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Cleaner production: Analysis of the role and path of green finance in controlling agricultural non-point source pollution

Yang Shen*, Xiuwu Zhang

Institute of Quantitative Economics, Huaqiao University, Xiamen 361021, China

* **Correspondence**

Yang Shen

yangs996@foxmail.com

Abstract:

This study evaluates the impact of green finance (GF) on agricultural non-point source pollution (ANPSP) control and emission reduction in 30 Chinese provinces from 2005 to 2021. Utilizing the entropy value method and the unit survey inventory method, the research measures the levels of green finance development and ANPSP. It employs a mediation effect model to empirically assess the pollution control efficacy of green finance and to elucidate the mechanisms underlying its influence. The findings indicate that GF development significantly curtails ANPSP emissions. It achieves this through government environmental regulation (ER) and land transfer mechanisms. However, in regions with low economic development, GF may inadvertently exacerbate ANPSP. Consequently, the study recommends enhancing GF infrastructure in rural areas, aligning GF policies with ER, promoting large-scale land operations, and implementing tailored strategies for regions with varying economic development levels. These measures aim to augment the role of GF in pollution treatment and emission reduction, thereby optimizing the green financial system, advancing environmental protection, and fostering sustainable development in China's agricultural sector.

Keywords Green finance; Agricultural non-point source pollution; Government environmental regulation; Land transfer; Mediation effect; Entropy evaluation method

Introduction

In response to global climate change, China has set forth the objectives of achieving "carbon peaking" by 2030 and "carbon neutrality" by 2060, demonstrating the nation's strong commitment to actively addressing climate change and embracing a path of green and low-carbon development.

Achieving the "dual-carbon" goal is contingent upon the support of green finance (GF). Through instruments like green credit, green bonds, and other financial mechanisms, GF channels funds towards low-carbon, clean energy, and environmental protection projects. This facilitates the transition of capital from high-pollution industries to low-pollution sectors, enhances returns on investments in green industries, improves fund availability, and mitigates pollution emissions (Tian et al., 2022). The 20th National Congress of the Communist Party of China (CPC) underscored the vital role of financial backing for green development. It explicitly advocated for the rational allocation of resources, promotion of resource transfer to green and low-carbon projects, and facilitation of the transition of traditional industries towards ecological practices and the development of new green industries. In this context, agricultural non-point source pollution (hereinafter referred to as ANPSP), as a significant driver of systemic environmental pollution, plays a crucial role in achieving sustainable agricultural development and ensuring human health and safety (Fan et al., 2024).

However, due to the characteristics of agricultural non-point source pollution (ANPSP), despite China's robust policy and financial support for controlling such pollution, administratively-driven fiscal policies have encountered a "dysfunctional" dilemma, making ANPSP control a key and challenging aspect of environmental governance. The dispersion, hidden nature, and delayed characteristics of ANPSP exacerbate the situation, leading to a yearly increase in government financial support. Urgent expansion and supplementation of the tools for managing ANPSP are necessary. In this regard, GF should serve as a means to manage ANPSP effectively and play its crucial role. The inclusion of "green financial standardization construction" as a key project during the "13th Five-Year Plan" period, along with the formulation of guiding opinions by the CPC Central Committee and the State Council to comprehensively strengthen ecological environmental protection and fight pollution, signifies the steady advancement of GF standardization in China. With a positive trend in financial market development, financial support has become a primary driver in promoting the management of ANPSP and the development of ecological civilization.

While GF yields positive effects in managing ANPSP, it faces numerous bottlenecks and challenges, including the imbalance and inadequacy of China's financial development. Hence, in this context, it is essential to examine the impact of GF on the governance of ANPSP in China. Does it effectively support pollution management? What mechanisms does GF employ in managing ANPSP? This paper aims to address these questions by exploring scientific issues, developing an assessment of the impact mechanism of GF on managing ANPSP, providing decision-making guidance for the government to promote ecological construction, and offering reference significance for other developing countries' pollution management efforts. This research aims to contribute to the improvement of the green financial system and achieve dual benefits in financial and environmental domains.

Literature review

The concept of GF, originating from global concerns for environmental protection and sustainable development, represents a novel paradigm in financial theory and practice. It is also referred to as environmental finance or sustainability finance in existing literature. GF primarily restructures the operational concepts, management policies, and business processes of the financial industry through an environmental protection lens, aiming to achieve sustainable development (Zhang et al., 2019). In recent years, the Chinese government has actively promoted the establishment of a green financial system through various policy measures, including the introduction of green credit, green bonds, and support for the development and implementation of green projects (Li et al., 2023). China's GF policy not only addresses urban environmental issues but also encompasses the agricultural sector, particularly focusing on the challenge of agricultural surface source pollution.

