Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 12 February 2025
DOI 10.3389/fsufs.2025.1467378

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OPEN ACCESS

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RECEIVED 19 July 2024
ACCEPTED 20 January 2025
PUBLISHED 12 February 2025

CITATION
Wang J, Zhao C and Chen S (2025) Analysis of convergence trends and driving factors of environmental efficiency of pig farming in China.
Front. Sustain. Food Syst. 9:1467378.
doi: 10.3389/fsufs.2025.1467378

Analysis of convergence trends and driving factors of environmental efficiency of pig farming in China

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Introduction: This study aims to clarify the development characteristics, differences, and convergence trends of environmental efficiency in China's pig industry, which helps promote the sustainable development of the pig industry.

Methods: Based on the data of 30 provinces (municipalities and autonomous regions) in China from 2008 to 2020, this article used the super-SBM model, log (t) test, and ordered probit model to estimate the environmental efficiency and convergence trend of pig farming in China and analyzed the driving factors affecting the convergence trend.

Results: The results showed that: (1) In recent years, the environmental efficiency of pig farming in China did not reach the optimal state, and the environmental efficiency of the potential growth region was the highest, reaching 71.6%. Scale efficiency is still the key to improving the environmental efficiency of pig farming, and in the future, it is necessary to focus on improving pure technical efficiency. (2) The environmental efficiency of pig farming across China's 30 provinces (including municipalities and autonomous regions) converges to four clubs. Most provinces within constrained development regions and potential growth regions converge to the high-level club, while the disparities in environmental efficiency of pig farming are most pronounced in key development regions. (3) The research results of driving factors show that scale level exhibits a "U-shaped" effect on the convergence of environmental efficiency in pig farming toward high-level clubs in China, and most provinces have surpassed the inflection point. The scale level of pig farming should be appropriately improved. In addition, improving the quality of the labor force can help the environmental efficiency of pig farming converge to a high-level club.

Discussion: We propose suggestions aimed at enhancing the efficiency of pig farming, promoting the scale processes of pig farming, and strengthening regional cooperation.

KEYWORDS

environmental efficiency, convergence trend, pig farming, driving factors, scale level

1 Introduction

The livestock industry is a significant source of greenhouse gases, emitting approximately 7.1 billion tons of carbon dioxide equivalent annually, which accounts for 14.5% of the total greenhouse gas emissions generated by human activities. The contribution of various livestock and poultry breeds to greenhouse gas emissions within the livestock industry varies considerably globally (Zhu et al., 2016). Sheep are significant contributors to greenhouse gas emissions in Africa and Latin America, while dairy farming is the primary source of elevated methane emissions in Southern Asia (Pradeep et al., 2022). An increase in pig farming has led to heightened greenhouse gas emissions in the European Union (Pexas et al., 2020). Likewise, pig farming is also the predominant source of greenhouse gas emissions in Eastern Asia (Yao, 2024).

China, which accounts for 40% of the world's pork production, has pig farming as the largest sector in animal husbandry. However, the intestinal fermentation and waste generated by farming contribute to the production of pollutants such as chemical oxygen demand (COD), total nitrogen, total phosphorus, copper, zinc, and ammonia nitrogen. These pollutants are significant sources of greenhouse gas emissions (Fan et al., 2020). In 2020, carbon emissions from pig farming reached 31% of the total carbon emissions from the livestock sector (Cheng and Yao, 2024). Concurrently, the rapid pace of urbanization and the ongoing rise in meat consumption are expected to further exacerbate nitrogen and phosphorus emissions (Andretta et al., 2021). To achieve sustainable and healthy development in the pig farming industry, the Ministry of Agriculture and Rural Affairs emphasized in 2021 the necessity of establishing a new paradigm for safe, efficient, and environmentally friendly pig production. Concurrently, the government has introduced a series of policies and regulations, including the "Regulations on the Prevention and Control of Pollution from Large-scale Livestock and Poultry Farming," the "Technical Guidelines for Delimitation of Prohibited Areas for Livestock and Poultry Farming," and the "National Pig Production Development Plan (2016–2020)." These measures aim to reorganize the pig industry to mitigate environmental pressures associated with pig farming. In addition, China's pig farming sector continues to grapple with the challenge of uneven regional development. Variations in human capital, feed resources, urbanization levels, and feed prices across different regions contribute to this disparity. In light of increasingly stringent resource constraints, it is imperative to explore strategies for achieving coordinated development of pig farming across regions and enhancing the environmental efficiency of the industry, as this represents a pressing issue for the sustainable advancement of the pig sector.

Enhancing the environmental efficiency of pig farming appears to be an effective strategy for addressing the pollution issues associated with this industry. Existing studies are in-depth on pig farming efficiency (Boudný and Špička, 2012; Li et al., 2017). Pig farming efficiency refers to the number of qualified pigs slaughtered by putting in a certain number of piglets, feed, veterinary drugs, labor, and equipment under the current pig feeding level. With the continuous development of the pig farming scale, some scholars have focused their studies on the technical efficiency of scale farming (Galanopoulos et al., 2006; Latruffe et al., 2013; Ly et al., 2016) and conducted regional heterogeneity analysis (Zhang et al., 2020). Chung et al. first included environmental costs in the production efficiency accounting framework (Chung et al., 1997), and treated environmental effects as undesirable outputs (Färe et al., 1989). In China, animal husbandry is the most important source of carbon emissions (Philippe and Nicks, 2015), and pig farming ranks second in GHG emissions in China (Zhou et al., 2018). An expansion of pig production has resulted in manure becoming a problematic waste product instead of a valuable farm input. Manure is rich in organic substances such as nitrogen and phosphorous, and improper treatment will pollute the air and soil (Yan et al., 2020). After 2015, China gradually paid attention to the coordinated development of pig farming and the environment. Some scholars considered the pig farming efficiency from an environmental perspective (Kuhn et al., 2020). When scholars consider environmental factors, environmental factors are mainly divided into two types: pollutant emission equivalent (Zhong et al., 2021) and carbon emission (Han et al., 2020). It also points out that with the increasing speed of global warming, carbon emission reduction is related to human survival and development. Among the factors affecting the environmental efficiency of pig farming, industrial agglomeration, environmental regulation, scale, feed production capacity, and human capital all have important effects (Lin and Zhang, 2023). Wang et al. (2020) pointed out that pig scale and farming efficiency showed nonlinear changes, and the environmental pollution caused by pig scale became increasingly serious (Wang et al., 2020).

