frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 03 February 2026
DOI 10.3389/fsufs.2026.1750502

Check for updates

OPEN ACCESS

EDITED BY
Christian Bux,
University of Foggia, Italy

REVIEWED BY
Buchun Si,
China Agricultural University, China
Tao He,
Shihezi University, China

*CORRESPONDENCE
Hui Zhou
✉ zhouhui@caas.cn

RECEIVED 23 November 2025
REVISED 10 January 2026
ACCEPTED 19 January 2026
PUBLISHED 03 February 2026

CITATION
Xu F, Xu Z, Hu X and Zhou H (2026) Study on the ecological efficiency of pig breeding based on the LCA-DEA method: evidence from China.
Front. Sustain. Food Syst. 10:1750502.
doi: 10.3389/fsufs.2026.1750502

Study on the ecological efficiency of pig breeding based on the LCA-DEA method: evidence from China

Fengqi Xu, Zhen Xu, Xiangdong Hu and Hui Zhou*

Institute of Agricultural Economics and Development, Chinese Academy of Agricultural Sciences, Beijing, China

Against the backdrop of the global dietary structure shifting toward high-protein livestock products, rising pork demand driven by population growth, and the in-depth integration of the "dual carbon" goal with the strategy for green and sustainable agricultural development, China—as the world's largest pig breeding and consuming country—bears the livelihood mission of ensuring meat supply through its pig industry while confronting practical challenges such as excessive resource consumption and worsening environmental pollution. To address the coordinated dilemma of "production efficiency-resource consumption-environmental impact," this study takes 199 self-breeding and self-raising pig farmers in three northeastern provinces of China as research objects, and systematically measures the ecological efficiency of fattening pig rearing and quantifies the greenhouse gas emission reduction potential by combining the Life Cycle Assessment (LCA) and Super-efficiency SBM-DEA models. The LCA results indicate that the manure treatment and feed processing stages are the core contributing links to global warming potential, acidification potential, and eutrophication potential. The DEA calculation shows that the ecological efficiency of large-scale farmers is significantly higher than that of small-scale scattered farmers: the former exhibits high redundancy in labor and epidemic prevention inputs, while the latter features comprehensive redundancy in factors such as the number of sows and land. The analysis of emission reduction potential reveals that the greenhouse gas reduction rate of small-scale scattered farmers is much higher than that of large-scale farmers, making them the key target for regional agricultural carbon emission reduction. This study reveals the scale differences and optimization paths of ecological efficiency in pig breeding in Northeast China from the micro-subject perspective, providing empirical support and decision-making basis for targeted industrial emission reduction, efficient resource allocation, and green transformation.

KEYWORDS

ecological efficiency, greenhouse gas emission reduction, Life Cycle Assessment, pig breeding, super-efficiency SBM model

1 Introduction

Over the past few decades, the global human diet has undergone a continuous and substantial shift towards including more livestock-derived foods (Komarek et al., 2021). Meanwhile, the rapid growth of the world's population has further increased the demand for pork (Marić et al., 2025). However, as a crucial component of the livestock industry, pig production not only provides meat products but also faces challenges such as environmental pollution and high resource consumption (Wu et al., 2024). According to the livestock greenhouse gas assessment report released by the Food and Agriculture Organization of the United Nations (FAO) in 2023, with 2015 as the base year, the global total greenhouse gas emissions from the livestock sector reach 6.2 gigatonnes of carbon dioxide equivalent (Gt CO_2eq). Pig emissions account for 14%, ranking as the second-largest source of emissions in the livestock sector, second only to cattle (62%) (FAO, 2023). Since the start of the 21st century, China's livestock industry has achieved sustained development and gradual expansion, evolving from a traditional household sideline into one of the key pillar industries of the agricultural and rural economy, and thus becoming an integral part of China's agriculture. As the world's largest pig producer and consumer, China accounts for 42% of global pork consumption (OECD, FAO, 2022). Due to its high consumption volume, pork has a greater environmental impact than other meats, contributing approximately 11% to China's food footprint (excluding feed-related emissions) (Halpern et al., 2022). Affected by the 2018 African swine fever (ASF) outbreak, China's pig industry has gradually recovered after experiencing a downturn in recent years. According to statistics from the National Bureau of Statistics of China, in 2023, the number of fattening pigs slaughtered in China reached 726.6 million head, with pork output hitting 57.9432 million tons—an increase compared with the number of fattening pigs slaughtered before the outbreak of the epidemic in 2018. China pledged at the general debate of the 75th Session of the United Nations General Assembly that "it will strive to peak carbon dioxide emissions before 2030 and achieve carbon neutrality before 2060." Against the backdrop of the current "dual carbon" goals (carbon peaking and carbon neutrality) and green development, a key issue lies in how China's pig farming industry can balance input–output efficiency, resource consumption, and environmental protection.

The concept of ecological efficiency was proposed by German scholars Schaltegger and Sturm (1990), aiming to transform the role of subjects from environmental destroyers to promoters of sustainable development (Schaltegger and Sturm, 1990). With the growing social attention to the environment, this concept has now evolved into a quantitative management tool for simultaneous assessment of environmental and economic performance (Rybaczewska-Błażejowska and Gierulski, 2018). In the field of animal husbandry, the core idea of ecological efficiency has been further expanded and applied. Its primary goal is to optimize waste management strategies and minimize adverse environmental impacts while meeting the demand for livestock products, thereby laying a solid foundation for the long-term sustainable development of animal husbandry. Numerous scholars have conducted research on the ecological efficiency of agricultural-related products across multiple sectors, including crop cultivation and animal breeding (Jiang et al., 2023; Mardani Najafabadi et al., 2023; Liang et al., 2023; Geffersa and Tabe-Ojong, 2024; Zhang et al., 2024). Among these studies, data envelopment analysis (DEA) is the most widely used measurement method. Data Envelopment Analysis is a classic non-parametric analysis method, first proposed by Charnes et al. (1978). Its core function lies in evaluating the relative efficiency level of homogeneous Decision Making Units (DMUs). Due to its ability to effectively avoid disputes caused by subjective weighting, it has been widely applied in various efficiency evaluation research fields, which also serves as the basic framework for the method selection in this study. Considering the actual production scenario of pig farming, traditional DEA (Data Envelopment Analysis) models tend to overlook the impact of input redundancy and undesirable outputs in radial and angular measurements, leading to a disconnect between efficiency evaluation and reality. In contrast, the Slacks-Based Measure (SBM) model proposed by Tone (2001), by incorporating slack variables and explicitly considering the negative effects of undesirable outputs, can more accurately reflect the true efficiency of resource allocation in breeding activities. Furthermore, when there may be multiple breeding entities with optimal efficiency in the research sample, the traditional SBM model is unable to differentiate and compare these efficient DMUs. The super-efficiency SBM model with undesirable outputs extended by Tone (2004) not only inherits the core advantages of the SBM model but also breaks through the limitation of 0–1 efficiency values, enabling the ranking of relative efficiency among efficient decision units. As a non-parametric method capable of effectively handling multiple inputs, multiple outputs, and undesirable outputs (such as greenhouse gas emissions and non-point source pollution), the SBM model and its super-efficiency extension have been widely used in various efficiency research fields. Specifically, Chai et al. (2026) applied the super-efficiency SBM model to measure farmland green productivity in the Yellow River Basin to explore the impact of farmland fragmentation. Zhang et al. (2023) employed a three-stage super-efficiency SBM-DEA model to assess China's agricultural carbon emission efficiency, providing insights into the regional differences and dynamic evolution of low-carbon agriculture. For the black soil region in Northeast China, Feng et al. (2023) and Dong et al. (2025) utilized the super-efficiency SBM model to evaluate cultivated land ecological efficiency and production efficiency of family agricultural management entities, respectively. Additionally, Zhang et al. (2025) extended the super-efficiency SBM model to the evaluation of water-energy-food-economy-ecosystem nexus efficiency in the Yellow River Basin, verifying its adaptability in complex system assessments.

While the Data Envelopment Analysis model can help interpret the concept of ecological efficiency in eco-efficiency evaluation, the scientific selection of evaluation indicators has undoubtedly become a crucial prerequisite for accurate measurement. In fact, the World Business Council for Sustainable Development (WBCSD) defined ecological efficiency as "providing competitively priced goods and services that meet human needs and enhance quality of life, while progressively reducing ecological impacts and resource intensity throughout the entire life cycle to a level at least consistent with the estimated carrying capacity of the Earth" (Schmidheiny and Stigson, 2000; ISO, 2006). It is evident that a more precise assessment of ecological efficiency requires consideration from the perspective of the entire product life cycle. Since its establishment in the 1960s, Life Cycle Assessment (LCA) has been widely applied across various industries to measure the environmental impacts of products and services. The International Organization for Standardization (ISO) has standardized this methodology, defining LCA as an approach to evaluating the environmental aspects and potential impacts throughout a product's entire life cycle (ISO, 2006). Consequently, the combined application of LCA and DEA has emerged as a pivotal method for calculating ecological efficiency. Life Cycle Assessment (LCA) is a method used to evaluate the environmental factors and potential impacts throughout the entire product life cycle (Suski et al., 2021). The assessment results can be applied to analyze the system's impacts on the environment, society, and economy (Popien et al., 2025). The main steps of the LCA method include: definition of goal and scope, inventory analysis, environmental impact assessment, interpretation of results, and improvement analysis (Rebitzer et al., 2004). Although numerous studies have adopted the integrated framework of LCA and DEA (Sun et al., 2022; Azizpanah et al., 2025; Nsabiyeze et al., 2024), such research remains scarce in the context of pig production (Sun et al., 2022), especially studies specifically focusing on its ecological efficiency.

