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Environmental regulation, hog scale production and the synergy of pollution control and carbon reduction

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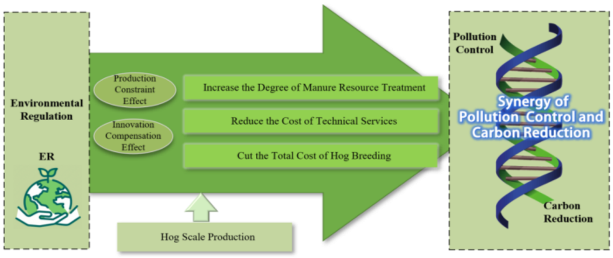
Graphical abstract



Abstract

The synergy of pollution control and carbon reduction is conducive to promoting the green transformation of the economy. Based on China's 30 provincial administrative panel data from 2002 to 2020, using the elastic concept to measure the synergy index and the panel fixed effect model to carry out empirical analysis, we analyzed the relation between environmental regulation and the synergy of pollution control and carbon reduction. The results revealed that: (1) Environmental regulation positively influenced the synergy of pollution control and carbon reduction in hog breeding. (2) Different types of pollution and carbon reduction had different synergistic effects. Compared with chemical oxygen demand and ammonia nitrogen, the positive effect of environmental regulation on the synergy of total phosphorus and carbon reduction was relatively weaker. (3) From the perspective of impact mechanisms, environmental regulation mainly achieved synergies through the "production constraint effect" and the "innovation compensation effect". (4) Further analysis showed that environmental regulation had a significant scale threshold effect on the synergy of pollution control and carbon reduction in hog breeding. Therefore, the heterogeneity of pollutants and industrial scale should be considered in the optimization of environmental regulation policies.

Keywords Environmental regulation, carbon emission, pollution control, synergy, hog scale production

1. Introduction

Reducing pollution and carbon has always been the focus of the attention of governments and scholars around the world. Greenhouse gas emissions will lead to food supply instability, biodiversity damage, sea level rise, and other problems (DeConto *et al.* 2021; Li *et al.* 2023; Ning *et al.* 2023; Xuan *et al.* 2023). Livestock breeding is an important source of greenhouse gas emissions, accounting for 14.5% of the total emissions, and the greenhouse gas emissions of the hog industry system account for 9% of the global livestock emissions (Gerber *et al*. 2013). According to the literature (Li *et al*. 2021), hog production's carbon footprint (including CO_2, N_2O and CH_4) is an average of 6.75 kg CO2 eq·kg−1 during its life cycle, and improper treatment of hog manure caused 42.87% the total carbon emissions. So, as the world's largest country in producing and consuming pork, China's hog production significantly influences on global greenhouse gas emissions.

Under the background of strengthening environmental regulation (ER), free-range farmers gradually withdraw from the market owing to the high environmental cost, or are forced to shut down by the government (Liu *et al.* 2017). On the contrary, due to the advantages of technology and management, scale farms have realized economies of scale, so they are less sensitive to ER policies (Huang *et al.* 2021). Therefore, it is an apparent trend that China's hog production is intensive and large-scale (Zheng *et al*. 2013; Qiao *et al*. 2016). However, hog scale breeding caused serious pollution problems due to the "separation of planting and livestock" (Wang *et al*. 2022). Nowadays, hog manure in China was more than 600 million tons (National Hog Production Development Plan 2016-2020). Although biogas production, organic fertilizer production, fermentation, returning to the field, and other treatment methods are used (Zheng *et al*. 2014), actual utilization rate is still less than 50% (National Hog Production Development Plan 2016-2020). Concurrently, the high density of hog breeding also increases the difficulty of resource treatment

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of hog manure. The emissions of organic waste containing nitrogen and carbon not only lead to water eutrophication but also make soil acidification and air quality decline (Sneeringer 2010; Wu *et al.* 2022).

To solve pollution problems, the State Council of China issued "the Regulations on Prevention and Control of Pollution from Livestock and Poultry Breeding" in 2014, making great progress in reducing pollution. According to the statistics of the latest two national pollution source survey bulletins, the chemical oxygen demand (COD) and ammonia nitrogen released in 2017 decreased by 21.21% and 84.54%, compared with 2007 (Bulletin of National Survey of Pollution Sources). However, compared with developed countries, China still has a large gap. For example, the carbon emissions of each hog are 1.55 kg CO_2 eq·kg^{-1} and 2.05 kg CO_2 eq·kg^{-1} higher than the average levels of Western Europe and North America respectively (Gerber *et al.* 2013; Li *et al.* 2021). In response, double carbon goals have put forward new challenges for China's sustainable development. To promote the collaborative efficiency of pollution control (POC) and carbon reduction (CBR) in the agricultural field, the State Council issued the "Implementation Plan for Synergy of Pollution Control and Carbon Reduction" in 2022, further deepening environmental governance through the policy of carbon peaking, promote high-quality peaking, strengthen regional regulatory coordination, and finally realize the green transformation of hog production. So, what influence will ER have on the synergy of POC and CBR in hog breeding in China? What is the influence mechanism? Will this influence changes significantly due to differences in hog production scale? This is what this study is trying to explore.