It is important to note that regional disparities in pig production in China are influenced by factors such as resource endowment and the level of economic development. The eastern region demonstrates a more pronounced environmental efficiency advantage in pig farming (Zhong et al., 2022), whereas other regions exhibit lower environmental efficiency. These regions are susceptible to falling into "low-level traps," making it challenging for them to escape. Tan et al. found that the pig farming industry in China is shifting toward regions with weaker environmental regulations (Tan et al., 2018). When scholars discuss how to alleviate the contradiction between pig production layout and resource constraints, they also further consider how to coordinate and promote the sustainable transformation of the pig industry in various regions (Zhu et al., 2023). Convergence theory is widely used in the study of coordinated trends. It is originally derived from the Solow model, which states that given the same exogenous factors, all economies eventually converge to the same stable state. After enriching the content of convergence theory, some important convergence mechanisms such as σ convergence, β convergence, and club convergence have been formed. In the club convergence theory, regions within the same club (or group) converge to the same steady-state level, resulting in a "club effect." If the gap between different clubs is reduced, areas with lower levels can be replaced by those with higher levels, positively impacting the region. At present, scholars have explored the convergence trend of environmental efficiency in different cities in Asian countries and China (Tang et al., 2021; Jadoon et al., 2023). In the study on the convergence trend of environmental efficiency in the aquaculture industry, Xu found that although the environmental efficiency of small-scale dairy farming in China is not converging overall, and the environmental efficiency of medium and large-scale dairy farming is converging overall, there is a club convergence trend for environmental efficiency of different scales. This study provides a reference for the convergence of environmental efficiency in pig farming (Xu et al., 2022).

In the study of research methods, most scholars used two methods: stochastic frontier analysis and non-parametric data envelopment analysis (Reinhard et al., 2000; Fu et al., 2018). Data Envelopment Analysis (DEA) is a non-parametric method for assessing technical efficiency, originally designed to evaluate the relative efficiency of decision-making units (DMU). Unlike the stochastic frontier model (SFA), DEA does not require the pre-establishment of a functional relationship between inputs and outputs, thereby minimizing the subjectivity associated with parameter weighting and enhancing the objectivity of the measurement results (Du et al., 2021). The traditional CCR and BCC models utilize radial measurements, which may yield inaccurate results in the presence of redundant values. To address these issues, Tone introduced a super-SBM model that modified the slack variables, giving a more nuanced consideration of the input and output slack problems stemming from radial and angle selection (Sun et al., 2023). The problem of excess input and insufficient output in efficiency measurement is solved directly (Zhang et al., 2017), and this model has been applied by various scholars in the livestock industry to measure green total factor productivity across different regions (Wen et al., 2022).

It can be seen from the literature review that most scholars consider the impact of carbon emissions when examining environmental efficiency, but few scholars discuss the coordinated trend of environmental efficiency in pig farming in different regions. In addition, the factors that can promote the coordinated development of the pig industry urgently need further analysis. This article aims to answer the following questions: What is the environmental efficiency of pig farming in China? Is there a club convergence in the environmental efficiency of pig farming in each province? What are the driving factors that form its convergence club?

Compared with previous research, the possible contributions of this article are as follows: First, existing research has considered the negative externalities caused by greenhouse gas emissions in pig farming. This article selects carbon emissions as undesirable output and uses the Super-SBM model. Calculate the environmental efficiency of China's pig farming from 2008 to 2020 and explore the green and sustainable development of the pig industry under carbon emission constraints. Second, this study explores the convergence trend of the environmental efficiency of pig farming in China based on the log(t) test method. Finally, the ordered probit model was used to explore the driving factors of the pig farming environmental efficiency club, providing a reference for future expansion or reduction of environmental efficiency in different regions.

2 Research methods and data sources

2.1 Model design

2.1.1 Super-SBM model

The radial DEA model is often used in the measurement of environmental efficiency. Tone proposed a non-radial SBM model based on slack variables (Tone, 2001), which has non-radial characteristics, avoids the radial measurement error, solves the problem of input–output slack, and makes up for the defects of the traditional DEA model. However, the efficiency value measured by the original SBM model is between 0 and 1. When multiple DUM efficiency values reach 1, the original SBM model is adopted, and DUM effective ranking becomes problematic. However, the super-SBM model, which allows the efficiency value to exceed 1, can effectively solve the DUM ranking problem. Considering that the environmental efficiency of pig farming in different provinces of China may be simultaneously at the frontier of DEA efficiency, this study adopts the super-SBM model to evaluate the environmental efficiency of pig farming in China. The model is constructed as follows:

$$\rho^* = \min \frac{\frac{1}{m}\sum_{i=1}^{m}\left(\overline{x_i} / x_{ik}\right)}{\frac{1}{s_1+s_2}\left(\sum_{r=1}^{s_1}\overline{y}_r^g / y_{rk}^g + \sum_{v=1}^{s_2}\overline{y}_v^b / y_{vk}^b\right)} \tag{1}$$

$$s.t.\begin{cases} \overline{x} \geq \sum_{j=1,j\neq k}^{n} x_{ij}\lambda_j ; \overline{y}^g \leq \sum_{j=1,j\neq k}^{n} y_{rj}^g\lambda_j ; \overline{y}^b \geq \sum_{j=1,j\neq k}^{n} y_{vj}^b\lambda_j ; \sum_{j=1,j\neq k}^{n}\lambda_j = 1 \\ \overline{x} \geq x_{ik} ; \overline{y}^g \leq y_{rk}^g ; \overline{y}^b \geq y_{vk}^b \\ \lambda_j \geq x_{ik} ; j = 1,2,\ldots,n\left(j \neq k\right) ; r = 1,2,\ldots,s_1 ; v = 1,2,\ldots,s_2 ; i = 1,2,\ldots,m \end{cases}$$