In summary, although numerous studies have been conducted on the ecological efficiency of pig breeding, there remains room for improvement and in-depth exploration. First, in terms of research scale, due to data accessibility constraints, studies on pig breeding ecological efficiency in China have mainly focused on the national and provincial levels, lacking micro-level research from the perspective of individual farmers. Second, in terms of research methods, relatively few studies have analyzed the ecological efficiency of pig breeding by combining the LCA and DEA methods. Therefore, based on the limitations of existing research, this study intends to make the following improvements: (1) Using survey data from 205 self-breeding and self-raising pig farmers in three northeastern provinces of China as the research unit, this study applies LCA to quantitatively analyze the relevant environmental impacts within the boundary of pig breeding, and selects the greenhouse gas emission intensity index as an undesirable output to be incorporated into the ecological efficiency evaluation system. (2) The cutting-edge super-efficiency SBM model is adopted, which not only takes undesirable outputs into account but also yields more realistic efficiency evaluation results. (3) Based on the calculated ecological efficiency of pig breeding, this study further analyzes the greenhouse gas emission reduction potential during the pig breeding process and proposes corresponding improvement measures and suggestions.

Beyond the introduction, the structure of this paper is organized as follows: Section 2 presents the materials and methods; Section 3 includes the results and discussion; Section 4 outlines the main conclusions of the study.

2 Materials and methods

2.1 Study area and data collection

The integration of livestock breeding belts with corn planting belts is a crucial experience in global agricultural production (Sulc and Tracy, 2007). The "pig-grain" structure is also a key feature of China's agricultural production, where many major grain-producing regions are often advantageous areas for pig breeding. According to the four types of pig production zones with distinct advantages defined in the National Plan for Pig Production Development (2016–2020) issued by China's Ministry of Agriculture and Rural Affairs, the three northeastern provinces, endowed with certain resource advantages, are designated as a "potential growth zone" for pig production.

In terms of resource endowment, Northeast China is rich in feed resources such as corn and soybeans. Data from the National Bureau of Statistics of China show that in 2023, the pork output in Northeast China reached 6.0942 million tons, accounting for 10.52% of the national total. Meanwhile, the region's total grain output exceeded 20% of China's total, with corn output alone accounting for over 30% of the national figure. In terms of environmental carrying capacity, Northeast China boasts a vast territory, relatively favorable climatic conditions, low pig breeding density, strong manure absorption capacity, and high environmental carrying capacity (Zhang et al., 2018). Theoretically, Northeast China possesses superior conditions for the development of the pig breeding industry (Chen and Liang, 2020).

This study selected 205 self-breeding and self-raising pig farmers in Northeast China as survey respondents. The questionnaire included content such as basic information of the farmers' pig farms and details of breeding costs and benefits. To clarify the research scope, the "Northeast" region in this study is strictly defined as the three traditional northeastern provinces of Heilongjiang, Jilin, and Liaoning. This definition aligns with the administrative and agricultural economic division commonly used in China's livestock industry research, excluding broader geographic areas that may be colloquially referred to as "Northeast" (e.g., parts of eastern Inner Mongolia). This precise demarcation ensures the consistency and comparability of the research data and results. To ensure the accuracy of the questionnaire data, on-site interviews were conducted for all surveys. A total of 205 questionnaires were distributed, and after excluding invalid ones, 199 valid questionnaires were recovered. The income status of the respondents' pig breeding operations is presented in Table 1. Table 1 presents the cost and benefit status of pig breeding among the respondents. Following the classification method specified in the China Animal Husbandry and Veterinary Yearbook, this study divides pig breeding scales into small-scale scattered farmers and large-scale farmers (annual slaughter $\geq$ 50 head). Ultimately, 48 valid questionnaires were collected from small-scale scattered farmers and 151 from large-scale farmers, totaling 199 valid samples. Table 2 presents some characteristics of the surveyed pig farms.

2.2 Life Cycle Assessment

Life Cycle Assessment (LCA) is a method for evaluating the environmental factors and potential impacts throughout a product's entire life cycle (Suski et al., 2021). The assessment results can be applied to analyze the system's impacts on the environment, society, and economy (Popien et al., 2025). The main steps of the LCA method include goal and scope definition, inventory analysis, environmental impact assessment, result interpretation, and improvement analysis (Rebitzer et al., 2004). When applied in livestock production, LCA usually focuses on the impacts at the farm level, namely the "cradle - to - gate" perspective.

2.2.1 Defining the evaluation objectives and scope

In accordance with the principles of continuity and functionality in the production process, and combined with the main characteristics of the swine production stages, the unit processes were divided and data were collected (Hui et al., 2016). In this study, the scope of the life cycle starts from the extraction of relevant ores and energy, and ends with the slaughter of finishing pigs and pollutant discharge. The entire life cycle of finishing pig breeding is divided into four phases, namely the agricultural resource phase, feed manufacture phase, breeding phase, and manure treatment phase (Figure 1).

The agricultural resource phase covers the resource consumption and environmental pollution caused by power generation, diesel extraction and other activities. Due to the different completion times

TABLE 1 Breeding status of pig farmers.

Variable names	Category	Mean value	Minimum value	Median	Maximum value	Note
Number of sows/head	Backyard Farming	6.82	0.00	5.00	30.00	The number of sows kept by pig farmer at the end of 2024
	Large-scale Farming	61.52	4.00	15.00	3,000.00	
Feed costs/yuan	Backyard Farming	40,223.28	5,940.00	25,905.00	175,950.00	The expenses of pig farmers on purchasing pig feed in the year 2024
	Large-scale Farming	448,004.67	13,455.00	129,000.00	10,890,000.00	
Labor input/person	Backyard Farming	2.48	1.00	2.00	4.00	The number of workers employed in pig farmers' breeding farms
	Large-scale Farming	2.71	1.00	3.00	8.00	
Epidemic prevention input/yuan	Backyard Farming	3,148.96	100.00	2,000.00	10,000.00	The expenses of pig farmer for purchasing epidemic prevention supplies such as vaccines and disinfectants
	Large-scale Farming	28,106.96	300.00	8,000.00	1,820,000.00	
Energy input/yuan	Backyard Farming	3,502.50	220.00	2,900.00	12,000.00	The total cost of energy used by pig farmers' facilities
	Large-scale Farming	13,331.85	300.00	5,000.00	267,000.00	
Land input/m^2	Backyard Farming	346.98	60.00	200.00	3,500.00	The area of land used by pig farmers for raising pigs (including pig pens and equipment)
	Large-scale Farming	2,927.93	60.00	400.00	100,000.00	
Total value of pig sales in 2024/yuan	Backyard Farming	109,975.31	4,200.00	66,350.00	592,000.00	The value obtained by pig farmers from selling fattened pigs in the year 2024
	Large-scale Farming	218,945.68	12,000.00	98,000.00	3,200,000.00	

TABLE 2 Characteristics of pig farms.

Item	Backyard farmers	Large-scale farmers
Pig farm scale	The annual number of marketed fattening pigs < 50 heads	The annual number of marketed fattening pigs ≥50 heads
Feed composition	Self-formulated protein feed (predominantly based on soybean meal) plus energy feed (predominantly based on corn)	Plant protein-dominant concentrated feed plus energy feed (predominantly based on corn)
Manure treatment mode	Composting and returning to the field or simple stacking	Equipped with biogas digesters and manure treatment facilities
Epidemic prevention and control measures	Predominantly based on traditional management, with a disinfection frequency of 1–2 times per month	Equipped with temperature control and ventilation equipment, with a disinfection frequency of 3–4 times per week
Geographical location	The farmer's own backyard, close to residential areas	Dedicated pig farms, far from residential areas

of various farms and the varying building materials used, building materials are not taken into account in this study. The feed manufacture phase mainly focuses on the processes of feed processing and maize production. The maize production process, ranging from planting to harvesting, includes links such as chemical fertilizer production and machinery application, which also falls within the scope of the "cradle - to - gate" perspective. The breeding phase mainly considers the electricity input and labor input during swine rearing. The manure treatment phase focuses on the environmental impacts caused by swine feces and urine. According to the results of field surveys, most farmers adopt the dry manure cleaning method for feces disposal; therefore, the environmental impacts of fermentation equipment are not considered in this study. This research takes a 110 kg finished pig as the functional unit to study the whole—life—cycle resource consumption and environmental impacts during the breeding process of producing a 110 kg finished pig.

