints of the national carbon market (limited industry coverage and insufficient carbon emission data transparency complicating dataset construction [55]) and the implementation

complexities of subsidy policies (multidimensional objectives, fragmented funding, and intricate policy instruments challenging regulatory effect quantification [56]).

Notably, the symbols in the above parentheses represent the measurement direction of each indicator for environmental regulation. "+" indicates that the indicator positively measures environmental regulation. "−" indicates that the indicator negatively measures environmental regulation. To amalgamate these diverse indicators into a cohesive environmental regulation index, the entropy method was employed.

(3) Moderating variable. The moderating variable in this study is agricultural economic scale (*scale*), measured by the gross agricultural output. In this context, agriculture is broadly defined, including agriculture, forestry, animal husbandry, and fishery. The consumption price index of rural residents was utilized to convert the total output value of these sectors in each year to a constant price in 2010.

(4) Control variables. Following the research of Huang et al. [57], Zhang et al. [49], and Huang et al. [58], this study selects the following variables as control variables.

(a) Agricultural machinery level. Increased agricultural mechanization directly increases productivity and technological sophistication, particularly in the management of agrochemicals. For example, the adoption of precision pesticide application technologies (e.g., drone spraying and smart sprayers) is higher in regions with higher levels of agricultural machinery. In this study, the agricultural machinery level is indicated by the total power of the agricultural machinery.

(b) Agricultural natural disasters. Natural disasters, such as droughts and floods, can inflict significant damage on crops, prompting farmers to increase pesticide use in an effort to combat pests and diseases. This indicator was calculated as the total disaster area in each province multiplied by the proportion of the grain sown area and then divided by the same proportion.

(c) Agricultural planting structure. The structure of agricultural planting directly influences both the quantity and methods of pesticide application through the selection of crop types, the diversity of planting patterns, and pest management strategies. In this study, this indicator was measured using the share of the grain sown area in the total sown area of crops.

(d) Agricultural operation scale. The expansion of agricultural operation scale can improve the efficiency of pesticide use and reduce the amount of pesticide applied per unit area through the popularization of unified control and management services, the application of green production standards, and the promotion of precision application techniques. This indicator was characterized by the proportion of the sown area of vegetable crops in the sown area of crops.

(e) Rural population density. Areas with relatively high population densities indicate an abundance of labor and may be more likely to use methods such as hand weeding instead of chemical pesticides. In this study, the rural population density is expressed as the number of people per unit of land area. To address heteroscedasticity, this variable was logarithmically transformed in the model.

(f) Governance capacity. The governance capacity of local governments has been enhanced by improving agricultural extension systems, optimizing resource allocation, and strengthening the effectiveness of grassroots services to promote the prevalence of precision application technologies, thereby helping to reduce the risk of pesticide over-use. This indicator is expressed in terms of the number of local regulations.

(g) Industrial structure level. Upgrading the industrial structure may bring about a change in agricultural production methods, thus affecting the intensity of pesticide use. This study used the proportion of the value added by the tertiary industry to the value added by the secondary industry to measure this indicator.

(h) Technological innovation. Regions with a relatively high level of technological innovation are better positioned to achieve "quality over quantity" in agricultural output while also driving advancements in green pest control technologies, which can contribute to reducing pesticide use. Technological innovation is represented by the number of domestic utility patents granted.

(i) Living standard. The improvement of living standards helps to enhance farmers' ability to adopt green production technology and increase environmental awareness, which affects the intensity of pesticide use. This study uses the GDP per capita as a proxy variable for living standards.

Table 1 provides definitions for all the aforementioned variables and their descriptive statistics. Figure 1 illustrates the trend in pesticide use intensity from 2010 to 2023. It is evident that there is a general decline, indicating that pesticide use has gradually decreased over this period.

Table 1. Descriptive statistics of variables.

Variable	Definition	Mean	Std. Dev.
Pesticide use (*pesticide*)	The amount of pesticide use divided by the sown area of crops (unit: tons/hectare)	0.011	0.009
Environmental regulation (*er*)	Includes command-and-control environmental regulation and market-based environmental regulation, measured using the entropy weight method	0.220	0.108
Agricultural economic scale (*scale*)	The total output value of agriculture, forestry, animal husbandry, and fishery (unit: CNY 100 million Yuan)	2485.303	1663.805
Agricultural machinery level	The total power of agricultural machinery (unit: hundred million kilowatts)	0.344	0.293
Agricultural natural disasters	Multiply the total area of disaster in the province by the proportion of the grain sown area in the total sown area of crops and then divide by the grain sown area (unit: %)	0.069	0.065
Agricultural planting structure	The grain sowing area divided by the total crop sowing area (unit: %)	0.657	0.147
Agricultural operation scale	The sown area of vegetable crops divided by the sown area of crops (unit: %)	0.154	0.1
Rural population density	The population per unit land area (unit: people per square kilometer, and logarithmic processing of the data)	4.543	1.132
Governance capability	The number of local regulators (unit: ten thousand)	0.515	0.482
Industrial structure level	The added value of the tertiary industry divided by the added value of the secondary industry (unit: %)	1.347	0.756
Technological innovation	The number of domestic utility model patent authorizations (unit: ten thousand items)	4.435	7.119
Living standard	GDP per capita (unit: ten thousand)	5.908	3.223

Furthermore, Figures 2 and 3 illustrate the distribution of pesticide use intensity and environmental regulation across various provinces in 2023, respectively. Upon observation, it becomes evident that, in general, some eastern coastal regions exhibit relatively high levels of pesticide use intensity and South China has relatively strict environmental regulation.