In Equation 1, where ρ^* represents the efficiency value, if $\rho^* \geq 1$, it indicates that the DUM is in an effective state; if $\rho^* \leq 1$, it indicates that the DUM has efficiency loss and is in an invalid state. x_{ik} represents the input index, $\overline{x}$ represents the mean value of DUM. y_{rk}^g represents the expected output, $\overline{y}^g$ represents the mean of the expected output. y_{vk}^b represents the undesired output, $\overline{y}^b$ represents the mean of the undesired output. In this article, when undesired output is considered, ρ is environmental efficiency (ETE), which can be further decomposed into pure environmental technical efficiency (EPTE) and environmental scale efficiency (ESE), ETE = EPTE*ESE.

2.1.2 Log(t) test method

Due to the lack of comparability between different years in the environmental efficiency values calculated by the super-SBM model, only interprovincial differences within the same year can be analyzed. Therefore, to further the characteristics of the dynamic evolution of the environmental efficiency of pig farming in China, this article will use the club convergence method to analyze the convergence of the environmental efficiency of pig farming in China.

The club convergence test method proposed by Phillips and Sul (2007) allows for various temporal trends and individual heterogeneity in data. The advantage of the club convergence test method is that when there is no convergence trend in the population sample, it can cluster the convergence situations of all individuals through continuous trial and error. Individuals converging to the same stable level will be divided into the same convergence club group. The club convergence test method can use statistical methods to identify all local convergence situations and form different convergence clubs.

The analysis process is as follows:

In econometrics, any panel data X_{it} can be broken down into the following forms:

$$X_{it} = \delta_{it}\mu_t \tag{2}$$

In Equation 2, where δ_{it} is the load coefficient of the time change factor; μ_t is the common factor.

Further, a semi-parametric equation can be used to express the load factor of the time change factor δ_{it}. The formula is as follows:

$$\delta_{it} = \delta_i + \frac{\delta_i}{L(t)t^a} \times \xi_{it} \tag{3}$$

In Equation 3, where δ_i is a fixed component that does not change with time;ξ_{it} follows a standard normal distribution and is independent and identically distributed. $L(t)$ is an equation that includes time t. Its main function is to eliminate the natural increase in variance over time so that panel data X_{it} becomes stable data. When X_{it} is panel data, for either one $a \geq 0$, δ_{it} will converge over δ_i when time $t \to +\infty$. Assuming there is such a situation where all individuals i in the panel data have the same common factors, that is $\delta_i = \delta$, then when $a \geq 0$, all individuals i will converge to the same steady state. As a result, in empirical analysis, the convergence of the model can be assessed by testing whether $a \geq 0$.

In specific operations, the convergence of panel data X_{it} can be tested by the following equation. The original hypothesis was $H_0 : \delta_1 = \delta$, that is $a \geq 0$. The test equation is structured as follows:

$$\log\left(\frac{H_1}{H_t}\right) - 2\log L(t) = c + b\log(t) + u_t \tag{4}$$

In the Equation 4:$h_{it} = \frac{X_{it}}{N^{-1}\sum_{i=1}^{N} X_{it}}$ and $b_0 = -2\log L(1) + u_1$.

Where $t = [rT],[rT+1],\cdots,T, r \in (0,1)$. This article takes $r = 0.2$, $L(t) = \log t$. If b is significantly non-negative, then there is convergence; if $t_{\hat{b}} < -1.65$, then there is no convergence.

2.1.3 Ordered probit model

To explore the driving factors of the club convergence formed by the environmental efficiency of pig farming in China, the convergence club 1, convergence club 2, convergence club 3, and convergence club 4 formed above were represented by the Ordered variables of 1–4, and the Ordered Probit/Ordered logit model was used for analysis. The specific expression is as follows:

$$Y_i^* = \sum_{i=1}^{n} \alpha_i F_i + \varepsilon_i \tag{5}$$

In Equation 5, where the dependent variable $Y_i^*$is club1 ~ club4; F_i is an independent variable, representing the driving factor of the club convergence group; α_i is the coefficient to be estimated, ε_i is a random perturbation term.

2.2 Variable selection and data sources

2.2.1 Selection of environmental efficiency indicators for pig farming

When utilizing the super-SBM model, the primary challenge lies in determining the appropriate input and output indicators. Initially, examining the correlation between input and output variables is essential. Feed input constitutes the fundamental resource for pig farming, representing the largest proportion of all input factors. Labor is also a crucial input factor in pig farming. Each pig incurs costs associated with electricity, coal, and other fuel and power expenditures during farming. Notably, the cost of fuel and power is the highest proportion of losses in pig farming production efficiency. Furthermore, due to the recent impacts of African swine fever and other pig epidemics, there has been a continuous increase in medical investment to ensure the healthy farming of pigs. Consequently, the input index in this article focuses on the number of labor employment (ω_1), the number of concentrate feeds (ω_2), the cost of fuel and power (ω_3), and the cost of medical and epidemic prevention (ω_4).