2.2.2 Inventory analysis

The agricultural resource phase includes power generation and diesel production, while the feed processing phase covers feed

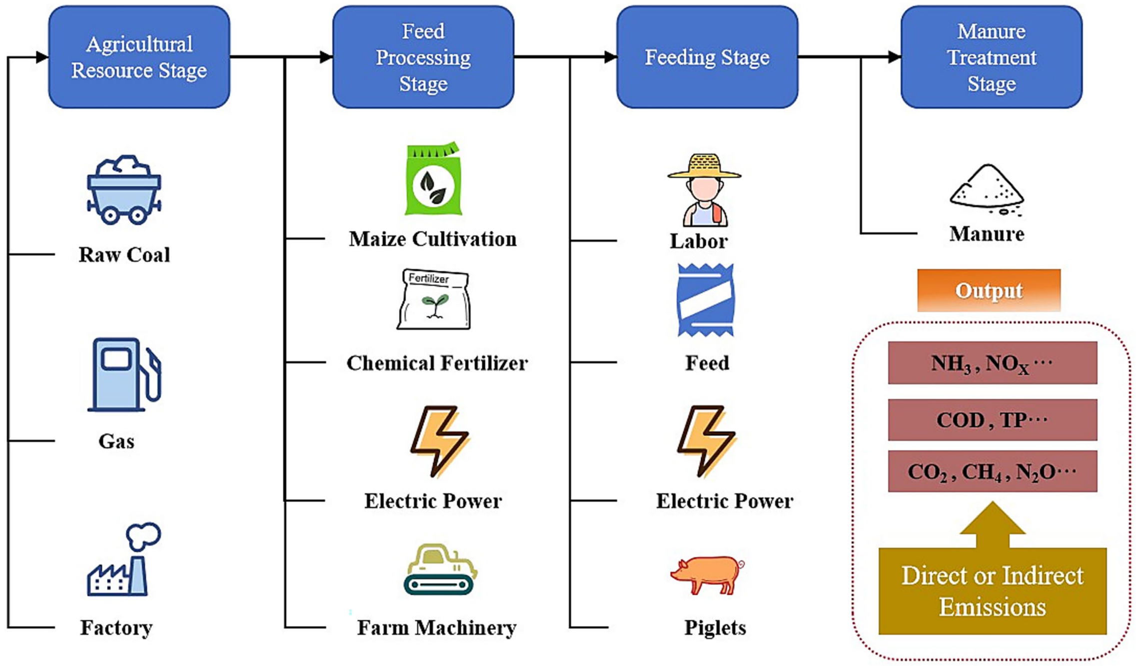

FIGURE 1
Scope of Life Cycle Assessment for the pig breeding system.

manufacturing as well as the processes of chemical fertilizer production and machinery application during maize cultivation. These data are derived from the Ecoinvent and Industry databases of the SimaPro9.5 software, along with previous studies (Hui, 2017; Gong et al., 2018). Data on water consumption and electricity input during the breeding phase are obtained through field investigations. The pollution generation data regarding the manure treatment phase is sourced from prior research (Dong et al., 2011; Guo et al., 2014). However, due to insufficient data, the environmental impact data arising from the operation of relevant equipment and transportation tools involved in each phase are not incorporated into the Life Cycle Assessment.

Regarding the feed intake and manure discharge during swine breeding, based on the actual field survey results and the statistical data from China Agricultural Products Cost–Benefit Compilation, the feeding period of the functional unit is defined as 164.68 days in this study. During the feeding cycle, the daily water consumption per pig is 5.1 L/d, and the electricity consumption is 3.69 kWh/Fu, details of farming inputs per functional unit are provided in Table 3. In the study conducted by Liu et al. (2012), pig rearing mainly relied on concentrated feed, which consisted of 70% corn, 9% soybean meal, 7% wheat bran, 4% rapeseed meal, 4% cottonseed meal, 2% fish meal, and 4% other mineral components. Meanwhile, based on field survey data, most large-scale farmers purchase concentrated feed (see Table 4 for the feed formulation) and mix it with corn at a ratio of 1:3 (concentrated feed to corn). In contrast, small-scale farmers mostly prepare protein feed by themselves, then add corn to it, and hardly add soybean meal, rapeseed meal, cottonseed meal, fish meal, or other such ingredients at all. In this study, the feed intake of the functional unit (a finished pig) is defined as 60 kg, including 180 kg of maize. The manure discharge amount refers to the research by Li and Jin (2011), with a daily output of 2 kg/d of feces and 3 kg/d of urine. The main gases emitted during pig manure treatment are CO_2, CH_4, NH_3, and N_2O, primarily derived from the volatilization of pig feces and urine.

2.2.3 Impact assessment and analysis

The purpose of impact assessment is to evaluate the environmental impacts of the product life cycle based on the results of inventory analysis, in accordance with the objectives and scope of the LCA (Jiang et al., 2019). Through impact assessment, various pollutants, resource consumption, and other factors can be comprehensively processed to derive various types of environmental impacts. Furthermore, it enables the description and evaluation of these environmental impacts, as well as the identification of resource consumption, pollutant generation, and environmental negative externalities caused to the entire system during the life cycle (Wu, 2022). Impact assessment typically consists of three parts: impact classification, characterization, and quantitative evaluation. The types of impact classification usually include three categories: resource consumption, human health impacts, and ecological environment impacts.

This study adopts the CML-IA (Centre of Environmental Science's Impact Assessment Method), a life cycle impact assessment (LCIA) methodology developed by the Centre for Environmental Sciences, Leiden University in the Netherlands, for the impact assessment and analysis of the swine breeding life cycle. This method considers global environmental background data to a certain extent, featuring global applicability while allowing adjustments based on the actual conditions of different regions. CML-IA covers a variety of typical environmental impact categories, enabling comprehensive evaluation of impacts caused by different environmental interventions (such as energy consumption and pollutant discharge). These categories include abiotic resource depletion (including fossil fuel—related resources, etc.), global warming (measured by the 100-year global warming potential, GWP100a), ozone layer depletion (characterized by the ozone depletion potential, ODP), human toxicity, various

TABLE 3 Functional unit feeding cost.

Item	Quantity	Data source
Feeding time	164.68d	Compilation of National Agricultural Products Cost–Benefit Data
Feeding cycle water intake	5.1 L/d/Fu	Compilation of National Agricultural Products Cost–Benefit Data
Electricity consumption	3.69kWh/Fu	Compilation of National Agricultural Products Cost–Benefit Data
Feed consumption	60 kg/Fu	Field research
Corn consumption	180 kg/Fu	Field research
Feces and urine	2 kg/d/Fu, 3 kg/d/Fu	Li and Jin

ecotoxicities (freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, etc.), photochemical oxidation, acidification, and eutrophication.

2.3 Data envelopment analysis

As a non-parametric method, Data Envelopment Analysis (DEA) was first proposed by Charnes et al. (1978). It is used to evaluate the relative efficiency of homogeneous Decision-Making Units (DMUs) and has been widely applied in efficiency assessment by avoiding the controversies associated with subjective weight assignment. With the advancement of relevant research, Tone (2001) put forward the Slacks-Based Measure (SBM) model. This model comprehensively assesses the efficiency of DMUs by taking slack variables into account, thereby overcoming the potential biases arising from the radial and directional measurements of traditional DEA models. In addition to accounting for the insufficiency of inputs and desired outputs, the SBM model also incorporates the impacts of undesired outputs, making efficiency evaluation more consistent with practical scenarios. Particularly when dealing with systems involving undesired outputs, the SBM model demonstrates remarkable advantages.

The efficiency values calculated by the traditional SBM model always fall within the range of 0–1: Decision-Making Units (DMUs) with optimal efficiency have an efficiency value of 1, while those with an efficiency value less than 1 are defined as inefficient. However, this model has certain limitations. When a considerable number of DMUs in the sample are identified as efficient (i.e., with an efficiency value of 1), the traditional SBM model cannot further distinguish or compare the efficiency levels of these efficient DMUs. In response to this, Tone (2004) constructed a super-efficiency SBM model incorporating undesired outputs based on previous research. This model can fully integrate the impacts of undesired outputs, thereby measuring the true efficiency levels of DMUs more scientifically and accurately.

Based on Tone's research, this study constructs a super-efficiency SBM (Slacks-Based Measure) model with Constant Returns to Scale (CRS) in the field of environmental science. We performed numerical calculations on ecological efficiency using MATLAB R2023b software [1] in combination with Equation (1) and (2), and conducted a comparative analysis of the calculated efficiency values. The usage right of the software has been legally licensed, ensuring the compliance of the research process.

