

Article

Halving Greenhouse Gas Emissions from China's Pork Supply Chain Under Food System Transformation

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Abstract

The intensification of pig production and the restructuring of pork supply-demand patterns have profoundly reshaped greenhouse gas (GHG) emissions across the pork supply chain. Understanding the environmental consequences of these food system transitions is essential for developing effective mitigation strategies. Focusing on technological and spatial transformations between 2002 and 2022, this study employed linear programming and life cycle assessment (LCA) to systematically quantify GHG emissions from China's pork supply system, applied the Logarithmic Mean Divisia Index to decompose the key drivers of emission changes, and conducted scenario analysis to assess mitigation potential by 2030. The results show that geographic shifts in pork production and consumption increased interprovincial food miles and associated transport emissions. With the intensification of pig production, carbon dioxide (CO₂) emissions surpassed methane (CH₄) to become the second-largest GHG source, driven primarily by greater reliance on commercial feed, synthetic fertilizers, and fossil energy inputs. Although the transition from smallholder to intensive production systems exerted a mitigation effect, this was outweighed by a substantially larger increase in emission intensities across all production systems. Between 2002 and 2022, total emissions rose by 110.1%, reaching 164.05 Mt CO₂eq. A full-chain optimization strategy integrating low-opportunity-cost feed substitution, enhanced manure recycling, biogas production, and green transportation could reduce emissions by 49.1% by 2030 while enabling an 8.2% increase in pork output. This work not only reveals the evolving emission structure of China's pork supply system but also identifies critical pathways for the low-carbon transformation of livestock systems globally.

Keywords: livestock transition; intensive production; interprovincial transport; life cycle assessment; GHG mitigation



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1. Introduction

Global food systems contribute over one-third of GHG emissions [1], with animal-based foods representing the largest share [2]. Pork accounts for more than one-third of global meat production [3], making the low-carbon transformation of its supply chain crucial for mitigating the climate impacts of food systems. As the world's largest pork producer, China accounts for approximately 50% of global pork output [4]. To meet growing domestic demand, China's pig industry has undergone a profound transformation from traditional backyard farming toward intensive operations aimed at improving productivity [5]. Simultaneously, regional economic disparities and environmental regulations have reshaped

the spatial configuration of pork supply and demand [6]. A notable example is the Water Pollution Prevention and Control Action Plan initiated in 2015, under which designated non-livestock production zones, especially in watercourse-intense southern China, have accelerated the so-called “South-to-North Pig Migration” [7]. However, the environmental implications of these food system transformations remain insufficiently understood.

Although numerous studies have quantified GHG emissions from the pig industry, important limitations persist in capturing the combined effects of technological change and spatial restructuring. First, most historical trend analyses rely on static emission factors [8–10]. While some studies have considered shifts in diet formulation or manure management [5,11,12], they have not fully accounted for other transformations associated with livestock intensification, such as increased on-farm energy use due to continuous ventilation, temperature control [13], and lighting in animal housing, as well as greater application of synthetic fertilizers driven by commercial feed dependence and crop-livestock decoupling [14,15]. Second, many existing LCAs adopt a farm-gate boundary and pay limited attention to downstream distribution processes [16–18]. As food supply chains expand spatially and cold-chain logistics develop rapidly, the environmental burden of transporting fresh agricultural products has grown substantially [9,19]. In particular, policies such as the “South-to-North Pig Migration” have inevitably altered food miles, yet these effects have not been rigorously quantified. Furthermore, although mitigation measures such as low-protein feeding [20], optimized manure management [21], and biogas projects have been proposed [22], there remains limited investigation into their synergistic mitigation potential across multiple stages of the supply chain.

To address these gaps, this study aims to answer three key questions: (i) How have China’s pork supply-demand patterns and associated food miles evolved spatially and temporally during 2002–2022? (ii) What are the magnitude, composition, and driving forces of GHG emissions from the pork supply chain when production intensification and supply–demand reallocation are considered simultaneously? (iii) What is the synergistic mitigation potential across multiple stages of the supply chain by 2030?

This study made three primary contributions. First, it developed a comprehensive GHG LCA framework that distinguishes emissions by production system, pig growth stage, and supply chain segment. Static emission factors were replaced with time- and technology-sensitive parameters to better capture the dynamics of livestock system transformation. Second, the system boundary was extended to include interprovincial transport, enabling assessment of the environmental consequences of production layout adjustment policies. Third, building on mainstream mitigation technologies, this study proposes integrated supply chain optimization strategies and quantifies their combined mitigation potential. By providing an integrated assessment of technological and spatial transitions, this study contributes to advancing the low-carbon transformation of China’s pork supply system and offers insights relevant to livestock systems worldwide.

2. Literature Review

2.1. GHG Accounting Methods for the Livestock Sector

GHG accounting in the livestock sector mainly relies on three approaches: inventory methods, input-output analysis, and LCA. Inventory methods estimate emissions by multiplying activity data by corresponding emission factors. Using this approach, Zhuang et al. [23] quantified non-CO₂ emissions from China’s livestock sector and reported that CH₄ and nitrous oxide (N₂O) emissions accounted for 18.7% and 23.4% of global livestock emissions, respectively. However, inventory-based methods typically rely on default emission factors provided by the IPCC, which may overlook regional heterogeneity and

production system differences. Moreover, they often exclude upstream and downstream stages of the supply chain [24,25].

Input-output analysis, grounded in national or multi-regional input-output tables, enables systematic tracking of both direct and indirect emissions across economic sectors. Pan et al. [26] employed a multi-regional input-output framework to assess embodied CH₄ emissions in China's interprovincial agricultural trade and identified livestock production as a dominant emission source. Nevertheless, input-output tables are generally constrained to sector-level aggregation, making it difficult to disaggregate the environmental impacts of specific livestock products (e.g., pork and beef). Downscaling techniques are therefore frequently employed to improve product-level resolution [27], although such approaches introduce additional assumptions.

LCA incorporates environmental impacts across the entire life cycle of a product and has been widely adopted for livestock GHG accounting. Building on this framework, previous studies have examined the influence of farming scale [13], feeding strategies [20], and management practices [28,29] on livestock-related emissions. For instance, Chen et al. [20] applied LCA to assess the impact of dietary crude fiber content on GHG emissions along the pork supply chain. Their findings revealed that increasing crude fiber content reduced emissions during crop cultivation but raised emissions during rearing and transport due to elevated enteric CH₄ production and longer feed transportation. Although LCA provides a comprehensive perspective on supply chain emissions, its results are sensitive to the choice of emission factors, particularly given the varying levels of methodological detail across IPCC Tier 1, Tier 2, and Tier 3 approaches [13].

2.2. Environmental Impacts of Intensive Livestock Production

Between 1980 and 2010, China's livestock sector experienced rapid intensification. Over this period, total livestock inventories nearly doubled, while the number of animals raised in intensive systems increased by nearly 70 times [30]. Intensive production systems markedly improved productivity and resource-use efficiency through the adoption of improved breeds, precision feeding technologies, and standardized management practices [27,31]. However, this system transition has also introduced substantial environmental pressures.