Agricultural surface source pollution refers to the contamination of the ecological environment due to excessive chemical inputs in the planting industry and improper treatment of crop straws and livestock manure in the farming industry. It is driven by factors such as rainfall, topography, and a variety of influencing factors, making its monitoring challenging. With the rapid development of agriculture since the 21st century, China's major lakes and rivers have been increasingly affected by surface pollution, leading to the dangerous problem of eutrophication (Li et al., 2023). Similarly, foreign countries also face agricultural surface source pollution due to extensive chemical fertilizer use and intensified modern agricultural practices (Shortle et al., 2012).

There are two main methods for measuring agricultural surface source pollution. The experimental method involves selecting representative farms to test and measure pollutants discharged using modeling and monitoring methods (Shen et al., 2020). The source strength estimation method, used for macro calculations, estimates pollutant loads per unit area from farmland fertilizers, livestock and poultry farming, farmland solid waste, and rural life (Ding et al., 2023). In terms of governance instruments, two broad categories exist: "Pegu's instruments" dominated by government macro-control and "Coase's instruments" driven by market regulation mechanisms (Simpson, 1996). Peguy's approach advocates top-down government intervention to reduce environmental pollution by taxing polluters or subsidizing environmental protection efforts. Conversely, Coasean means rely on clear property rights definitions to transform environmental goods into private goods, thereby preventing the tragedy of the commons phenomenon and optimizing societal interests (Sarr et al., 2019).

As the financial system continues to evolve, market-led green financial support has become an important tool for managing ANPSP. Financial institutions can influence the environmental protection capacity of the production sector by incorporating environmental values into their financial products or services, thereby directing social funds to participate in pollution management, particularly in less developed areas (Jiang et al., 2019). Measures such as promoting organic fertilizers, improving livestock and poultry management, and supporting eco-agriculture not only reduce pollution but also enhance agricultural production efficiency, achieving economic and environmental benefits (Bah et al., 2020; Wen et al., 2024). However, the application of GF in agriculture still faces numerous challenges. Scholtens et al. (2017) suggest that the imbalance in financial resource allocation can hinder efforts to combat ANPSP. Factors such as capital scarcity, technological limitations, and the immaturity of financial products and services may inhibit farmers' adoption of ecological practices for soil and water conservation (Spearing et al., 2022; Muthukannan et al., 2020).

Overall, research on GF and ANPSP appears to be both systematic and comprehensive, yielding significant findings across various dimensions. Nonetheless, as investigations advance, certain limitations in existing studies have become evident. In response, this paper utilizes panel data from 30 mainland Chinese provinces between 2005 and 2021. It constructs a GF index employing the entropy value method and assesses emissions from seven categories of agricultural non-point source pollutants (agricultural fertilizers, livestock and poultry farming, aquaculture, crops, rural life, pesticides, and agricultural films) using the inventory method. Moreover, the paper performs empirical analyses of the pollution control and emission reduction impacts of GF by developing a mediation effect model.

The significant contributions of this study are threefold. First, it innovatively consolidates GF and ANPSP within a unified framework. This approach facilitates an in-depth examination of the influence of GF on ANPSP. It also delves into the role of government environmental regulation and the extent of land transfer in this dynamic. This integration not only sheds light on the interaction between these elements but also provides empirical evidence supporting the development of an optimized green financial system. Such a system is instrumental in enhancing pollution and carbon reduction efforts.Second, this study broadens the analytical scope of ANPSP by employing an extensive set of indicators, thereby offering a more systematic and thorough evaluation of its comprehensive impacts in China. Third, the research deepens our understanding of the variations in both GF development and ANPSP. It investigates the differing dynamics between these two elements across various economic levels. Collectively, this study addresses existing gaps in the literature, furnishing more scientifically robust and comprehensive insights for enhancing the efficacy of GF in pollution control and emission reduction. Concurrently, it serves as a valuable reference for more effectively managing and preventing ANPSP.

Theoretical analysis and research hypotheses

Direct effect of GF on ANPSP

GF, an emerging financial mechanism aimed at promoting environmentally friendly investments and projects, significantly influences the prevalence of ANPSP. This impact is evidenced in several ways. Firstly, GF fosters the sustainability of agricultural production by reallocating resources, thereby mitigating the adverse environmental effects of agricultural activities at their source. For instance, green credit, China's primary green financial product, imposes stringent environmental criteria for loan recipients and emphasizes rigorous credit assessment processes, indirectly raising financing costs for enterprises with high pollution and energy consumption levels. Additionally, through resource reallocation, green credit reduces credit allocation to such enterprises, strictly prohibits support for restricted or newly established projects, increases the risk of exit for these high-polluting enterprises, sends market selection signals, and creates barriers for potential entrants. Furthermore, GF facilitates the management of ANPSP through technological advancements. It promotes the adoption of eco-friendly agricultural technologies such as soil testing, precision fertilization, commercial organic fertilizers, and integrated water and fertilizer management. By supporting innovative research and development initiatives of enterprises, GF elevates the technological prowess of the agricultural sector. Consequently, the increased scientific and technical sophistication of farming operations drives the transition of agricultural production to large-scale and industrialized modern green agriculture. This shift enhances the efficiency and quality of agricultural development, promotes sustainability, and reduces the burden of ANPSP. Hence, this paper posits the following hypothesis:

H1:GF helps to curb ANPSP.