In measuring the output of the pig industry, the expected output index is the net output of main pig products (y_1), which is expressed by the output of main pig products minus the weight of piglets. The non-expected output refers to the carbon emissions of pig farming (y_2). The greenhouse gas emission coefficient method was used to estimate the carbon emission effect of pig farming (Zhou et al., 2007); namely, the production of various carbon sources of pig farming was multiplied by their respective carbon emission factors, converted into carbon emission equivalents, and summed up to obtain the total carbon emission of each pig farming province. According to the IPCC assessment report in 2006, greenhouse gas emissions from pig farming mainly come from the sum of pig intestinal fermentation and manure management, and the greenhouse effect caused by 1 T is equivalent to the greenhouse effect caused by 6.8182 t carbon. 1 T is equivalent to the greenhouse effect produced by 81.2727 T carbon (Ai-E et al., 2018).

The specific calculation formula for carbon emissions from pig farming is as follows: $C_t = 6.8182CH_{4-1} + 6.8182CH_{4-2} + 81.2727N_2O$.

Where C_t is the total carbon emission of pig farming; CH_{4-1}, CH_{4-2} and N_2O is the production of H in intestinal fermentation and the sum of discharged during fecal treatment. The production of each carbon source is equal to the average annual pig production multiplied by the carbon emission factor of each carbon source. The average annual feed volume of pigs was adjusted according to the feeding cycle determined by IPCC and production volume at the current year. The average annual feed volume was the production volume at the current year × feeding cycle/365. According to IPCC data, the carbon emission factors of CH_4 produced by intestinal fermentation and CH_4 *and* N_2O released by fecal management were 1.0, 3.5 kg/head · a, and 0.53 kg/ head · a, respectively.

2.2.2 Selection of driving factor of the club convergence

This article mainly discusses the impact of the driving factor on the club convergence of pig farming. The selected indicators include environmental regulation (F_{Env}), scale level (F_{scale}), resource endowment (F_{corn}), technical input (F_{tech}), quality of labor force (F_{edu}), pig price (F_{price}).

Indicator selection basis and research hypothesis:

(1) Environmental regulation (F_{Env}). This article uses the adjustment coefficient method to improve the level of economic development and then calculate environmental regulations (Zeng et al., 2021). Environmental regulations may drive farms in the region to carry out non-productive activities such as pollution control, which in turn causes increased compliance costs. Complying with costs will not only increase the cost of raising pigs and reduce the willingness to green production but may also crowd out the technological investment of farms (Singbo et al., 2020), obstructing advancements in environmental efficiency. Environmental regulations are putting forward new requirements for the environmental efficiency of pig farming to move to a high-level club. Therefore, this study proposes hypothesis 1: Environmental regulation has a negative impact on the convergence of environmental efficiency to the high-level club.

(2) Scale level (F_{scale}). This article takes the proportion of pig output from farms with an annual output of over 500 pigs to the total pig output in the region as an indicator of scale level. According to the Environmental Kuznets Hypothesis, scale growth impacts carbon emissions and reduces the likelihood of a region converging to high-level clubs. Carbon emissions are expected to decrease as the scale of pig farming continues to expand, coupled with technological innovations and changes in production methods. This reduction in emissions can lead to lower production costs, enhanced economic benefits, improved environmental efficiency,

and an increased probability of the region's convergence to high-level clubs. Therefore, this article proposes hypothesis 2: Scale level has a "U-shape" impact on the convergence of environmental efficiency to the high-level club.

(3) Resource endowment (F_{corn}). This article uses corn production to measure resource endowment. Pig farming is a grain-consuming animal husbandry, and corn is the main raw material for pig feed. The corn production capacity of different regions is an important factor affecting the layout of pig farming, which can represent the quality of resource endowment between regions. The disparity of regional resource endowments has also widened the imbalance of regional environmental efficiency. Therefore, this article proposes hypothesis 3: Resource endowment has a negative impact on the convergence of environmental efficiency to the high-level club.

(4) Technical input (F_{tech}). This article uses the technology market turnover of each province to measure technology input. In the context of resource constraints, the new growth point for improving the environmental efficiency of pig farming lies in technological innovation, which can bring environmental benefits and dividends to various places, alleviate pollution problems to a certain extent, and improve the probability of convergence to a high-level club. Therefore, this article proposes hypothesis 4: Technical input has a positive impact on the convergence of environmental efficiency to the high-level club.

(5) Quality of labor force (F_{edu}). This article uses education level to measure the quality of the labor force in each province. Neoclassical economic growth theory points out that human capital is the endogenous driving force of economic growth. In the pig industry, the quality of the labor force is an important embodiment of human capital. The improvement of cultural quality and the ability of farmers to learn will help enhance their understanding and absorption of green agriculture and help them better adapt to the requirements of the modern development of the pig industry. The lack of human capital in some regions is an important factor that may restrict the balanced development of environmental efficiency in various regions. Therefore, this article proposes hypothesis 5: Quality of the labor force has a positive impact on the convergence of environmental efficiency to the high-level club.

(6) Pig price (F_{price}). This article selects pork prices to reflect the fluctuations in the market for pigs. The market price of live pigs has the function of information transmission, and breeders will rely on the price of the previous period to make production decisions. High prices may lead farmers to blindly expand production, wasting resources and exacerbating the imbalance in environmental efficiency across regions. Therefore, this article proposes hypothesis 6: Pig price has a negative impact on the convergence of environmental efficiency to the high-level club.