Intensive systems typically rely on higher inputs of concentrate feed, driving a substantial rise in demand for feed crops [32]. From 1980 to 2010, maize consumption for feed increased six times and soybean consumption increased nine times [30]. This shift intensified the use of agricultural inputs, such as fertilizers and pesticides, thereby increasing upstream environmental burdens associated with feed production. Simultaneously, livestock intensification has exacerbated the spatial decoupling of crop and livestock systems, reducing the recycling of manure nutrients to cropland [33,34]. The manure nitrogen recycling rate dropped from 33% in 1980 to 21% in 2010 [30], contributing to nutrient surpluses and environmental pollution. Furthermore, compliance with environmental regulations and the need to ensure animal welfare in intensive operations have led to increased mechanization, ventilation, temperature control, and lighting in animal housing facilities, thereby raising fossil energy consumption and GHG emissions during the rearing stage [35]. Overall, the environmental consequences of livestock intensification extend across the entire supply chain. Addressing these impacts requires integrated research and management approaches that balance productivity gains with environmental sustainability.

2.3. Spatiotemporal Evolution of Food Supply–Demand Patterns and Associated Environmental Footprints

Driven by population growth, economic development, and policy interventions, agricultural production systems have become increasingly centralized and intensive [36]. In

China, environmental regulations and land-use constraints have prompted the relocation of pig production from coastal regions to inland provinces, while consumption demand remains concentrated in coastal and metropolitan areas [6,37]. This spatial decoupling has substantially increased interprovincial agricultural transport. Food miles have emerged as an important component of food system emissions. Li et al. [38] estimated that global emissions from food transportation account for approximately 20% of total food system emissions. Zuo et al. [39] reported that cropland displacement in China contributed 60% of the increase in carbon emissions from grain transportation between 1990 and 2015. Furthermore, Li et al. [40] identified a trade-off between mitigating manure nitrogen surpluses and reducing GHG emissions when transportation emissions are considered. These findings highlight the importance of incorporating spatial restructuring and interprovincial transport into environmental assessments of agricultural supply chains. A comprehensive evaluation of supply chain environmental footprints, including production relocation and associated transportation, can reveal additional mitigation opportunities and support the development of more sustainable and spatially coordinated food systems.

3. Materials and Methods

3.1. System Boundary and Functional Unit

The system boundary encompassed the entire pork supply chain, including feed crop cultivation (covering both crop cultivation and upstream manufacturing of agricultural material inputs), feed processing, pig farming (covering on-farm energy consumption, enteric fermentation, and manure management), pig slaughtering, and interprovincial pork transport (Figure 1). We quantified four major GHGs emitted across the supply chain: CO₂, CH₄, N₂O, and hydrofluorocarbons (HFCs) associated with refrigerant leakage in the cold chain. Based on farm scale, feeding regime, and manure management practices, pig production systems in China were classified into three types: traditional, medium-scale, and industrial (see Supplementary Information S1 text for details). In recent years, driven by rising pork demand and technological advancement, the share of traditional systems has declined, while intensive operations (medium and industrial systems) have expanded. The functional unit was defined as 1 kg of pork carcass weight, enabling comparability with previous studies.

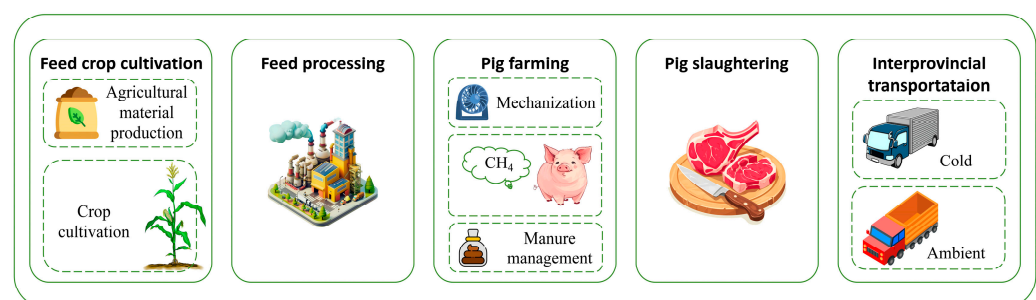


Figure 1. System boundary.

3.2. Accounting for Pork Supply-Demand and Food Miles

3.2.1. Quantifying Provincial Pork Supply and Demand

The supply-demand balance of pork for each province (T_p , t yr⁻¹) was calculated by the following equation:

$$T_p = P_p - (P_{total} \times Pop_p \times C_p / \sum_{p=1}^{31} Pop_p \times C_p) \quad (1)$$

where a positive T_p value identifies province p as a net pork exporter, while a negative value is a net importer. P_p , Pop_p and C_p denote the pork production, population, and per capita

pork consumption in province p , respectively. P_{total} denotes the national pork production. Data on pork production, population, and per capita consumption were sourced from the China Statistical Yearbook. For simplicity of calculation, we excluded international trade in the supply-demand balance equation due to China's extremely low pork import rate [41].

3.2.2. Accounting for Domestic Food Miles

The domestic food miles (FM , t-km) for pork were calculated as follows:

$$FM = FM_{cold} + FM_{ambient} \\ = \sum_{p=1}^m \sum_{q=1}^n W_{p,q,cold} \times D_{p,q} + \sum_{p=1}^m \sum_{q=1}^n W_{p,q,ambient} \times D_{p,q} \quad (2)$$

where $D_{p,q}$ represents the transportation distance between provinces p and q . $W_{p,q,cold}$ and $W_{p,q,ambient}$ denote the quantities of pork transported via cold chain and ambient-temperature transportation, respectively. Owing to the lack of statistical data on inter-provincial pork trade flows in China, a cost-minimization linear programming model was developed [42]. This model incorporated the assumption that each province must first satisfy its internal demand. Furthermore, based on the Agricultural Products Origin Cold Chain Research Report, the proportion of pork shipped via cold chain was set at 57%. Consequently, the model incorporated two transportation modes: cold chain and ambient-temperature transportation. The objective function and constraints of the linear programming model are presented below:

$$\min \sum_{p=1}^m \sum_{q=1}^n L_{p,q} \times FC_{p,q} \\ \text{subject to} \\ \begin{cases} \sum_{q=1}^n L_{p,q} \leq T_p \\ \sum_{p=1}^m L_{p,q} = |T_q| \\ T_{p,q} \geq 0 \end{cases} \quad (3)$$

where $FC_{p,q}$ represents the unit weight transportation cost from province p to q . In this study, the transportation cost between the two locations is weighted by distance [39]. The interprovincial road transportation distances are sourced from Baidu Maps.

3.3. LCA of GHG Emissions from the Pork Supply System in China

Total GHG emissions from the pork supply system (E_{GHG} , kg CO₂eq yr⁻¹) were calculated by the following equation:

$$E_{GHG} = E_{CP} + E_{FP} + E_{PF} + E_{ST} + E_{IT} \quad (4)$$

where E_{CP} , E_{FP} , E_{PF} , E_{ST} , and E_{IT} denote emissions from the feed crop cultivation, feed processing, pig farming, pig slaughtering, and interprovincial pork transport stages, respectively.

