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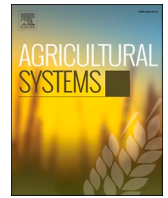
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Mitigating environmental footprints via cooperation between the enterprise and specialized livestock farms in pig production[☆]

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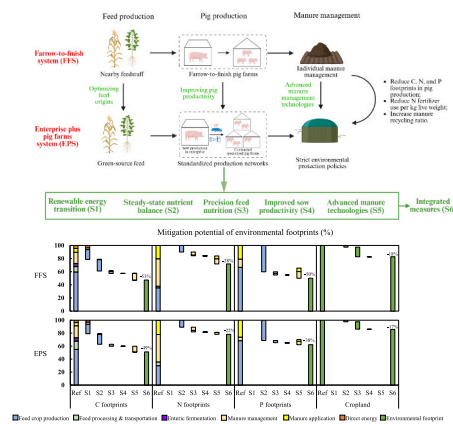
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HIGHLIGHTS

- Enterprise plus pig farms had lower environmental footprint and higher net benefits.
- Feed-to-meat conversion ratio had the greatest impact on C, P, and land footprints.
- N fertilizing rate had the greatest impact on N footprints.
- Whole-chain advanced technologies in pig farms reduce environmental footprints by 17–53 %.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Farrow-to-finish systems (FFS) are the primary pig production in China, but decoupled crop and livestock systems and inadequate farm management practices have caused environmental issues. The Enterprise Plus Pig Farms (EPS) model integrates specialized pig farms with livestock enterprises through contracts, forming standardized production networks and adopting new technologies to tackle challenges caused by FFS.

OBJECTIVE: This study provides a comprehensive comparative assessment of FFS and EPS across multiple environmental footprints and economic benefits, while quantitatively evaluating the farm-level mitigation potential of advanced technologies through pig production chain.

METHODS: Based on survey data of 162 pig farms in the hilly region of southeastern China (HSC) and North China Plain (NCP), life cycle assessment and cost-benefit analysis were employed to probe into the environmental and economic benefits of pig production. The main factors in pig production were estimated by adopting

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0308-521X/© 2025 Elsevier Ltd. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

generalized linear models. We estimated the potential of environmental mitigation in pig production through advanced technologies using scenario analysis and linear optimization.

RESULTS AND CONCLUSIONS: EPS had 9.5–38 % lower environmental footprints (C, N, P, and cropland use) and higher net ecosystem economic benefits (NEEB) per kg live weight than those in FFS. Feed crop production and manure management contributed 39–97 % to the difference in environmental footprints between EPS and FFS. The divergence in environmental emissions between the HSC and NCP regions primarily stems from contrasting feed origins patterns and manure management practices. The difference in NEEB between EPS and FFS was mainly due to feed costs and damage costs. Feed-to-meat conversion ratio had the greatest impact on C, P, and land footprints, whereas the N fertilizing rate had the highest impact on N footprints. Cooperation between the enterprise and specialized livestock farms reduces nitrogen losses through improving nutrient use efficiency in pig production, optimizing feed origins, and adopting advanced manure management technologies. Implementing integrated measures with renewable energy transition, steady-state nutrient balance in feed production, precision feed nutrition, improved sow productivity, and advanced manure treatment technologies could reduce 17–53 % of environmental footprints in pig production.

SIGNIFICANCE: Our study provides science-based evidence to support policymakers and specialized pig farms in enhancing environmental sustainability through cooperation with enterprises and implementing advanced technologies.

1. Introduction

The global livestock sector has significantly intensified in response to growing anthropogenic pressures from population expansion and dietary transitions towards animal-derived protein (Errickson et al., 2021). As a dominant component of livestock, pork production contributes 38 % of the global meat supply (FAO, 2023), while generating 16 % and 34 % of the livestock-related reactive nitrogen (Nr) and nitrous oxide (N₂O) emissions (Mueller and Lassaletta, 2020; Xu et al., 2022). Notably, pigs exert the highest cumulative environmental pressure from food production (Halpern et al., 2022). China's pivotal role in this context is particularly significant, hosting the global largest pig population and serving as both the primary producer and consumer of pork products globally (FAO, 2023). However, the rapid intensification and specialization of Chinese pig production systems have led to substantial decoupling of crop and livestock systems (Bai et al., 2018; Jin et al., 2020). This systemic divergence, coupled with inadequate manure management practices, has positioned China as a critical hotspot for anthropogenic environmental emissions, contributing substantially to global greenhouse gas (GHG) emissions and nutrient losses (Halpern et al., 2022; Zhang et al., 2024). Therefore, exploring an efficient way to achieve better environmental performance in pig production is necessary.

In China, pig production primarily adopts the farrow-to-finish system (FFS), where sows and fattening pigs are raised simultaneously. While FFS is less susceptible to piglet price volatility, it demands higher technical expertise in breeding management (Mbaso and Kamwana, 2013). However, FFS farms suffered more severe impacts from African Swine Fever in 2018 due to inadequate biosecurity measures and weak regulations (Penrith et al., 2022). Nutrient management in FFS remains a critical challenge, as production efficiency heavily depends on farmer knowledge and practices. The multi-phase production process requires precise feed formulations, yet labor shortages and technical constraints often lead to suboptimal feed preparation, causing nutrient imbalances between dietary inputs and animal requirements, thereby exacerbating environmental risks (Hu et al., 2023). Manure management further compounds sustainability issues in FFS operations. Partly FFS farms with limited cropland often apply manure amounts exceeding crop nutrient demands, resulting in nutrient surplus and losses (Tan et al., 2023). The remaining landless FFS farms, lacking disposal cropland, prefer to discharge manure directly and cause nutrient losses (Jin et al., 2021). Economic and technical barriers, including high operation costs, low benefit-cost ratios, and frequent technical failures, hinder the widespread adoption of advanced manure treatment technologies (Tan et al., 2021).

To address the environmental and economic challenges associated with FFS, a new combined model has been proposed in the pig

production chain - the enterprise plus pig farms system (EPS). In this system, specialized pig farms cooperate with livestock enterprises into standardized production networks through contractual agreements, while sharing new technical and quality control measures (Wan et al., 2018). The EPS model enables coordinated management across the entire pig production chain, including feed processing, precision feed formulation, standardized breeding practices, manure management, and comprehensive technical sharing (Ma et al., 2021; Tang, 2025). Therefore, specialized pig farms save market transaction costs by accessing professional guidance on feeding regimes and disease prevention from partner enterprises (Fu et al., 2020; Zheng, 2008). The EPS model creates shared interests between enterprise and specialized pig farms, distributing risks while reducing capital requirements of pig farms and expanding market access for enterprises (Hui, 2015; Mbaso and Kamwana, 2013). Moreover, regional implementation of EPS may enhance water resource management and environmental sustainability (Franks and Mc Gloin, 2007). However, EPS model introduces new challenges, including increased collective decision-making complexity, and higher operational and monitoring costs between multiple stakeholders (Asai et al., 2018; Guan et al., 2024). Previous research has primarily examined the economic performance of EPS and FFS through qualitative approaches. Therefore, quantitative analyses are urgently needed to assess environmental and economic performance in pig production of the two systems, and a comprehensive empirical analysis is needed before EPS is widely implemented.