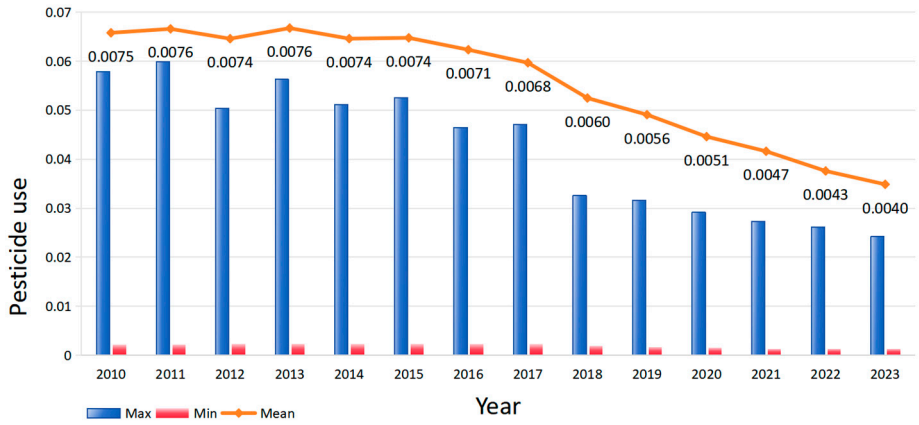


Figure 1. Line graph of pesticide use intensity from 2010 to 2023.

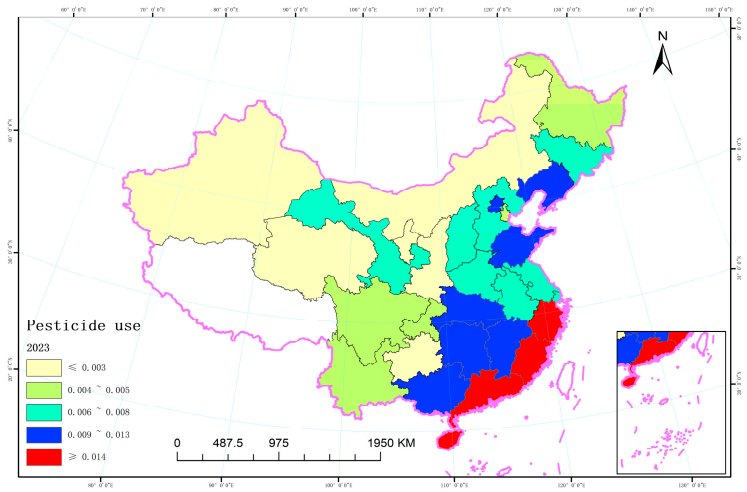


Figure 2. Distribution of pesticide use in various provinces in 2023.

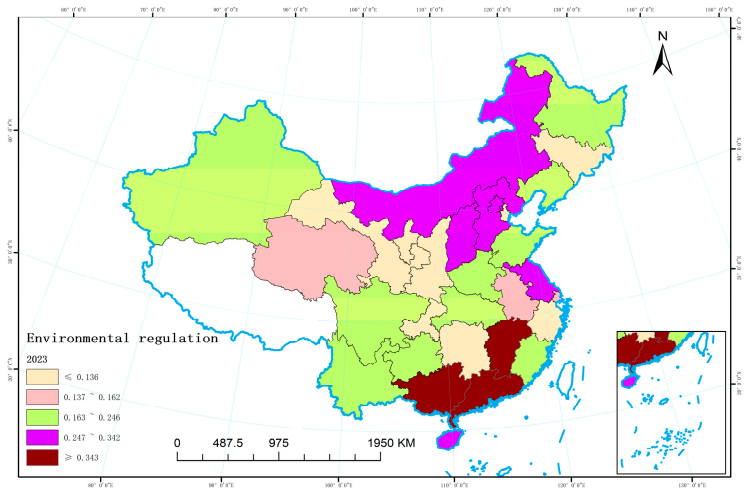


Figure 3. Distribution of environmental regulation in various provinces in 2023.

3.3. Model Settings

Based on the theoretical hypothesis analysis conducted above, this study established the following benchmark regression model to investigate the correlation between environmental regulation and pesticide use across various provinces.

$$pesticide_{i,t} = \alpha_0 + \alpha_1 er_{i,t} + \alpha_2 er_{i,t}^2 + \alpha_3 controls_{i,t} + \varepsilon_{i,t} \quad (1)$$

In Model (1), $pesticide_{i,t}$ is the dependent variable, representing the intensity of pesticide use; $er_{i,t}$ is the core explanatory variable, which denotes environmental regulation; and $controls_{i,t}$ comprises a set of control variables. Here, i denotes the province, t represents the year, α_0 is the constant term, α_1, α_2, and α_3 are the coefficients, and $\varepsilon_{i,t}$ stands for the random error term. If $\alpha_2 < 0$, it indicates an inverted U-shaped relationship between environmental regulation and pesticide use. If $\alpha_2 > 0$, a positive U-shaped relationship exists between environmental regulation and pesticide use. If $\alpha_1 > 0$ and $\alpha_2 = 0$, this indicates that stronger environmental regulation will enhance the intensity of pesticide use. If $\alpha_1 < 0$ and $\alpha_2 = 0$, this indicates that stronger environmental regulation will weaken the intensity of pesticide use.