3.3.1. GHG Emissions from Feed Crop Cultivation

The GHG emissions from feed crop cultivation (E_{CP} , kg CO₂eq yr⁻¹) were calculated as

$$E_{CP} = \sum_{i=1}^3 \sum_{j=1}^3 A_j \times Q_{input,i,j} \times EF_{input,i} + E_{FE} + E_{FF} \quad (5)$$

where i ($i = 1, 2, 3$) denotes the type of agricultural input (fertilizer, pesticides, and plastic films). j ($j = 1, 2, 3$) denotes the type of feed crop (wheat, corn, or soybean). A is the cultivated area for a specific feed crop, ha, calculated as the total feed requirement divided by the crop yield. Q_{input} is the application rate of agricultural inputs per unit area, kg ha⁻¹ yr⁻¹. Data on agricultural input application rates and crop yields were sourced from the China

Agricultural Cost and Benefit Data Compilation. EF_{input} represents the life cycle GHG emission factor for producing one unit of agricultural input, kg CO₂eq kg⁻¹ [43–45]. The amount of feed required was calculated in S2 of the SI. E_{FE} and E_{FF} denote emissions from energy consumption in crop fields and fertilizer application, respectively (see Table S1 for details).

3.3.2. GHG Emissions from Feed Processing

The GHG emissions from the feed processing stage (E_{FP} , kg CO₂eq yr⁻¹) were calculated as

$$E_{FP} = W_{FP_trans} \times D_{FP} \times EF_{trans} + \sum_{k=1}^3 W_{FP_trans} \times EI_{energy_FP_k} \times EF_{energy_k} \quad (6)$$

where k ($k = 1, 2, 3$) indicates energy categories such as electricity, coal, and diesel. W_{FP_trans} is the total weight of feed raw materials, t yr⁻¹; D_{FP} is the average distance for transporting feed raw materials from croplands to feed processing plants, assumed to be 20 km; EF_{trans} is the GHG emission factor of transporting one unit of product per km, kg CO₂ t⁻¹ km⁻¹; EI_{energy_FP} is the parameter for per unit feed dry matter processing energy consumption, (kW·h) yr⁻¹ (or kg yr⁻¹). EF_{energy} is the emission factor for a certain energy type, kg CO₂eq (kW·h)⁻¹ (or kg CO₂eq kg⁻¹). These parameters were sourced from the literature [43,46–48]. A feed loss rate of 1% during the processing stage was assumed.

3.3.3. GHG Emissions from Pig Farming

The GHG emissions from pig farming (E_{PF} , kg CO₂eq yr⁻¹) were calculated as follows:

$$E_{PF} = \sum_{k=1}^3 Q_{energy_PF_k} \times EF_{energy_k} + W_{PF_trans} \times D_{PF} \times EF_{trans} + E_{enteric} + E_{manure_CH_4} + E_{manure_N_2O} \quad (7)$$

where Q_{energy_PF} is the on-farm energy consumption, (kW·h) yr⁻¹ (or kg yr⁻¹), calculated as the total energy cost divided by the unit energy price. Energy costs were obtained from the China Agricultural Cost and Benefit Data Compilation. W_{PF_trans} is the total weight of commercial feed, t yr⁻¹; D_{PF} is the average transportation distance for commercial feed (assumed to be 20 km). $E_{enteric}$ is enteric CH₄ emission; $E_{manure_CH_4}$ and $E_{manure_N_2O}$ are CH₄ and N₂O emissions from manure management, respectively (see Table S1 for details).

3.3.4. GHG Emissions from Pig Slaughtering

The GHG emissions from the slaughtering stage (E_{ST} , kg CO₂eq yr⁻¹) were calculated as follows:

$$E_{ST} = W_{ST_trans} \times D_{ST} \times EF_{trans} + \sum_{k=1}^3 Q_{energy_ST_k} \times EF_{energy_k} \quad (8)$$

where W_{ST_trans} is the total live weight transported, t yr⁻¹; D_{ST} is the average transportation distance from pig farm to slaughterhouse (assumed to be 20 km) and Q_{energy_ST} is the energy consumption at the slaughterhouse, (kW·h) yr⁻¹ [14].

3.3.5. GHG Emissions from Interprovincial Pork Transport

The GHG emissions from interprovincial pork transport (E_{IT} , kg CO₂eq yr⁻¹) were calculated as follows:

$$E_{IT} = \sum_{p=1}^m \sum_{q=1}^n FM_{cold} \times EF_{cold} + \sum_{p=1}^m \sum_{q=1}^n FM_{ambient} \times EI_{energy_IT_k} \times EF_{energy_k} \quad (9)$$

where EF_{cold} is the GHG emission factor per tonne-kilometer for cold chain, kg CO₂eq·(t·km)⁻¹, which accounts for both direct energy use and refrigerant leakage; $EI_{energy_IT_k}$ is the energy intensity per tonne-kilometer for ambient-temperature transportation using energy type k , L·(t·km)⁻¹. These parameters were sourced from the China Transport Yearbook and Wu et al. [49].

3.4. Decomposition of Driving Factors of GHG Emission Change

This study employed the Logarithmic Mean Divisia Index (LMDI), a key analytical tool for decomposition analysis, to quantify how four driving factors contribute to changes in E_{GHG} . These factors are: emission intensity, production structure, per capita pork consumption, and population size. The decomposition is expressed as follows:

$$E_{GHG} = \sum_{u=1}^3 \frac{G_u}{Q_u} \times \frac{Q_u}{W} \times \frac{W}{P} \times P = \sum_{u=1}^3 I_u \times M_u \times R \times P \quad (10)$$

where u ($u = 1, 2, 3$) denotes the type of pig production systems (traditional, medium, and industrial). G and Q are the GHG emissions and pork production output from a certain system, respectively. W signifies the national pork production. I , M , R , and P denote the emission intensity of each system, production structure, per capita pork consumption, and population size, respectively.

Using logarithmic differentiation, the change in E_{GHG} between a base period (0) and a target period (T) can be decomposed into the additive contributions of four driving factors:

$$\Delta E_{GHG} = E_{GHG}^T - E_{GHG}^0 = \Delta E_I + \Delta E_M + \Delta E_R + \Delta E_P \quad (11)$$

Following the LMDI framework, the E_{GHG} change was thus additively decomposed into the following four components:

$$\Delta E_I = \sum_{u=1}^3 \left(\frac{E_u^T - E_u^0}{\ln E_u^T - \ln E_u^0} \right) \times \ln \frac{I_u^T}{I_u^0} \quad (12)$$

$$\Delta E_M = \sum_{u=1}^3 \left(\frac{E_u^T - E_u^0}{\ln E_u^T - \ln E_u^0} \right) \times \ln \frac{M_u^T}{M_u^0} \quad (13)$$

$$\Delta E_R = \sum_{u=1}^3 \left(\frac{E_u^T - E_u^0}{\ln E_u^T - \ln E_u^0} \right) \times \ln \frac{R^T}{R^0} \quad (14)$$

$$\Delta E_P = \sum_{u=1}^3 \left(\frac{E_u^T - E_u^0}{\ln E_u^T - \ln E_u^0} \right) \times \ln \frac{P^T}{P^0} \quad (15)$$

3.5. Scenario Analysis

We estimated GHG emissions from China's pork supply system in 2030 under a business-as-usual (BAU) scenario and five mitigation scenarios. National pork production and feed intake for 2030 were projected based on mean values from published studies, including Ma et al. [50], Zhao et al. [51], the China Agricultural Outlook Report (2021–2030), and the OECD-FAO Agricultural Outlook (2021–2030). All incremental pork output between 2022 and 2030 was assumed to originate from industrial systems, with each province's share of national production fixed at 2022 levels. Provincial pork consumption in 2030 was projected based on province-level population forecasts (see S3 in SI). The BAU scenario assumed no technological or management improvements across production systems. Building upon the BAU baseline, four individual mitigation measures and one integrated strategy were evaluated.