The model assumes that the production system consists of n Decision-Making Units (DMUs), with each DMU comprising three input–output vectors: inputs, desired outputs, and undesired outputs. These three vectors can be expressed as follows: $x \in R^m, y^g \in R^{s_1}, y^b \in R^{s_2}$. X, Y^g, Y^b are matrices defined as follows: $X = [x_1, x_2, \cdots, x_n] \in R^{m \times n}, Y^g = [y_1^g, y_2^g, \cdots, y_n^g] \in R^{s_1 \times n}, Y^b = [y_1^b, y_2^b, \cdots, y_n^b] \in R^{s_2 \times n}$.

The specific formulas are presented below:

$$\rho^* = \min \frac{\frac{1}{m}\sum_{i=1}^{m}\frac{\bar{x}_i}{x_{ik}}}{\frac{1}{s_1+s_2}\left(\sum_{r=1}^{s_1}\frac{\bar{y}_r^g}{y_{rk}^g}+\sum_{r=1}^{s_2}\frac{\bar{y}_r^b}{y_{rk}}\right)} \tag{1}$$

$$\text{s.t.}\begin{cases} \bar{x} \geq \sum_{j=1, j\neq k}^{n} x_j\lambda_j \\ \bar{y}^g \leq \sum_{j=1, j\neq k}^{n} y_j^g\lambda_j \\ \bar{y}^b \geq \sum_{j=1, j\neq k}^{n} y_j^b\lambda_j \\ \bar{x} \geq x_0, \bar{y}^g \leq y_0^g, \bar{y}^b \geq y_0^b, \bar{y}^g \geq 0, \lambda \geq 0 \end{cases} \tag{2}$$

Where: ρ^* is the objective function value, representing the efficiency value of the Decision-Making Unit (DMU), which can exceed 1.

- k denotes the k-th DMU among the n DMUs, the evaluated object.
- m indicates the number of inputs for each DMU.
- s_1 and s_2 represent the number of desired outputs and undesired outputs, respectively.
- λ is a constant vector, the corresponding factor weight.

3 Results and discussion

3.1 Analysis of Life Cycle Assessment results

Characterization refers to evaluating the magnitude of potential environmental impacts corresponding to various material flows and energy flows in the inventory. The various environmental impacts

1 Official website: https://www.mathworks.com/.

TABLE 4 Concentrate feed formula table.

Item	Ratio	Function
The early fattening stage (20-60 kg) concentrate feed (high-protein type, with crude protein ranging from 38 to 41%)	%	
Soybean meal	60–65%	Provide high-quality plant-based protein
Fish meal	5–8%	Supplement high-quality animal protein and increase lysine levels
Cottonseed meal/rapeseed meal	5–8%	Supplement protein
Calcium hydrogen phosphate	3–4%	Provide calcium and phosphorus
Limestone powder	1–2%	Supplement calcium
Salt	0.3–0.5%	Provide sodium and chlorine
Lysine	2–3%	The first limiting amino acid
Vitamin + Mineral Premix	1–2%	Provide comprehensive micronutrients
Probiotics + Organic Acids	0.5–1%	Improve intestinal health
The late fattening stage (60–120 kg) concentrate feed (medium protein type, crude protein 35–38%)		
Soybean meal	50–55%	Reduce protein level to control costs
Miscellaneous oilseed meals	8–12%	Increase the proportion of miscellaneous oilseed meals to further reduce costs
Calcium hydrogen phosphate	2–3%	Reduce the supply of calcium and phosphorus to adapt to late-stage growth
Limestone powder	1–1.5%	Supplement an appropriate amount of calcium
Salt	0.3–0.5%	Maintain electrolyte balance
Amino acid	1–2%	Reduce amino acid addition level for precise nutrition
Vitamin + Mineral Premix	1–1.5%	Maintain basic micronutrition
Enzyme preparations	0.2–0.5%	Improve the digestibility of energy feed

caused by swine breeding in Northeast China studied in this paper include abiotic resource depletion, global warming potential (GWP), ozone layer depletion, human toxicity, freshwater aquatic toxicity, terrestrial ecotoxicity, photochemical oxidation, acidification, and eutrophication. Referring to the research by Sun et al. (2022), this study focuses on three types of environmental impacts: global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP). The equivalent coefficient method is adopted for calculation: global warming is referenced to CO_2 equivalent; acidification is referenced to SO_2 equivalent; and eutrophication is referenced to PO_4^{3-} equivalent. The proportion of each environmental impact is shown in Figure 2.

Figure 2A illustrates the proportion of global warming potential (GWP) generated by the functional unit across the four phases. The total GWP throughout the entire life cycle is 685.47 kg CO_2 eq, primarily attributed to agricultural resource production, feed production, and manure treatment. GHG emissions from each link of swine breeding in Northeast China are significantly influenced by climate and breeding models. In the agricultural resource phase, the extraction of fossil energy and the process of thermal power generation release greenhouse gases such as CO_2 and CH_4. During the feed processing phase, energy consumption of production equipment and methane emissions during raw material storage contribute to increased GHG (Greenhouse Gases) emissions. In the breeding phase, the high demand for pig house heating in winter leads to substantial GHG emissions from the operation of temperature control equipment. Meanwhile, greenhouse gases are also produced through the respiratory activity of pigs and the anaerobic decomposition of breeding waste. In the manure treatment phase, the cold winters in Northeast China slow down the manure fermentation rate, resulting in the slow release of methane, carbon dioxide, and other gases during the fermentation period, making this phase a key contributor to GHG emissions. Specifically, the manure treatment phase can emit 286.38 kg CO_2 eq, most of which includes CO_2, N_2O and CH_4, as anaerobic fermentation and aerobic composting generate significant amounts of GHGs (Nordahl et al., 2023). In addition, the feed processing phase may emit 278.19 kg CO_2 eq, with GHG emissions in this phase mainly derived from diesel consumption during crop cultivation, the production and application of chemical fertilizers, and electricity consumption during feed processing. The proportions of GHG emissions from the agricultural resource phase and the breeding phase are relatively small.

Figure 2B presents the proportion of acidification across the four phases. The total AP is 6.23 kg SO_2 eq, with the feed processing phase contributing the highest proportion at 60.51%, followed by the manure treatment phase at 29.19%; the agricultural resource phase and breeding phase have relatively minor impacts. Nitrogen oxides, sulfur dioxide, and ammonia are the main substances causing environmental acidification (Margarita Theodorakidou and George I. Lambrou, 2017). Reflected in each phase, the manure treatment phase generates 1.82 kg SO_2 eq, primarily due to the substantial ammonia emissions during manure processing. The feed crop cultivation and feed production processes emit 3.77 kg SO_2 eq, leading to environmental acidification. This is mainly attributed to the application of nitrogen fertilizers during maize cultivation, while feed factories release large amounts of nitrogen oxides and ammonia