2.2.3 Data sources

In view of the availability of data, this article selects the statistical data of 30 provinces in China (excluding Hong Kong, Macao, Taiwan, and Tibet) from 2008 to 2020 to analyze the environmental efficiency of pig farming. The number of labor employment (ω_1), the number of concentrate feeds (ω_2), the cost of fuel and power (ω_3), and the cost of medical and epidemic prevention (ω_4), the weight of piglets, main products of pig production, and scale level (F_{scale}) from "National Agricultural Product Cost–Benefit Compilation." Environmental regulation (F_{Env}), resource endowment (F_{corn}), technical input (F_{tech}), quality of labor force (F_{edu}), pig price (F_{price}) from the "China statistical yearbook."

The descriptive statistical results of specific variables are shown in Table 1 In terms of environmental efficiency input factors, feed input cost is the highest, with an average of more than 300 yuan, followed by medical cost, with an average of 18.38 yuan. In terms of output, the average net output of main pig products is closer to 100 kg. In terms of driving factors, the environmental regulations of different provinces differ greatly. The scale of pig farming is not large; the average is 0.133, and the scale of pig farming in different provinces is relatively different.

3 Measurement and analysis of environmental efficiency of pig farming in China

3.1 Overall features

In general, the environmental efficiency of pig farming in China from 2008 to 2020 was lower than 1 (Table 2), indicating that there is a certain distance between the overall efficiency of the pig farming industry and the production frontier, and it is necessary to improve the input–output of pig farming in China. In 2020, the environmental efficiency of pig farming in China was 0.7114. It can be seen that environmental constraints have a restraining effect on technical efficiency, and there are environmental problems in the process of pig farming in China.

Environmental scale efficiency (ESE) is the key driving force for the growth of environmental efficiency of pig farming from 2008 to 2020. The overall environmental scale efficiency of pig farming in China was relatively high, with an average of 0.949. Pure environmental technical efficiency (EPTE) is increasing year by year. In 2020, pure environmental technical efficiency reached 0.9021. Pure environmental technical efficiency will become the main source of environmental efficiency for living pigs in China. The possible reason is that with the large-scale development of pig farming, more abundant funds can be invested in cleaner production technology, improving the environmental efficiency of pig farming. There is limited space to improve the environmental efficiency of pig farming by increasing scale.

3.2 Regional differences analysis

From the perspective of regional differences, when the undesired output was considered, the potential growth region was higher with an average of 0.71, followed by the environmental efficiency in the constrained development region with an average of 0.70, and the environmental efficiency in the key development region was the lowest (Table 3). Specifically, pure technical efficiency is the main reason for the obvious differences among regions.

The main possible reasons were that Northeast China is the main producing area of corn, with a sufficient supply of corn and a low cost of pig feed, which is beneficial to the large-scale development of pigs. However, the efficiency of pure environmental technology is low, and the scale efficiency is high, which indicates that the pig farming industry in Northeast China relies on extensive growth of factor input in the development process and ignores the investment in clean technology. The application of advanced technology needs to be enhanced. "The National Pig Production Development Plan

TABLE 1 Descriptive statistical results of variables.

Variable			Max.	Min.	Std.	Mean
The input index	ω_1	The weight of the number of labor (unit: yuan)	18.23	0	2.878	4.279
	ω_2	The number of concentrate feed (unit: kg)	453.65	0	43.30	305.77
	ω_3	The cost of fuel and power (unit: yuan)	39.77	0	5.66	7.38
	ω_4	The cost of medical and epidemic prevention (unit: yuan)	45.47	0	6.86	18.38
The expected output index	y_1	The net output of main pig products (unit: kg)	142.99	0	12.20	99.37
The non-expected output	y_2	The carbon emissions of pig farming (unit: ton)	300.89	0.71	72.52	89.02
The driving factor	F_{Env}	Environmental regulation	1300.95	2.81	209.47	182.33
	F_{scale}	Scale level (unit: %)	0.94	0	0.19	0.133
	F_{corn}	Resource endowment (unit: Ten thousand tons)	8.36	−0.16	1.95	5.54
	F_{tech}	Technical input(unit: Hundred million yuan)	6316.16	0.56	739.53	343.36
	F_{edu}	Quality of labor force(unit : year)	12.70	6.85	0.92	9.14
	F_{price}	Pig price(unit: Yuan /50 kg)	1853.62	0	284.71	823

TABLE 2 Environmental efficiency of pig farming in China from 2008 to 2020.

Year	Undesired output		
	ETE	EPTE	ESE
2008	0.6365	0.6525	0.9721
2009	0.6348	0.6597	0.9646
2010	0.6221	0.6329	0.9816
2011	0.5770	0.5950	0.9703
2012	0.5813	0.6141	0.9543
2013	0.5840	0.6215	0.9476
2014	0.5959	0.6324	0.9498
2015	0.6144	0.6477	0.9534
2016	0.6516	0.6804	0.9599
2017	0.6788	0.7117	0.9550
2018	0.6751	0.7370	0.9258
2019	0.6889	0.7493	0.9232
2020	0.7114	0.9021	0.8802

(2016–2020)" has quickly and effectively solved the water pollution problem in southern China and helped improve environmental efficiency in the region.

In addition, the combination of agriculture and animal husbandry in western China was better, so ecological farming could be carried out. Promoting advanced and efficient farming technology could improve pure technical efficiency, and environmental efficiency would be higher.

4 Convergence trend analysis of environmental efficiency of pig farming in China

This article uses the environmental efficiency of pig farming data from 30 provinces (municipalities and autonomous regions) in China from 2008 to 2020 to test the convergence of the overall panel. The test results are as follows:

Table 4 shows that $t_{\hat{b}} = -10.4630$, which is less than -1.65, allowing us to reject the null hypothesis at the 1% significance level. This implies that there is no overall convergence in the environmental efficiency of pig farming across China's 30 provinces (municipalities and autonomous regions) from 2008 to 2020. Building on this finding, the study explores the club convergence patterns in the environmental efficiency of pig farming among these regions.