The low-opportunity-cost feed (LCF) scenario partially replaced cereal grains and soybeans in pig diets with low-opportunity-cost feed sources, such as food waste and agro-industrial by-products [52,53]. Based on system-specific diet formulations and minimum digestible protein and energy requirements, we adopted the substitution ratios proposed by Fang et al. [54]. In traditional, medium, and industrial systems, cereal grains were replaced at rates of 98%, 22%, and 9%, respectively, and soybean feed at 85%, 36%, and 40%, respectively.

The manure-based fertilizer substitution (MFS) scenario assumed that all manure collected from animal housing in medium and industrial systems was composted, stored,

and returned to cropland in both solid and liquid forms. Following the principle of nitrogen-equivalent substitution, synthetic fertilizer application for feed crop cultivation was reduced accordingly.

The biogas fermentation (BFN) scenario assumed that pig manure from industrial systems was transported to centralized anaerobic digesters for biogas production. Nitrogen losses during digestion were assumed to be negligible. The biogas generated was used to replace fossil fuels consumed on industrial pig farms. The resulting digestate was separated into solid and liquid fractions prior to field application. Relative to undigested manure, we assumed a 46% reduction in the N_2O emission factor for solid digestate application and an 18% reduction in the ammonia emission factor for liquid digestate application [10,55].

The green transportation scenario (GEN) assumed full electrification of vehicles used for interprovincial pork transport. Within the cold chain, conventional R404A refrigerant was replaced with the low-global-warming-potential alternative R744 [16], and the refrigerant leakage rate was reduced from 15% to 5%.

The integrated optimization (ALL) scenario combined all four mitigation measures described above to assess their synergistic emission reduction potential across the entire supply chain.

3.6. Uncertainty Analysis

This study employed a Monte Carlo simulation to assess the uncertainty in projected GHG emissions for 2030. Probability density functions derived from the literature were assigned to key input parameters (Table S2). The simulation was performed with 10,000 iterations, and uncertainty ranges were reported as 95% confidence intervals of the resulting distributions.

4. Results

4.1. Spatial–Temporal Patterns of Pork Supply and Demand

China's pork production rose from 43.27 Mt in 2002 to a peak of 58.21 Mt in 2014, before dropping to 42.53 Mt in 2019 and recovering to 55.41 Mt in 2022 (Figure 2a). The sharp decline in 2019 was primarily attributable to the African swine fever outbreak. During the same period, the share of intensive operations expanded rapidly from 18.4% to 75.7%, representing an approximately 3.11 times increase (Figure 2a). Historically, pork production has been concentrated in southern China, accounting for 61.6–64.3% of the national total. Over the past 21 years, cumulative production increased by 6.81 Mt in the south and 5.35 Mt in the north (Figure 2b). However, during the nationwide production downturn between 2014 and 2022, declines in the south were more than five times greater than those in the north, reflecting the impact of the “South-to-North Pig Migration” policy. Under the National Swine Production Development Plan (2016–2020), regional production shares shifted modestly: potential-growth and moderate-development regions recorded increases, whereas restricted-development and prioritized-development regions experienced declines (Figure 2c). At the provincial level, pork production was concentrated in Sichuan, Hunan, Henan, and Shandong, which together contributed over 30% of national output. Heilongjiang exhibited the most rapid growth, with production rising from 0.82 Mt in 2002 to 1.92 Mt in 2022. Pork consumption was primarily concentrated in Guangdong, Sichuan, Hunan, and Jiangsu, together representing more than one-third of national consumption (Figure 2d–f).

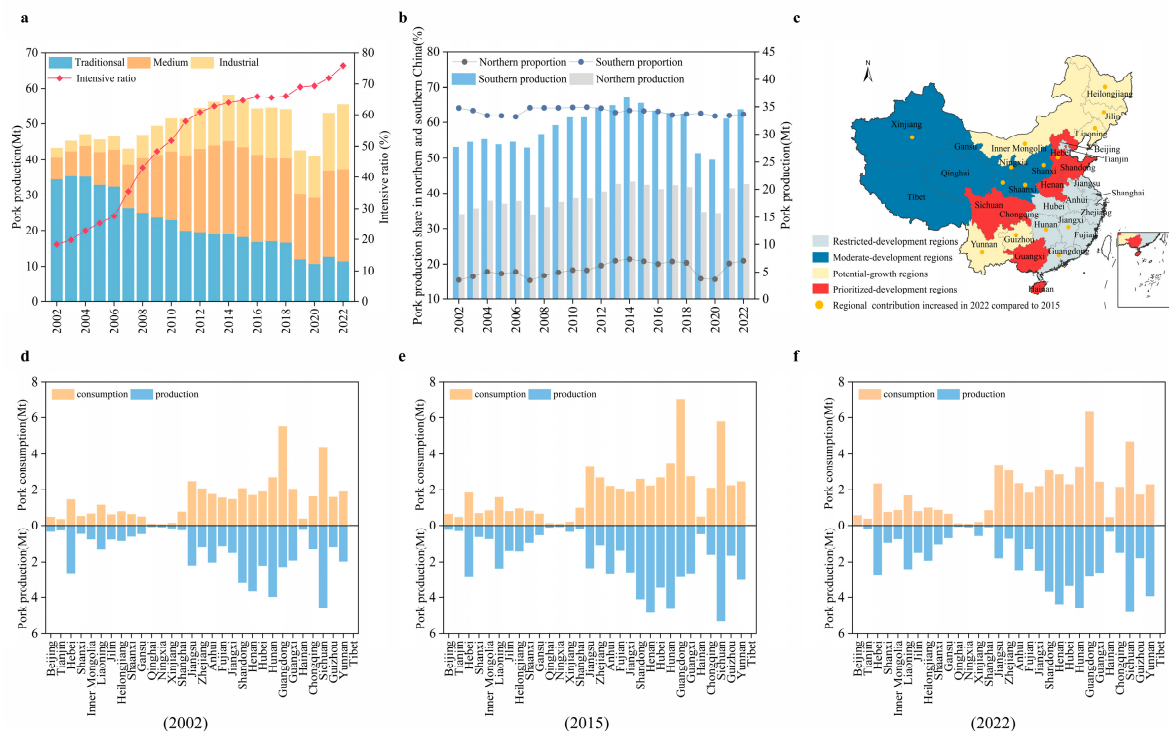


Figure 2. Spatial-temporal changes in pork production and consumption in 2000–2022. (a) National pork production and the percentage of intensive systems in the national pig population. (b) Pork production distribution in northern and southern China. (c) Changes in pork production contribution across regions from 2015 to 2022. (d–f) Provincial pork production and consumption in 2002, 2015, and 2022.