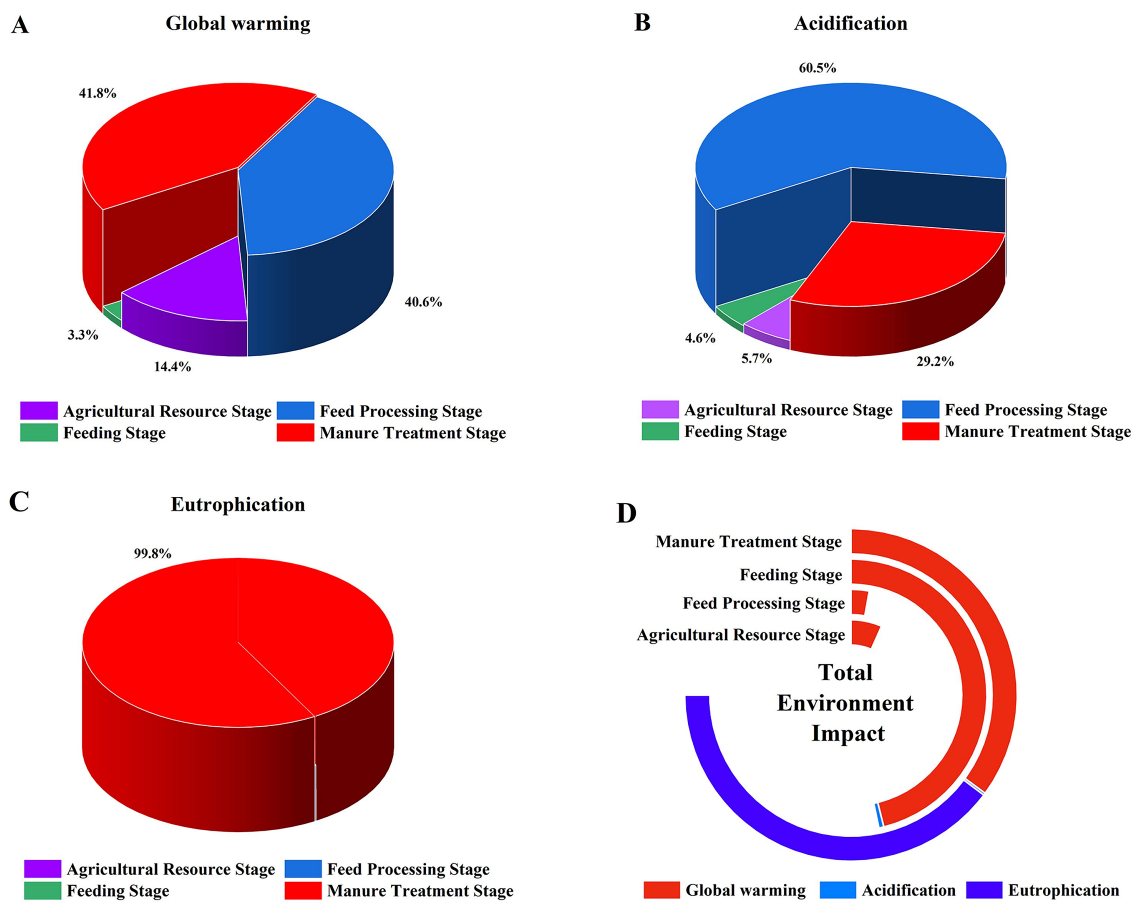

FIGURE 2
Environmental impact contributions of different stages in pig breeding. In the figure, Panel **A** shows the global warming status at each stage, Panel **B** depicts the acidification status at each stage, Panel **C** illustrates the eutrophication status at each stage, and Panel **D** presents the proportion of the three environmental impacts in the total environmental impacts across all pig production stages.

during feed manufacturing, thereby causing acidification hazards to ecosystems such as soil, water bodies, and vegetation.

Figure 2C reflects the proportion of eutrophication across the four phases. The total EP is 324.89 kg PO_4^{3-} eq, with the manure treatment phase accounting for the vast majority of eutrophication. The characteristics of water resources and agricultural production in Northeast China make nitrogen and phosphorus emissions have a significant impact on eutrophication. The intensive use of chemical fertilizers during spring ploughing results in the loss of some nitrogen and phosphorus, leading to eutrophication in the feed processing phase. During the breeding phase, pig manure contains substantial nitrogen and phosphorus, which enter the environment through excretion. In the manure treatment phase, processes such as manure fermentation for biogas production and urine treatment are involved. However, the cold and prolonged winters in Northeast China make biogas production technology difficult to operate, reduce the efficiency of compost fermentation, and particularly hinder the resource utilization of urine. Therefore, a large amount of nitrogen and phosphorus from manure processing enters water bodies, causing water eutrophication, which triggers problems such as excessive algal blooms and water quality deterioration, potentially posing serious impacts on both freshwater and marine ecosystems.

The proportions of the three environmental impacts among all environmental impacts in each phase are illustrated in Figure 2D. Energy is an essential prerequisite for various production activities. In the agricultural resource phase, the proportions of the three environmental impacts are relatively small, with fossil fuel combustion and water pollution being the main pollution processes in this phase. Regarding the feed production phase, although certain greenhouse gas emissions are generated during forage crop cultivation, they are still relatively low compared to the environmental impacts caused by chemical fertilizer production and the use of agricultural machinery. Therefore, energy sources such as diesel and the application of chemical fertilizers are the primary sources of environmental impacts in this phase. In the breeding phase, the greenhouse gas emissions generated by the functional unit are undoubtedly substantial. Additionally, this phase also causes a certain degree of ozone layer depletion, acidification, and water pollution. As for the manure treatment phase, greenhouse gas emissions, acidification, and eutrophication are key factors contributing to environmental impacts.

10.3389/fsufs.2026.1750502

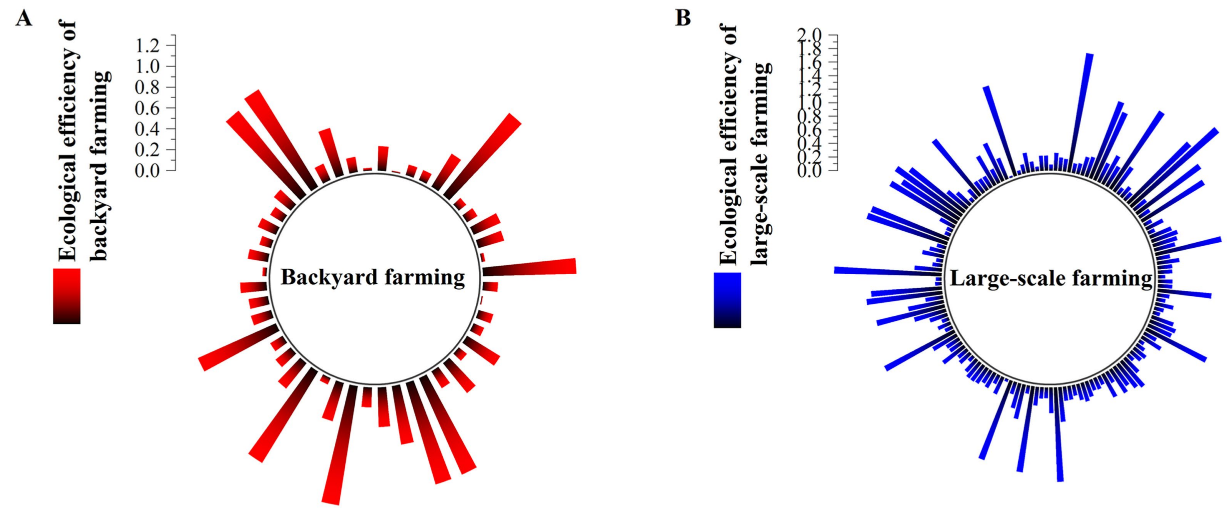

FIGURE 3
Ecological efficiency of pig breeding. In the figure, Panels **A** and **B** represent the ecological efficiency values of backyard pig farmers and large-scale pig farmers, respectively.

3.2 Ecological efficiency

The ecological efficiency results of the study area are presented in Figure 3. Overall, the average ecological efficiency of backyard farmers is 0.34 (Figure 3A), with only 17% of the free-range samples having an efficiency exceeding 0.5. In contrast, the average ecological efficiency of large-scale farmers can reach 0.43 (Figure 3B), indicating that large-scale farmers have higher ecological efficiency compared to backyard farmers. Due to the differences in resource input, economies of scale, and other aspects between large-scale and backyard farmers, they are discussed separately in this study.

3.2.1 Ecological efficiency of large-scale farmers

In this study, the average ecological efficiency of large-scale farmers is 0.43, indicating that their overall ecological efficiency is at a moderate level. However, the data shows a high degree of dispersion, with significant differences in ecological efficiency among individual large-scale farmers. Given the characteristics of large-scale breeding, large-scale farmers have certain advantages in resource integration and technology application. Nevertheless, variations in financial strength, management level, and acceptance of new technologies among different large-scale farmers lead to inconsistent ecological efficiency. An analysis of samples with ecological efficiency below 0.01 reveals a common homogeneity issue: these samples are characterized by high feed input and epidemic prevention costs, coupled with low returns and frequent occurrence of animal diseases. Such samples account for 4.0% of the total large-scale farmer samples.

Based on the redundancy rate results of the six input factors (number of sows: 22.88%, feed input: 15.57%, labor input: 64.31%, epidemic prevention input: 72.29%, energy input: 49.27%, land input: 20.53%), it is clear that the input redundancy of large-scale swine farmers in Northeast China presents the characteristic of "prominent redundancy in key factors and room for optimization in basic factors." Among these, labor input and epidemic prevention input are the core redundant items restricting ecological efficiency. In this study, "Redundancy" specifically refers to the part of production factors (such as feed, water resources, labor, etc.) actually invested in the pig breeding process that exceeds the input quantity required for the optimal production state under a given output level. Its value directly reflects the inefficiency of factor allocation and the potential for optimization.

From the perspective of each factor's performance, the redundancy rates of feed input, land input, and number of sows are at a moderate level, indicating that large-scale farmers have a certain degree of rationality in the allocation of these basic production resources. The relatively low redundancy rate of feed input reflects that they have a certain foundation in controlling the consumption of core breeding materials, but there is still room for optimization. The redundancy in the number of sows indicates that although there is no serious imbalance in the breeding scale and population structure planning of farmers, there is still a small number of idle sows with average reproductive performance. The redundancy rate of land input is related to the fixed input attribute of sheds and sites in large-scale breeding, most likely resulting from insufficient matching between some site planning and actual breeding scale or idle auxiliary land, and its negative impact on ecological efficiency is relatively limited.