Previous study found that implementation of a series of technological measures could reduce environmental footprints of pig production. Substituting soybean meal with distillers dried grains with soluble (DDGS) in the original feed reduces nitrogen and carbon footprints via using life cycle assessment (Wu et al., 2024). The packages of manure management technology, which combines solid-liquid separation, covered manure storage, and band application, significantly decreased nitrogen losses by 46–58 % (Qu et al., 2025). Matching nutrient fertilization and crop requirements can reduce environmental emissions in crop cultivation (You et al., 2024). Energy transformation efforts in synthetic nitrogen fertilizer would primarily reduce GHG emissions by 59 % (Luo et al., 2024). However, the above technologies are independent, and combined technologies are needed to explore the environmental mitigation potential in livestock production. Therefore, life cycle assessment (LCA), which assists in identifying opportunities to improve the environmental performance of products at various points in their life cycle, is employed to assess environmental footprints in pig production.

This study is geared towards enhancing a quantitative understanding of environmental and economic performance in cooperation between enterprises and specialized pig farms. The specific objectives were (1) to assess the multi-environmental footprints (carbon (C), nitrogen (N), phosphorus (P), and cropland) and economic benefit of FFS and EPS; (2)

to identify the relative importance of factors contributing to environmental and economic performance in pig production; (3) to explore environmental mitigation potential of optimization technologies for pig production at farm level.

2. Materials and methods

2.1. Study region

Farm surveys were conducted in two geographically and climatically distinct pig-producing regions of China: the hilly region of southeastern China (HSC) and North China Plain (NCP). HSC is humid and warm throughout most of the year, and hilly terrain is prone to nutrient runoff and erosion. NCP is a continental climate with cold, dry winters and hot, humid summers; the topography is predominantly flat plains. HSC and NCP are major pig-producing areas that contributed 26 % and 12 % of domestic pork in 2021. Pigs are the leading livestock-related CH₄ emitter (37.3 %) in HSC (Wang et al., 2024a). The NCP is recognized as a hotspot for livestock-related emissions (Xu et al., 2022; Zhu et al., 2022).

2.1.1. Pig production systems

Two contrasting pig production systems were investigated in two study regions, i.e., farrow-to-finish pig system (FFS) and enterprise plus pig farms system (EPS) (Fig. S1).

The FFS rears both sow and fattening pigs, eliminating the need for importing nursery pigs. FFS farms demonstrate operational flexibility by adjusting fattening periods and slaughter schedules in response to market price fluctuations. Manure management practices show regional variations influenced by local regulatory oversight. In HSC, solid manure employed microbial composting or covered storage, and liquid manure was treated via anaerobic digestion (AD), with the processed manure being either recycled within on-farm cropland or sold. By contrast, in the NCP region, pig farms typically employed static pile storage for solid manure and lagoon containment for liquid manure, where solid manure was either sold or applied on-farm cropland while liquid manure was either recycled or occasionally directly discharged.

In EPS, the specialized pig farms and enterprises signed formal cooperation contracts to improve pig productivity. The contract delineates responsibilities between enterprises and contracted pig farms. Enterprises guaranteed contracted pig farms a minimum price for acquiring slaughtered pigs in advance. Moreover, enterprises assume multiple obligations. They are responsible for sow breeding and piglet rearing to standard weights, as well as feed formulation and ration determination. Additionally, enterprises provide technical training programs for contracted pig farm operators and implement quality control measures. They also handle the marketing of slaughtered pigs. On the other hand, contracted pig farms are tasked with the daily feeding and rearing of fattening pigs. They must guarantee both pig production quantity and quality standards. Furthermore, contracted pig farms follow standardized manure management practices that vary by region. In HSC, pig farms implement composting for solid manure and AD for liquid manure. The manures were sold or recycled. In contrast, farms in the NCP region utilize covered storage for solid and liquid manure. The solid manure was sold or recycled to on-farm cropland, liquid manure was recycled or partly directly discharged.

2.1.2. Characteristics of feed origins

The pig feed formulation primarily consists of maize, soybean products, and bran in FFS and EPS (Table S1). With China importing 86 % of the soybean supply, our analysis mainly examines the feed origins of maize and wheat bran. Within HSC, FFS sourced maize from on-farm crop cultivation and imported from Northeast China, while obtaining wheat bran from NCP. Feed supply of EPS imported maize and wheat bran from Northeast China and NCP, respectively. By contrast, in NCP, FFS farms obtain maize and wheat bran from on-farm croplands or neighboring specialized crop farms, while EPS farms import maize and

wheat bran primarily from Northeast China and Shandong Province.

2.1.3. Questionnaire and farm survey

The initial questionnaire was designed jointly with local experts in agronomy, animal science, and environmental science. After being tested on 10 pig farms, a revised questionnaire was used in the farm surveys (Supplementary Information Section 1). Local government officials assisted in identifying surveyed pig farms. Through face-to-face interviews, we surveyed 126 pig farms in 2018 and 36 pig farms in 2023 (Fig. S2). The farm survey interval is due to the COVID-19 pandemic restrictions. The 2018 survey included 40 pig farms in HSC, which comprised 24 in Jiangshan County, Zhejiang Province, and 16 in Pinghe County, Fujian Province. Along with 86 farms in Hebei Province in NCP, between 65 in Quzhou County and 21 in Nanpi County. In 2023, we researched 36 pig farms exclusively in Pinghe County, Fujian Province. Notably, the emergence of EPS adoption in Hebei Province was driven by leading enterprises, whereas EPS in HSC responded to African swine fever impacts on traditional FFS pig farms combined with government incentives. The surveyed number of EPS farms was 12 in HSC and 42 in NCP.

We collected data from pig farms and enterprises covering four main aspects: (1) herd structure composition; (2) nutritional management including feed formulations, ingredient sourcing (local versus imported), and stage-specific daily rations for all production phases (piglets, nursery pigs, fattening pigs, pregnant sows, lactating sows, and gilts); (3) production performance metrics such as stage-specific growth cycles, weight gain, and mortality rates; and (4) manure management systems encompassing housing management with floor designs and cleaning protocols for each production stage, manure storage and treatment infrastructure including processing methods, containment designs and covering systems, as well as manure application practices covering manure types, application techniques and dosage rates. Moreover, information on on-farm cropland was collected including crop cultivation (varieties grown and planting areas), products (yield and straws) and distribution (sold, feed, recycle), and cropland management (irrigation volumes, seeding rates, and fertilization practices).

2.2. Assessment of environmental footprints

2.2.1. Objective and functional unit

The method of this study was to perform an ISO 14044-compliant (ISO, 2006) cradle-to-farm gate attributional environmental life cycle assessment (LCA) of pig production. The study employed activity data from one year to assess pig productivity based on characteristics of FFS and EPS. The functional unit (FU) is defined as one kg of pig live weight (LW).

2.2.2. System definition and boundaries

LCA was employed to evaluate the environmental footprints of pig production in FFS and EPS. The pig production system boundary is disaggregated into ancillary input production, feed production (on-farm and imported), feed processing and transportation, pig production (enteric fermentation and live weight gain), manure management (housing-storage-treatment), and manure application (Fig. S3). The system boundary includes all the activities of material, energy, and environmental emissions linked to all pig supply chain subsystems for one year of production. We also considered the effects of manure application, root growth, and crop residue return on soil organic carbon (SOC) change in on-farm crop cultivation.

