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Does Interregional Trade Lead to a Shift in CH_4 Emissions? A Study Based on a Multi-Region Input-Output Model and Structural Path Analysis

Yujie Wang [1,*], Tongsen Hao [1], Muyao Qin [1,*], Xinru Wang [2], Qing Miao [3], Liwei Jin [1] and Xiao Gu [4]

[1] School of Economics and Management, Taiyuan University of Technology, Taiyuan 030324, China
[2] School of Economics and Management, Shanghai University of Electric Power, Shanghai 200090, China
[3] School of Philosophy, Shanxi University, Taiyuan 030006, China
[4] School of Business, Shanghai Dianji University, Shanghai 201306, China
* Correspondence: wangyujie@tyut.edu.cn (Y.W.); qin_muyao@163.com (M.Q.)

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Abstract: As global climate change intensifies, the need to reduce emissions of methane (CH_4), a potent short-lived greenhouse gas, is becoming increasingly urgent. As the world's largest emitter of CH_4, China urgently needs to conduct in-depth research into the CH_4 emissions associated with interprovincial trade. This study first established a methane emission accounting model covering energy activities, waste and wastewater, and agricultural activities, and estimated CH_4 emissions for China's 31 provinces from 2012 to 2022. Building on this foundation, the study integrated methods such as multi-region input-output modeling, sectoral decomposition, structural path analysis, and sensitivity analysis to conduct an in-depth investigation into the patterns of CH_4 transfers implied by interprovincial trade in China in 2017, quantify indirect CH_4 emissions from household consumption in China, and identify key sectors and pathways for emissions reductions across different industrial sectors. The key findings are as follows: (1) From 2012 to 2022, China's annual CH_4 emissions averaged 58.1738 million metric tons, exhibiting a fluctuating trend characterized by a decline followed by an increase. (2) Interprovincial trade had a significant impact on China's CH_4 emissions. CH_4 emissions have shifted from east to west and from coastal to inland regions. There are marked differences in the total volume and structure of CH_4 emissions from both the production and consumption sides across provinces, with Zhejiang Province (3.022 million metric tons), Jiangsu Province (2.7337 million metric tons), and Guangdong Province (2.388 million metric tons) accounting for the largest outflows. (3) In 2017, indirect CH_4 emissions from household consumption were primarily concentrated in the first four industrial levels (PL^0~PL^3), mainly originating from four sectors: construction (S28), food and tobacco (S6), agricultural, forestry, livestock, and fishery products and services (S1), and water, environmental, and public facility management (S37). (4) At the 0th industrial level, key pathways for reducing indirect CH_4 emissions from household consumption include the sectors of agricultural, forestry, livestock, and fishery products and services, and water, environmental, and public infrastructure management. At the 1st to 3rd industrial levels, there are 10 key pathways for emission reductions, and a distinct "sectoral aggregation" phenomenon is observed. Finally, relevant policy recommendations are proposed to provide a scientific basis for CH_4 emission reductions at the provincial level in China.

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1. Introduction

As extreme weather events strike more often, ecosystems suffer greater disruption, and the threat of global warming intensifies, cutting greenhouse gas emissions has emerged as a shared priority for the international community. Methane (CH_4) is second only to carbon dioxide as a greenhouse gas, with a 100-year warming potential 20-fold higher than CO_2, and is responsible for about 30% of current global warming [1,2]. Studies suggest that a rapid strengthening of methane mitigation efforts has the potential to substantially curb near- to medium-term climate change, averting close to 0.3 °C of temperature rise by 2040 [3,4]. In recent years, the international community has placed significantly greater emphasis on methane management. Introduced at the 2021 COP26 summit, the Global Methane Pledge (GMP) unites more than 150 countries committed to reducing worldwide methane emissions by at least 30% below 2020 levels by 2030 [5]. At the 2025 COP30 summit, seven nations, including Britain, France, and Germany, vowed to virtually eliminate methane emissions originating from their fossil energy sectors. As one of the world's top greenhouse gas emitters, China contributes roughly one-fifth of global methane emissions [6]. For the first time, China incorporated methane into its list of non-CO_2 greenhouse gas control priorities under the 14th Five-Year Plan. In 2023, China officially released the "Action Plan for Methane Emission Control". By September 2025, China had incorporated methane into its 2035 Nationally Determined Contribution (NDC) targets. This marks a historic milestone in China's methane governance. Against this backdrop, this study systematically deconstructs the CH_4 emission characteristics across the entire upstream supply chain of household consumption and precisely identifies key sectors and priority emission reduction pathways. This holds significant importance for supporting China's non-CO_2 greenhouse gas governance and achieving its climate goals.

Extensive research on CH_4 emissions has been undertaken by researchers worldwide [7]. Existing studies primarily focus on the following areas. First, the accounting of greenhouse gas emissions such as methane, as well as the assessment of trends and uncertainties. Existing research suggests that China's non-CO_2 GHG emission estimates still carry considerable uncertainty, largely owing to discrepancies in activity data, gaps in source coverage, and outdated emission factors [8]. Second, research on methane reduction potential and costs in key sectors. Particular focus is placed on high-emission sectors such as coal mining [9,10], oil and gas [11,12], agriculture [13], and waste management [14,15]. These studies emphasize that China possesses substantial methane reduction potential by 2030, with some measures exhibiting negative costs [3,16]. Third, examining the economic determinants of methane emissions and the allocation of responsibility from supply-chain and final-demand standpoints. Existing research indicates that the global growth in methane emissions is closely linked to consumption expansion, supply chain division of labor, and adjustments in production structures, with trade and final demand playing a significant role in driving the cross-regional transfer of methane emissions [1,2,17]. Overall, existing research has provided a crucial foundation for understanding the sources of methane emissions, mitigation potential, and economic drivers.

Amid China's tightening interregional economic linkages and the growing specialization of industrial chains, the geographic decoupling of production from consumption has become ever more prevalent [18]. Final demand in a given region often does not fully correspond to local emissions. Rather, the associated emissions can be shifted to other regions via intermediate goods and cross-regional trade flows [6,19]. Focusing on methane emissions exclusively through a production- or consumption-based lens may neglect the interregional shifting of environmental loads, consequently undermining both the assignment of mitigation duties and equity [20]. From an interprovincial trade perspective, it is essential to systematically map the transfer patterns, differentiated responsibilities, and critical mitigation pathways associated with China's embodied CH_4 emissions. Such an endeavor constitutes both a theoretical prerequisite for unraveling the spatial linkages underpinning national methane emissions and a practical basis for refining coordinated regional abatement policies. However, existing research has paid relatively little attention to this issue. Most existing studies on methane have focused on national-level total emissions accounting, emission reduction potential in key sectors, or trade linkages at the global scale [1,2,17]. However, the spatial redistribution of methane emissions driven by interprovincial trade amid China's deepening regional specialization remains largely underexplored. The few studies addressing provincial-level CH_4 footprints or trade linkages in China have primarily examined the nested relationship between local emissions and global final demand [6] or focused on global-local interactions of non-CO_2 greenhouse gases in agriculture [21]. However, there remains a lack of direct and systematic identification of the redistribution of CH_4 emission responsibilities resulting from

interprovincial trade itself [22]. Furthermore, existing research still lacks an in-depth characterization of the transmission mechanisms, key nodes, and mitigation pathways of indirect CH_4 emissions driven by household consumption across different levels of the industrial chain.

Based on this, this study takes China's 31 provincial-level administrative regions as its research subjects and constructs a CH_4 emissions accounting model across three dimensions (energy activities, waste and wastewater, and agricultural activities) to systematically estimate provincial-level CH_4 emissions in China from 2012 to 2022. On this basis, the study incorporates a multi-regional input-output framework to trace the CH_4 emission flows embodied in interprovincial trade through both producer- and consumer-responsibility lenses, and further examines the net outflow and inflow profiles of various regions. Furthermore, by employing methods such as sectoral decomposition, structural path analysis, and sensitivity analysis, this study quantifies indirect CH_4 emissions driven by household consumption, identifies key sectors and core emission reduction pathways across different industrial tiers, and thereby provides more targeted scientific evidence for provincial-level CH_4 emission reduction and regional collaborative governance in China.