Therefore, this paper uses the panel data of 30 provincial administrative units in China from 2002 to 2020 as research samples, studying the influence of ER on the synergy of POC and CBR in hog breeding. Compared with the existing research, the possible marginal contribution lies in the following three aspects. Firstly, existing literature has only focused on the association between ER and a single environmental indicator like carbon or pollution reduction (Liu *et al.* 2022; Lu *et al.* 2022; Huang and Tian 2023), however, by focusing on the synergy of POC and CBR, we can expand the environmental effects of ER. Secondly, some studies have either theoretically analyzed the connotation of synergy of POC and CBR (Nam *et al.* 2014; Du and Li 2020), or practically explored the synergistic path (Chen *et al.* 2016; Pierer *et al.* 2016). Almost no way has been established for measuring the synergy between pollution control and carbon reduction, we used the elasticity to construct the synergy index to determine the synergistic or anti-synergistic effect, and examine the differences between different pollutants. In addition, Studies on ER mainly concern macro regions and industrial enterprises, and rarely on the micro hog industry. This paper studies how ER affects the synergy of POC and CBR in the hog industry, and further explores the threshold effect of production scale, which can expand the theoretical application field.

The paper proceeds as follows. Section 2 describes the materials and methods, including data sources, variables selection and model setting. In particular, the research framework proposes three hypotheses. Section 3 reports the empirical results, followed by robustness checks and a discussion on the impacts of hog production scale. Finally, Section 4 draws conclusions and policy suggestions

2. Materials and methods

2.1. Study area and data sources

Considering the availability and scientificity of the data, the panel data of 30 provincial administrative units in China (excluding Tibet, Hong Kong, Macao and Taiwan) from 2002 to 2020 were selected as the research samples. The data on various pollutants and carbon emissions are from the China Environmental Yearbook; The data of land bearing capacity, transportation convenience, scientific and technological progress are from the China Statistical Yearbook; the data for measuring the income of rural residents, the agricultural labor supply, the abundance of hog feed supply and the degree of manure resource treatment are from the China Rural Statistical Yearbook; the data of hog production scale and epidemic risk are from the Chinese Animal Husbandry and Veterinary Yearbook; the data on the costs of technical services and total costs of hog farming are from the National Agricultural Products Information Compendium; the data for the education of farmers are from the China Yearbook of Rural Household Survey; the data for the calculation of air flow coefficient are from the ERA-Interim database of European Centre for Medium-Range Weather Forecasts (ECMWF), and some missing data are supplemented by linear interpolation.

2.2. Basic analytical framework

2.2.1. Environmental regulation and the synergy of pollution control and carbon reduction

The impact of ER on the synergy of POC and CBR in hog breeding is mainly composed of the following two aspects. ER has a "production constraint effect" on hog production, which has continuously prompted hog farmers to increase investment in manure treatment equipment and promote the resourceful treatment of hog manure, and thus realizing the synergy of POC and CBR. Chinese government has formulated ER policies about CBR and POC to to control agricultural non-point source pollution (Jiang *et al.* 2023). The ER policies about POC run through the whole industrial chain of hog production. Regarding the site selection of farms, the government strictly approves whether there is enough land to absorb pollution and promotes the association of planting and livestock (Hu *et al.* 2022), which not only reduces environmental pollution but also reduces carbon emissions. During the breeding, improving environmental protection requirements also forced farmers to use low-protein feed to reduce the emission of nitrogen, phosphorus, and other elements in hog manure to realize the POC effect. Meanwhile, microecological agents and enzyme agents are added to improve feed utilization, reducing fecal emissions and malodorous gases, and achieving the goal of CBR (Lansink and Reinhard 2004; Pierer *et al*. 2016). In the end treatment of manure and sewage, measures such as rain sewage separation and solid-liquid separation, which can reduce manure and sewage and facilitate the collection of dry and clean manure. After collecting, manure can produce biogas for power generation through fermentation, reducing the use of fossil energy, and return it to the field as organic fertilizer to increase soil carbon sequestration finally. In addition, ER policies about CBR also enable farmers to transform the walls, roofs, and windows of the hog house, improve the insulation performance of the hog house, decrease the energy consumption of coal heating, reduce the emissions of sulfide, nitride, carbide, and soot, thus realizing the synergy of POC and CBR.

On the other hand, ER has triggered technological changes to continuously reduce the marginal cost, thus generating an "innovation compensation effect", which is favourable to achieving the synergy of POC and CBR in hog breeding. In the short term, the "forced emission reduction" mechanism of ER means that the production cost of hog breeding will increase. However, from a long-term perspective, the "compensation effect" of technical reform will neutralize or even exceed the environmental governance cost (Frondel 2007; Wei *et al*. 2022), which is conducive to reducing the total cost of hog farming and the cost of technology dissemination, and encouraging the farming enterprises to increase their investment in green technology (Shao *et al*. 2023). Take hog production for example, environment-friendly hog houses not only use thermal insulation materials, but use geothermal energy for heating, reducing heating costs, saving energy consumption, and achieving the goal of CBR and POC. Therefore, the following two hypotheses are proposed.

Hypothesis 1: ER significantly promotes the synergy of POC and CBR in hog production.

Hypothesis 2a: ER can promote the synergy of POC and CBR by "production constraint effect".

Hypothesis 2b: ER can promote the synergy of POC and CBR by "innovation compensation effect".