2.2.3. Co-products allocation

Economic allocation is the commonly used allocation method in environmental LCA of pig production (Long et al., 2021; Wu et al., 2024). The environmental footprints associated with FFS and EPS were allocated to the slaughtered pigs and co-products (e.g., sold manure and crop products) based on their respective economic values. Crop straws in

the surveyed region are mainly returned to cropland, we do not consider allocating the primary crop products (e.g., maize) and straws (maize straw). The economic allocation was applied for maize, wheat, and soybean to divide environmental impacts related to feed cultivation, processing, and transportation between feed ingredients (e.g., soybean meal, wheat bran, etc.) and corresponding co-products (e.g., soybean oil, wheat flour, etc.). The economic coefficients are shown in Table S2.

2.2.4. Environmental footprints calculation

The C footprint includes the emission sources of GHG emissions, which mainly include carbon dioxide (CO₂), methane (CH₄), and N₂O, from the production and application of agrochemicals (e.g., synthetic fertilizers, agricultural film, and pesticides), feed processing and transportation, enteric fermentation, manure management, manure application, and energy consumption. The adoption of AD systems for manure treatment offers potential GHG mitigation by displacing fossil fuel-based energy through biogas-derived heat and electricity production. Indirect N₂O emissions resulting from NH₃ emissions and N lost to water bodies were included. CO₂ emissions from manure management were excluded in this study. Moreover, we excluded embodied emissions from capital goods, including pig housing construction and equipment manufacturing. The conversion coefficient values of global warming potentials (GWP) for fossil CH₄, biogenic CH₄, and N₂O to CO₂ are equivalent to 29.8, 27, and 273, respectively (IPCC, 2021). N footprints are represented by Nr emissions, which include N lost to atmosphere (NH₃, N₂O, NO_x) and water bodies (NO₃⁻ via leaching, runoff, and erosion) from production and application of agrochemicals, feed processing and transportation, manure management, and manure application. P footprints, including P losses via leaching, runoff, and erosion, were almost the same as those of Nr emissions. The cropland footprint refers to the occupied cropland to produce 1 kg LW. The C, N, and P footprints are quantified based on calculation, activity data, and process-specific emission factors, which are detailed in Supplementary Information section 2.

2.2.5. Data sources

The emission parameters of agrochemical production are derived from related literature (Table S3). Agrochemical inputs and crop yield of domestic feed crop production were obtained from Chinese official statistics (Table S4). Emission factors of feed production were derived from the NUFER model and related literature (Table S5). Feed processing energy emissions (e.g., CO₂) were quantified using source-specific emission intensities and feed-type energy consumption data. Emissions from different transportation methods were calculated as a function of transportation distance and emission coefficients per product (Table S6). Pig farm energy-related emissions were quantified by assessing consumption of electricity, diesel, and coal, applying corresponding source-specific emission factors. Emission factors related to GHG, Nr emissions, and P loss from different technologies of manure management were derived from IPCC Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2019) and related literature (Table S7-S9).

2.3. Economic performance calculations

2.3.1. Net profit of pig production

Net profit is calculated as the revenues minus costs in pig farms. Revenues comprised income from selling slaughtered pigs and eliminating sows, crop products (e.g., wheat flour, pomelo, etc.), and manure sales. The farm costs included building depreciation, feed purchase, labor costs, energy costs (coal, electricity, and diesel), operation costs (e.g., renting land, insurance, breeding, veterinary drugs, etc.), and the cost of on-farm crop production. On-farm cropland costs include renting the cropland, agrochemicals costs (e.g., synthetic fertilizers, pesticide, seed, and film), irrigation systems, and machinery operations.

2.3.2. Net ecosystem economic benefits analysis

The net ecosystem economic benefits (NEEB) are defined as the net profits minus the damage costs for human health, ecosystem health, and climate effect (Yao et al., 2025; Zhu et al., 2022). The cost of ecosystems and human damage are considered soil acidification and water eutrophication effects incurred by Nr emissions, and the damage cost to climate warming caused by GHG emissions (Table S10). The details are in Supplementary Information section 3.

2.4. Defining scenarios

Effects of advanced measures in pig production on environmental footprints were examined for FFS and EPS through scenario analysis. Scenarios include renewable energy transition in pig production (S1), steady-state nutrient balance in feed production (S2), precision feed nutrition (S3), improved sow productivity (S4), advanced manure treatment technologies (S5), and integrated measures (S6). The scenarios are defined as follows.

Scenario S1 modeled the substitution of fossil fuel-based (coal/natural gas) electricity with low-carbon renewable power generation for pig production. GHG emissions per kWh from photovoltaic power generation (92 g) were lower than coal-fired power (973 g) (Zhang et al., 2023). Scenario S2 simulated steady-state nutrient balance in feed production, thereby increasing crop yield by 6–7 % and reducing the application of N fertilizer by 21–28 % and P fertilizer by 47.4 % (Gong et al., 2025; Yin et al., 2021). Scenario S3 employed linear optimization to formulate phase-tailored feeding regimes that precisely matched the dynamic nutrient demands of each pig stage, the details were in the Supplementary Information section 4. Scenario S4 enhanced reproductive performance by increasing 5 % of pigs weaned per sow per year (PSY) via optimizing farm management. Scenario S5 implemented advanced manure treatment technologies by prohibiting manure direct discharge, composting with additives for solid manure, and low leakage AD for liquid manure. Scenario S6 combined all technological interventions (S1-S5) to evaluate synergistic effects.

2.5. Statistical analysis

Differences between EPS and FFS in average environmental and economic performance were analyzed by an independent sample *t*-test followed by a two-tailed test conducted using SPSS Statistics 22. The main effects and their interactions with environmental and economic performance and each factor were assessed using generalized linear models (GLMs). Within each model, the independent variables were defined as influential factors, whereas environmental and economic performance were the dependent variables. Additionally, the variable importance rankings for environmental and economic benefits were predicted by the “RandomForest” package in R version 4.3.2. LCA calculations and cost-benefit analysis were performed using the GAMS programming software. The feed optimization model of pig diets was explored using linear optimization in GAMS.

3. Results

3.1. Characteristics of two pig production systems

Pig production in EPS had superior productivity performance compared to FFS (Table 1). EPS consumed 19–22 % lower feed per head than FFS. For sows rearing, EPS weaned 8.3–8.7 % more PSY than FFS. Notably, EPS has 22–25 % higher nitrogen use efficiency (NUE) and 50–66 % higher phosphorus use efficiency (PUE) than FFS in pig production. EPS consumed 8.0–27 % less synthetic fertilizer per kg LW than FFS.

Feed origins between FFS and EPS differed. FFS owned 1.9–59 % more on-farm cropland area compared to EPS, leading to tiny higher feed sufficiency. 78 % of feed in FFS was derived from within the

Table 1
Characteristics of pig production in farrow-to-finish pig system (FFS) and enterprise plus pig farms system (EPS).