The contributions of this research are threefold. First, concerning the dimensions of measurement and the assignment of responsibility, the study couples methane emissions accounting with an MRIO framework to build a dual-perspective provincial accounting system for trade-embodied methane, encompassing emissions from both the production side and the final demand side. This helps to more accurately clarify the attribution of emissions responsibility in the context of interprovincial trade. Second, regarding spatial transfer characteristics, this study examines provincial-level units nationwide to systematically reveal the flow patterns, net transfer patterns, and regional differences of CH_4 emissions embedded in China's interprovincial trade. This provides empirical evidence from a CH_4 perspective to understand the "Eastern consumption, Central and Western burden-bearing" model of environmental burden transfer. Third, regarding emission reduction pathways, this study goes beyond traditional total accounting approaches. By employing industry-level decomposition, structural pathway analysis, and sensitivity analysis, it systematically deconstructs the methane emission characteristics of the entire upstream supply chain of household consumption, precisely identifying key sectors and priority pathways. This provides a foundation for shifting CH_4 emission reduction policies from "end-of-pipe treatment" to "supply chain governance" and "coordinated governance".

The remainder of this paper is organized as follows. Section 2 describes the research methodology and data sources. Section 3 presents the results and discussion and Section 4 summarizes the paper and offers policy recommendations.

2. Research Methods and Data Sources

2.1. CH_4 Emissions Accounting Model

Several approaches can be employed to estimate greenhouse gas emissions, such as life cycle assessment (LCA), large-scale environmental input-output (EIO) analysis, a hybrid model that merges the two (Hybrid LCA-EIO), IPCC guidelines, and carbon footprint calculators [23]. After the release of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, the IPCC framework was quickly embraced. In the years that followed, researchers at home and abroad applied IPCC methods to study greenhouse gas emissions at both national and subnational scales. They further conducted significant investigations into uncertainty analysis, as outlined in the IPCC Fourth Assessment Report, and developed approaches for quantifying uncertainty during the compilation of provincial-level inventories. Accordingly, a methane emission inventory model was developed drawing on the methodologies and emission factors outlined in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories and their 2019 Refinement. Given the profile of anthropogenic methane emissions in China, the analysis concentrates on three principal Tier 1 categories and their nine constituent Tier 2 subcategories (Figure 1), namely: energy activities (coal mining and processing, oil and gas systems); waste and wastewater (landfill disposal, industrial wastewater, domestic sewage); and agricultural activities (enteric fermentation, manure management, straw burning, and rice cultivation). As indicated in the 2023 Third Biennial Update Report on Climate Change of the People's Republic of China, these sources jointly contribute nearly 93.8% of the country's total anthropogenic methane output, underscoring their strong representativeness [24].

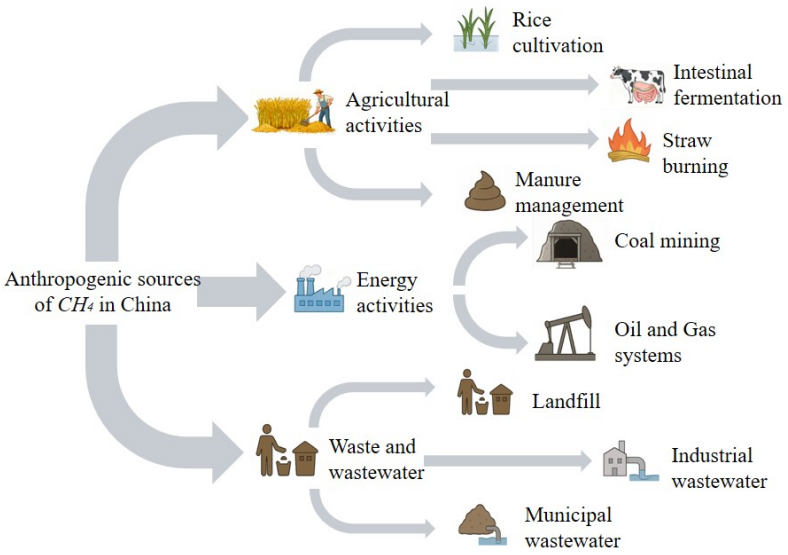

Figure 1. Composition of sources of anthropogenic methane emissions in China.

(1) Methane emissions from energy activities are estimated as follows. Coal mining and processing contribute roughly 83% of total methane emissions from energy activities, while oil and gas systems account for about 13% [25]. During post-mining stages, which include coal extraction, processing, and transportation, methane that was previously adsorbed onto coal matrix particles during coalification is released, resulting in emissions. Based on the calculation methods set out in the 2006 IPCC National Greenhouse Gas Inventory Guidelines, the main equations used in this study to quantify methane emissions from coal mining and processing are as follows:

$$EC_{CH_4} = Q_M \times r \times \rho \tag{1}$$

$$Q_X = Q_J T/(Q_M K_H) \tag{2}$$

$$r_i = \frac{1}{Q_{M_i}} \sum_{j=1}^{m_i} Q_{X_{ij}} Q_{M_{ij}} \tag{3}$$

$$Q_{M_i} = \sum_{i=1}^{n} Q_{M_{ij}} \tag{4}$$

where EC_{CH_4} represents total methane emissions (Gg). Q_M represents raw coal production ($10^6 t$). r denotes the methane outgassing factor (m^3/t), and ρ denotes the conversion factor ($Gg/10^6 m^3$). Where Q_X represents the relative methane outgassing rate (m^3/t). Q_J represents the total absolute methane outgassing volume (m^3), and T is the time conversion factor. K_H represents the correction factor for post-mining methane emissions, derived from the IPCC estimation approach and the mean figure presented in China's Second National Communication on Climate Change; its value is 1.16. Where r_i is the outgassing coefficient for coal mine type i (m^3/t. Note: i represents the three coal mine types, $i = 1, 2, 3$. j denotes a specific mine within a given type, $j = 1, 2, m$. m_i denotes the number of coal mines of type i. $Q_{X_{ij}}$ denotes the relative methane outflow rate of a specific coal mine of type i (m^3/t). $Q_{M_{ij}}$ denotes the raw coal production of a specific coal mine of type i (t). Q_{M_i} denotes the total raw coal production of coal mines of type i.

According to the IPCC 2006 Guidelines for National Greenhouse Gas Inventories (2019 Revision), substantial fugitive methane emissions in China's oil and gas sector arise from three main sources, namely equipment leaks, process venting, and flaring [26]. Drawing on the same Guidelines and considering data availability, this study applies a Tier 1 approach to quantify fugitive methane releases from the oil and gas system, as expressed by the following formula:

$$E_i = \sum (P_{i,k} \times EF_{i,k}) \tag{5}$$

where E represents the total methane fugitive emissions. P represents activity level data for each stage of the crude oil and natural gas systems. EF denotes the methane emission factor. i represents the oil or natural gas system. k denotes the activity category within the oil and natural gas systems.

(2) Accounting for methane emissions from waste and wastewater. Currently, anaerobic landfilling is still the predominant way of disposing of municipal solid waste in China. Accordingly, studies on CH_4 emissions from municipal solid waste mainly adopt the mass-based landfilling approach, and its calculation formula is presented below:

$$E_{CH_4} = MSW_T \times MSW_F \times L_0 \times (1 - f) \times (1 - OX) \tag{6}$$

$$L_0 = MCF \times DOC \times DOC_f \times F \times \frac{16}{12} \tag{7}$$

where E_{CH_4} represents total CH_4 emissions (t/a). MSW_T represents municipal solid waste generation (t/a). MSW_F represents the waste landfill disposal rate (%). L_0 represents CH_4 production potential (t/t). f represents the landfill gas collection and utilization rate (%). OX represents the oxidation factor. MCF denotes the methane correction factor. DOC refers to the degradable organic carbon content (expressed in %), while DOC_f stands for the fraction of that carbon which decomposes to methane (%). The constant 16/12 serves as the methane-to-carbon conversion ratio, and F indicates the percentage of methane present in the landfill gas produced.