Furthermore, building upon Model (1), the following model was developed to explore the influence of agricultural economic scale on the relationship between environmental regulation and pesticide use.

$$pesticide_{i,t} = \beta_0 + \beta_1 scale_{i,t} + \beta_2 er_{i,t} \times scale_{i,t} + \beta_3 er_{i,t}^2 \times scale_{i,t} + \beta_4 controls_{i,t} + \varepsilon_{i,t} \quad (2)$$

In Model (2), $scale_{i,t}$ represents the moderating variable. β_0 is the constant term, and β_1, β_2, β_3, and β_4 are the coefficients associated with the variables in the model.

4. Empirical Results

4.1. Benchmark Results

In this study, a two-way fixed effects model that considers both individual effect and time effect was used to conduct the regression analysis. The results of the baseline regression are shown in Table 2.

Table 2. The results of the benchmark model.

Variable	Coefficient	St.Err.
er	0.025 ***	0.006
er^2	−0.039 ***	0.010
Agricultural machinery level	0.008 ***	0.002
Agricultural natural disasters	0.006 **	0.003
Agricultural planting structure	−0.028 ***	0.007
Agricultural operation scale	−0.036 ***	0.011
Rural population density	−0.014 ***	0.004
Governance capability	0.003 ***	0.001
Industrial structure level	−0.006 ***	0.001
Technological innovation	−0.0002 ***	0.00004
Living standard	0.001 ***	0.0002
Constant	0.093 ***	0.020
Individual effect	Yes	
Time effect	Yes	
N	420	
Adj_R2	0.9322	

Note: *** and ** indicate statistical significance at 1% and 5%, respectively.

According to the results outlined in Table 2, the coefficients for both the linear and quadratic terms of environmental regulation are 0.025 and −0.039, respectively, both significant at the 1% level. The result indicates an inverted U-shaped relationship between environmental regulation and pesticide use, that is, the trend in pesticide use intensity initially rises and then declines. Consequently, hypothesis H1 is confirmed. In the early stages of environmental regulation, farmers tend to increase pesticide inputs to avoid yield risks due to lagging technology substitution and compliance cost pressures. As the intensity of regulation crosses a critical threshold, policy incentives and market premiums drive the

adoption of green technologies and the popularization of precision application techniques, and pesticide reductions are ultimately achieved.

Regarding the control variables, the regression coefficients of agricultural planting structure, agricultural operation scale, rural population density, industrial structure level, and technological innovation are all negative and significant at the 1% level, indicating that these variables have a significantly negative effect on pesticide use intensity. The regression coefficient for agricultural natural disasters is positive and significant at the 5% level, indicating a significantly positive effect on pesticide use intensity. All these results are in line with our expectations. The diversification of the planting structure inhibits pest and disease outbreaks through ecological niche competition and reduces dependence on chemical pesticides for single crops. Large-scale operators adopt unified control and green technology to reduce the amount of pesticide applied per unit area and improve the utilization rate. In high-density areas, where labor is abundant, manual weeding and biological control replace some of the functions of chemical pesticides. The increase in the proportion of non-agricultural industries reduces the dependence on agricultural income, forcing farmers to reduce high-cost pesticide inputs. Green technology (e.g., smart application equipment) has reduced the proportion of ineffective pesticide application and the total intensity of pesticide use. As crop resistance declines after a disaster, farmers tend to compensate for disaster losses by applying more pesticides and preventing the risk of secondary pests.

Additionally, the results show that the regression coefficients of agricultural machinery levels, governance capacity, and living standards are positive and significant at the 1% level, implying that these variables have a significant and positive effect on the intensity of pesticide use. These findings deviate from our initial hypotheses, which may be explained by the co-driven intensive production paradigm and its underlying risk mitigation strategies. Agricultural mechanization increases the risk of concentrated outbreaks of pests and diseases through large-scale monoculture contiguous planting, forcing frequent pesticide applications to maintain yield stability. In areas with high governance capacity, due to the improved agricultural infrastructure and policy implementation capacity, the path dependence of the intensive model dominated by chemical inputs is further strengthened, and pesticides are used as the core tool to ensure scale benefits. The improvement of living standards prompts farmers to use pesticides instead of manual management through the increase in labor costs and short-term profit orientation, compressing the production cycle and pursuing the maximization of income per unit area.

4.2. Endogeneity Analysis

To alleviate endogeneity bias caused by reverse causality and omitted variables, this study adopted a two-stage least squares (2SLS) regression method for analysis. Referring to the study of Ding et al. [59], the data of one period of environmental regulation lag were selected as the instrumental variable. The implementation of environmental regulation typically undergoes a process involving policy communication, enforcement, and the adjustment of farmers' behavior. As a result, the policy effects often manifest with a certain lag. Furthermore, environmental regulation in the lagged period demonstrates a low correlation with the error term associated with pesticide use in the current period. In other words, current pesticide usage does not influence the intensity of historical environmental policies. This satisfies the exogeneity requirement for instrumental variables, thereby avoiding potential estimation bias.

The test results are shown in Table 3. The results of the first stage reveal that both the instrumental variables for the linear and quadratic terms of environmental regulation exhibit a significant positive correlation, implying that each instrumental variable has a

strong explanatory power for its respective term. The results of the second-stage regression show that the coefficients of the linear and quadratic terms of environmental regulation are 0.038 and −0.062, respectively, and both coefficients are significant at the 1% level, thereby maintaining an inverted U-shaped relationship between environmental regulation and pesticide use. The findings signify the solidity of the benchmark regression model after considering the potential endogeneity problem.

Table 3. Results of 2SLS regression.