Item	Unit	North China Plain		Hilly region of southeastern China	
		FFS	EPS	FFS	EPS
Production performance					
Farm number	number	60	42	48	12
Slaughter pig per year	Head	430 ± 366	716 ± 360	2631 ± 3811	2612 ± 1741
Slaughter pig weight	kg head ⁻¹	116 ± 6	114 ± 6	123 ± 26	121 ± 22
Feed consumption	kg head ⁻¹	433 ± 88 ^a	349 ± 48 ^b	434 ± 79 ^a	337 ± 27 ^b
Feed-to-meat conversion ratio (FCR) of fattening pig	kg kg ⁻¹	3.2 ± 0.61 ^a	2.6 ± 0.32 ^b	2.9 ± 0.48 ^a	2.3 ± 0.27 ^b
Daily weight gain	kg day ⁻¹	0.62 ± 0.07 ^b	0.78 ± 0.10 ^b	0.64 ± 0.14	0.74 ± 0.17
Mortality rate	%	11 ± 1.7 ^a	9.1 ± 4.7 ^b	5.2 ± 2.6	4.9 ± 1.3
Pigs weaned per sow per year (PSY)	head sow ⁻¹	18 ± 9.6	23 ± 0.17	22 ± 3.9	24 ± 1.5
System NUE	%	24 ± 3.8 ^b	30 ± 4.5 ^a	23 ± 3.1	28 ± 2.9
System PUE	%	29 ± 6.1 ^b	48 ± 11 ^a	20 ± 4.7	30 ± 6.1
Feed origins (based on dry matter)					
On-farm feed	%	4.6	0	3.6	0
Within-province	%	73.4	0	0	0
Within-domestic	%	0	77	75.4	79
Overseas	%	22	23	21	21
Feed transportation distance	km kg ⁻¹	1.64 ± 0.22 ^b	3.59 ± 0.07 ^a	3.28 ± 0.92 ^b	3.88 ± 0.66 ^a
Crop management					
On-farm cropland	ha	0.52 ± 0.39	0.51 ± 0.45	5.9 ± 12	2.4 ± 5.3
Main crop rotation		Maize-wheat	Maize-wheat	Pomelo/Maize-vegetable	Pomelo/Maize
Fertilizer N use	kg N ha ⁻¹	245 ± 112	267 ± 85	211 ± 62	250 ± 77
Fertilizer P use	kg P ha ⁻¹	79 ± 13 ^b	108 ± 33 ^a	56 ± 37	79 ± 39
N surplus	kg N ha ⁻¹	345 ± 210 ^b	1740 ± 119 ^a	855 ± 390	1170 ± 300
P surplus	kg P ha ⁻¹	180 ± 67 ^b	420 ± 220 ^a	98 ± 83 ^b	210 ± 35 ^a
Manure N substitution ratio	%	56 ± 24	70 ± 30	89 ± 6.7	92 ± 6.5
Resource use					
N fertilizer use	g N kg LW ⁻¹	124 ± 25 ^a	90 ± 13 ^b	92 ± 39	75 ± 18
P fertilizer use	g P kg LW ⁻¹	40 ± 8.2 ^a	33 ± 4.8 ^b	32 ± 14	29 ± 7.5
K fertilizer use	g K kg LW ⁻¹	102 ± 26 ^a	90 ± 18 ^b	88 ± 39	81 ± 22
Manure management					
Manure N loss ratio	%	35 ± 10	31 ± 10	35 ± 6.8	28 ± 0.63
Manure export ratio	%	60 ± 33 ^a	27 ± 37 ^b	85 ± 23	82 ± 21
Manure recycling ratio	%	40 ± 33 ^b	73 ± 37 ^a	15 ± 23	18 ± 21
Manure N application	kg ha ⁻¹	432 ± 237 ^b	2314 ± 2181 ^a	1662 ± 524 ^b	2056 ± 788 ^a
Manure P application	kg ha ⁻¹	151 ± 102 ^b	389 ± 312 ^a	120 ± 116 ^b	177 ± 123 ^a

Note: different lowercase letters (a and b) indicate significantly different means of EPS and FFS in various regions, according to two-tail test, $p < 0.05$. On-farm feed means feed was derived from on-farm cropland; within-province means feed was derived from within the local province; within-domestic means feed

was derived from other provinces of China; and overseas means imported feed from other countries.

province in the NCP, while three-quarters of the origin was from outside the province in HSC. In contrast, three-quarters of the feed in EPS in two regions was sourced from outside the province but within the country. The feed transportation distance in EPS was 119 % and 18 % longer than in FFS in NCP and HSC.

Regarding manure management, EPS had an 11–20 % lower ratio of manure nitrogen loss and a 20–121 % higher ratio of manure N recycling to cropland compared to FFS. This resulted in EPS applying more manure N (24–436 %) and P (48–158 %) per hectare to on-farm cropland than FFS. Additionally, EPS used more synthetic fertilizer per hectare for N (9.0–19 %) and P (37–41 %) compared to FFS, leading to a higher N surplus (37–404 %) and P surplus (114–133 %) of on-farm in EPS than in FFS.

3.2. Environmental footprints

Pig production in EPS emitted 9.5–30 % lower net GHG emissions, 22–29 % lower Nr emissions, 20–38 % lower phosphorus losses, and occupied 21–24 % less cropland than that in FFS (Fig. 1). EPS and FFS showed significantly different N, P, and land footprints in both NCP and HSC ($p < 0.05$), while GHG emissions differed significantly only in NCP ($p > 0.05$ for HSC).

Feed crop production contributed 55–64 % of GHG emissions to pig production, followed by manure management (17–20 %). Manure management (33–44 %) was the dominant subsystem of Nr emissions, with lesser contributions from feed crop production (35–40 %). P loss was mainly derived from feed crop production (69–94 %), especially agrochemical production. The differential GHG emissions between EPS and FFS were primarily driven by feed crop production (76–83 %), whereas manure management contributed 44–51 % of the observed differences in N footprints. Maize cultivation occupied most cropland (62–71 %) in all feed ingredients, followed by soybean products (20–36 %). The difference in cropland occupation between the two pig production systems was maize cultivation.

3.3. Net ecosystem economic benefits

FFS had 21–81 % lower net profits of pig production than EPS (Fig. 2). The difference in net profits between the two pig productions was mainly due to farm costs, especially in feed cost (1.73–1.75 CNY per kg LW). Pig production in FFS had 38–48 % higher damage cost than in EPS. Thus, NEEB was relatively high in EPS in both regions.

3.4. Factors affecting environmental and economic performance in pig production

The importance of the investigated variables to environmental footprints and NEB was explored using a random-forest model (Fig. 3). FCR was the most critical factor for GHG emissions, P losses, cropland occupation, and NEEB, while nitrogen fertilizer uses (NFP) per kg LW was for Nr emissions, to a lesser extent of FCR.

3.5. Implications of various environmental mitigation strategies

Implementing combinations of environmental mitigation strategies had the potential to reduce 17–53 % of environmental footprints in pig production (Fig. 4). Renewable energy transition (S1) would reduce GHG emissions by 21–23 % compared to EPS and FFS in pig production. Steady-state nutrient balance in feed production (S2) had the potential to further reduce GHG emissions (16–18 %), Nr emissions (10–11 %), P losses (29–40 %), and cropland use (2.55–2.98 %). Precision feed nutrition (S3) built upon S2 to incrementally lower impact by 2.9–3.7 % of GHG emissions, 5.7–7.2 % of Nr emissions, 4.8–5.0 % of P losses, and