In the wastewater treatment process, direct methane emissions primarily occur in primary settling tanks and during anaerobic processes in the biological treatment stage. Methane emissions in this study are estimated following the methodologies specified in the IPCC 2006 Guidelines for National Greenhouse Gas Inventories and their 2019 Refinement [25,26]. The detailed calculation formula is presented below:

$$E_{CH_{4\text{-}dw}} = \sum (T \times EF) - R \tag{8}$$

$$EF = B_0 \times M \tag{9}$$

$$E_{CH_{4\text{-}iw}} = \sum_i [(T_i - S_i) \times EF_i] \tag{10}$$

$$E_{CH_4} = E_{CH_{4\text{-}dw}} + E_{CH_{4\text{-}iw}} \tag{11}$$

where $E_{CH_{4\text{-}dw}}$ represents the total annual methane emissions from domestic wastewater, in Gg CH_4/a. T represents the annual organic load of domestic wastewater, in kg BOD/a. Biochemical oxygen demand (BOD) indicates the amount of organic matter in domestic wastewater, i.e., the amount of organic matter that could be biodegraded under aerobic conditions. EF represents the emission factor, kg CH_4/kg BOD. Where B_0 represents the maximum methane production capacity, with a default value of 0.6 kg CH_4/kg BOD or 0.25 kg CH_4/kg COD, where COD stands for Chemical Oxygen Demand, representing the amount of organic matter in industrial wastewater, i.e., the amount of oxygen required to oxidize organic pollutants in water using chemical oxidants. M is the methane correction factor ($M = 0.165$ for domestic wastewater, $M = 0.4674$ for industrial wastewater). Where $E_{CH_{4\text{-}iw}}$ represents the total annual methane emissions from industrial wastewater, in Gg CH_4/a. T_i represents the total amount of biodegradable organic matter in wastewater from various industrial sectors in a given year, in kg BOD/a. S_i represents the organic matter removed via sludge annually, kg COD/a. EF_i represents the emission factor for each discharge system, kg CH_4/kg COD, calculated as shown in Equation (9), with a default value of 0.25 kg CH_4/kg COD. Where 0.25 kg CH_4/kg COD represents the total annual methane emissions, kg CH_4/a.

(3) Methane emissions from agricultural activities. While livestock farming brings economic benefits to farmers, it also poses environmental pollution issues stemming from unscientific management practices [25,26]. Enteric CH_4 emissions were quantified for a range of animal species, namely dairy and non-dairy cattle, water buffalo, goats, sheep, camels, pigs, horses, donkeys, and mules. Although methane emission factors from poultry manure management are relatively small, given China's massive poultry population, the resulting CH_4 emissions cannot be ignored and are therefore included in the calculations of this study. The specific calculation formula is as follows:

$$E = \sum_{i=1}^{n} [(C_{ki} + F_{ki}) \times (N_{ki} + G_{ki}) \times 10] \tag{12}$$

where C_{ki} represents the methane emission factor from animal enteric fermentation, kg/(n·y). F_{ki} represents the methane emission factor from manure management, kg/(n·y). N_{ki} represents the number of animals marketed (10^4). G_{ki} represents the year-end livestock inventory (10^4) and k represents the animal species (pigs, cattle, sheep, poultry). E represents the total methane greenhouse gas emissions from animals (i). Rice cultivation represents another notable source of methane. Drawing upon the methodologies set out in the IPCC 2006 National Greenhouse Gas Inventory Guidelines (2019 Revised Edition) and the Provincial Greenhouse Gas Inventory Compilation Guidelines (Trial Version) [26,27]. This study estimates emissions by multiplying the acreage of rice under distinct cropping systems by the seasonal methane emission factors. The equation is:

$$E_{CH_4} = \sum (EF_i \times AD_i) \quad (i = 1,2,3) \tag{13}$$

where E_{CH_4} represents methane emissions from rice cultivation (tons). EF_i represents the methane emission factor for a specific type of paddy field (kg/ha). AD_i refers to the harvested area of rice associated with the respective emission factor (in thousand hectares). Where the index i indicates the paddy field category, which can be single-cropping rice, early double-cropping rice, or late double-cropping rice.

Based on the realities of China's agricultural sector, the study focuses on residues from rice, wheat, corn, cotton, soybeans, tubers, and other grains, following the estimation approaches specified in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [25]. To evaluate the atmospheric impact of straw burning more precisely, the following formula is applied in the quantitative assessment:

$$E_i = \sum (P_{i,k} \times C_k \times R_k \times F \times EF_k) \tag{14}$$

where i denotes a province. k denotes a crop type. E_i denotes the methane emissions from crop straw burning in province i. $P_{i,k}$ denotes the yield of crop k in province i. C_k denotes the grain-to-straw ratio of crop k, %. R_k denotes the proportion of crop k straw burned in the open air, %. F denotes the combustion efficiency. EF_k denotes the emission factor for open-air burning of crop k's straw, in g/kg.

2.2. CH_4 Shift Characteristic Identification Model

Proposed by the American economist Wassily Leontief in the 1930s, the Input-Output Model (IOM) is a quantitative economic framework designed to investigate and describe the structure and operation of a national economy. Its theoretical foundation and mathematical methods are primarily derived from Walras's "General Equilibrium Theory" and the mathematical methods employed therein [28]. From the 1970s onward, the limitations of conventional environmental assessment techniques in tracing systemic interlinkages and indirect effects prompted scholars to expand input-output analysis into the environmental sphere, leading to the development of the Environmental Extended Input-Output (EE-IO) framework. According to particular analytical objectives, this model can be divided into single-region, multi-region, and sectoral input-output varieties [29]. Relative to standard life cycle assessment approaches, the EE-IO model excels at uncovering the fundamental connections between environmental and economic systems and at reconciling economic growth with environmental stewardship [30]. Consequently, it has been widely applied in research on energy consumption structure analysis [31,32] and carbon emissions accounting [33,34].

2.2.1. Multi-Region Input-Output Model

A multi-region input-output table constitutes the central component of a multi-region input-output model. Such a table is built by internalizing the inflows and outflows of goods and services, drawing on inter-regional input-output data and consolidating them under a uniform sectoral classification. Its primary purpose is to examine the resource and environmental consequences arising from the cross-regional movement of products, encompassing both international trade and domestic interregional transactions. Drawing on the input-output table, this study developed a multi-region input-output model. The formula is as follows:

(1) The Baseline Model of the Multi-Region Input-Output Model:

$$X_i^r = \sum_{s=1}^{m} \sum_{j=1}^{n} x_{ij}^{rs} + \sum_{s=1}^{m} Y_i^{rs} + EX_i^r \tag{15}$$

where X_i^r denotes the total output of sector i in region r. x_{ij}^{rs} denotes the intermediate inputs supplied by sector i in region r to sector j in region s. Y_i^{rs} denotes the final output supplied by sector i in region r to region s. EX_i^r denotes the total exports of sector i in region r.

(2) Matrix Form of the Multi-Region Input-Output Model:

$$\begin{bmatrix} X^1 \\ X^2 \\ \vdots \\ X^m \end{bmatrix} = \begin{bmatrix} A^{11} & A^{12} & \cdots & A^{1m} \\ A^{21} & A^{22} & \cdots & A^{2m} \\ \vdots & \vdots & \ddots & \vdots \\ A^{m1} & A^{m2} & \cdots & A^{mm} \end{bmatrix} \cdot \begin{bmatrix} X^1 \\ X^2 \\ \vdots \\ X^m \end{bmatrix} + \begin{bmatrix} Y^{11} & Y^{12} & \cdots & Y^{1m} \\ Y^{21} & Y^{22} & \cdots & Y^{2m} \\ \vdots & \vdots & \ddots & \vdots \\ Y^{m1} & Y^{m2} & \cdots & Y^{mm} \end{bmatrix} + \begin{bmatrix} EX^1 \\ EX^2 \\ \vdots \\ EX^m \end{bmatrix} \tag{16}$$

where X^r denotes the column vector representing the total output of all sectors in region r. The block matrix A^{rs} denotes the matrix of direct consumption coefficients for intermediate goods supplied by region r to region s. Y^{rs} denotes the column vector representing the final goods supplied by region r to region s and EX^r denotes the column vector representing the total exports of region r. From Equation (16), an alternative representation of X^r could be derived:

$$X^r = L^{rr}\left(\sum_{\substack{s=1 \\ s\neq r}}^{m} A^{rs}X^s + \sum_{\substack{s=1 \\ s\neq r}}^{m} Y^{rs} + Y^{rr} + EX^r\right) \tag{17}$$

where $L^{rr} = (I - A^{rr})^{-1}$ denotes the Leontief inverse matrix. $L^{rr}\sum_{\substack{s=1 \\ s\neq r}}^{m} A^{rs}X^s$, $L^{rr}\sum_{\substack{s=1 \\ s\neq r}}^{m} Y^{rs}$ and $L^{rr}\sum_{\substack{s=1 \\ s\neq r}}^{m} Y^{rs}$ denote the output required for region r to supply intermediate and final goods to region s. $L^{rr}Y^{rr}$ denotes the output required for region r to meet its own demand for final goods and $L^{rr}EX^r$ denotes the output required for region r to meet its export demand.