Variable	The First Stage				The Second Stage	
	er		er^2		*Pesticide*	
	Coefficient	**St.Err.**	**Coefficient**	**St.Err.**	**Coefficient**	**St.Err.**
er					0.038 ***	0.012
er^2					−0.062 ***	0.020
L.er	0.657 ***	0.143	0.100	0.098		
$L.er^2$	−0.006	0.223	0.450 ***	0.152		
Agricultural machinery level	0.101 *	0.058	0.085 **	0.040	0.008 ***	0.003
Agricultural natural disasters	0.039	0.060	0.041	0.041	0.007 ***	0.003
Agricultural planting structure	−0.099	0.166	−0.054	0.113	−0.027 ***	0.007
Agricultural operation scale	0.317	0.276	0.146	0.188	−0.041 ***	0.012
Rural population density	0.077	0.106	0.038	0.072	−0.018 ***	0.005
Governance capability	−0.029 *	0.016	−0.020 *	0.011	0.003 ***	0.0007
Industrial structure level	0.045 **	0.020	0.020	0.014	−0.006 ***	0.0009
Technological innovation	0.002 *	0.001	0.001	0.0007	−0.0002 ***	0.00004
Living standard	−0.005	0.005	−0.003	0.003	0.001 ***	0.0002
Constant	−0.491	0.553	−0.246	0.376	0.151 ***	0.023
Anderson canon. corr. LM statistic	72.08 ***		72.08 ***			
Cragg–Donald Wald F statistic	38.21		38.21			
Individual effect	Yes	Yes	Yes	Yes	Yes	Yes
Time effect	Yes	Yes	Yes	Yes	Yes	Yes
N	390	390	390	390	390	390
Adj_R2	0.7565		0.6662		0.9414	

Note: ***, **, and * indicate statistical significance at 1%, 5%, and 10%, respectively.

4.3. Robustness Checks

(1) Replace the explanatory variables. This study re-measured pesticide use intensity using one-period lagged data. Pesticide use is susceptible to short-term factors such as climate, pests, and diseases, while the policy effects of environmental regulation may be reflected in long-term observations. Therefore, the use of one-period lagged data can highlight the continuity of policy effects. Moreover, by comparing the regression results of the current period and the lagged period, it is possible to test whether the inverted U-shaped relationship is consistent across time dimensions. Should the findings align, this would serve to further corroborate the robustness of the results.

(2) Adjust the sample time. To further bolster the model's robustness, this study adjusted the sample timeframe. Recognizing the pivotal year of 2015, where governments at various levels initiated measures to foster ecological civilization, leading to a gradual decline in pesticide use intensity in China, the sample period was revised to span from 2010 to 2015.

The regression results obtained from the aforementioned methods are presented in Table 4. The results show that the linear term of environmental regulation has a significantly positive effect on pesticide use, and the quadratic term of environmental regulation has a significantly negative effect on pesticide use, suggesting an inverted U-shaped relationship

between environmental regulation and pesticide use. This result underscores the robust nature of the model constructed in this study.

Table 4. The results of the robustness checks.

Variable	(1)		(2)	
	Coefficient	**St.Err.**	**Coefficient**	**St.Err.**
er	0.023 ***	0.006	0.020 **	0.008
er^2	−0.033 ***	0.010	−0.030 **	0.012
Agricultural machinery level	0.006 **	0.003	0.005	0.004
Agricultural natural disasters	0.005 *	0.003	0.005 **	0.002
Agricultural planting structure	−0.031 ***	0.007	0.007	0.011
Agricultural operation scale	−0.032 ***	0.012	0.037 **	0.018
Rural population density	−0.018 ***	0.005	−0.002	0.005
Governance capability	0.003 **	0.001	−0.001	0.004
Industrial structure level	−0.006 ***	0.001	−0.002	0.001
Technological innovation	−0.0002 ***	0.00004	−0.00008	0.0002
Living standard	0.001 ***	0.0002	−0.0002	0.0005
Constant	0.114 ***	0.022	0.009	0.026
Individual effect	Yes		Yes	
Time effect	Yes		Yes	
N	390		180	
Adj_R2	0.9395		0.9860	

Note: ***, **, and * indicate statistical significance at 1%, 5%, and 10%, respectively.

4.4. Moderating Effect Results

According to Model (2), the moderating effect of agricultural economic scale was further tested. The results are presented in Table 5.

Table 5. The results of the moderating effect.

Variable	Coefficient	St.Err.
scale	-4.69×10^{-7}	6.09×10^{-7}
*er*scale*	4.22×10^{-6} **	2.09×10^{-6}
er^2**scale*	-6.76×10^{-6} **	3.16×10^{-6}
Agricultural machinery level	0.007 ***	0.003
Agricultural natural disasters	0.006 **	0.003
Agricultural planting structure	−0.028 ***	0.007
Agricultural operation scale	−0.033 ***	0.012
Rural population density	−0.013 ***	0.004
Governance capability	0.003 ***	0.001
Industrial structure level	−0.005 ***	0.001
Technological innovation	−0.0002 ***	0.00004
Living standard	0.001 ***	0.0002
Constant	0.089 ***	0.021
Individual effect	Yes	
Time effect	Yes	
N	420	
Adj_R2	0.9299	

Note: *** and ** indicate statistical significance at 1% and 5%, respectively.