Transmission Mechanisms for GF to Exert Effects on Pollution Control and Emission Reduction I

Existing research indicates that intensifying government environmental regulation (hereinafter referred to as ER) may initially reduce resource utilization efficiency (Boyd et al., 1999), yet it is crucial to recognize that such regulation is instrumental in enhancing the effectiveness of environmental pollution control (Bu et al., 2022). This is evident in two key aspects: First, ER creates cost-based comparative advantages across various agricultural sectors, thereby facilitating control and reduction of non-point source pollution. Specifically, sectors with high pollution levels incur greater "environmental taxes", leading to increased production costs. These sectors often lack the research and development capacity to innovate technologically in the short term, thus eroding their comparative advantage. Conversely, green agriculture, with its inherent green competitive advantages, can mitigate environmental costs through optimized resource allocation and accelerated technological progress (Czyżewski et al., 2020). Second, ER spurs technological innovation and fosters the green transformation of the agricultural industry. As a result, agricultural enterprises enhance the quality of factor inputs, simultaneously phasing out obsolete production capacities and fostering emerging technological leaders. This process facilitates the diffusion of new knowledge, industries, and technologies, thereby advancing the green development of regional agriculture. Based on these considerations, this paper proposes the following hypothesis:

H2: GF inhibits the development of ANPSP through ER.

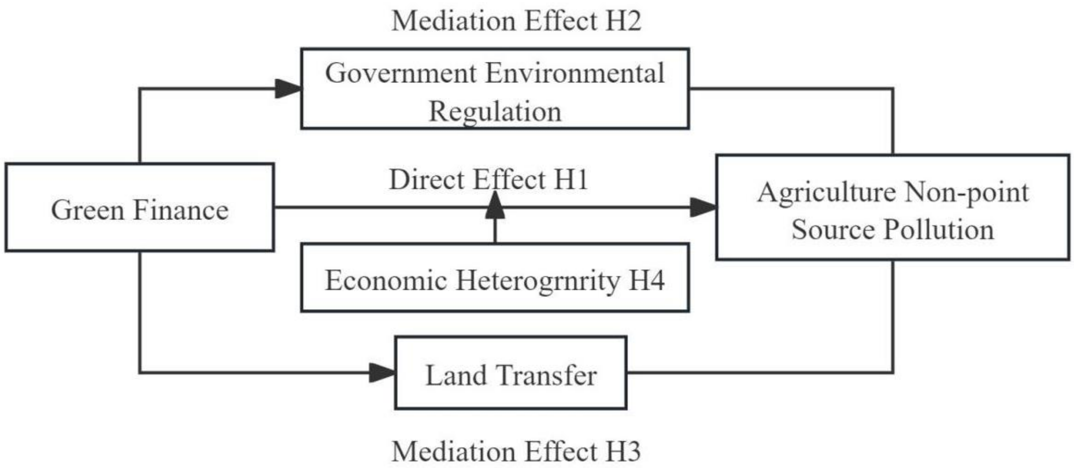
Transmission Mechanism for GF to Exert Pollution Control and Emission Reduction Effect II

GF has the potential to curtail the advancement of ANPSP through land transfer, and its transmission mechanism can be delineated through the following three dimensions:1.Optimization of Land Resource Allocation: GF, bolstered by financial backing, encourages agricultural stakeholders to embrace more efficient farming techniques. Consequently, this reduces the demand for land and other ecosystem resources, leading to diminished usage of ineffective inputs like chemical fertilizers and pesticides. This optimization effectively mitigates the negative externalities associated with agricultural production, fostering pollution control and emission reduction endeavors.2.Economic Incentives for Land Transfer: GF incentivizes land transfer by providing economic inducements to agricultural producers who adopt sustainable agricultural practices. Through lowered financing costs and more lenient loan conditions, it facilitates financial support for agricultural producers, thereby facilitating the transition towards environmentally friendly agricultural production (Zang et al., 2022). 3.Investment in Agri-Environmental Technologies: Green financial support encompasses investment in environmentally friendly agricultural technologies. This implies that agricultural producers can secure funds to procure environmentally friendly agricultural tools such as conservation irrigation systems and eco-fertilizers. The application of these technologies aids in alleviating ecological pressures on land. Therefore, based on these observations, this paper posits the following hypothesis:

H3: GF inhibits the development of ANPSP through the degree of land transfer.