(3) Environmental-extended input-output model. Proceeding from the discussion above, the environmental extension is combined with a multi-region framework by incorporating the vector t, which captures the direct methane emission intensity of each sector. This yields an environmental-extended multi-region input-output model, which is then applied to estimate the indirect emissions generated by household consumption. The relevant formula is given as:

$$t_i = E_i / X_i \tag{18}$$

$$T = t(I - A)^{-1}Y \tag{19}$$

where t_i represents the elements of vector t, i.e., the direct CH_4 emission intensity of each sector. E_i denotes the direct CH_4 emissions of sector i. X_i denotes the total output of sector i in the input-output table. T is the row vector of indirect CH_4 emissions from household consumption across all sectors. Y is the diagonal matrix of final household consumption.

2.2.2. CH_4 Emission Transfer Accounting Model

(1) A model for accounting for CH_4 emissions embedded in interprovincial trade. This study centers on embodied methane emissions associated with interprovincial trade within China. Therefore, in the calculations, this study excludes methane emissions embedded in exports. This study calculates the methane emissions from the production of goods in each province that meet domestic demand. The formula for calculating the volume of CH_4 emissions embedded in interprovincial trade is as follows:

$$CT^{R,S} = \widehat{E}^S(I - A)^{-1}\widehat{F}^R \tag{20}$$

$$CT^{S,R} = \widehat{E}^R(I - A)^{-1}\widehat{F}^S \tag{21}$$

$$CT^{R,S}_{net} = CT^{R,S} - CT^{S,R} \tag{22}$$

$$ECPE_R = \sum_{S=1}^{N} CT^{R,S};\ S \neq R \tag{23}$$

$$ECPI_R = \sum_{S=1}^{N} CT^{S,R};\ S \neq R \tag{24}$$

where the symbol ^ denotes a diagonal matrix. $\widehat{E}^S$ and $\widehat{E}^R$ represent the methane emission intensity coefficients for Province S and Province R. That is, this diagonal matrix contains only the methane emission intensity coefficients for Province S or Province R, while those for other provinces are all zero. $\widehat{F}^S$ and $\widehat{F}^R$ represent the final product consumption diagonal matrices for Province S and Province R, including both domestically supplied and imported final products. $CT^{R,S}$ represents the methane emissions in Province S resulting from Province R's final product consumption across the industrial chain. In this study, $CT^{R,S}$ denotes the embodied methane flow originating from Province R and destined for Province S. Similarly, $CT^{S,R}$ captures the corresponding transfer in the reverse direction (from S to R). $CT_{net}^{R,S}$ measures the net embodied methane exchange between the two provinces, with a positive reading signifying a net outflow from Province R to Province S (i.e., Province R shifts part of its methane emissions to Province S through interprovincial trade, which is beneficial for Province R in terms of methane emission control), a negative value indicates a net inflow to Province R from Province S (i.e., Province R has shifted part of its methane emissions to Province S through interprovincial trade, which is disadvantageous for Province R in terms of methane emission control). $ECPE_R$ represents the total methane emissions embedded in products exported by Province R to other provinces, and $ECPI_R$ represents the total methane emissions embedded in products imported by Province R from other provinces.

(2) An accounting framework designed to quantify embodied CH_4 flows under both producer and consumer responsibility viewpoints. CE_P^R denotes the methane emissions attributed to Province R on a producer-responsibility basis, namely the aggregate CH_4 released within Province R driven by domestic final demand originating from Province R and from all other provinces. The formula used for calculation is:

$$CE_P^R = \sum_S \widehat{E}^R (I - A^d)^{-1} \widehat{F}^S \tag{25}$$

Let CE_C^R stand for the methane emissions for which Province R is responsible on the consumption side. In other words, it is the sum of methane emitted in Province R itself and in other provinces as a consequence of Province R's domestic final demand. The detailed equation is presented below:

$$CE_C^R = \sum_S \widehat{E}^S (I - A^d)^{-1} \widehat{F}^R \tag{26}$$

Let CT_{net}^R stand for the net methane transfer implied by Province R's trade with other provinces, i.e., the difference between Province R's methane emissions from the consumer's perspective and those from the producer's perspective. A positive figure signifies a net outward transfer from Province R to other provinces, meaning that Province R displaces a portion of its methane emissions to those provinces by consuming their products, while a negative value indicates a net inflow to Province R from other provinces (i.e., Province R absorbs a portion of other provinces' methane emissions through interprovincial trade). The specific calculation formula is as follows:

$$CT_{net}^R = CE_C^R - CE_P^R \tag{27}$$

The meanings of all letters in the equation are as defined above and will not be repeated here.

2.3. CH_4 Emission Reduction Pathway Analysis Model

2.3.1. Structural Pathway Analysis

Structural Path Analysis (SPA) is a decomposition technique based on input-output models and serves as a key extension of the Multi-Region Input-Output (MRIO) model. The conceptual framework for this method was first proposed by Leontief within the context of input-output analysis in 1970 [35]. Following systematic developments by scholars such as Bullard, Herendeen, and Treloar, a comprehensive analytical framework was gradually established [36,37]. Its core concept involves mathematically decomposing the Leontief inverse matrix to break down the total impact of a given final demand into specific transmission pathways across different regions and sectors. This clearly illustrates the complete "source-transmission-destination" chain of impacts. The SPA method is currently applied primarily in environmental extended input-output analysis fields, such as greenhouse gas emissions accounting and supply chain traceability, energy consumption analysis, carbon footprint tracking, and environmental impact assessments of supply chains.

Express the coefficient matrix in Equation (28) in terms of a Taylor series in the form of Equation (20). The specific calculation formula is as follows:

$$(I - A)^{-1} = I + A + A^2 + A^3 + \cdots + A^w + \cdots \tag{28}$$

Combining Equations (19) and (20) yields a model for calculating CH_4 emissions across different industrial sectors. The calculation formula is as follows:

$$T = t(I - A)^{-1}Y = \overbrace{tIY}^{PL^0} + \overbrace{tAY}^{PL^1} + \overbrace{tA^2Y}^{PL^2} + \overbrace{tA^3Y}^{PL^3} + \overbrace{\cdots}^{\cdots} + \overbrace{tA^WY}^{PL^W} + \cdots \tag{29}$$

where tIY denotes emissions generated at the 0th production level (PL^0), i.e., emissions from the production of goods or services consumed by households. tAY denotes emissions generated at the 1st production level (PL^1), i.e., emissions from first-tier suppliers in the production of goods or services consumed by households and so on, where tA^WY denotes emissions generated at the Wth production level (PL^W).

For each individual matrix element, Equation (29) could be expressed as

$$\begin{aligned} T &= \sum_{i,j=1}^{n} t_i(\delta_{ij}+\alpha_{ij}+\alpha_{ij}^2+\alpha_{ij}^3+\cdots)y_j \\ &= \sum_{i,j=1}^{n} t_i\left(\delta_{ij}+\alpha_{ij}+\sum_{k=1}^{n}\alpha_{ik}\alpha_{kj}+\sum_{l=1}^{n}\sum_{k=1}^{n}\alpha_{ik}\alpha_{kl}\alpha_{lj}+\cdots\right)y_j \\ &= \underbrace{\sum_{i=1}^{n} t_i y_j}_{PL^0} + \underbrace{\sum_{i=1}^{n} t_i \sum_{j=1}^{n}\alpha_{ij}y_j}_{PL^1} + \underbrace{\sum_{i=1}^{n} t_i \sum_{k=1}^{n}\alpha_{ik}\sum_{j=1}^{n}\alpha_{kj}y_j}_{PL^2} + \underbrace{\sum_{i=1}^{n} t_i \sum_{k=1}^{n}\alpha_{ik}\sum_{l=1}^{n}\alpha_{kl}\sum_{j=1}^{n}\alpha_{lj}y_j}_{PL^3} + \cdots \end{aligned} \tag{30}$$

where the subscripts i, j, k, and l represent sectors. t_i, $\propto_{ij}$ and y_j are elements of t, A and Y. δ_{ij} is an element of the identity matrix (taking the value 1 when $i = j$. When $i \neq j$, it is 0). $t_i\alpha_{ik}\alpha_{kj}y_j$ reflects the flow through two stages of the industrial chain (sector $i \rightarrow$ sector $k \rightarrow$ sector j), meaning that final demand for sector j triggers production in sector k, which in turn triggers production activity in sector i.