In the first step, all provinces (municipalities and autonomous regions) were sorted according to the average environmental efficiency of pig farming in the last 5 years of the study period. The averages were sorted from high to low: Beijing, Shanghai, Ningxia, Yunnan, Jilin, Hunan, Inner Mongolia, Qinghai, Guizhou, Fujian, Tianjin, Jiangxi, Gansu, Shanxi, Hebei, Hainan, Zhejiang, Hubei, Xinjiang, Guangxi,

TABLE 3 Environmental efficiency of pig farming in different provinces in China from 2008 to 2020.

Region	Province	ETE	EPTE	ESE
Key development region	Shandong	0.4967	0.5032	0.9898
	Henan	0.3980	0.4138	0.9643
	Sichuan	0.4647	0.4649	0.9997
	Hebei	0.6524	0.6526	0.9997
	Guangxi	0.5764	0.5795	0.9949
	Chongqing	0.3451	0.3472	0.9934
	Hainan	0.5118	0.5187	0.9895
	Ave.	0.4922	0.4971	0.9902
Constrained development region	Beijing	0.7078	1.0086	0.9180
	Shanghai	0.9909	0.9933	0.9975
	Tianjin	0.7775	0.7887	0.9871
	Guangdong	0.4589	0.4772	0.9645
	Jiangsu	0.5223	0.5373	0.9746
	Hubei	0.5460	0.5958	0.9165
	Hunan	0.7325	0.8112	0.9032
	Zhejiang	0.5908	0.6719	0.8926
	Anhui	0.4480	0.4738	0.9549
	Fujian	0.7942	0.8728	0.9067
	Jiangxi	0.6062	0.8192	0.7663
	Ave.	0.7064	0.7938	0.9387
Potential growth region	Heilongjiang	0.5310	0.5646	0.9416
	Jilin	0.8577	0.8785	0.9747
	Liaoning	0.5247	0.6235	0.8440
	Inner Mongolia	0.8386	0.8972	0.9359
	Yunnan	0.7370	0.7784	0.9394
	Guizhou	0.7504	0.7852	0.9590
	Ave.	0.7159	0.7614	0.9366
Moderate development region	Shaanxi	0.5224	0.5684	0.9175
	Shanxi	0.5650	0.6228	0.9075
	Xinjiang	0.6591	0.6818	0.9714
	Gansu	0.6701	0.6793	0.9850
	Ningxia	0.9630	0.9723	0.9906
	Qinghai	0.8031	0.8100	0.9923
	Ave.	0.6971	0.7224	0.9607

TABLE 4 Convergence test of environmental efficiency of pig farming in China.

Variable	Coeff	SE	T-stat
Log(t)	−1.4173	0.1355	−10.4630

Jiangsu, Liaoning, Shandong, Heilongjiang, Guangdong, Anhui, Shaanxi, Sichuan, Henan, Chongqing.

In the second step, the region with the greatest environmental efficiency of pig farming ($2 \leq k < N$) was extracted to construct the first convergence club, and its convergence was tested by $\log(t)$. If the original hypothesis cannot be rejected, the remaining provinces will join the club one by one, and the $\log(t)$ test will be carried out together to screen out the regions that meet $t > -1.65$, and the province with the largest t value will be merged with the previous two provinces. Assuming that the club composed of the first and second provinces fails to pass the test, the second province will be eliminated, and the second and third provinces will be formed into a new club. If the convergence result does not meet the convergence condition, repeat the above operation. If the above conditions are not met at the end of the calculation, there is no club convergence. If some provinces pass the club convergence test in the second step, the remaining regions will join the club individually.

TABLE 5 Convergence club of environmental efficiency of pig farming in China.

Convergence Club	Provinces (municipalities and autonomous regions)
Convergence Club 1	Beijing, Shanghai, Ningxia, Yunnan, Jilin, Hunan, Inner Mongolia, Qinghai, Guizhou, Fujian, Tianjin, Jiangxi
Convergence Club 2	Gansu, Shanxi, Hebei, Hainan, Zhejiang, Hubei, Xinjiang, Guangxi, Jiangsu, Liaoning, Shandong, Heilongjiang, Guangdong, Anhui, Shaanxi
Convergence Club 3	Sichuan, Henan
Convergence Club 4	Chongqing

The regions not included in the second step were regrouped in the third step, and the $\log(t)$ test was continued. If there is convergence, another club is formed. If convergence is rejected, repeat the above steps for the remaining regions.

As can be seen from Table 5, Convergence Club 1 includes most eastern regions such as Beijing, Shanghai, Fujian, Jilin, etc. These provinces have a high degree of pig industry intensification, early development of pig scale, mature production, breeding technology, and effective transformation of livestock and poultry. Convergence Club 2 includes Gansu, Shanxi, Hebei, Hainan, Zhejiang, Hubei, Xinjiang, Guangxi, Jiangsu, Liaoning, Shandong, Heilongjiang, Guangdong, Anhui, and Shaanxi. Most of these provinces are traditional pig-producing regions. The pig industry in these areas exhibits a low degree of intensification, a limited level of breeding technology, and inadequate pollution control measures. Nevertheless, due to the abundant labor force, these regions possess certain geographical advantages and have developed a notable trend of regional convergence.

Convergence Club 3 and Convergence Club 4 include three provinces. These provinces have a large number of live pigs, but the difficulty of pollution control has also increased accordingly. Under the environmental protection policy of "whoever raises the pig will treat it," the cost of manure treatment for farmers is higher than their affordability, dampening farmers' enthusiasm. The scale of industrial organizations is low (Cui et al., 2018), resulting in low carbon emission efficiency.