Economic heterogeneity in the impact of GF and ANPSP

Due to variations in economic development, resource distribution, and industrial composition across China's regions, the advancement of GF also diverges accordingly. GF may further impede the proliferation of ANPSP in economically disadvantaged regions. This phenomenon can be attributed to two main factors:1.Marginal Improvement Effect: In economically disadvantaged regions, the impact of GF interventions on environmental enhancement may be more pronounced due to the lower starting point of environmental governance. Even modest green investments and policy alterations could yield significant positive outcomes in these areas (Letmathe et al., 2018).2.Potential for Technological Catch-up: Backward regions have the capacity to directly adopt advanced environmental technologies and practices, bypassing traditional developmental stages. GF can furnish these regions with the requisite capital to embrace more efficient technologies, facilitating technological advancement. Through the integration of advanced technologies, lagging regions can expedite a synergistic relationship between environmental management and agricultural production, thereby further mitigating ANPSP. Based on these observations, this paper posits the following hypothesis:



H4: There is economic heterogeneity in the role of GF on ANPSP.

Grounded in the aforementioned assumptions, this paper develops a theoretical model to examine the impact of GF on ANPSP. Within this framework, GF is conceptualized as the 'knowledge bandwagon', with ANPSP serving as the outcome variable. The model also incorporates additional ER and the mediating effect of land transfer degree to elucidate the underlying mechanisms. The theoretical analysis model is depicted in Figure 1.

Fig. 1 Theoretical analytical framework for the impact of GF on ANPSP

Research Design

Basic Modeling Setting

This study conducts a preliminary test to evaluate the effectiveness of GF in promoting pollution control and emission reduction in ANPSP. The framework for the basic model is outlined as follows:

$$ANPSP_{it} = \alpha_1 + \beta_1 GF_{it} + \theta_1 Controls_{it} + \sigma_t + \varepsilon_{it} \quad (1)$$

Where: $ANPSP_{it}$ denotes the level of ANPSP emissions; GF_{it} denotes the level of GF development; $Controls_{it}$ is the set of control variables; σ_t denotes time fixed effects; ε_{it} denotes the random error term;subscript i denotes the region;and subscript t denotes the year.

Mediating effects modeling

Building upon prior analysis, it is posited that GF can influence ANPSP both directly and indirectly, through the promotion of ER and the facilitation of land transfer. This paper advances the basic model (1) to model (2), aiming to explore the mediating roles of ER and land transfer degree in the nexus between GF and ANPSP. The specific formulation of the model is presented as follows:

$$ANPSP_{it} = \alpha_1 + \beta_1 GF_{it} + \beta_2 \ln MED_{it} + \theta_1 Controls_{it} + \sigma_t + \varepsilon_{it} \qquad (2)$$

In equation (2), $\ln MED_{it}$ denotes the mediating variables after taking logarithm, including two variables of ER and the degree of land transfer. The rest of the variables are explained in the same way as in equation (1).

Variable Selection

Explained variables:ANPSP

Agricultural production generates various forms of surface source pollution, predominantly consisting of total nitrogen (TN), total phosphorus (TP), chemical oxygen demand (COD), carbon emissions, and residues from pesticides and agricultural films. This pollution impacts the soil environment directly and also reaches water bodies through a combination of precipitation, topography-driven runoff (both surface and subsurface), and plant interception (Sun et al., 2012). To measure agricultural pollution, this study employs the inventory analysis method based on unit surveys. This method encompasses pollution from both aquaculture and the use of pesticides and agricultural films. It estimates ANPSP across seven dimensions: agricultural fertilizers, livestock and poultry farming, aquaculture, crops, rural population, pesticides, and agricultural plastic films. The indicators used for this analysis are detailed in **Table 1**.

Table 1 Indicator set for ANPSP

Categories	Elements of Pollution Production	Survey Indicators	Unit	Pollutants
Agricultural fertilizers	Nitrogen fertilizer, phosphorus fertilizer, compound fertilizer	Refractive index of application	10,000 tons	TN、TP
Livestock and poultry breeding	Pigs, cows, sheep	Inventory/output	10,000 heads	TN、TP、COD
Aquaculture	Freshwater fish, crustaceans, shellfish, others	Total production	10,000 tons	TN、TP、COD
Farm crops	Rice, corn, wheat, beans, potatoes, oilseeds, vegetables	Total production	10,000 tons	TN、TP、COD
Rural life	Rural domestic sewage	Agricultural population	10,000 persons	TN、TP、COD
Pesticides	Pesticides	Utilization amount	10,000 tons	Pesticide loss
Agricultural plastic film	Agricultural plastic film	Utilization amount	10,000 tons	Agricultural plastic film loss

The emission intensity of ANPSP is calculated as:

$$ANPSP = E_{TP} + E_{TN} + E_{COD} \tag{3}$$

$$E = \sum_{i}^{n} EU_i \rho_i \theta_i \tag{4}$$

In equation (3), the TE is the total emission of ANPSP; E_{TP} 、 E_{TN} 、 E_{COD} are the total emission of total nitrogen (TN), total phosphorus (TP) and chemical oxygen demand (COD), respectively.In equation (4), the EU_i is the statistic of the pollution unit i ; ρ_i is the pollution production coefficient of the pollution unit;and θ_i is the emission coefficient or loss rate.The pollution intensity of various units differs due to distinct influencing factors. For the calculation of emissions from ANPSP, the coefficients for the seven pollution units are utilized as follows:

(1) Agricultural fertilizers. The primary pollutants from agricultural fertilizers include nitrogen, phosphorus, and compound fertilizers. This paper employs the output coefficient method to account for the variances in fertilizer loss rates due to different planting methods. Since the focus is on TN and TP pollution from fertilizer inputs, and the phosphorus fertilizer inputs in statistical yearbooks are indicated as phosphorus pentoxide (P2O5), these inputs are adjusted by multiplying them by 43.66%. Additionally, in line with recent domestic fertilizer practices and prior research findings, the compound fertilizer is converted to TN at 40% and P2O5 at 32%. The fertilizer loss coefficient is derived by averaging the results from different regional samples, based on existing studies (Wang et al., 2019). This specific accounting approach is in accordance with the methods used in the second national pollution source census.

(2) Livestock and poultry farming. The pollution emissions are calculated as the product of the total quantity of livestock and poultry (either in stock or slaughtered), multiplied by both the pollution discharge coefficient and the wastage coefficient. The discharge coefficients for feces and urine of livestock and poultry are sourced from SEPA data (2022). The formula applied is: Livestock and poultry pollution intensity (kg per head per annum) = Rearing cycle × Fecal (urine) emission factor × Fecal (urine) pollutant excretion coefficient. In this study, livestock and poultry statistics encompass cattle, sheep, and pigs. For cattle and sheep, which have a rearing period of more than one year, the total breeding amount is based on the year-end stock. For pigs, due to their rearing period of less than one year, the total breeding amount is determined by the current year's output.

(3) Aquaculture. ANPSP primarily arises from bait residues, aquaculture excreta, and chemicals. The extent of this pollution is contingent on the aquaculture type and method. The China Statistical Yearbook classifies aquaculture production into marine and freshwater categories. Given that artificial aquaculture is a significant pollution contributor, this paper exclusively utilizes data from freshwater aquaculture for its analyses. The primary aquaculture species include

freshwater fish, crustaceans, shellfish, and other aquatic organisms. The production and discharge coefficients for aquaculture are derived from the First National Pollution Source Census: Handbook of Production and Discharge Coefficients for Pollution Sources in Aquaculture, supplemented by additional literature (Feng et al., 2023).

(4) Crops. The primary pollutants from crops include residues, vegetable wastes, and other debris from agricultural production (Norse, 2005). Given the diverse range of crops, this paper focuses on the seven most representative ones for analysis: rice, wheat, maize, beans, potatoes, oilseeds, and vegetables. The estimation of surface source pollution from agricultural solid waste involves calculating the crop residue yield based on the grass to grain ratio and determining the total nitrogen (TN), total phosphorus (TP), and chemical oxygen demand (COD) content from the nutrient composition of the straw. Recognizing the varied straw utilization methods in rural areas, each with different nutrient loss rates, the final emission formula for farmland solid waste pollution is: Emissions (tons) = Total crop production (tons) × Production coefficient × Straw utilization structure × Straw nutrient loss rate, where the production coefficient equals the grass to grain ratio multiplied by the straw nutrient content (Ma et al., 2019).

(5) Rural life. Pollution in rural life primarily comprises domestic sewage and human feces. The annual production coefficients per capita for COD, TN, and TP in domestic wastewater are 5.84 kg/person, 0.584 kg/person, and 0.146 kg/person, respectively, with an emission factor of 100%. For human feces, the corresponding coefficients are 19.8 kg/person, 3.06 kg/person, and 0.64 kg/person, respectively, with an emission factor of 10% (Luo et al. 2019).

(6) Pesticides. Pesticide residues are calculated as the amount of pesticides applied multiplied by a residue factor of 0.5.

(7) Agricultural film. The amount of agricultural film residue is determined by multiplying the quantity of agricultural film used by a residue factor of 0.1.

Explanatory variables: level of GF development

GF primarily aims to adhere to market economy principles while focusing on building an ecological civilization. It employs a range of financial tools, including credit, securities, insurance, and funds, to foster energy conservation, reduce consumption, and achieve a harmonious balance between economic resources and the environment. In the realm of existing literature, methodologies such as principal component analysis, the entropy value method, and hierarchical analysis are commonly used to determine the weights of GF development indicators. Following the approach of Li et al. (2022), this paper develops indicators in seven domains: green credit, green investment, green insurance, green bonds, green support, green fund, and green rights and interests. These indicators are then integrated using the entropy method to formulate a GF index, which assesses the level of GF development. For this assessment, raw data is initially standardized, followed by the computation of the indicators. The detailed measurement methodology is presented in **Table 2**.