2.3.2. Sensitivity Analysis

To identify the sectors and pathways most sensitive to indirect CH_4 emissions from household consumption, this study adopts the sensitivity analysis method proposed by Mattila et al. (2013) using an input-output analysis model [38]. The study then calculates three types of emission elasticity coefficients: the ratio of the rate of change in indirect emissions from household consumption (T) to the rate of change in direct emission intensity (t), the relationship between the direct consumption coefficient and the variation in final household consumption (Y), together with the linkage between changes in final household consumption (Y) and variations in direct consumption. The calculation formula is as follows:

$$T = t(I - A)^{-1}Y = mY = tY \tag{31}$$

Equation (19) is further rearranged to yield Equation (31). Where m denotes the matrix of total emission intensity, capturing emissions from the full upstream supply chain across all sectors. X represents the total output needed to supply the final household consumption Y. Taking the partial derivatives of Equation (31) yields the following sensitivity indices, resulting in Equations (32), (33) and (37):

$$S_{t,ij} = \frac{\partial T_i/T_i}{\partial t_{ij}/t_{ij}} = X_j\frac{t_{ij}}{T_i} \tag{32}$$

$$S_{\alpha,ikj} = \frac{\partial T_i/T_i}{\partial \alpha_{kj}/\alpha_{kj}} = m_{ik}X_j\frac{\alpha_{kj}}{T_i} \tag{33}$$

$$S_{y,ik} = \frac{\partial T_i/T_i}{\partial y_k/y_k} = m_{ik}\frac{y_k}{T_i} \tag{34}$$

where the subscripts i and j represent different sectors. S_t is the sensitivity of direct emission intensity (CH_4). S_y is the sensitivity of final residential consumption and S_α is the sensitivity of the direct consumption coefficient (α_{ij}). To analyze the sensitivity of the original input coefficient α_{kk} to emissions, when calculating S_α, its diagonal elements ($1 - \alpha_{kk}$) could be adjusted using the ratio $\alpha_{kk}/(1 - \alpha_{kk})$. In Equations (22) and (23), m_{ik} is an element of matrix m.

Following the findings of Zhen et al. (2018) [39], this study sets the sensitivity analysis thresholds S_t, S_α or S_y to 0.01, indicating that a 1% change in indirect emissions from household consumption (T) corresponds to a 100% change in direct emission intensity (t), direct consumption coefficient (A), and household final consumption (Y). When S_t, S_α or S_y is greater than 0.01, the results are considered sensitive to the aforementioned variables. Otherwise, they are considered insensitive.

2.4. Study Samples and Data Sources

The sample of this study consists of China's 31 provincial-level administrative regions (including municipalities directly under the central government and autonomous regions). The sample was selected based on differences in regional economic development levels, resource endowments, and emission structures. The analysis focuses on three typical types of provinces: (1) Provinces rich in resources, including Shanxi, Inner Mongolia, and Shaanxi, are characterized by methane emissions dominated by energy-related activities. (2) Provinces where agriculture plays a dominant role (for instance, Tibet, Hunan, and Jiangxi) whose emissions originate mainly from livestock farming, straw burning, and rice cultivation. (3) Provinces with high urbanization levels, including Beijing, Shanghai, and Guangdong, see their methane emissions largely originating from waste and wastewater.

In terms of data, the methane emission inventory is mainly based on the methods and emission factors set out in the IPCC 2006 National Greenhouse Gas Inventory Guidelines (2019 Revision), supplemented by the China Statistical Yearbook (2012–2022), the China Environmental Statistics Yearbook (2012–2022), and the China Rural Statistics Yearbook (2012–2022), to obtain key indicators for each province, including raw coal production, oil and gas extraction, crop cultivation area, livestock inventory, waste landfill volume, and wastewater treatment volume.

Considering that this study focuses more on interprovincial differences in methane emissions when analyzing the characteristics of CH_4 transfers implied by interprovincial trade, the service sector and other manufacturing sectors from the original input-output table's 42 industries were merged. Consequently, the national economy was ultimately divided into 17 industries, as shown in Table 1.

Table 1. The industrial categories in the multi-regional input-output table of China.

No.	Sectoral Classification of Input-Output Tables for Multiple Regions Across China's 31 Provinces	No.	Sector Codes and Names in the Input-Output Tables of Each Province and Region
1	Agriculture, Forestry, Livestock, and Fisheries	1	Agricultural, Forestry, Livestock, and Fishery Products and Services
2	Coal Mining and Washing	2	Coal Mining and Beneficiation Products
3	Oil and Natural Gas Extraction	3	Oil and Natural Gas Extraction Products
4	Mining	4–5	Metal Mining and Beneficiation Products; Non-metallic Mineral and Other Mining and Beneficiation Products
5	Food, Beverage, Tobacco, Textile, Apparel, Wood, Paper, and Printing, and Sporting Goods Manufacturing	6–10	Food and Tobacco; Textiles; Textile, Apparel, Footwear, Leather, and Down Products; Wood Products and Furniture; Paper, Printing, and Educational, Cultural, and Sporting Goods
6	Processing of Petroleum, Coking Products, and Nuclear Fuel	11	Petroleum, Coking Products, and Processed Nuclear Fuel
7	Chemical Industry	12	Chemical Products
8	Non-metallic Mineral Products Manufacturing	13	Non-metallic mineral products
9	Metal Smelting, Rolling, and Processing	14	Metallurgical and rolled metal products
10	Other Manufacturing	15–24	Metal products, general-purpose machinery, specialized machinery, transportation equipment, electrical machinery and equipment, telecommunications equipment, computers and other electronic equipment, instruments and meters, other manufactured products, scrap and waste, repair services for metal products, machinery, and equipment
11	Electricity and Heat Production and Supply	25	Electricity and heat production and supply
12	Gas Production and Supply	26	Gas production and supply
13	Water Production and Supply	27	Water production and supply
14	Construction	28	Construction
15	Transportation, Warehousing, and Postal Services	30	Transportation, warehousing, and postal services
16	Services	29, 31–36, 38–42	Wholesale and retail trade; accommodation and food services; information transmission, software, and information technology services; financial services; real estate, leasing, and business services; scientific research and technical services; personal and household services; repair and other services; education; health and social work; culture, sports, and recreation; public administration; social security and social organizations
17	Water, Environmental, and Public Utilities Management	37	Water conservancy, environmental protection, and public utilities management

3. Results and Discussion

3.1. Analysis of the Spatiotemporal Characteristics of CH_4 Emissions at the Provincial Level in China

3.1.1. Temporal Distribution Characteristics

Based on the previously introduced Formulas (1)–(14), CH_4 emissions were estimated for each Chinese province across the 11-year span of 2012–2022. Figure 2 displays the results.

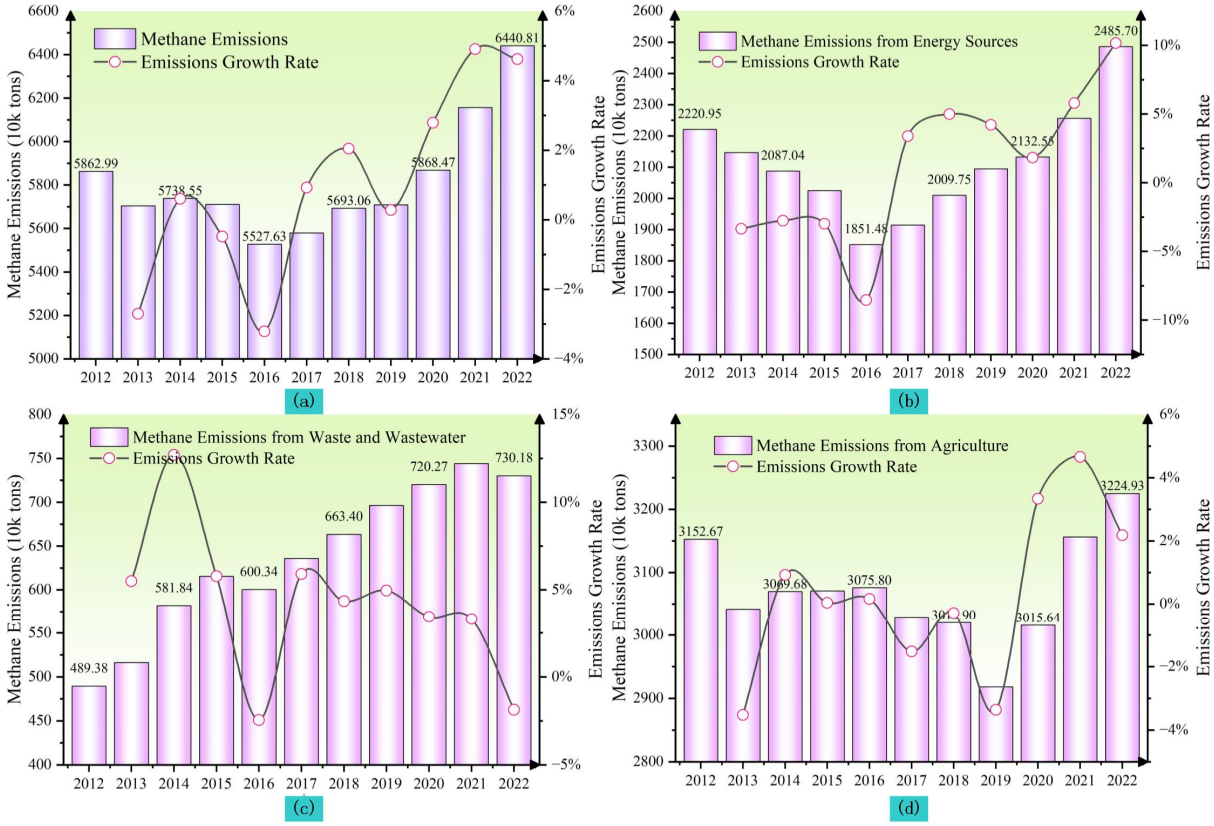

Figure 2. Total National CH_4 Emissions and Emissions by Sector, 2012–2022: (**a**) Total methane emissions; (**b**) Methane emissions from energy sources; (**c**) Methane emissions from waste and wastewater; (**d**) Methane emissions from agriculture.