In terms of supply-demand balance, surplus provinces were mainly located in North-east, North, and Central China, whereas deficit regions were concentrated along the southeast coast and in major metropolitan areas. By 2022, Shanxi, Shaanxi, and Gansu (moderate-development areas), Jiangxi (restricted-development area), and Guizhou (potential-growth area) had transitioned from deficit to surplus status, while Inner Mongolia and Ningxia shifted from surplus to deficit (Figure 3a–c). The designation of no-breeding zones and stricter environmental regulations constrained livestock expansion in Inner Mongolia and Ningxia. Although the local self-sufficiency ratio remained consistently above 82.0% (Figure 3d), spatial supply-demand imbalances stimulated substantial interprovincial trade. Trade volumes increased from 6.84 Mt in 2002 to 11.45 Mt in 2017, before declining to 10.39 Mt in 2022. The proportion of cross-provincial pork consumption rose steadily, reaching 18.7% by 2022 (Figure 3d). Interprovincial transport distances grew from 72.43×10^3 km in 2002 to 106.97×10^3 km in 2014 and then fell to 79.47×10^3 km in 2022 (Figure 3e). Domestic food miles followed a similar trend, rising from 6786.39 Mt·km in 2002 to 16,424.10 Mt·km in 2014 before declining to 13,588.60 Mt·km in 2022. Cold-chain transport accounted for 44.0–70.4% of total food miles (Figure 3f). This trend reflected that, in the early stage, rapid expansion of intensive production concentrated capacity in advantageous regions, exacerbating the spatial mismatch between production and consumption and driving up interprovincial transport. The subsequent decline was largely attributable to the 2019 African swine fever outbreak, which sharply reduced national pig production. After 2020, interprovincial transport rebounded alongside production recovery.

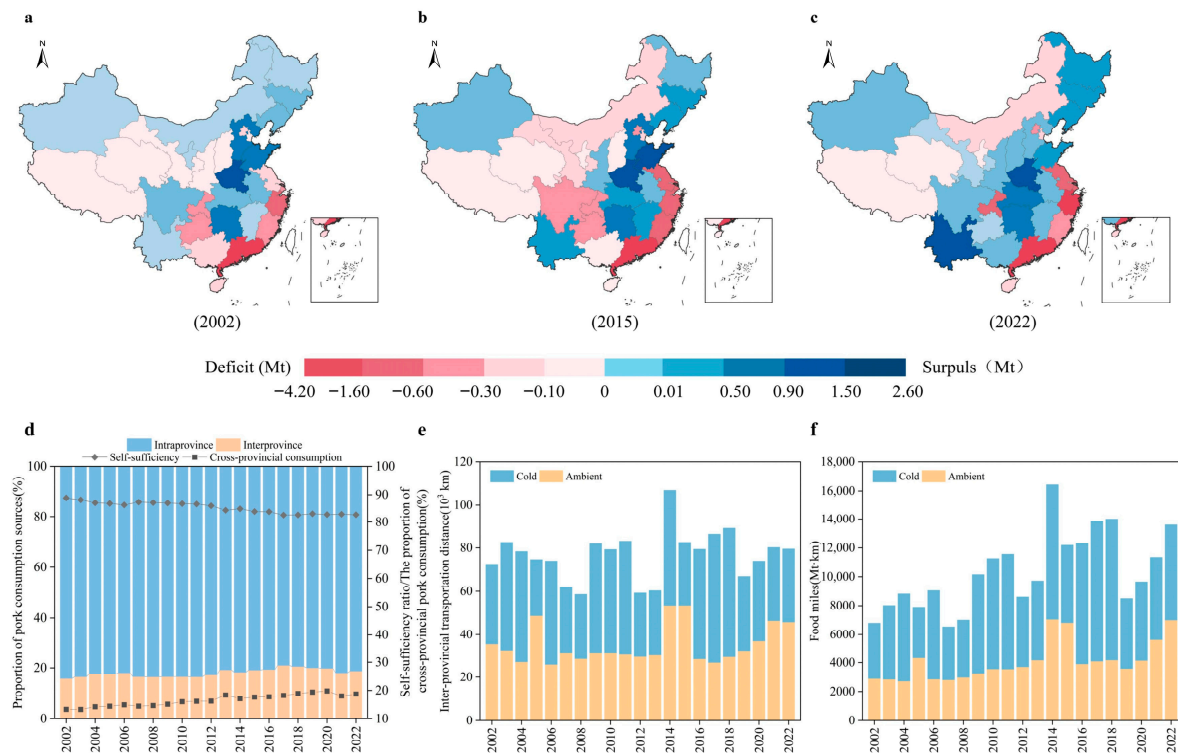


Figure 3. Pork surplus and deficit provinces and interprovincial trade in 2000–2022. (a–c) Pork surplus and deficit distribution in 2002, 2015, and 2022. (d) Origin of pork supply for consumption (locally produced pork and pork supplied through interprovincial trade) and self-sufficiency ratio (proportion of population supplied by local pork production, see S4 in SI). (e) Interprovincial transportation distances for pork. (f) Domestic food miles for pork.

4.2. GHG Emissions of the Pork Supply System

From 2002 to 2022, total GHG emissions from China's pork supply system increased by 110.1%, rising from 78.08 to 164.05 Mt CO₂eq (Figure 4a). The medium system drove much of this growth, with its share rising from 14.3% to 46.9%. The industrial system expanded from 5.4% to 25.4%, while the traditional system's share declined sharply from 80.2% to 23.6% (Figure 4b). Across the supply chain, pig farming remained the dominant emission source, contributing 50.4–62.7% of total emissions, followed by feed crop cultivation (29.7–42.1%), interprovincial pork transport (2.4–4.3%), pig slaughtering (2.4–4.4%), and feed processing (0.7–0.9%). Over time, the relative contribution of pig farming decreased, whereas that of feed crop cultivation increased (Figure 4c). Although emissions from interprovincial pork transport remained modest, they showed an overall upward trend (Figure S1). Regarding gas composition, N₂O represented the largest share at 35.1–40.2% of total emissions, primarily originating from manure management. Notably, after 2009, CO₂ emissions surpassed CH₄ emissions to become the second-largest contributor, maintaining a share of 32.8–36.7%. This increase was largely driven by emissions from feed crop cultivation (Figure 4d). This shift aligned with the accelerated intensification of pig farming following China's 2007 policy to promote pig production and stabilize market supply. Intensive systems relied heavily on commercial feed, mechanization, and energy inputs, thereby increasing CO₂ emissions from feed crop cultivation and animal breeding activities. Concurrently, the share of CH₄ emissions declined to approximately 27.0% by 2022, mainly originating from enteric fermentation and manure management (Figure 4d).