Table 2 Comprehensive evaluation system of GF indicators

Name	Norm	Measurement
Green credit	Percentage of credits for environmental projects	Total credit for environmental projects in the province/total credit in the province
Green investment	Investment in environmental pollution control as % of GDP	Investment in environmental pollution control/GDP
Green insurance	Extent of promotion of environmental pollution liability insurance	Environmental pollution liability insurance income/total premium income
Green bonds	Extent of green bond development	Total green bond issuance/total all bond issuance
Green support	Percentage of fiscal expenditure on environmental protection	Financial environmental protection expenditures/financial general budget expenditures
Green fund	Percentage of green funds	Total market capitalization of green funds/total market capitalization of all funds
Green equity	Green equity development depth	Carbon trading, energy rights trading, emissions trading/total equity market transactions

Mediator Variables

1.ER

The selection of the ER variable follows the methodology of Chen et al. (2018). This approach utilizes the frequency of terms related to "environmental protection" in local government work reports compared to the total word count of the report as an indicator. A higher frequency indicates a stronger commitment to environmental governance, thus reflecting the intensity of ER and addressing endogeneity concerns. Relevant terms include ecology, green, low-carbon, pollution, energy consumption, emission reduction, sewage, sulfur dioxide, and carbon dioxide. As local government work reports are typically published early in the year, they predate and thus are not influenced by that year's environmental conditions, further mitigating endogeneity issues.

2.Extent of Land Transfers

For the degree of land transfer (LAND), this paper adopts the rate of agricultural land transfer (calculated as the total area of family-contracted arable land transferred divided by the total area of family-contracted arable land operated) as the proxy variable. This rate is an effective measure of agricultural land transfer levels and is widely used in inter-provincial level studies.

Control Variables

In alignment with existing literature (Abid et al., 2022), this study selects seven indicators as control variables: industrial structure (STR), economic development (GDP), fixed investment (INV), research and development (R&D) intensity (RD), marketization level (MAR), human capital (LAO), and openness to external influences (OP). The specific methodologies for these measures are detailed in **Table 3**.

Table 3 Description of how control variables are measured

Variable Name	Measurement

Industrial structure	Value added of tertiary industry
Economic development	GDP per capita
Fixed investment level	Regional fixed investment volume
R&D intensity	Regional R&D expenditures
Level of marketization	Obtained from the Fan Gang China Marketization Index report
Human capital	Average years of schooling
Egypt's open-door policy towards the outside world	Total exports and imports of goods

Data Sources

To ensure data availability and continuity, this study utilizes panel data from 30 provinces, autonomous regions, and municipalities in China, excluding Tibet, Hong Kong, Macao, and Taiwan, for the period 2005-2021 for empirical analysis. The primary data sources include the CSMAR and Wind databases, the Green Patent Database of the China Research Data Service Platform, and various annual publications such as the China Statistical Yearbook, China Demographic Statistical Yearbook, China Science and Technology Statistical Yearbook, China Energy Statistical Yearbook, China Financial Yearbook, China Rural Statistical Yearbook, China Industrial Statistical Yearbook, and China Agricultural and Forestry Management Statistical Yearbook. To address any minor data gaps, linear interpolation was employed, and logarithmic transformations were applied to all variables to mitigate heteroskedasticity bias arising from data extremes. Descriptive statistics of the empirical data are presented in **Table 4**.

Table 4 Descriptive statistics of variables

Variable	Mean	Median	Standard Deviation	Min	Max
ANPSP	-1.472	-1.270	0.785	-4.787	-0.135
GF	-1.939	-1.964	0.507	-3.121	-0.120
ER	9.776	9.791	0.199	8.533	10.715
LAND	-1.789	-1.572	0.998	-4.301	-0.093
STR	0.009	-0.069	0.412	-0.694	1.667
GDP	9.261	9.142	0.487	8.091	10.781
INV	9.084	9.186	1.052	5.745	11.041
RD	14.345	14.365	1.496	9.677	17.505
MAR	2.005	2.031	0.259	1.212	2.517
LAO	2.180	2.181	0.114	1.853	2.548
OP	16.995	16.846	1.656	12.335	20.532

Empirical Results and Analysis

Benchmark Regression Results

After calculating the correlation coefficients, it is noted that most variables exhibit significance at the 1% level, which is highly satisfactory. Additionally, the variance inflation factor (VIF) test for the regression variables yields a VIF of 4.84, indicating the absence of severe multicollinearity issues. For the multiple regression analysis in this study, the two-way fixed effects model is employed, and the benchmark regression outcomes are presented in Table 5. Analysis of column (1) of Table 5 reveals that the coefficient estimate of GF on ANPSP is significantly negative at the 5% significance level when no control variables are incorporated. This underscores the significant inhibitory effect of GF on the development of ANPSP, thereby validating hypothesis H1 of this paper. Subsequently, examination of column (2) of Table 5 demonstrates that upon inclusion of control variables such as industrial structure (STR), economic development (GDP), fixed investment (INV), research and development intensity (RD), level of marketization (MAR), human capital (LAO), and level of openness to the outside world (OP), the estimated coefficient of GF on ANPSP remains -0.446, retaining its significance at the 5% level. This suggests that even after accounting for other influencing factors, GF continues to exert a notable negative influence on ANPSP. Notably, neglecting the influence of control variables may overstate the inhibitory effect of GF on ANPSP, further affirming hypothesis H1 of this paper.