5 Analysis of driving factors of convergence trend of pig farming in China

In this article, the dependent variable is defined by club levels, which are ranked from high to low as levels 1–4. Therefore, appropriate conversions must be applied when analyzing the effects of driving factors on club convergence.

According to the estimation results (Table 6), the primary term of scale level of the pig industry is positive, while the quadratic term of scale level is negative, both of which are significant, indicating that there is a "U-shaped" relationship between scale level and the environmental efficiency of pig farming entering the high-level club. The effect of scale on club convergence results is negative and then positive, indicating that the probability of scale helping to converge to high-level clubs decreases first and then increases. The extreme points are further calculated to better describe the effect of scale level on club convergence results. According to the calculation, the extreme point of the scale of the pig industry is 0.13, and the scale level e of pig farming in China is 0.133 on average. This shows that at this stage, the

TABLE 6 Regression result by ordered logit/probit model.

Variable	Ordered probit	Ordered logit
F_{Env}	0.0028*** (0.0004)	0.0049*** (0.0007)
F_{scale}	4.373** (2.045)	7.350** (3.584)
$F_{scale}{}^{2}$	−16.81*** (5.810)	−27.08*** (10.35)
F_{corn}	0.258*** (0.0396)	0.464*** (0.0722)
F_{edu}	−0.311** (0.131)	−0.549** (0.257)
F_{tech}	−0.0002 (0.0001)	−0.0002 (0.0002)
F_{price}	−0.0002 (0.0002)	−0.0004 (0.0004)
LR chi2(8)	111.77	100.12
Prob > chi2	0.000	0.000
R^2	0.1582	0.1627
Obs.	383	383

impact of the scale level of pig farming on the convergence of high-level clubs has crossed the inflection point. With the improvement of the scale of pig farming, pig farmers have gradually changed their production mode and paid attention to the coordinated development of economic benefits and environmental effects, improving the environmental efficiency of pig farming.

The quality of the labor force has a positive impact on club convergence at a significant level of 1%, indicating that improving the professional quality of pig farmers is conducive to converging to high-level clubs.

The resource endowment has a negative impact on the pig breeding entering the high-level club at a significant level of 1%. The possible reason is that the resource gap widens the imbalance of environmental efficiency in different regions.

The environmental regulation has a negative impact on pig breeding entering the high-level club at a significant level of 1%, indicating that the government's regulation of pig production has increased the environmental pressure on key development areas to a certain extent, and there are obstacles to the coordinated development of different regions.

The above conclusion aligns with the "agricultural treadmill theory" (Cochrane, 1958), which posits that pig farmers must continuously expand farming scales and enhance production methods to maintain competitiveness in the pig industry. Simultaneously, the Environmental Kuznets Hypothesis suggests that large-scale development leads to the input of resources. More output also increases carbon emissions in the region, thus affecting the low-level club to high-level convergence. However, after reaching a certain level of scale, with technological innovation and changes in production methods, carbon emissions will decrease, which will help low-level clubs converge toward high-level clubs (Kaika and Zervas, 2013). Consequently, scale efficiency has consistently been a primary driver of total factor productivity growth in pig farming. Moving forward, it is essential to continue promoting the scale of pig farming to achieve coordinated development across different regions. In this process, we should pay attention to the power of the quality of the labor force to enhance the technological innovation capabilities of various regions and boost technical efficiency.

In this article, the ordered logit model is used to replace the ordered probit model for the robustness test, and the results are shown in Table 6. Scale level still has a "U-shaped" influence on the convergence trend, and other results are consistent with the above results, which also indicates the credibility of this study.

6 Discussion

This article solves the problems raised in the introduction, such as the measurement and regional differences in the environmental efficiency of pig farming in China and the convergence trend and driving factors of the environmental efficiency of pig farming in China.

Firstly, the environmental efficiency of pig farming in China showed an upward trend from 2008 to 2020, confirming Guo's point of view (Guo et al., 2023). Various regions should focus on improving pure technical efficiency in improving environmental efficiency. It can be seen from the research results that the environmental efficiency of pig farming in our country is not optimal. Large-scale farming is an important way for the sustainable development of the pig industry, and more attention should be paid to technological progress in the future (Zhou et al., 2023).

Secondly, this article finds that the environmental efficiency of pig farming in China can be divided into four convergence clubs, and the regional development is not coordinated. To be specific, most of the provinces in the high-level club belong to the potential growth region and constrained development region in the eastern part of China, which indicates that China's pig industry planning has produced certain results (Yan et al., 2023). However, the difference in environmental efficiency is most obvious in key development regions, with most provinces located in the second club, and Chongqing, Sichuan, and Henan are in the low-level club. The findings are similar to Wang et al. (2023). This phenomenon will have a negative impact on promoting the sustainable development of the pig industry. In conjunction with the results of the efficiency breakdown, all regions should promote technological innovation and strengthen regional exchanges and cooperation. It is essential to fully leverage the technological advancements in pig farming within key development areas, enhance the level of technical input, and focus on improving pure technical efficiency. Ultimately, the goal is to facilitate the effective dissemination of lower-level clubs to high-level clubs, thereby narrowing the regional development gap (Lei et al., 2023).

Thirdly, the results of the driving factors show that the influence of scale level on the convergence of environmental efficiency of pig farming to high-level clubs in China presents a "U-shape." Results from descriptive statistical analysis indicate that most regions in China have surpassed this inflection point. This suggests that continuing to promote large-scale pig farming is beneficial for achieving balance in the environmental efficiency of pig farming across different regions. The global pig industry is gradually integrating with large-scale enterprises experiencing rapid growth; for instance, the number of large-scale farms in Vietnam increased dramatically from 120,000 in 2014 to 190,000 in 2018 (Huong et al., 2024). Large-scale farms streamline all aspects of production, simplify processes, reduce internal input costs, and maximize profits, thereby minimizing environmental impact (Kim et al., 2024). In China, the contribution rate of the top 10 listed companies in the pig industry has reached approximately 14%. The scale effect in pig farming can mitigate random price fluctuations to some extent (Yang et al., 2024), which is a key factor regulated by the Chinese government. Consequently, the Chinese government can foster the development of large-scale pig farming under the scientific framework of "moderate-scale farming," guiding the allocation of economic and social resources toward a high concentration of large-scale pig farms and continuously promoting the pig farming industry toward a stage of green and efficient development.