2.2.2. Threshold effect of hog production scale

The impact of ER on the synergy of POC and CBR will vary from the hog production scale. The implementation of ER will lead to a "resource allocation effect". The dual role of market and administrative resources appropriately increases the scale of hog farming, reduces the marginal cost owing to the economies of scale, and incentivizes farmers and enterprises to purchase environmentally friendly facilities and apply green technologies (Shao *et al*. 2018), thus further promoting the synergistic effect of POC and CBR. However, the excessive hog breeding scale will increase the difficulty of synergy. Ultra-large scale hog farming may lead to low management efficiency (Yang *et al*. 2024) and an invalid combination of POC and CBR policies (Pan *et al*. 2021; Wu *et al*. 2022), which can easily cause ER policies about CBR not to achieve the POC effect, or ER policies about CBR not to achieve POC effect well. Meanwhile, the scale is too large to connect grean production in the hog industry chain effectively, and this will also weaken the synergy of POC and CBR. Therefore, the positive impact of ER on the synergy of POC and CBR in ultra-large scale hog production will be weakened. Hypothesis 3 is, thus, proposed.

Hypothesis 3: The impact of ER on the synergy of POC and CBR has a threshold effect of scale.

The above analysis framework is shown in Figure 1.

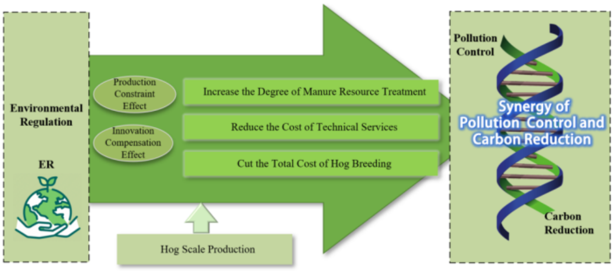

Figure 1. Theoretical analysis frame diagram

2.3. Variables selection

2.3.1. Synergy of POC and CBR

(1) Pollution reduction effect

According to the "Emissions Standard of Pollutants for Livestock and Poultry Breeding Industry" (GB18596-2001), the POC effect is measured by the total amount of COD, ammonia nitrogen, and total phosphorus in hog production in province i during period t. The pollution emissions of hog breeding are measured by building the overall pollution emissions intensity (Shao *et al*. 2018; Liu *et al*. 2022). The specific calculation is as follows:

First, the three pollutants are standardized as follows:

$$ps_{ij} = \frac{P_{ij} - P_{jmin}}{P_{jmax} - P_{jmin}} \tag{1}$$

Here, ps_{ij} is the standardized value of pollutant j emissions of province i; P_{ij} is the emissions of pollutant j in the province i; P_{jmax}、P_{jmm} is the maximum and minimum value of pollutant j in all samples. Then, calculate the adjustment index of each pollutant:

$$w_j = \frac{pe_{ij}}{pe_{avij}} \tag{2}$$

Where, w_j is the adjustment coefficient; pe_{ij} and pe_{avij} is the emissions of pollutant j in the unit output value of province i and the average level of all sample the provinces. Finally, the overall pollution emissions intensity of livestock and poultry breeding in province i can be expressed as:

$$Poll_{ij} = \frac{\sum_{j=1}^{n} w_j \times ps_{ij}}{n} \tag{3}$$

(2) Carbon reduction effect

Carbon emissions from hog farming include not only direct emissions from hog intestinal systems (CH_4) and manure management systems (CH_4 and N_2O), but also indirect carbon emissions from hog farming because of the consumption of electricity and feed (FAO 2006; IPCC 2006; Zhou *et al*. 2018). The calculation formula for indirect carbon emissions from hog breeding is as follows:

$$EF_{i,t,s}^{indir}=\sum_{n=1}^{4}P_{i,t,s}\times Q_{i,t,s,n}\times C_n \tag{4}$$

Here, i and t represent provinces and years respectively, s = 1, 2, 3, 4 respectively refer to the four breeding models of free-range farmers, small-scale, medium-scale, and large-scale farmers. And n = 1,2,3,4 respectively refer to coal, electricity, feed, and tap water. $EF_{i,t,s}^{indir}$ represents the indirect carbon emissions from hog breeding of the s breeding model in time t in province i. $P_{i,t,s}$ represents the number of hogs slaughtered in the s breeding mode in time t in province i. $Q_{i,t,s,n}$ represents the consumption of the input n per hog, C_n represents the CO_2 Emissions coefficient of the input n. The calculation formula of direct carbon emissions is as follows:

$$EF_{i,t,s}^{dir}=\sum_{n=5}^{7}P_{i,t,s}\times C_n\times Days_{i,t,s}\times CO_2E_n \tag{5}$$

where n = 5,6,7 respectively represent intestinal tract (CH_4), fecal management (CH_4 and N_2O) emissions. $EF_{i,t,s}^{dir}$ represents the direct carbon emissions of the s hog breeding model in time t in province i, while C_n represents the emissions coefficient of the hog daily CH_4 and N_2O. $Days_{i,t,s}$ represents the average growth cycle of the s hog breeding model in time t in province i. CO_2 E_n represents respectively CH_4 and N_2O converted to CO_2 (where CH_4 conversion coefficient is 21 and N_2O conversion coefficient is 310). The measurement formula of carbon emissions in the whole hog growth cycle is as follows:

$$EF_{i,t,s}=EF_{i,t,s}^{indir}+EF_{i,t,s}^{dir} \tag{6}$$

where $EF_{i,t,s}$ represents the carbon emissions during the growth cycle of the s hog breeding model in time t in province i. The formula for total carbon emissions is as follows by summing up different types of breeding models:

$$AC_{it}=\sum_{S=1}^{4}EF_{i,t,s} \tag{7}$$

(3) Synergy of POC and CBR in hog breeding

With reference to relevant research methods (Mao *et al*. 2012), the cross-elasticity index is used to measure the synergy of POC and CBR. This indicator can reflect the synergy and degree of different pollutants and carbon emissions. The specific formula is as follows:

$$E_c=\frac{EAC_{ghg}/AC_{ghg}}{EPoll_{lap}/Poll_{lap}} \tag{8}$$

Where E_c represents the synergetic index between poll and AC. EAC_{ghg} refers to the total carbon emissions of the last year, $poll_{lap}$ is the pollutant emissions of the last year; EAC_{ghg} represents the current year's pollutant emissions minus the last year's emissions. $EPoll_{lap}$ represents the pollutant the current year's pollutant emissions minus the emissions of the last year. Since three pollutants are selected for hog breeding, to further study the synergy of POC and CBR, the synergetic index of carbon emissions and COD (E_{oc}), the synergetic index of carbon emissions and ammonia nitrogen (E_{ac}), the synergetic index of carbon emissions and total phosphorus (E_{pc}), and they are also calculated by using the above formula.

Considering the E_c of the measure, it is fuzzy to measure the synergy directly. For example, if the E_c value is positive, it is difficult to determine whether *Poll* and *AC* decrease or increase simultaneously. Only by further discussing the positive and negative values of its numerator and denominator can accurate recognition be made (Gao *et al*. 2022). Therefore, the synergetic index is divided into three levels: "anti-synergy", "weak-synergy" and "strong-synergy", which equals the values − 1, 0, and 1 respectively. First, if the numerator and denominator of E_c are both positive, it means that *AC* and *Poll* emissions increase at the same time, and E_c will be valued −1, indicating "anti-synergy". Second, if the positive and negative signs of the numerator and denominator of E_c are opposite, E_c will be valued 0, indicating "weak-synergy". Third, both the numerator and denominator of E_c are negative, and E_c will be valued 1, meaning pollution and carbon emissions have been reduced, compared with the last year, namely "strong-synergy".

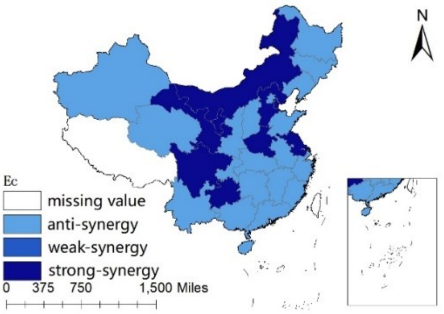

Figure 2. Synergy of POC and CBR in hog breeding during the "11th Five-Year Plan" period

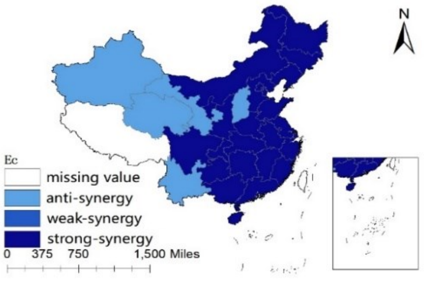

Figure 3. Synergy of POC and CBR in hog breeding during the "13th Five-Year Plan" period

The Chinese government implemented the "Regulations on Prevention and Control of Pollution from Scale Breeding of Livestock and Poultry" in 2014. The strength of ER varied greatly between before and after 2014. In order to intuitively understand the impact of ER on the synergy of POC and CBR, the data of the first year and the last year of the "11th Five-Year Plan" period (2006-2010) and the "13th Five-Year Plan" period (2016-2020), compared to calculate E_c, as shown in Figures 2 and 3. It can be seen from Figure 2 that in most regions of China during the "11th Five Year Plan" period, the synergy of POC and CBR in hog breeding is basically “anti-synergy”, stating carbon and pollutant emissions increase simultaneously. From Figure 3, we can see that during the “13th Five Year Plan” period, in most regions, the synergy of POC and CBR is basically “strong-synergy”. From the comprehensive analysis of the two figures, strengthening ER is conducive to the green transformation of hog production.

2.3.2. Environmental regulation

Nowadays, scholars have not unified the criteria for measuring ER. According to Zhao *et al.* (2022), ER is mainly related to regional economic development. Referring to Zeng *et al.* (2021), the measurement formula of ER is as follows:

$$ER_{it} = GDP_{it} \times \frac{1}{2/3 \times \sqrt{area_{it} / \pi}} \tag{9}$$

Where GDP_{it} is the gross domestic product of province i in period *t*, $area_{it}$ represents the area under the jurisdiction of province i during period *t*, and π represents P_i.