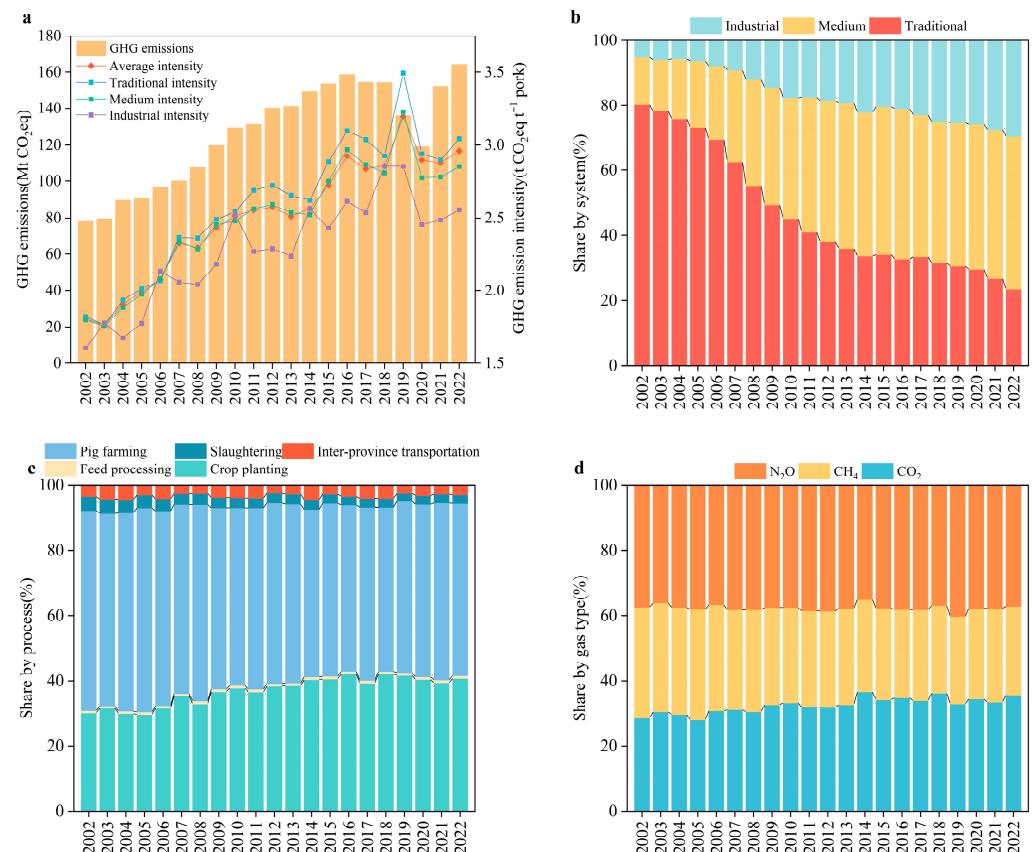


Figure 4. GHG emissions of China's pork supply system during 2002–2022. (a) GHG emissions and emission intensities. (b) Emission share by pig production systems. (c) Emission share by supply chain stages. (d) Emission share by gas types.

Among production systems, the industrial system exhibited the lowest emission intensity, reflecting economies of scale and improved feed conversion efficiency. In 2022, the industrial system accounted for 29.6% of total emissions while contributing 32.2% of national pork output (Figures 2a and 4a). Nevertheless, GHG emission intensity increased across all production systems over the 21-year period. In the traditional system, the rise was primarily driven by the pig farming stage, which accounted for 37.6% of the total increase (Figure 5a). In medium and industrial systems, the increase originated primarily from feed crop cultivation, where emission intensity grew by 0.63 t CO₂eq t⁻¹ and 0.54 t CO₂eq t⁻¹ pork, respectively (Figure 5b,c). This trend reflected the greater reliance of intensive operations on commercial feed and the low rate of manure nutrient recycling, which together raised synthetic fertilizer inputs for feed crop cultivation (Figure S2). By 2022, the average emission intensity of pork production in China reached 2.96 t CO₂eq per tonne of pork (range: 2.75–2.96), a value 1.64 times higher than in 2002 (Figure 4a). Consequently, although pork output in 2019 was lower than in 2002, total GHG emissions were higher (Figures 2a and 4a).

4.3. Drivers of Temporal Changes in GHG Emissions

Over the past two decades, GHG emissions from China's pork supply system followed a rise-and-fall trajectory, peaking in 2014. Using 2014 as a turning point, we employed the LMDI method to decompose the drivers of emission changes in two phases.

Between 2002 and 2014, total GHG emissions increased by 91.2%. This growth was mainly driven by rising emission intensity and increasing per capita pork consumption, which contributed 49.3% and 35.3% of the total increase, respectively. Conversely, shifts

in production structure exerted a modest mitigation effect, reducing emissions by 3.5% during this period. From 2014 to 2022, total emissions increased by 9.9%. Increasing emission intensity exerted an upward pressure of 12.40%, while declining per capita pork consumption offset emissions by 10.24%. Changes in production structure also contributed to a modest reduction of 1.3% (Figure 6).

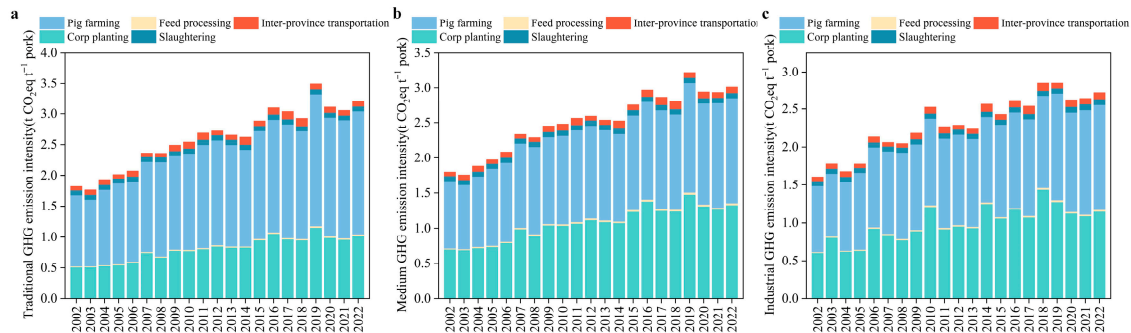


Figure 5. GHG emission intensity of pork supply chain in different systems, 2002–2022. (a) Traditional system. (b) Medium system. (c) Industrial system.

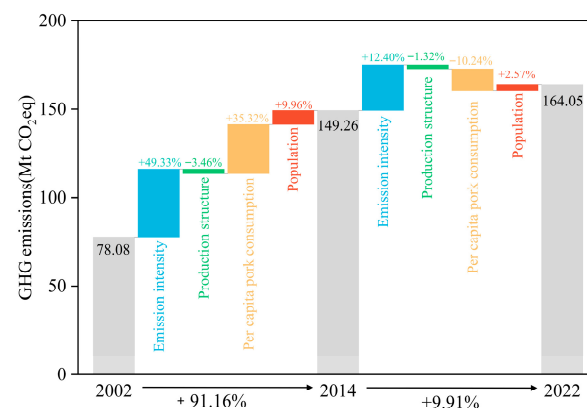


Figure 6. Contributions of key drivers to GHG emission changes in China's pork supply system (2002–2022).

Changes in emission intensity reflected intensification within each production system, whereas changes in production structure captured the shift between systems. The transition from smallholders to intensive operations had a limited but negative (mitigating) effect on GHG emissions. However, this effect was substantially outweighed by the positive effect of intensification within individual systems. As the livestock sector intensified, greater inputs of synthetic fertilizers, feed, and energy were adopted across all systems to raise productivity, thereby increasing emission intensities.

4.4. Projected Reduction of GHG Emissions from China's Pork Production in 2030

By 2030, China's pork production was projected to increase by 8.2% relative to 2020 levels, with intensive systems accounting for over 76.3% of total output. Pork production was expected to remain concentrated in Sichuan, Hunan, Henan, and Shandong (Figure 7a). The projected supply-demand pattern closely resembled that of 2022, with surplus provinces located in Northeast, North, and Central China, and deficits concentrated along the southeastern coast and in major metropolitan areas (Figure 7b). Under the BAU scenario, total GHG emissions from the pork supply system were projected to reach 158.85 Mt CO₂e. Medium and industrial systems were estimated to contribute 37.8% and 36.1% of total emissions, respectively. N₂O remained the dominant gas (39.2%), followed by CO₂ (34.6%) and CH₄ (26.1%). Across supply chain stages, pig farming accounted for 51.7%

of emissions, followed by feed crop cultivation (41.3%), interprovincial transportation (3.2%), pig slaughtering (2.9%), and feed processing (0.9%) (Figure 7c).