In sharp contrast, the redundancy rates of labor input and epidemic prevention input are extremely high, with the redundancy rate of epidemic prevention input being particularly prominent. This means that more than 70% of the actual epidemic prevention input by farmers is ineffective—only about 27.71% of the current epidemic prevention input needs to be retained to achieve the same epidemic prevention effect without reducing output levels or increasing epidemic risks. Essentially, this reflects significant shortcomings in farmers' allocation of epidemic prevention resources, technological application, and management capabilities, with the dual problems of "excessive epidemic prevention" and "insufficient precision." Blindly invested epidemic prevention materials and redundant processes not only drive up costs but may also trigger negative effects on the breeding environment and the physical condition of pigs.

The high redundancy of labor input indicates that more than 60% of the labor input is ineffective consumption, and only about 35.69% of the current labor allocation needs to be retained to maintain the current output. This is mainly due to the fact that some farmers still rely on the traditional family breeding model, characterized by unclear labor division, redundant operational processes, and low penetration rate of automated equipment, failing to improve labor efficiency through technological substitution.

In addition, the redundancy rate of energy input reaches 49.27%, reflecting obvious waste in energy utilization among large-scale farmers. This may be related to factors such as insufficient energy-saving performance of breeding equipment and disordered energy use management, making it an important auxiliary redundant item affecting ecological efficiency.

3.2.2 Analysis of ecological efficiency of backyard farmers

The average ecological efficiency of backyard farmers is 0.34, lower than that of large-scale farmers, indicating a relatively poorer overall ecological efficiency. Although there is a certain degree of dispersion in the ecological efficiency of backyard farmers, it is relatively smaller compared to large-scale farmers. Backyard farmers typically operate on a small breeding scale, with relatively traditional and similar technologies and management practices, which may be the reason for the relatively small differences in their ecological efficiency. The lower average value may be attributed to the limitations of backyard farmers in resource utilization, environmental protection measures, and other aspects.

For backyard farmers, based on the redundancy rate results of the six input factors (number of sows: 69.88%, feed input: 33.91%, labor input: 63.56%, epidemic prevention input: 74.59%, energy input: 64.67%, land input: 71.86%), it is clear that the input redundancy of swine breeding by small-scale free-range farmers presents the characteristic of "comprehensively high redundancy." Except for feed input, the redundancy rates of the other five factors all exceed 60%, becoming the bottleneck restricting ecological efficiency.

Among the relatively low-redundancy factors, although the redundancy rate of feed input is the lowest among the six, it is still at a high level. This reflects obvious shortcomings in feed management among backyard farmers, resulting in actual input exceeding the optimal demand. However, the fact that this redundancy rate is lower than that of other factors only indicates that backyard farmers attach slightly more importance to feed as a core production material, without forming a systematic and efficient utilization model.

In addition, the redundancy rates of the number of sows and land input are close to or exceed 70%, reflecting the blindness of backyard farmers in breeding planning. The selection and retention of sows are not combined with market demand and their own breeding capacity, which may lead to the idleness of sows with outdated breeds and low reproductive performance. For land use, the scattered layout of pig houses and the mismatch between breeding scale and site area result in a large amount of land being idle or used inefficiently.

The redundancy rates of labor input, epidemic prevention input, and energy input all exceed 60%, highlighting key issues as well. The redundancy of labor input stems from backyard farmers' reliance on the traditional family breeding model, characterized by vague division of labor, redundant operational processes, and lack of automated equipment to replace manual work, leading to extremely low labor efficiency. The redundancy of epidemic prevention input is the contradictory result of the coexistence of "excessive epidemic prevention" and "insufficient epidemic prevention." The redundancy of energy input is closely related to outdated breeding equipment and disordered energy management.

3.3 Greenhouse gas emission reduction potential in swine breeding

The analysis results of GHG emission reduction potential show significant differences in GHG emission characteristics and reduction potential between large-scale farmers and backyard farmers in Northeast China. Yan et al. (2023) also indicated that the spatiotemporal pattern of greenhouse gas emissions from pig production in China conforms to the Hu Huanyong Line pattern (higher emissions in the east and lower emissions in the west). Northeast China's three provinces fall into the high-emission zone in the east, making them key emission reduction regions. In contrast, this study focuses on the specific emission reduction potential of pig farmers of different scales in Northeast China. Xue and Luan (2017) investigated the structure and spatial distribution of greenhouse gas emissions from livestock manure management in Liaoning Province. They found that pig farming is the primary source of such emissions in the province, which is consistent with the conclusion of this study that manure management is the primary source of greenhouse gas emissions in the pig farming process.

Specifically, for large-scale farmers, the achievable GHG emission reduction amount is 234.18, with a reduction rate of 34.16%. This indicates that although Northeast China has established a certain foundation for GHG emission control in swine breeding, there is still a gap from the optimal level under current breeding technologies and management conditions, leaving a 34.16% potential for emission reduction. In contrast, backyard farmers have an achievable GHG emission reduction amount of 383.67 and an impressive reduction rate of 55.97%. This means their actual emissions exceed the theoretical optimal emission level by 55.97%, possessing a huge emission reduction potential of nearly 60%, making them a key focus for regional agricultural carbon emission reduction.

In terms of emission control efficiency and relative reduction potential, the 34.16% reduction rate of large-scale farmers reflects that they have a certain foundation in controlling GHG emission intensity, but there is still significant room for optimization. The existing control effects mainly rely on technological advantages and management synergy under the large-scale breeding model. On the one hand, the popularization of manure treatment facilities such as biogas digesters among large-scale pig farmers has effectively reduced the unregulated emission of CH_4 during the anaerobic fermentation of manure. Nevertheless, manure treatment processes remain a critical component in the greenhouse gas emission reduction of pig manure. In intensive pig production systems adopting slurry-based manure management, over 90% of greenhouse gas (GHG) emissions from farms consist of methane (CH_4), and approximately 70–80% of this CH_4 is generated during the treatment and storage of slurry

(FAOSTAT, 2024). Targeting pig manure management, Ambrose et al. (2025) proposed a novel biological emission reduction technology, which can reduce methane (CH_4) emissions from pig slurry by up to 95%, while simultaneously cutting down carbon dioxide (CO_2) and ammonia (NH_3) emissions. On the other hand, it is feasible to reduce the amount of greenhouse gases generated from pig feeding at the source by using high-quality feed. Acosta et al. (2025) investigated the practice of replacing corn with hybrid rye in the diet of growing pigs, and found that this substitution does not affect greenhouse gas emissions or nitrogen balance, but it can lower the ratio of carbon dioxide production to oxygen consumption, as well as the digestibility of apparent energy expenditure (AEE) and amino acids. Therefore, hybrid rye can be used as an alternative to corn without exerting any negative impacts on the environmental footprint of pig production systems. This also provides a scientific basis for the diversification of pig feed formulations. Chen et al. (2025) also proposed optimizing the feed supply in pig farming through measures such as controlling the crude fiber ratio to reduce methane from enteric fermentation and promoting low-protein + amino acid diets to improve feed conversion rate, which is conducive to reducing greenhouse gas emissions during pig farming. From the perspective of absolute emission reduction scale and practical emission reduction demands, the characteristics of large-scale farmers—with a reducible amount of 234.18 and a reduction rate of 34.16%—indicate that their absolute emission reduction task is of considerable magnitude. If this emission reduction potential can be fully unleashed, it will make a positive contribution to the overall greenhouse gas emission reduction of regional pig farming. By adopting digital and intelligent breeding technologies (Zhang et al., 2024), upgrading manure treatment processes, optimizing feed composition and sources, improving energy consumption control and other measures, the 34.16% emission reduction potential can be gradually realized.

In contrast, the high reduction rate of 55.97% among backyard farmers highlights their obvious shortcomings in emission control efficiency, and also indicates that their relative emission reduction potential is far greater than that of large-scale farmers. These shortcomings mainly stem from three major production bottlenecks. First, they lack professional manure treatment facilities, and manure is mostly stockpiled in the open air or discharged randomly, leading to the massive release of potent greenhouse gases such as CH_4 and N_2O. Wang et al. (2024) pointed out that greenhouse gas emissions during the composting process can cause such problems as climate change, ecological damage, and resource depletion. Second, the feed feeding pattern is extensive, and the nutritional structure is not dynamically adjusted according to the growth stages of pigs. This not only causes the waste of feed resources, but also increases greenhouse gas emission intensity due to low intestinal fermentation efficiency. Third, the layout of breeding sites and facilities is scattered, lacking unified environmental control standards and technical guidance, which makes it difficult to achieve the effect of centralized treatment. From the perspective of absolute emission reduction scale and practical emission reduction demands, the high reducible amount of 383.67 for backyard farmers corresponds to a larger absolute emission reduction scale. The effectiveness of unleashing their emission reduction potential directly determines the degree of achievement of regional agricultural carbon emission reduction goals.