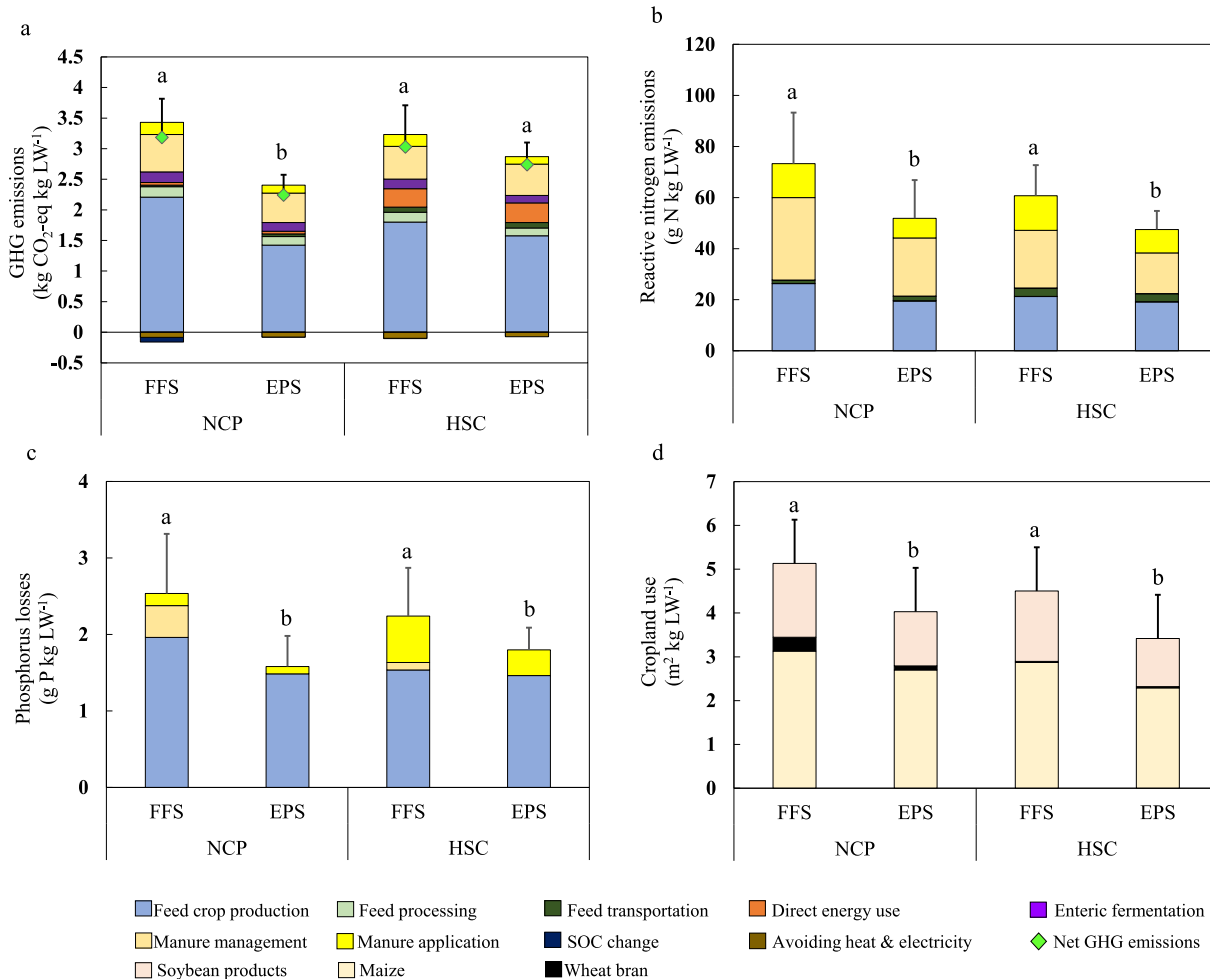


Fig. 1. Environmental footprints of farrow-to-finish pig system (FFS) and enterprise plus pig farms system (EPS) in North China Plain (NCP) and hilly region of southeastern China (HSC). Letters above bars (a and b) denote significant differences at the 0.05 level for environmental footprints between the FFS and EPS. Line bars indicate the standard deviations of environmental footprints.

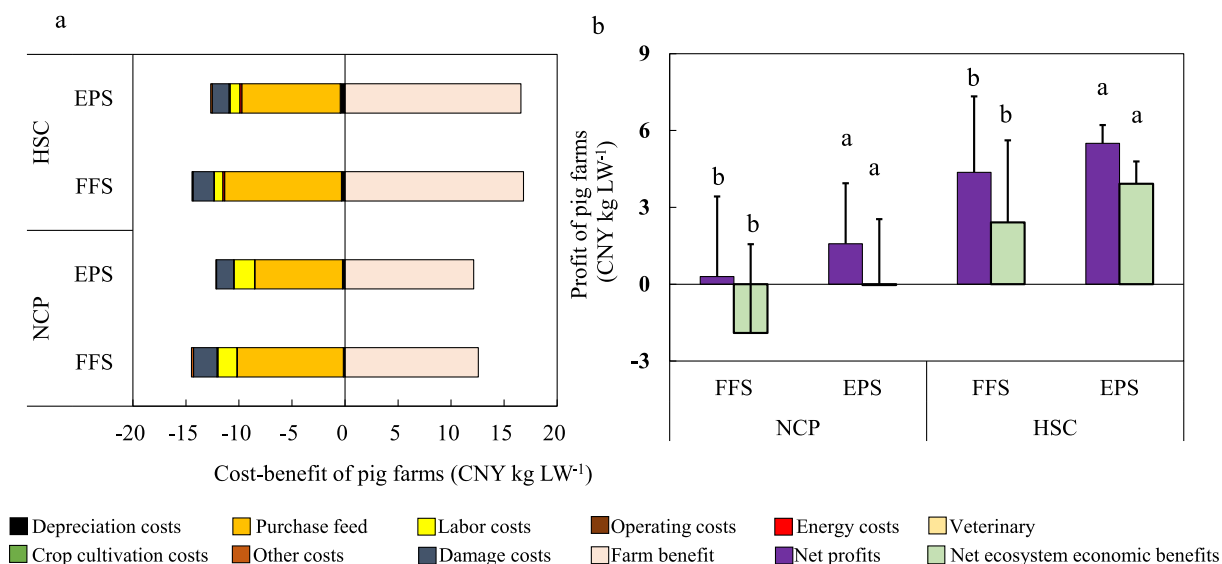


Fig. 2. Cost-benefit (a) and profit (b) per kg LW of farrow-to-finish pig system (FFS) and enterprise plus pig farms system (EPS) in North China Plain (NCP) and hilly region of southeastern China (HSC). Letters above bars (a and b) denote significant differences at the 0.05 level for net profits (NP) and net ecosystem economic benefits (NEEB) between EPS and FFS. Line bars are the standard deviation of NP and NEEB.