Table 1. Descriptive statistics for variables

Variable		Definition	Mean	Std. Dev
Synergistic index of POC and CBR	E_c	Synergistic index of carbon emissions and total pollutants	-0.3333	1.9037
	E_{oc}	Synergistic index of carbon emissions and COD	-0.3298	1.9982
	E_{ac}	Synergistic index of carbon emissions and ammonia nitrogen	-0.3263	1.9624
	E_{pc}	Synergistic index of carbon emissions and total phosphorus	-0.3317	1.9741
Carbon emissions	lnAC	All carbon emissions（CO_2, N_2O and CH_4）(10,000 tons)	5.9655	1.1504
Pollutant emissions	COD	Chemical oxygen demand (10,000 tons)	1.2039	0.9953
	AN	Ammonia nitrogen (10,000 tons)	0.2407	0.1991
	TP	Total phosphorus (10,000 tons)	0.0241	0.0199
	Poll	Total pollutants（COD, AN and TP） (10,000 tons)	1.4688	1.2142
ER	lnER	ER index	3.4509	1.3223
Hog production scale	Scale	Farms with more than 50 hogs /all farms（%）	9.7787	10.9248
Income of rural residents	lnDIR	Disposable income of rural residents (yuan)	8.8237	0.7159
Education of farmers	EDU	Farmers with high school education/all farmers（%）	10.6465	3.5625
Agricultural labor supply	lnNAL	Number of agricultural labor force (10,000)	6.4062	1.0911
Abundance of hog feed supply	HFS	Ratio of corn output to total grain output（%）	32.3984	25.2938
Land bearing capacity	LBC	Area of cultivated land/national cultivated land area（%）	3.3824	2.9473
Transportation convenience	TC	Total mileage of highways, railways and inland waterways/Land area（%）	0.8681	0.6053
Scientific and technological progress	STP	Ratio of patent authorization/ GDP（%）	1.2349	1.1015
Epidemic risk	lnPK	Total number of hogs killed and culled due to 8 common epidemics (head)	4.5455	3.1274
Manure resource treatment	MRT	Proportion of regional biogas digester gas production to total gas production of rural biogas digester in China (%)	3.3064	4.0220
The total cost of hog breeding	TCH	Total cost of hog breeding (Yuan/head)	1487.63	522.0599
The cost of technical services	CTS	Technical service fee (Yuan)	1.5013	2.3040

2.3.3. Mechanism variables

Based on hypothesis 2, we will test the mechanism from “production constraint effect” and “innovation compensation effect”. For the former, it is expressed by increasing the degree of manure resource treatment, and the ratio of regional biogas production to national total biogas production is used as a proxy indicator. For the latter, it is measured by reducing the cost of technical services and the total cost of hog breeding.

2.3.4. Control variables

By reference to relevant studies (Herrero *et al.* 2013; Huang *et al.* 2021; Zhang *et al.* 2022; Jiang *et al.* 2023), the following control variables are selected: (1) Income level of rural residents; (2) Education of farmers; (3) Agricultural labor supply; (4) The abundance of hog feed supply. It is represented by the ratio of regional corn output in total grain output; (5) The carrying capacity of hog breeding land. It is expressed by the proportion of each province’s cultivated land area in the country’s total area; (6) Traffic convenience. It is measured by dividing the total navigable mileage of railways, highways, and inland waterways in each province by the regional area; (7) Scientific and technological progress; (8) Epidemic risk. It uses the sum of the number of hogs killed and culled by the eight common hog diseases in the Veterinary Bulletin as the proxy variable. (9) Hog production scale. According to the “Chinese Animal Husbandry and Veterinary Yearbook”, the hog production scale refers to the proportion of hog farms with more than 50 hogs in the total number of hog farms. The specific measurement formula is as follows:

$$scale_{it} = \frac{SFG_{it}}{NLL_{it}} \times 100 \tag{10}$$

Where SFG_{it} refers to the number of hog farms with more than 50 hogs in year t of province i, $NILL_{it}$ refers to the total number of hog farm in year t of province i.

Notably, the definition and descriptive statistics for variables are given in Table 1.

2.4. Datum model setting

To verify the hypotheses, first, this study examines the CBR effect caused by the ER, and constructs the following econometric model:

$$lnAC_{it} = \alpha_0 + \alpha_1 ER_{it} + \sigma CV_{it} + \varepsilon_i + \varepsilon_t + \varepsilon_{it} \qquad (11)$$

Here, *i* and *t* represent provinces and years respectively, AC_{it} represents carbon emissions; ER_{it} means environmental regulation; CV_{it} represents a series of control variables; ε_i and ε_t represents the fixed effect of province and year respectively; ε_{it} denotes the random error term.

Table 2. Regression results of the impact of ER on POC and CBR in hog production

VARIABLES	Carbon emissions	Pollutant emissions	Chemical oxygen demand	Ammonia nitrogen	Total phosphorus
lnER	-0.1230**	-0.2190***	-0.1790***	-0.0358***	-0.0147***
	(0.0552)	(0.0534)	(0.0438)	(0.0087)	(0.0001)
Control	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes	Yes
N	570	570	570	570	570
R^2	0.3910	0.3530	0.3526	0.3580	0.3500

*Note: *, **, and *** indicate significance at the 10, 5 and 1% levels, respectively. The figures in parentheses indicate the standard errors.*

Source: Author's own conception, using STATA software.