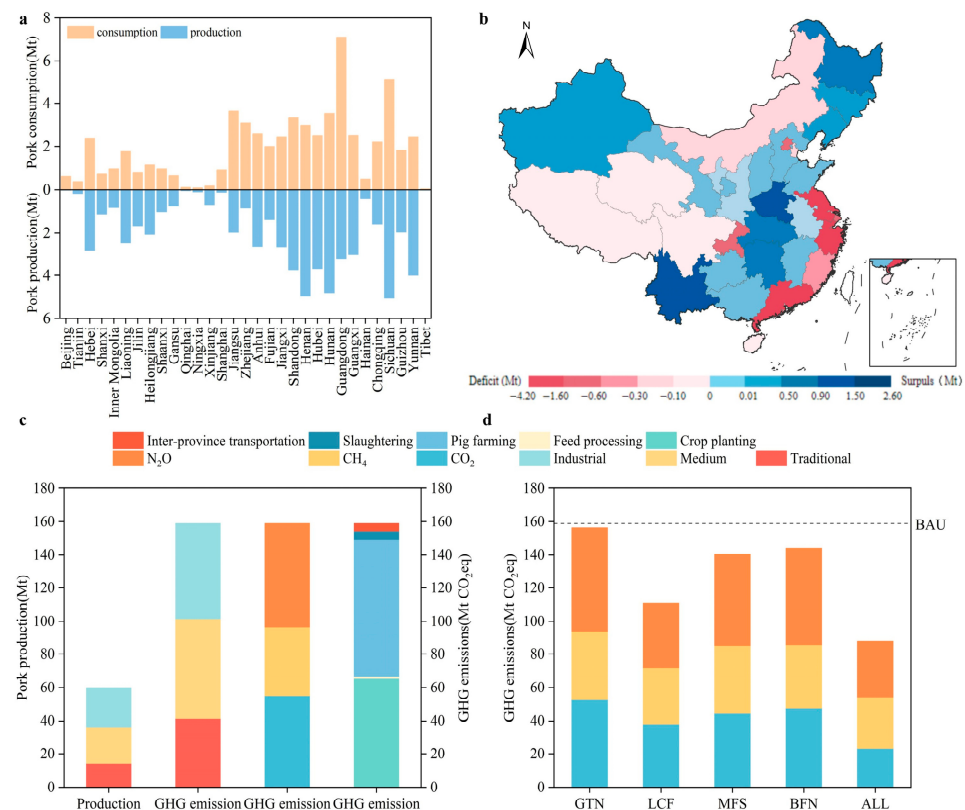


Figure 7. GHG emissions from China's pork supply system in 2030 under baseline and mitigation scenarios. (a) Provincial pork production and consumption in 2030. (b) Pork surplus and deficit distribution in 2030. (c) Baseline emissions. (d) Emissions under mitigation scenarios.

Among individual mitigation strategies, low-opportunity-cost feed substitution (LCF) achieved the greatest reduction, lowering total emissions by 30.3%. This reduction resulted primarily from decreased production and application of synthetic fertilizers. Manure-based fertilizer substitution (MFS) and biogas fermentation (BFN) reduced emissions by 11.5% and 9.4%, respectively, highlighting the mitigation potential of circular agricultural practices that enhance nitrogen recycling and renewable energy recovery. Green transport (GTN) contributed a smaller reduction (1.6%) but supported broader decarbonization objectives.

When all measures were combined in the integrated optimization scenario (ALL), national emissions fell to 80.82 Mt CO₂eq, 49.1% below the projected 2030 BAU level and 50.7% lower than 2022 emissions (Figure 7d). These findings demonstrated that coordinated improvements in feeding practices, manure management, biogas utilization, and transportation decarbonization can simultaneously support increased pork production and substantial supply chain emission reductions, offering both environmental and economic co-benefits.

5. Discussion

5.1. Comparison with Existing Research

Previous studies have estimated GHG emissions from China's pork production between 2014 and 2022 to be 118.57–159.13 Mt [17,21,56], and our estimate (excluding the interprovincial pork transport stage) fell within this range. In terms of emission intensity, our results were also consistent with the existing literature (2.20–5.96 kg CO₂eq kg^{−1}

pork) [14,57,58]. For 2017, we estimated total emissions at 154 Tg, closely aligning with Long et al. [17] (152 Tg). The minor discrepancy primarily arises from differences in system boundaries: our study included interprovincial transportation, whereas Long et al. [17] excluded this stage but incorporated land-use change emissions from overseas feed production. Zhang et al. [59] reported a higher emission value of 159.13 Tg, likely due to their use of an inventory-based method with IPCC default emission factors. Luo et al. [57] estimated the emission intensity for Sichuan Province in 2012 at 5.96 kg CO₂eq kg^{−1} pork, substantially higher than our national average of 2.57 kg CO₂eq kg^{−1} in the same year. This difference mainly reflects variations in regional scope and system boundaries. Xu et al. [58] reported a lower value of 2.2 kg CO₂eq kg^{−1} pork, attributable to their narrower system boundary limited to pig farming and the application of IPCC Tier 1 methodology.

A key innovation of this study was its systematic integration of the shift toward intensive pig production into the dynamic temporal analysis of GHG emissions. Intensification not only increased pork productivity but also reshaped energy use patterns, feeding practices, and manure management. First, growing reliance on fossil energy for feed crop cultivation, pig farming, and interprovincial pork transport has steadily increased CO₂ emissions, which have surpassed CH₄ to become the second-largest emission source in the pork supply system (Figure 4d). In our historical analysis, improvements in China's electricity generation mix were accounted for by incorporating time-varying grid carbon intensity, partially offsetting electricity-related CO₂ emissions. Second, intensive pig farms increased reliance on feed grains and reduced the use of kitchen waste and agricultural by-products. This shift in diet formulation affected not only feed crop cultivation, processing, and transportation, but also animal performance and manure nitrogen excretion, making it a critical leverage point for GHG mitigation [20]. Our model explicitly captured the dynamic linkage between feed composition and GHG emissions, identifying feed grain reduction and substitution as the single most effective technological pathway for emission reduction. Third, intensification has further decoupled livestock production from cropland, complicating manure management and increasing dependence on synthetic fertilizers for feed crop cultivation. Consequently, N₂O emissions from manure management and fertilizer application have risen and remain the largest contributor to total GHG emissions in the pork supply system.

Another innovation of this study was the incorporation of spatial supply–demand dynamics into GHG accounting by quantifying emissions from interprovincial pork transport. While previous studies have examined the regional environmental consequences of China's "South-to-North Pig Migration" policy [6,37], the environmental footprint of cross-regional food transport has often been overlooked. Our findings showed that although over 80% of pork demand was met locally, the local self-sufficiency ratio has declined, while interprovincial food miles and associated transport emissions have increased (Figures 3d–f and S1). Including interprovincial pork transport within the GHG accounting boundary is therefore essential to prevent carbon leakage arising from industrial relocation and spatial restructuring [39].