As shown in Figure 2a, China's CH_4 emissions followed an overall fluctuating upward trend from 2012 to 2022, with an average of 58.1738 million metric tons, divided into two distinct phases. In the first phase, emissions decreased from 58.6299 million metric tons in 2012 to 55.2763 million metric tons in 2016. The second phase saw an increase from 55.2763 million metric tons in 2016 to 64.4081 million metric tons in 2022. The growth rates for these two phases were 5.72% and 16.52%, with the total emissions showing a marked acceleration in growth after 2019. Figures 2b through 2d show the changes in methane emissions from energy activities, waste and sewage, and agricultural activities from 2012 to 2022. Figure 2b shows that methane emissions from energy activities first decreased and then increased, but overall changes were minimal. Figure 2c indicates that methane emissions from waste and wastewater exhibit a slow upward trend. Figure 2d shows that methane emissions from agricultural activities first decreased and then increased, with a relatively rapid growth rate after 2019. It is worth noting that the trough in the growth rate of emissions from agricultural activities occurred in 2019, which was later than the trough observed in the energy and waste/sewage sectors around 2016. This temporal discrepancy is primarily related to the structural characteristics of emissions from agricultural sources. Agricultural emissions primarily stem from rice cultivation and livestock and poultry farming. Changes in these emissions are influenced by agricultural production cycles, adjustments in the scale of crop cultivation and livestock farming, and relevant agricultural policies, such as requirements for the resource utilization of livestock and poultry manure and policies on crop structure adjustments. Policy implementation and industry responses in the agricultural sector are more gradual than in the energy and industrial sectors, resulting in a lag in the appearance of the trough.

3.1.2. Spatial Distribution Characteristics

This study further mapped the spatial distribution of energy activities, waste and wastewater, agricultural activities, and total emissions (see Figure 3) to investigate the regional distribution patterns of CH_4 emissions in China.

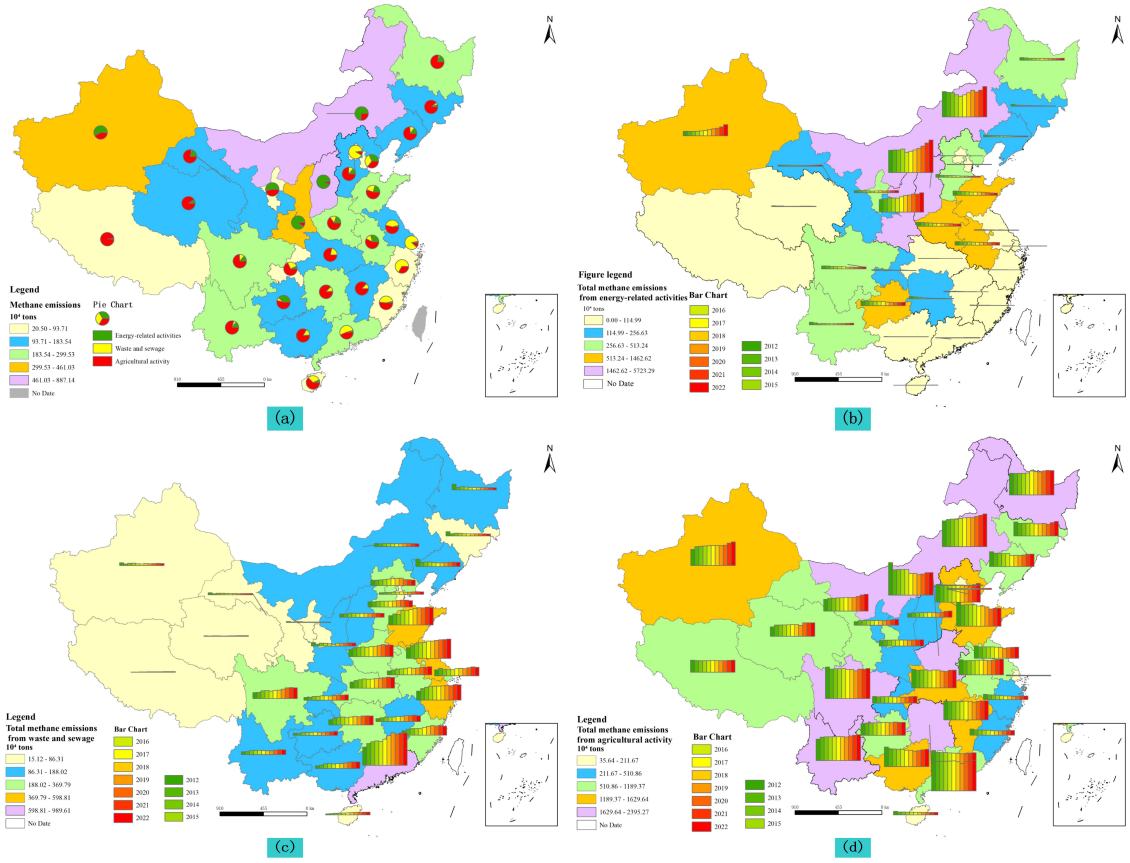

Figure 3. Characteristics of CH_4 emissions distribution across China: (**a**) Total CH_4 emissions by province; (**b**) CH_4 emissions from energy activities by province; (**c**) CH_4 emissions from waste and wastewater by province; (**d**) CH_4 emissions from agricultural activities by province.

Figure 3 illustrates the geographic pattern of CH_4 emissions across China. Figure 3a reveals that, on the whole, high methane emissions are mainly clustered in Northeast China, North China, and Southwest China, whereas the Northwest registers relatively low emissions. In 2022, the regions with the highest CH_4 emissions in China were, in order, Inner Mongolia, Shanxi, Shaanxi, the Xinjiang Uygur Autonomous Region, and Sichuan, while Beijing, Tianjin, Shanghai, Ningxia, and Tibet had relatively lower emissions.

As shown in Figure 3b, CH_4 emissions from energy activities are primarily concentrated in Shanxi, Shaanxi, Inner Mongolia, and Xinjiang. In 2022, CH_4 emissions from energy activities in Shanxi, Inner Mongolia, and Shaanxi accounted for 27.51%, 25.70%, and 16.26% of total emissions from energy activities making them the provinces with the highest CH_4 emissions from energy activities in China. As shown in Figure 3c, CH_4 emissions from waste and wastewater treatment are primarily concentrated in Beijing, Shanghai, and Zhejiang. In 2022, Guangdong, Shandong, and Zhejiang accounted for 14.78%, 7.88%, and 7.03% of total CH_4 emissions from waste and wastewater treatment making them the provinces with the highest methane emissions from this sector in China. These regions are economically developed, densely populated, and handle relatively large volumes of waste and sewage. As shown in Figure 3d, CH_4 emissions from agricultural activities are primarily concentrated in Tibet, Qinghai, Jilin, Jiangxi, and Hunan. Among these, Inner Mongolia, Hunan, and Sichuan accounted for 7.40%, 6.96%, and 6.87% of total CH_4 emissions from agricultural activities making them the provinces with the highest CH_4 emissions from agricultural activities in China. In Tibet, Qinghai, and Jilin, emissions primarily stem from intestinal fermentation in livestock. These regions are arid or semi-arid areas with well-developed livestock industries, relatively underdeveloped economies, and low population densities. Additionally, in Jiangxi and Hunan, emissions primarily originate from rice cultivation. These regions are major rice-producing areas in China, and methane emissions from rice cultivation account for a significant proportion of total emissions.