(The following table is the same)

Table 3. Basic regression results of the impact of ER on the synergy of POC and CBR

VARIABLES	E_c	E_{oc}	E_{ac}	E_{pc}
lnER	0.6280***	0.5940***	0.7020***	0.2990*
	(0.1020)	(0.0160)	(0.1100)	(0.1750)
Scale	0.0256	0.0226	0.0246	0.0357
	(0.0288)	(0.0489)	(0.0262)	(0.0412)
lnDIR	1.3270**	1.3050**	1.3110**	1.7870**
	(0.6181)	(0.6200)	(0.6180)	(0.7380)
STP	-0.0595	-0.0611	-0.0672	-0.0628
	(0.1740)	(0.1750)	(0.1749)	(0.2094)
lnPK	0.1570***	0.1580***	0.1669***	0.3970***
	(0.0334)	(0.0336)	(0.0335)	(0.0574)
HFS	-0.0094	-0.0081	-0.0110	-0.0087
	(0.0196)	(0.0197)	(0.0197)	(0.0135)
EDU	0.0485***	0.0590***	0.0367**	0.0334**
	(0.0174)	(0.0201)	(0.0165)	(0.0133)
TC	0.3570	0.3620*	0.3630*	0.4678
	(0.2180)	(0.2190)	(0.2180)	(0.2921)
lnNAL	0.4460	0.4260	0.4540	0.4573
	(0.5020)	(0.5050)	(0.5030)	(0.8325)
LBC	0.0082	0.0026	0.0440	0.0046
	(0.6220)	(0.6250)	(0.6220)	(0.8356)
Constant	-14.0400**	-13.7100**	-14.2400**	-15.1473**
	(6.0340)	(6.0620)	(6.0400)	(7.0269)
Year	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes
N	570	570	570	570
R^2	0.1261	0.1240	0.1264	0.1260

Further, test the POC effect caused by the ER, and build the following econometric model:

$$lnPoll_{it} = \beta_0 + \beta_1 ER_{it} + \varphi CV_{it} + \varepsilon_i + \varepsilon_t + \varepsilon_{it} \qquad (12)$$

Where $Poll_{it}$ refers to pollutant emissions, including COD, ammonia nitrogen, and total phosphorus. Finally, the impact of ER on the synergy of POC and CBR in hog breeding is investigated, and the following econometric model is constructed:

$$E_{cit} = \gamma_0 + \gamma_1 ER_{it} + \omega CV_{it} + \varepsilon_i + \varepsilon_t + \varepsilon_{it} \qquad (13)$$

Where $E_{c_{it}}$ represents the synergy index of carbon emissions and total pollutants, which is further subdivided into synergy index of carbon emissions and COD (E_{oc}), synergy index of carbon emissions and ammonia nitrogen (E_{ac}), and synergy index of carbon emissions and total phosphorus (E_{pc}).

Table 4 Results of mechanism analysis

VARIABLES	Manure resource treatment	The cost of technical services	The total cost of hog breeding
lnER	0.5550**	-0.7300***	-158.8000***
	(0.2400)	(0.1920)	(28.4000)
Control	Yes	Yes	Yes
Year	Yes	Yes	Yes
Province	Yes	Yes	Yes
N	570	570	570
R^2	0.2457	0.1045	0.7479

3. Results and discussions

3.1. Basic regression analysis

The basic regression results are shown in Tables 2 and 3. In Table 2, it is found that ER reduced carbon emissions from hog production significantly at 5%, that is, ER is conducive to the realization of the CBR effect of hog breeding. Meanwhile, the coefficient between ER and pollutant emissions was negative and significant at 1%, indicating that ER can promote the POC effect of hog breeding and effectively reduces total pollutant emissions including COD, ammonia nitrogen, and total phosphorus.

As shown in Table 3, the impact coefficient of ER and synergistic index was 0.6280, significantly at 1%. It should be noted that, according to the above calculation of the synergistic index of POC and CBR, when the numerator and denominator of the cross-elasticity index are both negative. Then the synergistic index is equal to a positive number, indicating that the synergistic index has also been achieved. Therefore, when the impact coefficient is positive, it indicates that ER is positively promoting the synergy of POC and CBR in hog breeding. From the three indicators selected for pollutants, the impact coefficients between ER and the synergy of CBR and COD, CBR and ammonia nitrogen, and CBR and total phosphorus were positive, and significant at 1%, 1%, and 10%. Therefore, strengthening ER is conducive to the synergy of POC and CBR in hog breeding, and hypothesis 1 is tested.

Further, the impact of ER on the synergy of different pollutants and carbon emissions was significantly different. *ER* had the most enormous effect on E_{ac}, followed by E_{oc} and E_{pc}. Among them, the correlation coefficient between ER and E_{pc} was only 0.2990, significantly at 10%. The reason is that COD and ammonia nitrogen produced in hog breeding are higher than total phosphorus. On the one hand, COD and ammonia nitrogen are mainly produced from hog manure and urine. As ER strengthen, through helping hog farmers to transport manure and return them to the field through social service, the government can effectively reduce the emissions of COD and ammonia nitrogen. On the other hand, total phosphorus pollution mainly comes from the hog feeding. With the scale of hog breeding, hog feed is from the unified feed companies, and its quality is standardized, so it is difficult to reach the non-phosphorus feed further, so the synergy of phosphorus reduction and CBR is relatively lower.

From the results of the control variables, the hog production scale had no marked impact on the synergy of POC and CBR, however, the income and education of rural residents could significantly promote the synergy. The higher the education of farmers was, the stronger their environmental awareness was, and higher income could also increase the effective investment in environmental protection equipment. Moreover, convenient transportation also could effectively improve E_{oc} and E_{ac}, but the impact on E_{pc} was not significant. The reason is that COD and ammonia nitrogen are the primary pollutants in hog breeding, and the proportion of total phosphorus is relatively small, so transportation convenience has no noticeable effect on E_{pc}.