This article proposes the following policy recommendations. First, it is essential to focus on enhancing the technical efficiency of pig farming. This can be achieved by increasing technological investments in key development regions in pig farming, providing comprehensive technical training for farming personnel, establishing dedicated training institutions, organizing experience exchange meetings, and ultimately improving overall technical efficiency. Second, it is necessary to advance the scale processes of pig farming in our country further, aiming to drive the integration of environmental efficiency of pig farming into a high-level club. The government should direct funds and social resources toward high-scale pig farms while continuing to support free-range and small-scale farming initiatives. Finally, it is imperative to strengthen cooperation among regions. Provinces within similar club convergence should thoroughly assess their resource endowments and environmental policy experiences. Enhancing inter-regional exchanges and collaboration can facilitate the effective transfer of advanced practices from high-club regions to those with lower clubs, thereby bridging the gap between different areas. Optimizing the spatial layout of pig farming will ensure that the industry progresses toward green, efficient, and sustainable development.

This article still has some limitations and space for further research. First, in terms of data collection, this article collects statistical information related to pig farming to the maximum extent possible. Considering the completeness of the data, the period is limited to 2008–2020, covering the important stages of changes in the layout of the pig industry. Notably, during the Twelfth Five-Year Plan period (2010–2015), environmental restrictions on livestock and poultry farming peaked, significantly influencing the production layout of farms and related industries. In the thirteenth Five-Year Plan (2016–2020), the Ministry of Agriculture introduced the "National Pig Production Development Plan (2016–2020)" to enhance support and guidance for pig production development. The "Northern Diversion" policy has led to a gradual shift in pig farming distribution from the southeast, characterized by dense waterways, to the northeast and southwest. This timeframe represents a critical juncture for transforming and upgrading China's pig industry. However, African swine fever and the COVID-19 pandemic in early 2020 have adversely affected China's pig production capacity. Post-2020, the pig industry has prioritized resuming production. Therefore, this research has not studied the convergence of environmental efficiency after 2020, and further tracking and observation are needed in the later stage. Second, in terms of carbon emission measurement, this article uses the greenhouse gas emission coefficient method to measure the carbon emissions of pig farming, focusing on direct carbon emissions, including pig intestinal CH4 emissions and manure management system CH4 and N2O emissions, because these are major sources of carbon emissions from pig production. However, this study does not account for indirect carbon emissions from pig production, such as those generated by the extensive use of coal, electricity, tap water, feed, and other inputs. Estimating carbon emissions from pig farming from a life cycle perspective is a key area for future research in this article.

7 Conclusion

Based on the panel data of 30 provinces (municipalities and autonomous regions excluding Hong Kong, Macao, Taiwan, and Tibet) in China from 2008 to 2020, this article calculates the environmental efficiency of pig farming in China and tests the club convergence. Finally, based on the club convergence of pig farming environmental efficiency in various regions, this article discusses the driving factors affecting the environmental efficiency of pig farming entering the high-level club. The specific conclusions are as follows:

First, the environmental efficiency of pig farming in China shows an upward trend. Through efficiency decomposition, we can see that scale efficiency has been the main source of environmental efficiency of pig farming for a long time, and improving pure technical efficiency deserves attention in the future. There are differences in environmental efficiency among different regions; the environmental efficiency of the potential growth region is the highest, and the environmental efficiency of the key development region is the lowest.

Second, according to the results of club convergence grouping, the environmental efficiency of pig farming in China converges to 4 clubs. Most of the potential growth regions and constrained development regions in China are involved in Club 1, including Shandong, Jiangsu, Heilongjiang, Anhui, Chongqing, Hunan, Beijing, Yunnan, Zhejiang, Sichuan, and Shanghai. Club 2 includes Gansu, Shanxi, Hebei, Hainan, Zhejiang, Hubei, Xinjiang, Guangxi, Jiangsu, Liaoning, Shandong, Heilongjiang, Guangdong, Anhui and Shaanxi; Club 3 includes Sichuan and Henan provinces, and Club 4 includes Chongqing, both of which belong to the key development region, which is also a traditional main producing area of pig farming.

Third, by analyzing the driving factors of club convergence, it is observed that the scale level exhibits a "U-shaped" effect on the convergence of environmental efficiency in pig farming toward high-level clubs in China. Notably, the highest scale level of the pig farming industry in China has already surpassed this inflection point, indicating that further increases in scale can enhance environmental efficiency, facilitating movement toward high-level clubs. Additionally, improving the quality of the labor force is beneficial for achieving convergence with these high-level clubs. However, the government's environmental regulation policies regarding pig production can, to some extent, exacerbate environmental pressures in some regions, thereby impacting the coordinated development of different regions.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

JW: Conceptualization, Methodology, Software, Writing – original draft, Writing – review & editing. C'eZ: Data curation, Formal analysis, Writing – original draft. SC: Data curation, Resources, Writing – original draft.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This work was supported by the special project of Philosophy and Social Science Research in Heilongjiang Province in China (Grant no. 23XZT045) and the Natural Science Foundation of Heilongjiang Province in China (Grant no. LH2024G001).

Conflict of interest

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

Publisher's note

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