3.2. Analysis Characteristics of CH_4 Transfers Implied by Interprovincial Trade in China

3.2.1. Characteristics of CH_4 Transport at the Regional Level

Formulas (25)-(27) were used to calculate the CH_4 transfers implied by interprovincial trade across China's 31 provinces in 2017 (as shown in Table 2), including total outflows, total inflows, producer responsibility, consumer responsibility, and net outflows. A positive net outflow indicates that the province has transferred a portion of its CH_4 emissions to other provinces through the consumption of products from those provinces. A negative net outflow indicates that the province has absorbed a portion of CH_4 emissions from other provinces through interprovincial trade. Based on Table 2, a chord diagram was used to visualize the CH_4 emission flows implied by interprovincial trade, resulting in Figure 4. Different colors represent different provinces, while the connecting lines indicate flow direction and volume, corresponding to both exporting and importing regions.

Table 2. Interprovincial trade-implied CH_4 transfers in China in 2017 (10^4t CH_4).

Province/City	Total Outflow	Total Inflow	Producer Responsibility	Consumer Responsibility	Net Outflow
Beijing	81.47	4.69	28.96	105.74	76.78
Tianjin	36.32	6.37	22.14	52.09	29.95
Hebei	211.91	56.24	176.82	332.49	155.67
Shanxi	34.23	406.73	496.92	124.41	−372.50
Inner Mongolia	28.08	501.41	685.06	211.73	−473.33
Liaoning	51.12	32.66	114.44	132.90	18.46
Jilin	50.79	47.62	105.01	108.19	3.17
Heilongjiang	35.02	122.13	221.89	134.78	−87.10
Shanghai	67.50	2.20	28.00	93.30	65.29
Jiangsu	273.37	23.52	147.07	396.92	249.85
Zhejiang	302.20	7.75	72.40	366.85	294.45
Anhui	73.16	52.18	191.20	212.18	20.97
Fujian	40.45	6.50	65.37	99.32	33.96
Jiangxi	75.32	48.57	158.98	185.73	26.75
Shandong	49.02	60.83	269.83	258.02	−11.81
Henan	146.89	86.23	252.62	313.27	60.66
Hubei	62.40	8.89	164.06	217.58	53.52
Hunan	82.99	50.92	256.09	288.15	32.06
Guangdong	238.80	26.27	184.42	396.95	212.53
Guangxi	45.43	34.24	138.21	149.40	11.19
Hainan	20.54	9.11	25.14	36.58	11.44
Chongqing	77.55	16.71	69.69	130.52	60.84
Sichuan	49.04	32.87	285.14	301.31	16.16
Guizhou	29.21	94.45	188.58	123.34	−65.24
Yunnan	42.01	63.38	211.79	190.42	−21.37
Tibet	7.85	4.84	88.65	91.67	3.02
Shaanxi	73.65	283.49	370.54	160.70	−209.84
Gansu	12.75	45.90	123.72	90.57	−33.14
Qinghai	4.25	30.97	95.00	68.28	−26.72
Ningxia	9.23	36.50	75.78	48.51	−27.27
Xinjiang	21.50	129.89	263.78	155.39	−108.39

In terms of total volume, the three provinces with the highest implied CH_4 outflows are, in order, Zhejiang (3.022 million metric tons), Jiangsu (2.7337 million metric tons), and Guangdong (2.388 million metric tons). These three provinces have high levels of economic development and well-developed manufacturing sectors. To sustain their economic growth, they must import large quantities of energy, raw materials, and consumer goods from other provinces, which is why their total interprovincial trade-implicit CH_4 outflows rank among the top three nationwide. The three provinces with the highest total implicit CH_4 inflows are, in order, Inner Mongolia (5.0141 million tons), Shanxi (4.0673 million tons), and Shaanxi (2.8349 million tons). Among these three provinces, Inner Mongolia and Shanxi are major coal-producing regions in China, while Shaanxi also holds a significant position in the national energy sector. Their high total implied CH_4 outflows are primarily due to the supply of energy or energy-intensive products to other provinces. In addition to these provinces, Hebei and Henan also have relatively high total implied CH_4 outflows from trade. Provinces with relatively high total implied CH_4 inflows from trade include Xinjiang and Heilongjiang.

In terms of net transfer volume, 11 provinces showed a net inflow of CH_4 implied by interprovincial trade. That is, these 11 provinces had higher CH_4 emissions from the producer's perspective than from the consumer's

perspective. Among them, the top three provinces by net inflow were Inner Mongolia (4.7333 million metric tons), Shanxi (3.725 million metric tons), and Shaanxi (2.0984 million metric tons). These provinces export more high-CH_4 products and import more low-CH_4 products in interprovincial trade. Consequently, their implied CH_4 inflow exceeds their outflow, meaning they absorb a portion of CH_4 emissions from other provinces. There are 20 provinces with a net CH_4 outflow implied by interprovincial trade, i.e., the 20 provinces where CH_4 emissions are higher from the consumer perspective than from the producer perspective. The top three provinces in this category are Zhejiang (2.9445 million tons), Jiangsu (2.4985 million tons), and Guangdong (2.1253 million tons). These provinces import large quantities of high-CH_4 products while exporting low-CH_4 products in interprovincial trade. Consequently, their implied CH_4 outflow exceeds their inflow, shifting a portion of their CH_4 emissions to other provinces.

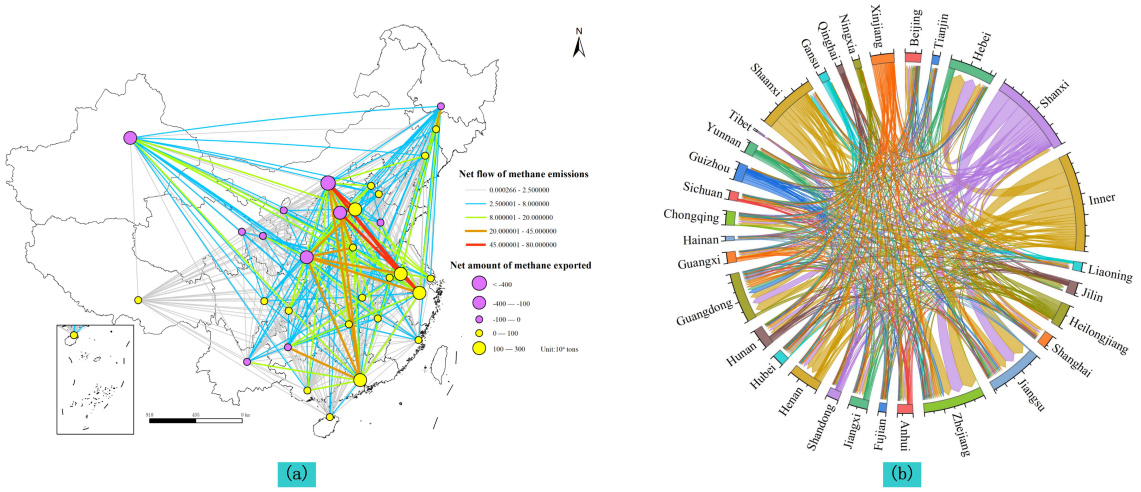

Figure 4. Pathways of CH_4 Implicit in Interprovincial Trade in China in 2017: (**a**) Spatial flow network diagram; (**b**) Inter-provincial bidirectional chord diagram.

3.2.2. Characteristics of CH_4 Production and Consumption Shifts

Figure 5 depicts the 2017 CH_4 emissions under both producer and consumer responsibility views. In the producer-responsibility framework, the ten provinces with the highest emission levels are ranked as follows: Inner Mongolia, Shanxi, Shaanxi, Sichuan, Shandong, Xinjiang, Hunan, Henan, Heilongjiang, and Yunnan. From the consumer responsibility perspective, the top 10 provinces by CH_4 emissions are, in order: Guangdong, Jiangsu, Zhejiang, Hebei, Henan, Sichuan, Hunan, Shandong, Hubei, and Anhui. Among these, Sichuan, Shandong, Hunan, and Henan are major CH_4 emitters in China under both perspectives.