3.2. Mechanism analysis

The basic regression results suggest that ER significantly contributed to the synergy of POC and CBR in hog production. However, through what mechanisms does ER produce this effect? Based on hypothesis 2, we tested the "production constraint effect" and "innovation compensation effect", and the results are shown in Table 4. For the "production constraint effect", ER significantly promoted the degree of resource utilization of hog manure, which in turn realized the synergistic effect of POC and CBR. It has been proven that promoting the resource treatment of hog manure is the key to reducing pollution (Zheng *et al.* 2014). For one thing, hog manure is the main source of COD and ammonia nitrogen, and hog manure resource treatment can directly reduce the emission of pollutants; for another thing, the residue of manure resource treatment is returned to the field to increase soil fertility, thus playing the function of carbon sequestration. For the "innovation compensation effect", in the long run, ER significantly reduced the cost of technical services and the total cost of hog breeding, incentivizing farmers to adopt green technologies, realizing the dual efficiencies of "economy" and "greenness", and thus achieving the synergy of POC and CBR. In summary, hypothesis 2 is verified.

3.3. Discussion on endogeneities

As mentioned above, ER can promote the synergy of POC and CBR. On the contrary, the better synergetic effect of POC and CBR can also improve ER. There may be a causal relationship between ER and the synergy of POC and CBR. Additionally, some variables may be omitted from the model. Therefore, there may be endogenous problems. In this regard, this paper draws on relevant research methods (Hering *et al.* 2014) and uses the air flow coefficient as the tool variable of ER. The reason is that when carbon emissions and pollutant emissions are the same, ER in areas with low air flow coefficient is stricter. Therefore, the ER variable is related to the tool variable. However, the air flow coefficient is equal to the wind speed multiplied by the boundary layer's height, which is unrelated to the synergy of POC and CBR in hog breeding, meeting the exogenous requirements.

Table 5 Endogenous test results

VARIABLES	The first stage	The second stage
lnER		0.2568***
		(0.0471)
Air flow coefficient	0.3748***	
	(0.0749)	
Control	Yes	Yes
Year	Yes	Yes
Province	Yes	Yes
N	570	570
Wald test		103.4839
F	38.2894***	
R^2	0.6382	0.1395

Table 6 Robustness test results

VARIABLES	Replace core arguments	Excluding the sample from 2015 to 2020	Time trend of control variables fixed effect	High-dimensional
lnER	0.6038***	0.5531**	0.7103***	0.4638***
	(0.1207)	(0.2398)	(0.2048)	(0.1071)
Control	Yes	Yes	Yes	Yes
Year	Yes	no	Yes	Yes
Province	Yes	Yes	Yes	Yes
N	570	390	570	570
R^2	0.1270	0.3720	0.1250	0.1240

Took the logarithm of the air flow coefficient and conducted a two-stage least square (2SLS) regression. The regression results of the first and second stages were shown in Table 5. From the regression results of the first stage, the F test value was more prominent than 10 significantly, meaning the air flow coefficient is a robust instrumental variable. The second stage results denoted the correlation coefficient between ER and the synergy of POC and CBR was 0.2568. Although the coefficient value has decreased, it was still significant at the level of 1%, which does not affect the basic conclusion that the improvement of ER is conducive to the synergy of POC and CBR in hog production.

3.4. Robustness test

To increase accuracy of the conclusions, this paper used various methods to conduct robustness tests. The empirical results are shown in Table 6. First, replace the explanatory variable. Considering that the measurement method of ER is unclear, by drawing on relevant research (Levinson, 1999), the logarithm of the number of environmental policies in region i within time t was used as the proxy variable of ER. Second, exclude the number of samples from 2015 to 2020. In 2014, China officially implemented the "Regulations on Prevention and Control of Pollution from scale Livestock and Poultry Breeding", which significantly improved the intensity of ER compared with previous years. To reduce the interference of regional policy interaction on the research conclusions, the samples from 2015 to 2020 were deleted for robust testing. Third, control fixed effects. The change in the macro system environment makes the research results face potential endogenous problems, so the empirical test is conducted by controlling the fixed effect. Two methods were used to mitigate the problems caused by the macro environment: time trend of the control variables and high-dimensional fixed effect. From the results of the above robustness tests, ER had a positive impact on the synergy of POC and CBR, which was significant at 1% and was almost consistent with the previous research conclusions.

3.5. Further discussion

The previous section of this paper has confirmed that the larger the hog production scale is, the more apparent the positive role of ER on the synergy of POC and CBR. However, this is different from some research conclusions. For example, Hu *et al*. (2022) thought that excessive hog breeding scale may cause more environmental pollution owing to insufficient land to absorb manure. Therefore, this paper further explores whether ER has a significant threshold effect on the synergy of POC and CBR. To test the above question, this paper used the threshold effect model proposed by Hansen (1999), to obtain the optimal breeding scale range. The following threshold model is established:

$$\begin{aligned} E_{c_{it}} &= \vartheta_0 + \vartheta_1 ER_{it} IScale_{it} < \gamma_1 + \vartheta_2 ER_{it} I \gamma_1 \leq Scale_{it} \leq \gamma_2 \\ &+ \vartheta_n ER_{it} IScale_{it} \geq \gamma_n + \gamma_m CV + RE_i + YE_t + \varepsilon_{it} \end{aligned} \tag{14}$$

Here, i and t mean province and time respectively, I(•) represents an exponential function, $Scale_{it}$represents the threshold variable, $\gamma_1 \cdots \gamma_n$ represents the threshold value,

$\vartheta_1 \cdots \vartheta_n$ represents the regression influence coefficient, γ_m represents the coefficient of the control variables, and n depends on the number of threshold values, ε_{it} stands for perturbation term, RE_i and YE_t represent province and time fixed effect.