Based on this, backyard farmers should prioritize addressing the deficiency in basic efficiency. First, promote the centralized treatment of manure. By adopting a model of led by the government, organized by village collectives, and co-operated with organic fertilizer enterprises, establish regionally centralized manure treatment centers operated under a market-oriented model. These centers will integrate the scattered manure resources from small-scale farms for unified disposal, control the scale of greenhouse gas emissions at the source, and unleash the emission reduction potential in the manure management process. Second, popularize low-cost and easy-to-operate emission reduction technology models. Examples of such measures include applying cost-effective feed formulations, upgrading pen facilities, adopting slatted floors or scraper manure removal systems to reduce the formation of anaerobic environments, and constructing simple sealed tanks. These measures can directly cut down greenhouse gas emissions during the breeding process by reducing the release of CH_4 and NH_3 during manure storage. Third, strengthen policy guidance and resource inclination. Prioritize directing emission reduction support resources toward small-scale farmers. Through technical training, equipment subsidies and other approaches, improve their adoption rate and application capacity of emission reduction technologies, achieve an efficient match between input and emission reduction volume, and provide strong support for the realization of regional agricultural carbon peaking and carbon neutrality goals.

4 Conclusion

This study takes 199 self-breeding and self-raising swine farmers in three northeastern provinces of China as the research objects. By combining Life Cycle Assessment and the super-efficiency SBM model, it systematically measures the ecological efficiency of fattening pig breeding and analyzes the GHG emission reduction potential. The main conclusions are as follows:

Firstly, in terms of life cycle environmental impacts, the core environmental impacts throughout the entire life cycle of swine breeding in Northeast China are global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP). The total GWP is 685.47 kg CO_2 eq, with the manure treatment phase and feed processing phase being the main contributors. The feed processing phase accounts for the highest proportion of AP at 60.51%, followed by the manure treatment phase. For EP, the manure treatment phase becomes the absolute dominant contributing link due to low fermentation efficiency in winter and severe nitrogen and phosphorus loss. This indicates that manure treatment and feed processing are the core links for environmental impact control in swine breeding in Northeast China, and targeted optimization of technologies and management models is required.

Secondly, the ecological efficiency of swine farmers shows significant scale differences, and the ecological advantages of large-scale breeding are prominent. The average ecological efficiency of large-scale farmers (0.43) is higher than that of backyard farmers (0.34), and the dispersion of ecological efficiency among backyard farmers is smaller. This indirectly reflects the homogeneity of

10.3389/fsufs.2026.1750502

traditional breeding models. In contrast, due to differences in financial strength, management level, and technical acceptance, the internal ecological efficiency of large-scale farmers is significantly differentiated. From the perspective of input factor redundancy, large-scale farmers present the characteristic of "prominent redundancy in key factors and rationality in basic factors." Labor input and epidemic prevention input are the core redundant items, with the energy input redundancy rate reaching 49.27%, while the redundancy rates of basic factors such as feed, land, and number of sows are relatively low. Backyard farmers, however, exhibit "comprehensively high redundancy." Except for feed input, the redundancy rates of number of sows, labor, epidemic prevention, energy, and land all exceed 60%, reflecting their comprehensive shortcomings in resource allocation, technological application, and management capabilities.

Thirdly, there is significant differentiation in GHG emission reduction potential among different breeding scales, and backyard farmers are the key targets for regional carbon emission reduction. Large-scale farmers have a GHG emission reduction rate of 34.16%, indicating a certain foundation for emission control but still having room for systematic optimization. Backyard farmers have an achievable emission reduction amount of 383.67 and a reduction rate of 55.97%, with actual emissions exceeding the optimal level by more than 50%, showing enormous emission reduction potential. Specifically, large-scale farmers need to release emission reduction potential through refined measures such as intelligent upgrading of manure treatment equipment, optimization of feed additives, and energy consumption control. Backyard farmers, on the other hand, must first improve centralized manure treatment facilities, promote low-cost emission reduction technologies, and rely on policy support to make up for the lack of basic capabilities, so as to achieve efficient matching between "investment and emission reduction volume."

This study reveals the scale differences and optimization paths of ecological efficiency in swine breeding in Northeast China through micro-level farmer data, but it still has certain limitations. The research area only covers the three northeastern provinces and does not include major southern swine-producing regions, so the regional generalizability of the conclusions needs further verification. Meanwhile, the LCA evaluation does not incorporate the environmental impacts of building materials for breeding facilities, and the DEA model fails to consider the dynamic impacts of market-oriented factors on ecological efficiency.

Future research can expand the sample coverage, conduct dynamic analysis of the evolution trend of ecological efficiency using panel data, and introduce market-oriented variables and policy tools to construct a more comprehensive optimization framework for the ecological efficiency of swine breeding. This will provide more accurate decision support for the green transformation of the national swine industry.

Data availability statement

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

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the [patients/participants OR patients/participants legal guardian/next of kin] was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

FX: Writing – original draft. ZX: Writing – original draft. XH: Writing – review & editing. HZ: Writing – review & editing.

Funding

The author(s) declared that financial support was received for this work and/or its publication. This work was supported by The Agricultural Science and Technology Innovation Program (10-IAED-01-2025); The "Central Public-interest Scientific Institution Basal Research Funds (No: Y2025YC63).

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that Generative AI was not used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

References

Acosta, J. P., Lee, S. A., and Stein, H. H. (2025). 36 greenhouse gas emission, nitrogen balance, and ileal digestibility of amino acids and acid hydrolyzed ether extract in diets containing different inclusion rates of hybrid rye fed to growing pigs. *J. Anim. Sci.* 103, 186–187. doi: 10.1093/jas/skaf300.224

Ambrose, H. W., Bambace, M. F., Marietou, A., Hosek, J., Feilberg, A., Kofoed, M. V. W., et al. (2025). Novel biological approach to mitigate methane emissions from livestock slurry through microbial conversion of glycerol. *Environ. Sci. Technol.* 59, 20512–20525. doi: 10.1021/acs.est.4c12999

Azizpanah, A., Namdari, M., and Abed, A. K. (2025). Integrated life cycle and data envelopment analysis of input optimization and environmental impacts in silage corn farming. *Results Eng*, 27:106380. doi: 10.1016/j.rineng.2025.106380

Chai, C., Zhu, H., Wang, H., Zhang, H., Wen, R., Li, Y., et al (2026). Assessing the impact of farmland fragmentation on green productivity in Yellow River basin: a "quantity-spatial" scale effects perspective and EKC hypothesis test. *Habitat International* 167:103653. doi: 10.1016/j.habitatint.2025.103653

Charnes, A., Cooper, W. W., and Rhodes, E. (1978). Measuring the efficiency of decision making units. *Eur. J. Oper. Res.* 2, 429–444. doi: 10.1016/0377-2217(78)90138-8

Chen, S., Chen, K., Wu, F., and You, J. (2025). Life cycle greenhouse gas emission of pork production in China: carbon inequality embodied in supply chain. *Resour. Conserv. Recycling* 220:108386. doi: 10.1016/j.resconrec.2025.108386

Chen, X. P., and Liang, Q. D. (2020). The analysis of influencing factors and the choice of policy direction on development of pig breeding industry in three provinces of Northeast China. *Econ. Rev. J.*, 9:120–128. doi: 10.16528/j.cnki.22-1054/f.202009120

Dong, S., Hou, R., Li, T., Fu, Q., Xue, P., Gao, Y., et al. (2025). Simulation study of the production efficiency of family-type agricultural management entities under regulation measures on farmland: three-stage super-SBM model considering greenhouse gas emissions. *Agric. Syst.* 224:104265. doi: 10.1016/j.agsy.2025.104265

Dong, H. M., Zhu, Z. P., Huang, H. K., Chen, Y. X., Shang, B., Tao, X. P., et al. (2011). Pollutant generation coefficient and discharge coefficient in animal production. *Trans. Chinese Soc. Agric. Eng.* 27, 303–308.

FAO (2023). Pathways towards lower emissions — A global assessment of the greenhouse gas emissions and mitigation options from livestock agrifood systems. Rome, Italy: FAO.

FAOSTAT (2024). Emissions from livestock. Rome, Italy: FAOSTAT.

Feng, L., Lei, G., and Nie, Y. (2023). Exploring the eco-efficiency of cultivated land utilization and its influencing factors in black soil region of Northeast China under the goal of reducing non-point pollution and net carbon emission. *Environ. Earth Sci.* 82:94. doi: 10.1007/s12665-023-10770-0

Geffersa, A. G., and Tabe-Ojong, M. P. J. (2024). Smallholder commercialisation and rural household welfare: panel data evidence from Ethiopia. *Eur. Rev. Agric. Econ.* 51, 54–90. doi: 10.1093/erae/jbad040

Gong, Z. X., Li, Y. Y., and Chen, S. T. (2018). Environmental impact assessment of corn life cycle in Northeast China. *J. Green Sci. Technol.*, 22:29–33. doi: 10.16663/j.cnki.lskj.2018.22.011

Guo, H. N., Li, J. H., Ma, H., Xue, H. B., Yin, W. Q., Wwang, X. Z., et al. (2014). Greenhouse gas emissions in different pig raising modes. *J. Agro-Environ. Sci.* 33, 2457–2462.