Table 5 Benchmark regression results

Variable	（1） ANPSP	（2） ANPSP	（3） ER	（4） LAND
GF	-0.390**	-0.446**	-1.040*	0.406***
	(0.175)	(0.191)	(0.537)	(0.033)
Regional effect	YES	YES	YES	YES
Time effect	YES	YES	YES	YES
Control Variables	NO	YES	YES	YES
Constant Term	-2.681***	-2.294	6.996	3.434***
	(0.431)	(2.039)	(5.730)	(0.351)
N	510.000	510.000	510.000	510.000
R^2	0.216	0.220	0.196	0.873

Note: ***, ** and * indicate significant at the 1%, 5% and 10% levels, respectively, t-values in parentheses.

Tests for Mediating Effects

The traditional three-step approach to mediating effects is widely used in psychology research, yet its reliability in economic studies is questioned due to issues like endogeneity bias and unclear channel identification. Therefore, this paper adopts the research approach proposed by Liu and Mao (2019) to examine the mechanism by assessing the impact of core independent variables on mediating variables. The theoretical mechanism section has already elucidated the effects of ER strength and the degree of land transfer on ANPSP, and the testing steps of these mechanisms are presented in **Table 5**, columns (3) and (4).

ER strength: In column (3) of **Table 5,** the regression coefficient of GF is -1.040, significant at the

10% level, indicating that the development of GF can significantly reduce ANPSP. This result suggests that GF may influence ANPSP by altering the strength of ER, confirming hypothesis H2 as per the earlier theoretical analysis.

Degree of land transfer: In column (4) of **Table 5**, the coefficient of GF is 0.406, significant at the 1% level, with an R-squared value of 0.873, indicating a strong explanatory power of the model. This implies that the advancement of GF can mitigate agricultural surface source pollution by increasing the degree of land transfer, supporting hypothesis H3 in line with the prior theoretical analysis.

In conclusion, ER and the degree of land transfer serve as significant mediators in the relationship between GF and ANPSP. Strengthening ER can mitigate ANPSP, whereas an increase in the degree of land transfer may have an adverse effect on it. This analysis provides a deeper understanding of the impact mechanism of GF on ANPSP..

Robustness Tests

To ensure the reliability of the empirical findings, this study employs three robustness testing methods. Firstly, it replaces the static panel fixed effects model with a dynamic panel fixed effects model, conducting regression analyses on the explanatory variables to assess the models' mutual causality and endogeneity. Secondly, it employs two-stage least squares (2SLS), using lagged explanatory variables as an instrumental variable to address endogeneity. Lastly, additional control variables are introduced. Given the multitude of objective factors influencing ANPSP, controlling for the regional agricultural disaster rate (Gao et al., 2015) through the ratio of affected crop area to sown crop area.

The regression outcomes in **Table 6** consistently demonstrate significantly negative coefficients of GF on ANPSP following these robustness tests, aligning with previous empirical findings. This underscores the robustness of the paper's conclusions across diverse model specifications and control variables, indicating high reliability. Specifically, Model (5) after replacing the GMM model maintains a significantly negative coefficient for GF, reaffirming its robustness. Model (6), utilizing lagged one-period IV, continues to show a significant negative impact of GF on ANPSP, unaffected by endogeneity issues. Finally, Model (7) with added control variables exhibits altered coefficients, yet GF retains a significant negative influence on ANPSP, further bolstering the robustness of its inhibitory effect.

Table 6 Robustness test results

	（5）	（6）	（7）
Variable	Replacement model GMM	Lag phase IV	Adding control variables
GF	-1.067***	-0.866***	-0.400**

	(0.145)	(0.128)	(0.190)
Regional effect	YES	YES	YES
Time effect	YES	YES	YES
Control Variables	YES	YES	YES
Constant Term	-3.732***	-0.168	-2.200
	(1.274)	(1.163)	(2.028)
N	510.000	480.000	503.000
R^2	—	0.653	0.235

Heterogeneity Analysis

To investigate whether regional economic disparities influence the effectiveness of GF in mitigating ANPSP, this study calculated the average per capita GDP across 30 provinces within the sample year. By comparing each province's total per capita GDP against the average value of 12,078.75, the sample was divided into two groups: high and low economic development. The high economic development group consists of ten provinces: Beijing, Tianjin, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Hubei, Guangdong, and Chongqing. In contrast, the low economic development group includes twenty provinces: Hebei, Liaoning, Anhui, Jiangxi, Henan, Hunan, Sichuan, Shaanxi, Shanxi, Inner Mongolia, Jilin, Heilongjiang, Guangxi, Hainan, Guizhou, Yunnan, Gansu, Qinghai, Ningxia, and Xinjiang. As demonstrated in Table 7, a comparison of the estimated coefficients' magnitude and significance reveals that GF's impact on ANPSP is only pronounced in regions of low economic development and is notably positive. In these areas, agricultural practices may rely more on outdated technologies and methods, which are typically less environmentally sustainable. Furthermore, these regions might lack efficient resource allocation mechanisms, leading to suboptimal use of GF for pollution reduction. Additionally, areas with lower economic development often have weaker ER and enforcement, posing challenges to effective implementation of environmental protection measures, even with GF support (Wang et al., 2023).