The findings reveal that the coefficient of the interaction term between the moderating variable and the quadratic term of environmental regulation is significantly negative, while the coefficient of the interaction term between the moderating variable and the linear term of environmental regulation is significantly positive. The results suggest that agricultural economic scale intensifies the slope of the relationship curve that links

environmental regulation to pesticide use. Generally, the expansion of the agricultural economic scale drives the forward shift of the inverted U-shaped inflection point threshold of environmental regulation on pesticide use by optimizing the efficiency of technology diffusion and the integration ability of the industrial chain. These results confirm that agricultural economic scale exerts a significant moderating influence on the relationship between environmental regulation and pesticide use, thereby supporting hypothesis H2.

4.5. Heterogeneity Analysis

4.5.1. Regional Heterogeneity Analysis

To examine the regional variations in the impact of regulatory measures on pesticide use, this study categorized the 30 provinces in the sample into three distinct regions—eastern, central, and western—and performed regression analysis accordingly. The eastern region includes Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Hainan, and Liaoning. The central region includes Shanxi, Anhui, Jiangxi, Henan, Hubei, Hunan, Jilin, and Heilongjiang. The western region includes Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang.

Table 6 shows the results of the regression analysis for the eastern, central, and western regions, respectively. The results show that the linear term of environmental regulation has a positive and significant effect on pesticide use in the eastern and central regions, while the quadratic term of environmental regulation has a negative and significant effect on pesticide use, implying that there is a significant inverted U-shape between environmental regulation and pesticide use intensity. In contrast, the coefficients of both the linear and quadratic terms of environmental regulation in the western region are statistically insignificant. This result suggests that the impact of environmental regulation on pesticide use intensity in the western region is relatively weak.

Table 6. Regional heterogeneity results.

Variable	Eastern Region		Central Region		Western Region	
	Coefficient	**St.Err.**	**Coefficient**	**St.Err.**	**Coefficient**	**St.Err.**
er	0.054 ***	0.014	0.010 **	0.004	0.002	0.007
er^2	−0.079 ***	0.022	−0.020 ***	0.006	−0.001	0.011
Agricultural machinery level	−0.011 *	0.006	0.004 ***	0.001	0.003	0.005
Agricultural natural disasters	0.014 **	0.006	−0.005 **	0.002	0.004	0.002
Agricultural planting structure	−0.038 **	0.016	−0.025 ***	0.009	0.006	0.009
Agricultural operation scale	−0.090 ***	0.028	−0.117 ***	0.027	0.006	0.008
Rural population density	−0.018 *	0.009	0.006	0.011	0.018 ***	0.006
Governance capability	0.003 **	0.001	0.001	0.001	0.004 **	0.002
Industrial structure level	−0.006 ***	0.002	−0.002 **	0.001	−0.003 **	0.002
Technological innovation	−0.0001 *	0.00007	−0.0001	0.0001	−0.0002	0.0002
Living standard	0.002 ***	0.0003	−0.001 ***	0.0004	0.001 ***	0.0005
Constant	0.142 ***	0.047	0.015	0.052	−0.071 ***	0.023
Individual effect	Yes		Yes		Yes	
Time effect	Yes		Yes		Yes	
N	154		112		154	
Adj_R2	0.9276		0.9580		0.9029	

Note: ***, **, and * indicate statistical significance at 1%, 5%, and 10%, respectively.

4.5.2. Environmental Regulation Dimensional Heterogeneity Analysis

This study conducted an analysis of the impact of different dimensions of environmental regulation—namely, command-and-control environmental regulation and market-based environmental regulation—on pesticide use intensity. Such an investigation provides in-

sights and contributes to a more comprehensive understanding of how environmental regulation can play a critical role in managing agricultural surface pollution. The regression results are shown in Table 7.

Table 7. Heterogeneity results of environmental regulation dimensions.

Variable	Command-and-Control Environmental Regulation		Market-Based Environmental Regulation	
	Coefficient	**St.Err.**	**Coefficient**	**St.Err.**
er	0.005	0.004	4.086 ***	1.072
er^2	−0.006	0.004	−981.491 ***	306.058
Agricultural machinery level	0.006 **	0.003	0.008 ***	0.003
Agricultural natural disasters	0.006 **	0.003	0.006 **	0.003
Agricultural planting structure	−0.027 ***	0.007	−0.025 ***	0.007
Agricultural operation scale	−0.029 **	0.012	−0.036 ***	0.011
Rural population density	−0.012 ***	0.004	−0.012 ***	0.004
Governance capability	0.003 ***	0.001	0.003 ***	0.001
Industrial structure level	−0.005 ***	0.001	−0.006 ***	0.001
Technological innovation	−0.0002 ***	0.00004	−0.0002 ***	0.00004
Living standard	0.001 ***	0.0002	0.001 ***	0.0002
Constant	0.086 ***	0.020	0.086 ***	0.020
Individual effect	Yes		Yes	
Time effect	Yes		Yes	
N	420		420	
Adj_R^2	0.9296		0.9319	

Note: *** and ** indicate statistical significance at 1% and 5%, respectively.

The results reveal that the linear term of market-based environmental regulation has a significantly positive effect on pesticide use, while the quadratic term of market-based environmental regulation has a significantly negative effect on pesticide use. This finding implies that there is an inverted U-shaped relationship between market-based environmental regulation and pesticide use intensity. The coefficients of both the linear and quadratic terms associated with command-and-control environmental regulation are statistically insignificant. This finding implies that the influence of such regulatory measures on pesticide use intensity is relatively limited.