Halpern, B. S., Frazier, M., Verstaen, J., Rayner, P.-E., Clawson, G., Blanchard, J. L., et al. (2022). The environmental footprint of global food production. *Nat. Sustain.* 5, 1027–1039. doi: 10.1038/s41893-022-00965-x

Hui, X. H. (2017). Study on evaluating the pig breeding system in Hubei Province using life cycle assessment and ecological efficiency method. Wuhan: Huazhong Agricultural University.

Hui, X. H., Liu, Z. X., Zhang, N. Y., Xia, S. L., Rong, F., and Peng, J. (2016). Evaluation on environmental impact of intensive pig production system in Hubei province. *Trans. Chin. Soc. Agric. Eng.* 32, 183–189.

ISO (2006). ISO, 2006a. ISO 14040. 2006. Environmental managements life cycle assessments principles and framework. Geneva: International Organization for Standardization (ISO).

Jiang, M. H., Liu, X. C., Tang, H. J., Xin, X. P., Chen, J. G., Dong, G., et al. (2019). Research progress and prospect of life cycle assessment in animal husbandry. *Sci. Agric. Sin.* 52, 1635–1645.

Jiang, W., Su, B., and Fan, S. (2023). Spatial disequilibrium and dynamic evolution of eco-efficiency in China's tea industry. *Sustainability* 15:9597. doi: 10.3390/su15129597

Komarek, A. M., Dunston, S., Enahoro, D., Godfray, H. C. J., Herrero, M., Mason-D'Croz, D., et al. (2021). Income, consumer preferences, and the future of livestock-derived food demand. *Glob. Environ. Change* 70:102343. doi: 10.1016/j.gloenvcha.2021.102343

Li, S. T., and Jin, J. Y. (2011). Characteristics of nutrient input/output and nutrient balance in different regions of China. *Scientia Agric. Sin.* 44, 4207–4229.

Liang, Y. W., Wang, M. L., Ma, X. P., and Li, P. C. (2023). Study on the spatial and temporal characteristics and spillover effects of eco-efficiency in China's animal husbandry. *Chin. J. Agric. Resour. Reg. Plan.* 44, 189–201.

Liu, M. D., Zhao, Y., Liu, X. J., and Wang, Y. J. (2012). Life cycle assessment of environmental impacts from finishing pig production in Liaoning Province, China. *J. Agro-Environ. Sci.* 31, 1250–1255.

Mardani Najafabadi, M., Rastegaripour, F., Yavari, F., and Ahani, E. (2023). Material balance principle to estimate eco-efficiency of saffron-producers aiming reduction in greenhouse gas emissions in Iran. *Front. Environ. Sci.* 11:1184458. doi: 10.3389/fenvs.2023.1184458

Marić, K., Gvozdanović, K., Djurkin Kušec, I., Kušec, G., and Margeta, V. (2025). Smart pig farms: integration and application of digital technologies in pig production. *Agriculture* 15:937. doi: 10.3390/agriculture15090937

Nordahl, S. L., Preble, C. V., Kirchstetter, T. W., and Scown, C. D. (2023). Greenhouse gas and air pollutant emissions from composting. *Environ. Sci. Technol.* 57, 2235–2247. doi: 10.1021/acs.est.2c05846

Nsabiyeze, A., Ma, R., Li, J., Zhao, Q., and Zhang, M. (2024). Mitigating greenhouse gas emissions from sheep production system in China: an integrated approach of data envelopment analysis and life cycle assessment. *Resour. Conserv. Recycl.* 207:107695. doi: 10.1016/j.resconrec.2024.107695

OECD, FAO (2022). OECD-FAO Agricultural Outlook 2022–2031. Paris and Rome: OCED-FAO.

Popien, J.-L., Barke, A., Ginster, R., Striecks, T., Thies, C., and Spengler, T. S. (2025). DEALA — a novel economic life cycle impact assessment method for differentiated economic assessments in the context of life cycle sustainability assessments. *J. Ind. Ecol.* 29, 19–33. doi: 10.1111/jiec.13584

Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., et al. (2004). Life cycle assessment: part 1: framework, goal and scope definition, inventory analysis, and applications. *Environ. Int.* 30, 701–720. doi: 10.1016/j.envint.2003.11.005

Rybaczewska-Błażejowska, M., and Gierulski, W. (2018). Eco-efficiency evaluation of agricultural production in the EU-28. *Sustainability* 10:4544. doi: 10.3390/su10124544

Schaltegger, S., and Sturm, A. (1990). Okologische rationalitat, ansatzpunkte zur ausgestaltung you okologieorienttierten management instrumenten. *Die Unternehmung* 4, 273–290.

Schmidheiny, S., and Stigson, B. (2000). Eco-efficiency: creating more value with less impact. Geneva: World Business Council for Sustainable Development.

Sulc, R. M., and Tracy, B. F. (2007). Integrated crop–livestock systems in the U.S. corn belt. *Agron. J.* 99, 335–345. doi: 10.2134/agronj2006.0086

Sun, R., Liu, X., Li, D., Zhuang, J., Qi, S., Meng, B., et al. (2022). Optimization of China's pig production system to reduce environmental impacts based on a data envelopment and life cycle analysis model. *Resour. Conserv. Recycl.* 185:106483. doi: 10.1016/j.resconrec.2022.106483

Suski, P., Speck, M., and Liedtke, C. (2021). Promoting sustainable consumption with LCA – a social practice based perspective. *J. Clean. Prod.* 283:125234. doi: 10.1016/j.jclepro.2020.125234

Tone, K. (2001). A slacks-based measure of efficiency in data envelopment analysis. *Eur. J. Oper. Res.* 130, 498–509. doi: 10.1016/S0377-2217(99)00407-5

Tone, K. (2004). Dealing with undesirable outputs in DEA: a slacks-based measure (SBM) approach. Toronto: Presentation At NAPW.

Theodorakidou, M., and Lambrou, G. I. (2017). Public health issues from the exposure to nitrogen oxides: a brief review. *ARC J. Public Health Community Med.* 2:44–56. doi: 10.20431/2456-0596.0204008

Wang, N., He, Y., Zhao, K., Lin, X., He, X., Chen, A., et al. (2024). Greenhouse gas emission characteristics and influencing factors of agricultural waste composting process: a review. *J. Environ. Manag.* 354:120337. doi: 10.1016/j.jenvman.2024.120337

Wu, X. Y. (2022). Ecological efficiency evaluation of wheat production in the North China plain. Xianyang: Northwest A&F University.

Wu, H., Liu, Y., Zhang, L., Zhu, H., Fang, W., and Mei, W. (2024). Insights into carbon and nitrogen footprints of large-scale intensive pig production with different feedstuffs in China. *Resour. Environ. Sustain.* 18:100181. doi: 10.1016/j.resenv.2024.100181

Xue, Y.-N., and Luan, W.-X. (2017). "Structure and spatial distribution of greenhouse gas emissions from livestock and poultry manure management" in Materials in environmental engineering: Proceedings of the 4th annual international conference on materials science and environmental engineering. ed. H. Haeri (Berlin, Boston: De Gruyter), 1107–1116. doi: 10.1515/9783110516623-109

Yan, B., Li, Y., Yan, J., and Shi, W. (2023). Potential reduction of greenhouse gas emissions from pig production in China on the basis of households' pork consumption. *Environ. Int.* 177:108008. doi: 10.1016/j.envint.2023.108008

Zhang, L., Mao, Y., Chen, Z., Hu, X., Wang, C., Lu, C., et al. (2024). A systematic review of life-cycle GHG emissions from intensive pig farming: accounting and mitigation. *Sci. Total Environ.* 907:168112. doi: 10.1016/j.scitotenv.2023.168112

Zhang, C., Wei, Y., Zhao, X., and Hu, J. (2025). Assessment and enhancement pathways of the water-energy-food-economy-ecosystem nexus in China's yellow river basin. *Energy* 316:134492. doi: 10.1016/j.energy.2025.134492

Zhang, X., Zhou, X., and Liao, K. (2023). Regional differences and dynamic evolution of China's agricultural carbon emission efficiency. *Int. J. Environ. Sci. Technol.* 20, 4307–4324. doi: 10.1007/s13762-022-04196-7

Zhang, N., Zhu, Z. Y., Zhang, L. Y., and Liu, C. S. (2018). The situation and suggestions for the development of pig industry in Northeast China. *China Feed*, 09:72–75. doi: 10.15906/j.cnki.cn11-2975/s.20180916