Table 7 Regional economic heterogeneity in the impact of GF on ANPSP

Variable	（8）	（9）
	High-economy group	Low-economy group
GF	0.282(0.565)	0.270*(0.143)
Regional effect	YES	YES
Time effect	YES	YES
Control Variables	YES	YES
Constant Term	-1.343(5.378)	-0.386(2.115)
N	170.000	340.000
R^2	0.385	0.371

Conclusions and Policy implication

Conclusions

This paper examines the significant impact of GF on reducing industrial pollution and explores its direct effects and mechanisms on ANPSP at a theoretical level. Utilizing panel data from 30 Chinese provinces from 2005 to 2021, the study applies panel fixed effect and intermediary effect models to assess the impact and influence mechanisms of GF on industrial pollution emissions from a multi-dimensional perspective. The key findings are: (1) GF notably suppresses ANPSP. (2) It achieves pollution control and emission reduction in ANPSP through ER and land transfer. (3) Heterogeneity analysis indicates that GF's effect on ANPSP is significant and positive only in regions with low economic development.

Policy implication

Based on these findings, the paper recommends the following actions:

(1) Strengthening GF in Rural Areas: To maximize the impact of GF on addressing ANPSP, it is imperative to clearly define the strategic direction and functional roles of financial institutions in supporting rural ecological civilization. This involves enhancing the provision of green credit by small and medium-sized banks, expanding the scope of financial subsidies, and increasing incentives for investments in GF, particularly in areas of taxation and technological innovation. These measures aim to effectively curb the financial constraints associated with managing ANPSP. Additionally, optimizing the policy framework for the growth of agriculture-related GF is essential. This includes offering preferential treatment to green credit products and prioritizing compensation rights for green bonds and other financial instruments. Furthermore, the development and reinforcement of legal and regulatory measures to address financial, credit, and moral risks in rural enterprises are crucial. These measures are intended to mitigate the risks of sunk and opportunity costs arising from ineffective agricultural green financial instruments.

(2) Harmonizing GF and ER Policies: Creating synergies between GF policies and ER is vital for effectively tackling ANPSP. Firstly, governments and regulatory bodies should establish and enforce transparent, equitable ERs, including the implementation of environmental administrative agreements. These agreements should recognize the equal standing of governments and entities responsible for ANPSP, ensuring clear communication during negotiations to balance economic and environmental benefits. Secondly, enhancing environmental support through initial lenient ER policies encourages innovation that improves the efficiency of ANPSP control. Specific measures include offering subsidies, loans, or other financial aid for technological upgrades and industrial transformation to meet new environmental standards. Lastly, financial institutions must innovate green financial products and services in line with the requirements of ER.

(3) Optimizing Land Transfer Policies: To encourage farmer participation in land transfer and

facilitate large-scale agricultural land management, government departments must enhance the rural land transfer system and environment. This includes refining the mechanism to incentivize practices that reduce ANPSP, implementing and improving the "three-rights partition" system of agricultural land, and establishing an efficient and reliable platform for agricultural land transfer and trading. A focus should be placed on ensuring an orderly transfer of agricultural land through a standardized process and effective legal frameworks. Additionally, increasing awareness and trust among farmers in land transfer policies through enhanced public outreach is crucial.

(4) Tailoring Policies to Regional Economic Heterogeneity: Policies must be adapted to the varying levels of regional economic development. In less economically developed areas, it is essential to strengthen and refine the rural financial system. This involves using tax incentives and other policies to motivate rural financial institutions, like the Agricultural Credit Union, to expand their lending to green agricultural production. Moreover, increasing awareness and education about GF in rural areas can improve farmers' recognition and participation in green financial initiatives, fostering the growth and interaction of ecological products and GF. In contrast, regions with higher economic development require not only policy-based financial support for agriculture and improved financial literacy but also the establishment of a comprehensive rural financial supervision system. This system should regulate the financial activities of rural financial institutions through laws and regulations, aiming to redirect their investments from non-agricultural sectors to agricultural ones.

Data Availability Statement

The datasets used during the current study are available from the corresponding author on reasonable request.

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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.

Author contributions:

Conceptualization, X.Z.; methodology, Y.S.; software, Y.S.; formal analysis, Y.S.; investigation, X.Z; resources, X.Z.; writing – original draft, Y.S; writing – review and editing, X.Z; supervision, X.Z.; project administration, X.Z. All authors have read and agreed to the published version of the manuscript.

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