5.2. Scenario Feasibility

Systemic solutions are increasingly advocated to address the issues arising from the transformation of the global agri-food system [60]. Our results indicated that supply chain optimization (ALL), integrating low-opportunity-cost feed use, manure-based fertilizer substitution, biogas production, and green transportation, could reduce GHG emissions by nearly 50% while supporting continued growth in pork production (Figure 7d). Among individual interventions, low-opportunity-cost feed substitution exhibited the greatest mitigation potential. Globally, around 1.3 billion tons of food are lost or wasted annually,

much of which contains substantial crude protein and essential nutrients [61]. Redirecting these resources to livestock feed can reduce dependence on soybean imports, decrease upstream land and water use, and lower synthetic fertilizer demand associated with feed production [54,62]. Considering that the conserved land can be used to grow food directly consumed by humans or for afforestation, this strategy also contributes to food security and ecological protection [54,63]. Potential disease risks associated with such alternative feeds could be effectively mitigated through thermal treatment [64]. Empirical feeding trials have confirmed that partial substitution does not significantly compromise animal growth or meat quality [65]. In terms of social acceptance, farmer surveys further suggest broad support for this practice when food safety is ensured [66]. Moreover, the longstanding practice of feeding food waste to livestock among smallholders in China reinforces its practical feasibility. Since 2018, national policies promoting soybean meal reduction and substitution have provided institutional support for implementation.

Substituting manure for synthetic fertilizers can mitigate GHG emissions from fertilizer production while improving soil health [67,68]. However, spatial decoupling between crop and livestock systems has limited its adoption. In China, the share of rural households practicing integrated crop-livestock farming declined from 71% in 1986 to 12% in 2017 [34], increasing the logistical cost of manure transport, particularly for liquid forms [69]. Nevertheless, intensive farms possess greater technological and financial capacity to improve solid-liquid separation and manure processing, facilitating cross-regional nutrient recycling [70]. Yin et al. [71] estimated that compared to the implementation costs (including capital investment in facility upgrades, transportation, and labor), the social benefits combining climate, public health, and ecosystem benefits of returning manure to fields were three times higher. Circular agriculture pilot programs in China have promoted manure reuse through financial incentives and technical support [72], with anaerobic digestion serving as a key management pathway [73]. To promote broader adoption, policy frameworks should extend beyond infrastructure subsidies to include priority grid access for biogas electricity, organic fertilizer certification systems, and subsidies for recycled nutrient application.

Although green transportation reduces total GHG emissions by only 1.6% (Figure 7d), it is highly scalable with existing technologies. Transport electrification is widely recognized as an immediate and effective mitigation strategy [59]. Advances in new-energy commercial vehicles and the rapid expansion of charging infrastructure in China provide a strong foundation for this transition. Combined with operational subsidies and supportive policies, the electrification of freight transport can further accelerate decarbonization [74].

5.3. Uncertainty and Limitations

While this study incorporated spatial supply–demand dynamics into transport emission estimates, it did not fully account for spatial heterogeneity in production-related emissions. In practice, GHG emission intensity in pork production varies across regions due to differences in climate, technology, and management practices. To evaluate the uncertainty in our estimates, we performed a Monte Carlo simulation of the 2030 pork supply chain emissions. The results showed that within a 95% confidence interval, supply chain emissions varied by -11.0% to $+11.9\%$ (Figure S3a). Uncertainties in intensification rates and slaughter rates contributed approximately $\pm 0.1\%$ variation (Figure S3b). Fluctuations in crop yield per unit area, as well as in the application rates of fertilizer, plastic mulch, and pesticides, led to emission variations ranging from -5.6% to $+5.7\%$ (Figure S3c). Uncertainties in nitrogen emission factors for synthetic fertilizer application and manure management resulted in variations of -5.2% to $+5.1\%$ and -8.0% to $+7.6\%$, respectively (Figure S3d,e). Variability in energy consumption across the supply chain

contributed to a -4.4% to $+4.2\%$ range in total emissions (Figure S3f). Future studies should incorporate region-specific emission factors and higher-resolution activity data to improve estimation accuracy.

In our scenario analysis, mitigation potential depended on key parameter assumptions, such as technology adoption rates, which may evolve with technological progress, market conditions, and policy support. Future work could adopt approaches such as the regional reference group method to incorporate perspectives from industry and policymakers, thereby refining parameter calibration [75]. Furthermore, our study analyzed the spatial adjustment at the provincial level, limiting spatial resolution. Future research could employ higher-resolution survey data to enhance spatial granularity and support more targeted policy design.

6. Conclusions

This study examined the dynamics of GHG emissions in China's pork supply system under ongoing production intensification and spatial reconfiguration of supply and demand between 2002 and 2022. The results indicated that the South-to-North Pig Migration policy reshaped the spatial distribution of pig production, although southern China remained dominant in national output. Changes in the geographic configuration of pork supply and demand increased the proportion of cross-provincial consumption and extended average food miles. While emissions from interprovincial pork transport remained relatively modest, they exhibited an upward trend over time. Simultaneously, the shift toward intensive pig farming altered the emission structure of the supply chain. From a production-system perspective, medium and industrial operations became the primary contributors to total emissions, with their combined share rising from 18.4% to 75.7%. In terms of gas composition, CO₂ emissions surpassed CH₄ to become the second-largest GHG source, largely driven by increased inputs of synthetic fertilizers and fossil energy associated with intensification. Across supply chain stages, the relative contribution of pig farming declined, whereas that of feed crop cultivation increased, reflecting greater reliance on commercial feed and reduced manure nutrient recycling to cropland. In China, the GHG emission intensity of pork production increased from 1.80 t CO₂eq t⁻¹ pork in 2002 to 2.79 t CO₂eq t⁻¹ pork in 2022, with the industrial system exhibiting the lowest emission intensity among all production systems. Decomposition analysis showed that the transition from smallholders to intensive operations had an inhibitory effect on GHG emissions, but this was offset by a much larger positive effect from rising emission intensities across all systems. Interventions targeting individual stages offered limited mitigation potential. In contrast, an integrated optimization strategy combining improved feeding practices, enhanced waste resource recovery, clean energy substitution, and green logistics could achieve a 49.1% reduction in total emissions by 2030 relative to a baseline scenario. The theoretical contribution of this study resides in its systematic elucidation of how pork supply–demand dynamics and production intensification shape the environmental footprint of pork supply systems. It enriches the broader research agenda on food system transformation and livestock sustainability. On a practical level, the findings provide policymakers with both empirical evidence and actionable strategies for mitigating GHG emissions through spatial and technological optimization, not only within China's pork supply system but also in analogous food systems worldwide. By systematically examining low-carbon transition pathways, this research furnishes robust analytical support for the implementation of national sustainable development strategies.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/su18052395/s1>: Figure S1: Interprovincial pork transport GHG emissions during 2002–2022; Figure S2: Feed grain use and synthetic fertilizer inputs in pig farming during 2002–2022; Figure S3: Uncertainty analysis of GHG emissions from China’s pork supply chain in 2030; Table S1: The calculation formulas and data sources used in this study; Table S2: Summary of uncertainty values assumed for the GHG estimation model parameters and data inputs used in the Monte Carlo analysis. References [76–131] are cited in the Supplementary Materials.

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