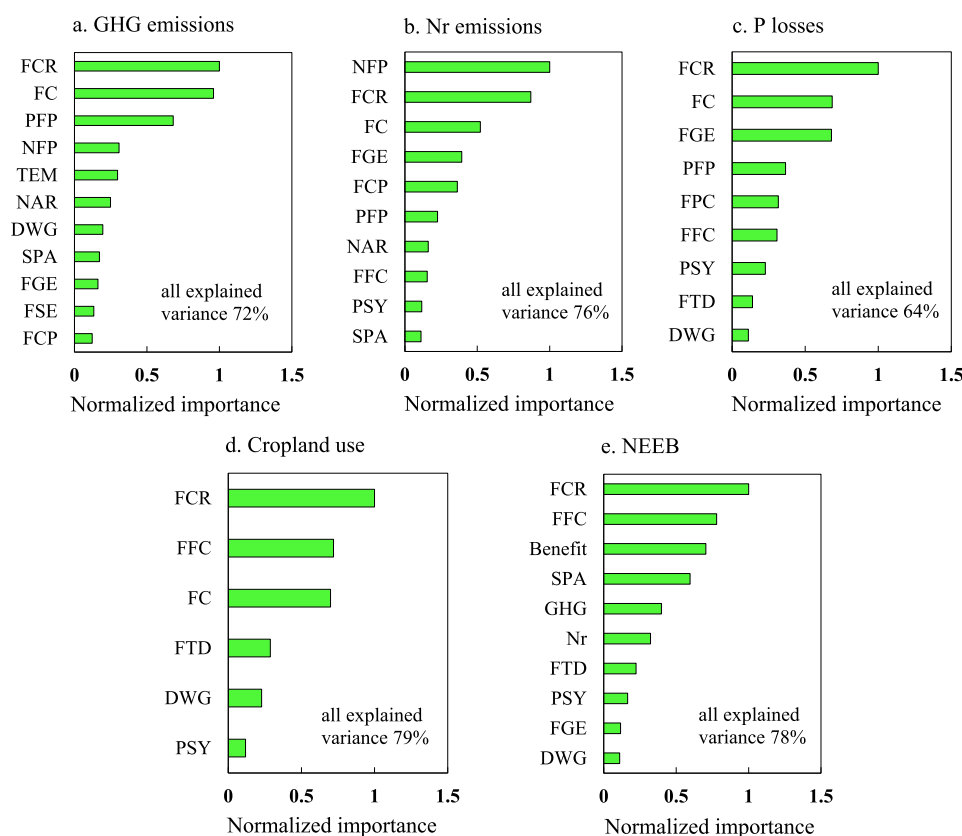


Fig. 3. Importance of different variables to the environmental footprints (a-d) and economic performance (e).

Note: GHG means greenhouse gas emissions per kg LW, Nr means reactive nitrogen emissions per kg LW, NEEB means net ecosystem economic benefits, FCR means feed-to-meat conversion ratio, FC means feed consumption per kg LW, PFP means phosphorus fertilizer use per kg LW, NFP means nitrogen fertilizer uses per kg LW, TEM means average temperature of study region, NAR means ratio of manure nitrogen application to excretion, DWG means daily weight gain per fattening pig, SPA means slaughtered pig amount per year, FGE means gross energy per kg feed, FSE means feed self-efficiency, FCP means feed crude protein content, PSY means productivity per sow per year, FTD means average transport distance of feed, FFC means farm feed cost per year, FPC means feed phosphorus content, Benefit means benefit per kg LW of farms.

14–15 % of cropland use. Improved sow productivity (S4) had negligible effects (<1 %) on environmental mitigation. Implementing advanced manure treatment (S5) can reduce GHG, Nr emissions, and P losses by 3.0–12 % compared to S4 in pig production.

4. Discussion

4.1. Environmental and economic performance of different pig production

EPS had 9.5–38 % lower footprints per kg LW than FFS in pig production, with the main difference being derived from feed production and manure management (Fig. 1). Key drives of this performance gap included three aspects. First, superior productivity metrics in EPS are evidenced by higher PSY than FFS. Higher PSY due to improved farrowing rates of sow and reduced fattening pig mortality. Moreover, EPS had a 19–21 % lower feed-to-meat conversion ratio than FFS and consequently reduced per-head feed consumption. Second, feed origins cause various environmental footprints in crop cultivation (Song et al., 2023). The maize of EPS was derived from Northeast China, which had higher crop yield and lower synthetic fertilizer application than other regions (Table S4 and S11), resulting in lower environmental emissions from feed crop production. This result is in line with the observation that imported green-source feed decreases GHG and NH₃ emissions (Du et al., 2018). Finally, EPS had higher NUE and PUE than FFS, leading to lower N and P excretion. Moreover, contractual obligations mandated advanced manure treatment technologies and prohibited direct manure discharge in EPS, collectively reducing environmental emissions from

manure management.

The cost-benefit analysis demonstrated that FFS had 21–81 % lower net profits than EPS in pig production (Fig. 2), with feed costs representing the primary divergence factor. Specialized pig farms in EPS reduced feed consumption by 19–22 % per head through optimized productivity, including higher PSY and lower pig mortality rate, enabled by standardized technical guidance and precise feeding throughout the pig production chain (Tang, 2025). Notably, in EPS, the net profits were distributed to enterprises (52–71 %) and smallholders (29–48 %) followed contractual agreements. The distribution coefficient is dynamically adjusted based on pork market fluctuations through predetermined rearing fee structures (Hui, 2015; Zheng, 2008). Beyond direct economic gains, EPS also exhibited 38–48 % lower damage costs than FFS (Fig. 2), primarily due to reduced environmental risks from Nr and GHG emissions. Damage cost, which is related to ecosystems, climate warming, and human damage incurred by Nr emissions and GHG emissions (Zhu et al., 2022), accounts for 12–15 % of farm cost in pig production. GHG and Nr were the important critical factors for NEEB (Fig. 3). Consequently, the NEEB was significantly higher in EPS (Fig. 3), underscoring mitigating environmental footprints synergistically enhanced both ecological sustainability and economic viability in pig production.

In our study, in EPS, Nr emissions (48–52 g N) and P losses (1.58–2.53 g P) per kg LW were lower than average in China (59 g Nr and 4.4 g P) (Long et al., 2021; Tong et al., 2023). The reduction of Nr emissions and P losses is attributed to contracted pig farms implementing advanced manure management technologies mandated by environmental policies (MEE, 2022). However, net GHG emission