4.6. Further Analysis

This study delved further into alternative policies to direct government regulation, exploring measures such as incentivizing sustainable agricultural practices. As a case in point, the research examines a pilot policy for the construction of field complexes that has been implemented in China. The policy promotes sustainable agricultural practices through financial rewards and subsidies, industrial integration, and market-oriented incentive mechanisms. Specifically, this policy integrates ecological agriculture, rural tourism, and community co-construction. It guides the application of green technologies (e.g., organic farming and ecological circulation systems) with financial subsidies. Moreover, it enhances the economic benefits of sustainable agriculture through the extension of the industrial chain (e.g., the integration of agriculture and tourism), encourages farmers to actively reduce their reliance on chemical pesticides, forms a virtuous cycle of "ecological benefits—economic benefits", and avoids the high implementation costs and farmers' resistance to traditional supervision.

In 2017, the Ministry of Finance issued the Circular on the Pilot Work on the Construction of Field Complexes [60], which explicitly proposed that the central financial government make overall arrangements from the comprehensive rural reform transfer

funds, modern agricultural production development funds, and comprehensive agricultural development subsidy funds to support the pilot work. Meanwhile, the 18 provinces of Hebei, Shanxi, Inner Mongolia, Jiangsu, Zhejiang, Fujian, Jiangxi, Shandong, Henan, Hunan, Guangdong, Guangxi, Hainan, Chongqing, Sichuan, Yunnan, Shaanxi, and Gansu are identified to carry out the pilot construction of field complexes. Therefore, this study finally chose the above 18 provinces as the experimental group in the double-difference (DID) regression analysis and took the remaining 12 provinces as the control group. The following model was set up:

$$pesticide_{i,t} = \alpha_0 + \alpha_1 post_t * treat_er_i + \alpha_2 treat_er + \alpha_3 controls_{i,t} + \varepsilon_{i,t} \quad (3)$$

where *post* is a time dummy variable expressed as 0 during 2010–2017 and 1 during 2018–2023. If the province is the experimental group (control group), *treat_er* equals 1 (0). The interaction term *post*treat_er* represents the change in pesticide use intensity between the experimental and control groups before and after the policy was issued.

Before the implementation of the policy, the experimental group and the control group should meet the parallel trend assumption, that is, the intensity of pesticide use needs to maintain a relatively stable trend of change. Therefore, this study utilized the event study method to conduct the parallel trend test. To avoid the effect of multicollinearity, this study dropped *pre_1* in the regression, and its regression results are shown in Table 8. The regression coefficients of the interaction terms *pre3*treat_er* and *pre2*treat_er* are insignificant, while the regression coefficients of *post1*treat_er*, *post2*treat_er*, and *post3*treat_er* are significantly negative. The results indicate that the parallel trend test is applicable to the DID research design of this study.

Table 8. Regression results of parallel trend test.

Variable	Coefficient	St.Err.
*pre3*treat_er*	0.0007	0.001
*pre2*treat_er*	0.0003	0.001
*current*treat_er*	−0.001	0.001
*post1*treat_er*	−0.002 **	0.001
*post2*treat_er*	−0.002 **	0.001
*post3*treat_er*	−0.002 **	0.001
Agricultural machinery level	0.005 *	0.003
Agricultural natural disasters	0.006 **	0.003
Agricultural planting structure	−0.027 ***	0.007
Agricultural operation scale	−0.029 **	0.011
Rural population density	−0.013 ***	0.004
Governance capability	0.003 ***	0.0007
Industrial structure level	−0.005 ***	0.0008
Technological innovation	−0.0002 ***	0.00004
Living standard	0.001 ***	0.0002
Constant	0.090 ***	0.0204
Individual effect	Yes	
Time effect	Yes	
N	420	
Adj_R^2	0.9312	

Note: ***, **, and * indicate statistical significance at 1%, 5%, and 10%, respectively.

Figure 4 presents a graphical illustration of the test results. As can be clearly observed from the graph, the estimated coefficient for the pre-event period is close to zero. This result suggests that there is no significant difference between the experimental and control groups during the pre-event period, thereby satisfying the parallel trend assumption. After the event, the intensity of pesticide use shows a decreasing trend, indicating that the policy

has a significantly negative effect on pesticide use. Table 9 then reports the regression results for DID. The results show that the estimated coefficient of the interaction term is significantly negative, indicating that environmental regulation significantly reduces the intensity of pesticide use.

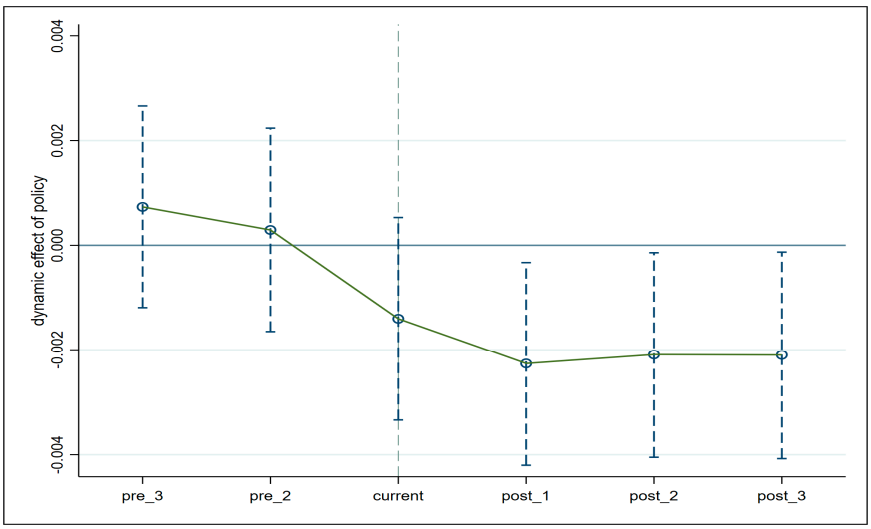


Figure 4. Parallel trend test chart. The solid line in the figure illustrates the estimated coefficient values, highlighting the variations between the control group and the experimental group across different time points. The dashed line denotes the confidence interval, which serves as a critical tool for assessing the statistical significance of the estimated coefficient values.