3.5.1. Threshold number test and threshold estimation

Firstly, the threshold effect of the research samples was tested, and the empirical test results were presented in Table 7. The F statistic obtained from the hog breeding scale is significant. There were two threshold values of E_c, 3.7727 and 4.7581, respectively. Therefore, the regression model of the synergistic effect of ER on POC and CBR was set as a double threshold model. In terms of synergy of different pollutions, E_{oc}, E_{ac} and E_{pc} also had two threshold values, which also passed the significance test.

Table 7. Threshold quantity test and threshold value estimation results

VARIABLES	Threshold number	F	Thresholdvalue	95% confidence interval
E_c	Single	13.40***	3.7727	（3.7125，3.8392）
	Double	22.60***	4.7581	（4.4359，4.9707）
E_{oc}	Single	55.48***	2.9457	（2.7236，3.2522）
	Double	38.46***	0.6332	（0.3873，7.0951）
E_{ac}	Single	55.48***	2.9457	（2.7236，3.2522）
	Double	38.46***	0.6332	（0.3873，7.0951）
E_{Pc}	Single	57.56***	13.8127	（12.8940，14.2351）
	Double	29.44***	0.6332	（0.3873，0.7431）

Table 8. Threshold regression results of the breeding scale

Variables	E_c	E_{oc}	E_{ac}	E_{pc}
ϑ_1	0.4010***	2.0400***	1.5306***	0.4910**
	(0.0740)	(0.6260)	(0.2668)	(0.1940)
ϑ_2	0.5680**	1.4530**	1.0952**	0.3510*
	(0.2780)	(0.6390)	(0.5297)	(0.1970)
ϑ_3	0.4490	1.0400	0.7719	0.1990
	(0.5790)	(0.6430)	(0.8255)	(0.1990)
Control	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes

3.5.2. Analysis of regression results of the threshold model

The regression result of the threshold model was demonstrated in Table 8. According to the two threshold values determined by the hog breeding scale, it was classified three threshold intervals, ϑ_1–ϑ_3 are the regression coefficients of different threshold ranges. Regardless of the threshold range of hog breeding scale, ER had a positive role in promoting the synergy of POC and CBR. When the hog breeding scale was in the first threshold range ($Scale_{it} \leq 3.7727$), ER significantly promoted the synergy of POC and CBR, stating that strengthen environmental supervision is conducive to green transformation in hog breeding. When the breeding scale was in the second threshold range (3.7727 < Scaleit<4.7581), the regression coefficient was 0.5680, significantly at 5%. At the same time, ER can still effectively achieve the synergy of POC and CBR. However, when the breeding scale was in the third threshold range ($Scale_{it} \geq 4.7581$), the regression coefficient was positive but not significant, indicating that with the excessive expansion of hog breeding scale, the positive promotion of ER on the synergy is gradually weakened, and the marginal contribution is gradually reduced. E_{oc}, E_{ac} and E_{pc} also have a similar change process, which will not be repeated here. It is worth mentioning that the correlation coefficient of *ER* and E_{pc} is the smallest, and the significance level is no exception, compared with E_{oc} and E_{ac}. Therefore, the government should pay more attention to the effective synergy of low-carbon and phosphorus reduction policies for hog production. So, hypothesis 3 is tested.

4. Conclusions and suggestions

This paper explores the impact mechanism of ER on the synergy of POC and CBR in hog breeding, and uses 30 provincial panel data in China from 2002 to 2020 for empirical testing, providing a new perspective for the policy evaluation of ER. From the basic regression results, ER had a significant positive impact on the synergy of POC and CBR in hog production, and different types of pollution and carbon reduction had different synergistic effects. Compared with COD and ammonia nitrogen, the effect of ER on the synergy of total phosphorus and carbon reduction was a little weaker. From the perspective of impact mechanisms, ER could achieve synergies through the “production constraint effect” and the “innovation compensation effect”. Further analysis in hog production scale showed that, ER had a significant scale threshold effect on the synergy of POC and CBR, and the changing trend of different types of pollutants is consistent with total pollutants. When the hog breeding scale was below 4.7581, ER effectively promoted the synergy of POC and CBR, however, when the hog breeding scale was larger than 4.7581, the promotion effect was insignificant.

Based on the above research results, the following policy suggestions are drawn: Firstly, there is a need to continuously enhance ER policies, such as establishing a comprehensive big data platform for animal husbandry regulation and adhering to the principles of collaborative construction and information sharing. Secondly, it is crucial to prioritize targeted policy measures, particularly by synergizing phosphorus control and carbon reduction policies, and further promote the green transformation of hog production. Thirdly, it is also advisable to encourage moderate-scale hog farming operations and improve land carrying capacity, therefore emphasis should be placed on integrating "planting and breeding" approaches while promoting resource utilization of manure within a moderate-scale production system, to realize the synergy of POC and CBR in hog breeding Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Data availability

Data can be requested from the corresponding author.

Competing interests

The authors declare no conflicts of interest.

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Author contributions

Conceptualization Y.J., S.C. and R.Y.; methodology Y.J., Y Z. and S.Q., writing—original draft and editing Y.J., S.Q., S.C., and R.Y. All the authors were committed to improving this paper and are responsible for the viewpoints mentioned in this work.

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