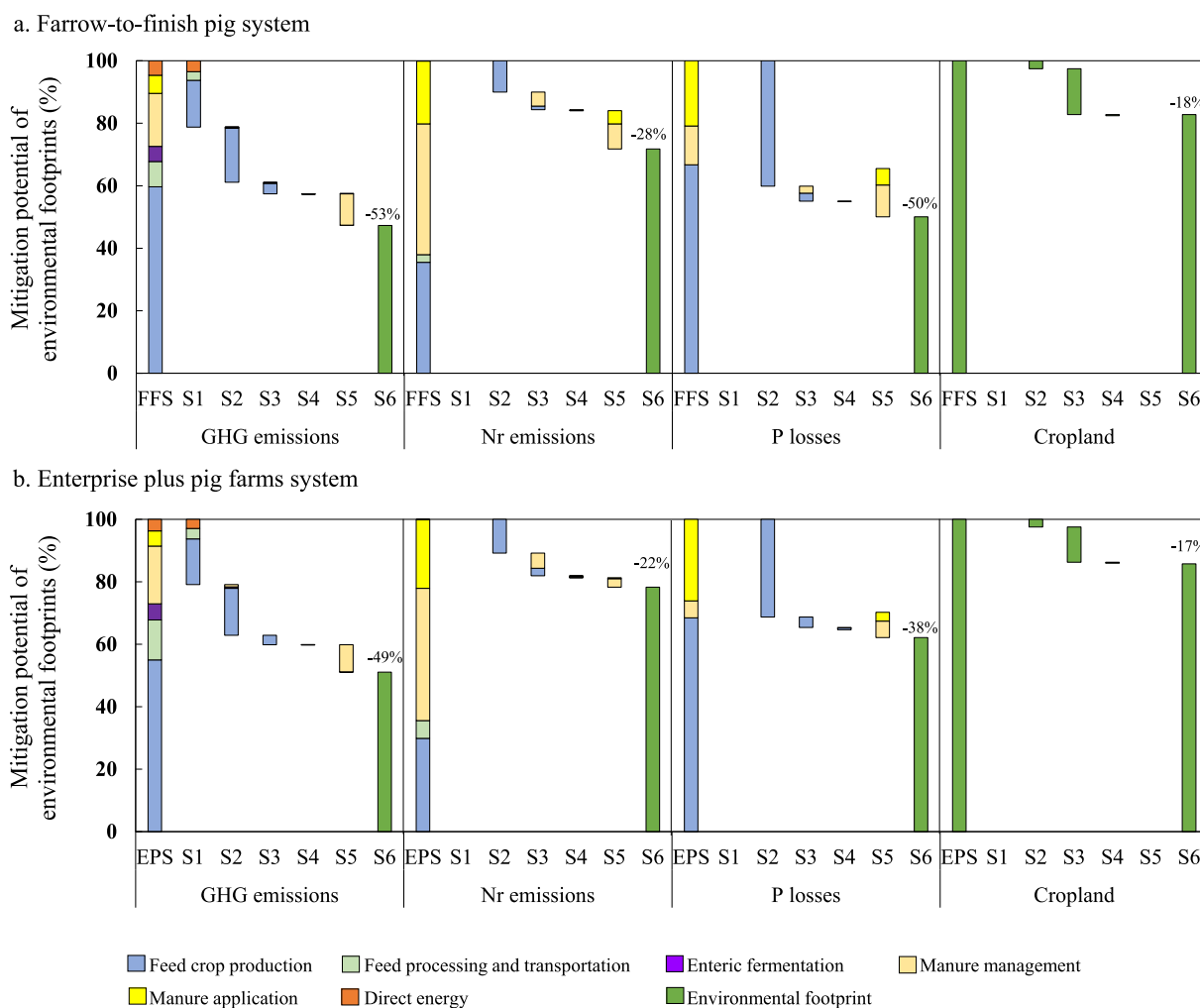


Fig. 4. Mitigation potential of environmental footprints through various environmental mitigation strategies in the pig production chain. Note: S1 means renewable energy transition in pig production, S2 means steady-state nutrient balance in crop production, S3 means precision feed nutrition, S4 means improved sow productivity, S5 means advanced manure treatment technologies, and S6 means integrated measures S1-S5. GHG emissions means greenhouse gas emissions, Nr emissions means reactive nitrogen emissions, P losses mean phosphorus losses.

(2.24–2.74 kg CO₂-eq) and P losses per kg LW of EPS were higher than average in the European Union (2.36 kg CO₂-eq, 0.3 g P kg⁻¹) (Lesschen et al., 2011; Reckmann et al., 2013). The difference in GHG emissions is mainly due to N-fertilizer produced and used in China are 1.65 times higher than in Europe (Luo et al., 2024). Therefore, there are opportunities for further pollution mitigation across the pig production chain through targeted improvements in energy use, feed efficiency, and circular nutrient management practices.

4.2. Environmental and economic performance of different regions

Environmental footprints of pig production were various in regions. The difference between regions was derived from feed origins. In the NCP region, EPS reduced environmental footprints by 14–36 % from feed production compared to FFS, attributable to EPS procurement of green-source feed. However, compared to FFS, EPS had 31–65 % higher GHG and Nr emissions from feed transportation due to 2.2 times longer distances to transport per kg feed. Conversely, the HSC region presented a contrasting scenario where EPS and FFS showed no statistical difference in environmental emissions from feed crop production (*p* > 0.05). This equivalence occurred because both systems relied heavily (>95 %) on interprovincial or overseas feed imports, such as maize, soybean, and wheat production failed to meet regional demand in HSC. Pig farms in HSC had higher GHG emissions from feed transportation than in NCP.

Higher transportation-related GHG and Nr emissions due to longer distances, a trade-off potentially mitigated by adopting cleaner transport modes (e.g., highways and railways) (Zuo et al., 2023).

Secondly, pig farms in HSC had higher GHG emissions from direct energy use than in NCP, primarily attributable to more electricity consumption for subtropical climates. In manure management, HSC demonstrated elevated GHG emissions but lower N and P footprints relative to NCP. This divergence stems from two key factors: (1) higher methane emission factors in HSC due to elevated temperatures, which intensify environmental emissions even under identical manure treatment methods (IPCC, 2019); and (2) comprehensive adoption of advanced manure management technologies (AD and composting) across pig farms in HSC, driven by stringent environmental policies. Notably, the combination of heavier precipitation and steeper terrain in HSC resulted in greater nutrient losses during manure applications compared to NCP, particularly through excessive manure applications and losses of leaching, runoff, and erosion (Table 1).

The contrasting regional characteristics necessitate differentiated optimization strategies. In the NCP, priority should be given to enhanced manure management through strict discharge regulations and government subsidies for advanced treatment technologies, complemented by improved crop nutrient management to mitigate feed production impacts. Conversely, the HSC region requires feed system restructuring to boost local resource utilization, including potential food waste

incorporation, along with optimized field manure application protocols to minimize nutrient losses through erosion and runoff.

4.3. Implication of scenario analysis

Energy production and consumption are major sources of GHG emissions, which account for two-thirds of anthropogenic GHG emissions in the world (Wei et al., 2022). Energy transition towards photovoltaic and wind has the potential to reduce GHG emissions and achieve carbon neutrality by 2060 (Wang et al., 2023). Renewable energy transition in pig production (S1) can effectively reduce GHG emissions by 21–23 % (Fig. 4). The promotion of the S1 approach needs building energy storage, expanding transmission capacity, and adjusting power load at the demand side for photovoltaic and wind (Wang et al., 2023). Moreover, lowering facility and operation energy inputs in pig farms by 30 % would decrease fossil fuel use by 10 % and slightly decrease GHG emissions (Tallaksen et al., 2020).

Feed crop production was responsible for 55–60 % of GHG emissions, 30–36 % of Nr emissions, and 64–69 % of P loss (Fig. 1). N fertilizer use per kg LW was the main factor for GHG and Nr emissions, while P fertilizer use per kg LW was the important factor for P losses. Thus, reducing synthetic fertilizer application can effectively abate environmental footprints. Crop cultivation consumes overused synthetic fertilizer in China (Yu et al., 2019), and field experiments have proved that adopting a steady-state nutrient balance approach increases cereal yield and reduces fertilizer use (Cui et al., 2018; Gong et al., 2025; Yin et al., 2021). Therefore, steady-state nutrient balance in feed production (S2) has the potential to reduce 2.55–40 % of environmental footprints in pig production (Fig. 4). S2 can decrease N, P, and K synthetic fertilizer use by 25–29 %, 45–49 %, and 68–72 %, and is beneficial to achieving the “zero fertilizer growth” policy (MARA, 2015). The promotion of S2 in crop farms may require a cooperation network (e.g., governments, enterprises, researchers, agricultural extension workers, and crop farms), policy incentives, and the “4Rs” approach (right rate, right place, right time, and right source) for nutrient manure management.

Pig diet shift from traditional (e.g., greenfeed, food waste) to maize-soybean over five decades has exacerbated environmental impacts and feed-food competition in China, which feed optimization strategies can mitigate (Dai et al., 2023). Our results show that precision feed nutrition (S3) in pig production can mitigate environmental emissions by 0.1–15 % by replacing soybean with other protein feed (Fig. 4), consistent with recent findings by (Wu et al., 2024). This approach aligns with China’s national policy to reduce dependence on imported soybeans (MARA, 2023). However, implementing an optimal feed formula requires addressing anti-nutritional factors (e.g., gossypol, niacin, choline, and tannin) in alternative protein sources like peanut and rapeseed meal through processing innovations. Moreover, 75–77 % of field-based data show food waste feeding in pig diet increases animal productivity (Wang et al., 2024b). Mini-livestock production (insects) for feed may further lead to decreased GHG emissions and achieve carbon neutrality in China (Bai et al., 2023). Future research should prioritize evaluating the food safety, nutritional adequacy, and scalability of unconventional protein sources (e.g., processed food waste, microbial protein, insect meal, etc.) to establish their viability as sustainable alternatives that can decouple pig production from environmental degradation while ensuring food security.