Table 9. Regression results of DID.

Variable	Coefficient	St.Err.
*post*treat_er*	−0.004 ***	0.0005
Agricultural machinery level	0.003	0.002
Agricultural natural disasters	0.006 **	0.002
Agricultural planting structure	−0.032 ***	0.007
Agricultural operation scale	−0.027 **	0.011
Rural population density	−0.015 ***	0.004
Governance capability	0.004 ***	0.0007
Industrial structure level	−0.005 ***	0.0008
Technological innovation	−0.0002 ***	0.00004
Living standard	0.0009 ***	0.0002
Constant	0.104 ***	0.019
Individual effect	Yes	
Time effect	Yes	
N	420	
Adj_R^2	0.9381	

Note: *** and ** indicate statistical significance at 1% and 5%, respectively.

5. Discussion

Delving into the mechanism through which environmental regulations induce a decrease in pesticide use can significantly bolster policy efficacy, preserve the quality and safety of agricultural products, and nurture sustainable green development. Overall, the study revealsed an inverted U-shaped correlation between environmental regulation and pesticide use. This result is consistent with our expectations and also corroborates the findings of Zhou et al. [46], who posit an inverted U-shaped relationship between environmental regulation and environmental pollution. Notably, while existing studies predominantly concentrate on macro indicators such as industrial pollution or carbon

emissions, this research substantiates the presence of an inverted U-shaped relationship, specifically in pesticide use intensity. The findings indicate that an initial increase in the intensity of environmental regulation does not significantly curtail pesticide use when regulations are relatively weak. However, once a critical threshold is exceeded, environmental regulation begins to promote pesticide reduction. This phenomenon may be attributed to several factors. In the nascent stages of environmental regulation, the low cost of non-compliance, limited environmental awareness, and insufficient technological and financial support for green production impede farmers' ability to swiftly adapt their production practices. Moreover, farmers tend to adhere to traditional application methods to mitigate risks, potentially leading to pesticide overuse due to regulatory pressures. Conversely, when the intensity of environmental regulation surpasses the threshold, two significant dynamics emerge. First, stringent environmental regulation compels governments to implement supportive incentive policies, such as subsidies for precision pesticide application and ecological subsidies, thereby lowering barriers to the adoption of green technologies. Simultaneously, as regulatory intensity increases, governments tighten oversight and impose stricter penalties for environmental violations [43]. Second, market-based environmental regulation tools guide agribusinesses to expedite the development of green technologies through price signals, fostering regional networks for disseminating integrated pest management technologies. Farmers, driven by profit maximization, adopt more scientific and rational pesticide application methods, avoiding excessive use and consequently reducing pesticide intensity.

Furthermore, the findings of our study revealed that agricultural economic scale has a significantly moderating effect on the relationship between environmental regulation and pesticide use. It is evident that economic development exerts an influence on environmental regulations, thereby impacting the quality of the environment. This observation aligns with the research findings of Orubu and Omotor [40]. As agricultural economic scale continues to improve, environmental regulation becomes more effective in reducing pesticide use. Agricultural economic scale can enhance the threshold effect of environmental regulation on pesticide use, contributing to a reduction in pesticide use. Possible reasons include stricter environmental legislation and government regulation in regions with higher levels of economic development. To avoid economic penalties, farmers in these regions tend to reduce pesticide use. Moreover, compared to regions with lower agricultural economic scale, regions with higher agricultural economic scale boast more sophisticated agricultural production conditions and a higher level of education among the rural labor force, which is conducive to improving the adoption of precision application technologies or biopesticides.

Moreover, the heterogeneity analysis revealed distinct regional patterns in the relationship between environmental regulation and pesticide use. Specifically, a significant inverted U-shaped relationship emerges in the eastern and central regions, whereas this dynamic is absent in the western region. This divergence can be attributed to regional disparities in agricultural production systems and regulatory adaptability. In the eastern region, characterized by high land intensification, large-scale agricultural entities leverage resource integration capabilities to adopt precision pesticide application technologies, enabling effective alignment with environmental regulation. Concurrently, the central region's relatively short agricultural supply chain compels environmental regulation to foster green synergies between production and processing stages, thereby mitigating pesticide reduction risks through enhanced whole-chain efficiency. Conversely, the western region's fragmented landholdings and smallholder-dominated farming model hinder technological adaptation to regulatory requirements, leading to a greater reliance on conventional pesticide practices.

Further dimensional heterogeneity analysis demonstrated that market-based environmental regulation exhibits a robust inverted U-shaped relationship with pesticide use intensity, while command-and-control environmental regulation shows no statistically significant effect. The weakness of command-and-control environmental regulations on pesticide use may stem from the mismatch between their rigid constraints and the complexity of agricultural systems. Such regulation relies on uniform mandatory standards and ignores regional differences in resource endowments and the diversity of agricultural production patterns. In reality, the intensity of pesticide use is influenced by multiple complex factors. Relying solely on administrative orders is difficult to precisely match the dynamically changing agricultural production needs, resulting in the policy effect being interfered with by other variables and unable to show significance at the statistical level. This phenomenon implies that environmental regulation needs to combine means such as market incentives and technology promotion to form collaborative governance in order to achieve the sustainable effect of reducing pesticide use.