Livestock manure contributes considerably to NH₃, CH₄, and N₂O emissions in China (Wang et al., 2024b; Xu et al., 2022). Additives reduced NH₃, CH₄, and N₂O emissions during composting (Cao et al., 2019). Biogas generated from anaerobic digestion can partly offset GHG emissions through electricity and heating (Whiting and Azapagic, 2014). Low leakage AD reduced CH₄ emissions by 92 % compared to high leakage AD (IPCC, 2019). Therefore, implementing advanced manure treatment technologies (S5) could reduce 9.0–10 % of GHG emissions, 3.0–12 % of Nr emissions, and 2.5–4.9 % of P losses in pig production (Fig. 4), which is in line with findings by (Tong et al., 2023). However,

individual manure management technologies were insufficient to reduce environmental losses from manure management chains due to compensatory losses (Qu et al., 2025). Effective implementation of manure management technologies must account for the economic-environmental tradeoffs inherent in nutrient recycling systems (Tan et al., 2021). Future research should comprehensively consider environmental and economic benefits of whole manure management chain “housing-storage-treatment-application” in pig production.

Overall, combinations of strategies S1-S5 have the potential to reduce half of GHG emissions, 22–28 % of Nr emissions, 38–50 % of P loss, and 17–18 % of cropland (Fig. 4). Therefore, achieving substantial abatement of environmental footprints from pig production requires a holistic policy package promoting renewable energy transition at the country level, steady-state nutrient balance in feed production, precision feed nutrition, and advanced manure treatment technologies in pig production chain. However, the economic and environmental performance of pig production systems varies significantly across farm scales, large-scale technology deployment must account for regional and operational-scale disparities in technology adoption preferences.

4.4. Obstacles to cooperation between enterprises and specialized pig farms

The mode of enterprise plus pig smallholder system has been expanded in recent years for efficient feeding management, lower farm costs, and more resilience to face market fluctuations. Specialized pig farms expressed relatively low environmental footprints and high NEEB when collaborating with enterprises. However, cooperation among enterprises and smallholders also faces a range of social and economic constraints and challenges. Firstly, some partnerships between enterprises and smallholders appeared unstable due to poor communication and contract inflexibility (Asai et al., 2018). For instance, some pig smallholders break the contracts and sell slaughtered pigs when capitalizing on high pork prices. Secondly, the utilization of complete feed disrupts the closed-loop nutrient on-farm for smallholders engaged in maize-wheat cultivation and pig production. Increasing feed self-sufficiency on farms has been shown to reduce environmental emissions in livestock production (Ma et al., 2022). It, therefore, raises questions about the rationality of inter-regional transportation to segregation of crop and livestock production at a local scale juxtaposed with nutrient cycling at country level. Third, specialized pig farms return generated manure to their on-farm cropland, but the area of cropland is limited to dispose of manure appropriately, which increases the risk of environmental pollution, especially in East China. Also, transportation-induced stress in piglets and finishing pigs will be exacerbated by prolonged distances. Too long transportation of animals and/or feed increases GHG emissions. With the normalization of African swine fever, long transportation of pig and feed transfers increases prevention and control pressure and environmental risks. Hence, the signaled hurdles must be addressed carefully through targeted guidance and incentives before fully reaping the benefits of cooperative agreements between enterprises and pig smallholders. For example, the enterprise can organize the establishment of a centralized treatment center for manure in intensive breeding areas (Shi et al., 2023); the enterprise can consider importing maize, soybean, and wheat from areas with low feed environmental emissions (He et al., 2019); or changes the planting structure to meet feed needs in local level (Dai et al., 2023). The economic imperative to transition production systems remains substantial, yet integrated mitigation strategies combining production and consumption measures can yield benefit-cost ratios exceeding 5:1 when accounting for avoided damages to human health and ecosystems (Zhu et al., 2022). This underscores the critical role of governmental intervention through strengthened environmental regulations for livestock emissions and targeted subsidies for advanced technologies to accelerate sustainable transformation.

4.5. Uncertainties

This study can be viewed as the beginning of quantitatively analyzing the environmental and economic performances of collaborative systems between enterprises and livestock farms in China. Agricultural production patterns, climatic conditions, and resource availability in different regions may affect the study results. Additional quantitative analyses of the impacts of the collaboration between enterprise and livestock farms need to be conducted in other regions of the world. More potential environmental impacts (e.g., water depletion, biodiversity impacts, etc.) should be considered in further study. The transition from FFS to EPS requires careful consideration of socio-economic factors (e.g., pig farms' income stability, policy incentives, and technology adoption rates, etc.) as these variables critically influence system sustainability and scalability. Future research should prioritize quantifying these drivers through integrated assessment models that couple environmental benefits with livelihood impacts.

Uncertainties of results may originate from inaccuracies of activity data and emission factors. The crude protein (CP) contents of major feed types (maize, soybean meal, wheat bran, etc.) were measured (snap-shot samples). The impacts of changes in main emission factors on environmental footprints in two modes were explored through sensitivity analysis, which showed that GHG, Nr, and P loss varied within a range of 4.0 % (Table S15). Our model can be improved further by using measured data from field experiments.

5. Conclusions

Quantifying the environmental-economic tradeoffs of cooperating between enterprises and specialized livestock farms is a prerequisite to effective policy design. This study is the first to evaluate multiple environmental footprints and economic performance of FFS and EPS in pig production. EPS had 9.5–38 % lower footprints per kg LW of pig production than FFS via increasing nutrient use efficiency, with the main difference being derived from feed crop production and manure management. Notably, EPS decreased feed sufficiency via imported green-sourced feed and increased ratio of manure recycling via strict environmental protection policy than in FFS, which led to excessive manure application and nutrient accumulation in limited on-farm cropland. NEEB per kg LW was relatively higher in EPS than in FFS because of lower feed costs and damage costs. The feed-to-meat conversion ratio was the most critical factor for GHG emissions, P losses, land use, and NEEB, whereas N fertilizer uses per kg LW had the highest impact on Nr emissions. Overall, compared to FFS, EPS reduces environmental impact (e.g., C, N, and P losses) by boosting pig production efficiency, optimizing feed origins, and adopting superior manure management. Our results establish that coordinated implementation of environmental mitigation strategies from cradle to gate in pig production can reduce environmental footprints by 17–53 %, providing a validated pathway to achieve agriculture green development goals in China. The practical implementation of these technologies requires careful consideration of regional-specific conditions and technological compatibility factors. Future policy should prioritize: (i) improved manure management in pig farms, (ii) transport infrastructure upgrades to mitigate feed logistics emissions, and (iii) tiered manure application standards tailored to regional carrying capacities.

CRedit authorship contribution statement

Yifei Ma: Writing – original draft, Visualization, Formal analysis, Data curation. **Pan Liu:** Data curation. **Xiaoying Zhang:** Data curation. **Xiaoqing Shi:** Data curation. **Yong Hou:** Project administration, Conceptualization. **Hongliang Wang:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.agsy.2025.104482>.

Data availability

Data will be made available on request.

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