Additionally, this study revealed the effectiveness of policy alternatives to direct government regulation in the green transformation of agriculture through a quasi-natural experiment of the pilot policy for the construction of field complexes. Through the leverage effect of financial incentives and subsidies, the policy of the construction of field complexes organically combines ecological agricultural practices (e.g., organic cultivation) with value-added rural industries (e.g., agri-tourism integration). This enables farmers to reduce their dependence on pesticides while securing sustainable livelihoods, thus solving the dilemma of high compliance costs and strong resistance from farmers in traditional environmental regulation. This result provides empirical evidence that developing countries can use to explore environmental governance paths.

This study acknowledges certain limitations. First, while the analysis based on provincial panel data can capture the macro-level association between environmental regulation and pesticide use, it falls short in revealing the variations in farmers' behavior at the county level. For instance, micro-level factors such as risk preferences and cost sensitivity to technology adoption may create nonlinear perturbations in policy responses. This limitation risks underestimating the individual dynamic differences in how policies are received and acted upon. Second, with regard to the measurement of environmental regulation indicators, this study distinguishes between command-and-control and market-based environmental regulations but does not adequately account for voluntary environmental regulation. Furthermore, at the mechanism analysis level, a comprehensive multi-level transmission framework encompassing "policy tools—subject response—technology diffusion" has yet to be established. Future research could address these gaps by integrating satellite remote sensing data with farmer survey data to construct a nested analytical model. Additionally, refining the typological analysis of regulatory tools would enhance both the precision and adaptability of policy design, ensuring that recommendations are more contextually relevant and effective.

6. Conclusions and Implications

Drawing upon panel data from 30 regions in China spanning from 2010 to 2023, this study empirically examined the impact of environmental regulation and agricultural economic scale on pesticide use intensity through a fixed-effect model. The findings indicate that, overall, environmental regulation indeed has a notable influence on pesticide use. Specifically, an inverted U-shaped relationship is observed between environmental regulation and pesticide use, where the intensity initially rises and then declines. Furthermore, agricultural economic scale, acting as a moderating variable, enhances the positive effect of environmental regulation on reducing pesticide use and accelerates the achievement

of the inflection point in the inverted U-shaped curve. Heterogeneity analysis shows that there is an inverted U-shaped relationship between environmental regulation and pesticide use intensity in the eastern and central regions compared to the western region. Additionally, the analysis of dimensions of environmental regulation shows an inverted U-shaped relationship between market-based environmental regulation and pesticide use intensity, while the relationship between command-and-control environmental regulation and pesticide use intensity is not significant. This study expands the applicability boundary of the EKC theory in the field of agricultural non-point source pollution control by verifying the inverted U-shaped relationship between environmental regulation and pesticide use intensity, revealing the regulatory mechanism of agricultural economic scale on policy effectiveness. The research results have important reference significance for improving environmental regulatory tools and formulating regional differentiation policies. Based on these empirical findings, this study offers the following policy recommendations.

(1) The optimization of environmental regulatory tools to enhance policy effectiveness. First, market-based regulatory innovations should be deepened. For example, implementing dynamically adjusted tiered subsidies for farmers adopting biopesticides and green control technologies, and expanding green finance mechanisms to strengthen support for eco-friendly agricultural technologies. Second, a dual incentive-constraint framework can be established, imposing ecological compensation fees on entities exceeding pesticide use thresholds while rewarding compliance. Moreover, the capabilities of grassroots law enforcement can be enhanced by equipping key ecological areas with advanced pesticide testing equipment and drone patrol technology. Additionally, the enforcement of mandatory regulations can be reinforced through the establishment of a digital traceability system that spans the entire process from pesticide production to application.

(2) The construction of a differentiated regional governance framework. In the eastern region, leveraging digital technology can be prioritized to establish a dynamic monitoring system for pesticide use. Market-oriented tools, such as green credit and carbon emissions trading, can incentivize agricultural entities to adopt intelligent pesticide application technologies. For the central region, efforts should focus on enhancing financial subsidies and agricultural technology promotion. Special funds can be allocated to support the research and development of pesticide substitution technologies, while a cross-county digital collaborative network can be established to share early warning information on pests and diseases. Western region strategies should focus on upgrading farmland irrigation infrastructure, subsidizing smart agricultural machinery to address land fragmentation, and implementing ecologically integrated pesticide reduction models in vulnerable ecosystems. Moreover, a trans-provincial collaborative governance platform should be institutionalized to facilitate joint technological innovation and policy alignment across administrative boundaries.

(3) Strengthening synergies between agricultural economic growth and environmental regulation. Investments in biopesticide research and development and intelligent agricultural equipment can be intensified, with pesticide reduction targets embedded in quality certification systems to create a tripartite value chain linking chemical reduction, product premiumization, and brand differentiation. Furthermore, integrating agriculture with cultural tourism, education, and other sectors can spur the development of eco-tourism agriculture and other innovative business models. These initiatives will extend the agricultural value chain, amplify the benefits of green transformation for farmers, and strengthen their intrinsic motivation to comply with environmental regulation. Additionally, establishing a dynamic linkage mechanism between the level of agricultural economic development and the intensity of environmental regulation may ensure that policies evolve in tandem with economic progress, fostering sustainable agricultural development nationwide.

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