In 11 of the 31 Chinese provinces, CH_4 emissions calculated from the producer side exceed those calculated from the consumer side. Inner Mongolia, Shanxi, Shaanxi, and Xinjiang show the most significant differences. These provinces are characterized by a high concentration of fossil fuel production or an industrial structure heavily weighted toward agriculture and animal husbandry. While supplying large quantities of energy-intensive products and agricultural and livestock products to other provinces, they also experience a significant increase in their own emissions, making them CH_4 emission-importing provinces. Conversely, from the consumer responsibility perspective, 20 provinces have higher CH_4 emissions than from the producer perspective. Among them, Zhejiang, Jiangsu, Guangdong, and Hebei stand out the most. These provinces could generally be divided into two categories. One category includes economically developed provinces such as Zhejiang, Jiangsu, Guangdong, Beijing, and Shanghai. These provinces avoid CH_4 emissions from local production by consuming large quantities of products from other provinces. The other category includes provinces such as Hebei, Guangxi, and Tibet. These provinces have relatively monolithic industrial structures. At the same time, their local consumption relies heavily on products imported from other provinces, which also results in higher CH_4 emissions from a consumer perspective than from a producer perspective. Both categories of provinces are classified as CH_4 emission-exporting provinces. Thus, interprovincial trade has led to the transfer of CH_4 emissions across provincial borders and has had a significant impact on the CH_4 emissions of each province.

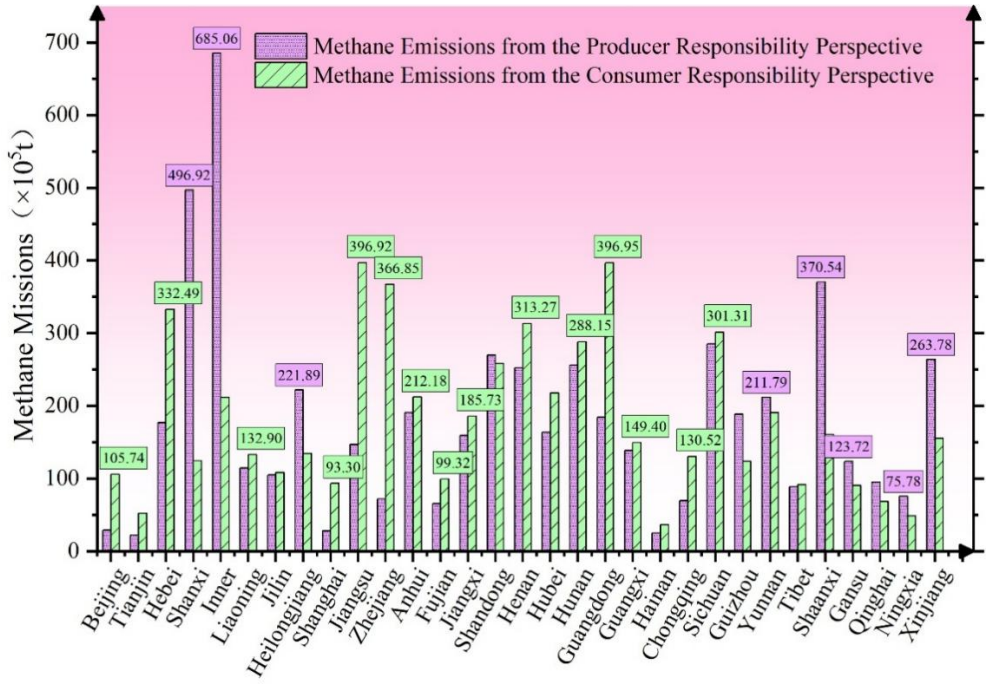

Figure 5. CH_4 emissions in 2017 from the perspectives of producer responsibility and consumer responsibility.

3.3. Analysis of Industrial-Level Breakdown and Mitigation Pathways for Indirect CH_4 Emissions in China

3.3.1. Distribution of Industrial Sectors by Indirect CH_4 Emissions

Drawing on the input-output tables, the study further estimated the indirect CH_4 emissions generated by household consumption across 42 industrial sectors in 2017. Figure 6 presents these findings.

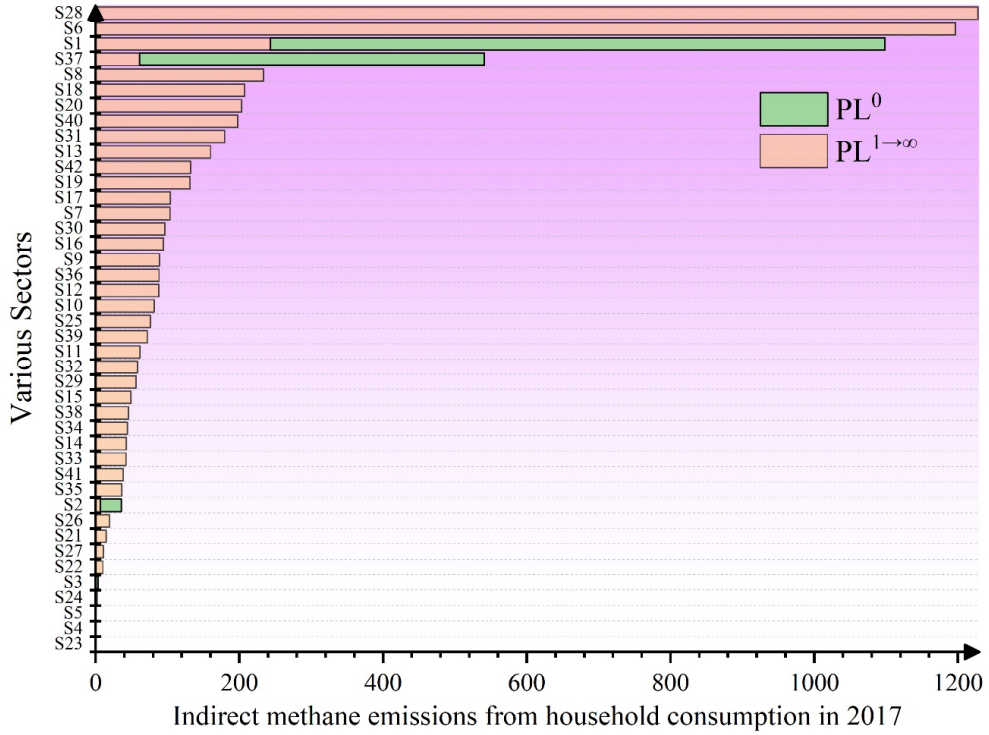

Figure 6. Indirect CH_4 emissions from consumption across different sectors in China in 2017.

As shown in Figure 6, indirect CH_4 emissions vary significantly across different sectors in China. Among them, construction (S28), food and tobacco (S6), agricultural, forestry, livestock, and fishery products and services (S1), and water, environmental, and public facility management (S37) are the four sectors with the highest indirect CH_4 emissions from household consumption, collectively accounting for 58.26% of total emissions. In today's

society, the construction sector (S28) generates large amounts of organic waste and wastewater during construction processes. If not properly treated, these could release significant amounts of CH_4, making the construction sector (S28) the largest contributor to indirect CH_4 emissions across all sectors (17.61%). Meanwhile, the Food and Tobacco (S6) and Agriculture, Forestry, Livestock, and Fisheries Products and Services (S1) sectors account for 17.16% and 15.74% of total indirect CH_4 emissions across all sectors. This is because they are closely linked to agricultural activities, resulting in high levels of indirect CH_4 emissions. Similarly, Water Supply, Environmental Protection, and Public Utilities (S37) account for 7.76% of total indirect CH_4 emissions due to the significant CH_4 emissions from wastewater and waste treatment.

A detailed sector-by-sector analysis shows that just four sectors are responsible for over half of the PL^0-level emissions embedded in indirect household CH_4 emissions. These are: agricultural, forestry, livestock, and fishery products and services (S1); water, environmental, and public facility management (S37); coal mining and beneficiation products (S2) and oil and natural gas extraction products (S3). These sectors supply final consumer goods to households and have relatively short downstream supply chains. In contrast, indirect emissions from most other sectors originate entirely from the first tier and higher in the supply chain ($PL^{1\rightarrow\infty}$). This includes 38 sectors, primarily Construction (S28) and Food and Tobacco (S6), which together account for 75.93% of indirect CH_4 emissions from household consumption. These sectors chiefly provide intermediate inputs to downstream industries that manufacture goods and services destined for final household consumption. Households do not directly consume the products of these sectors, but their final consumption triggers raw material production and processing in these sectors, thereby resulting in indirect emissions.

3.3.2. Breakdown of Indirect CH_4 Emissions by Industry Sector

This study employed a sectoral decomposition approach to estimate the sector-level distribution of indirect CH_4 emissions from household consumption in China for 2012, 2015, and 2017. The findings are presented in Table 3 and Figure 7.

Table 3. Indirect CH_4 emissions from household consumption across different industrial sectors in 2012, 2015, and 2017.

CH_4	Indicator	PL^0	PL^1	PL^2	PL^3	PL^4	PL^5	$PL^{6\rightarrow\infty}$
2012	Emissions (10,000 tons)	1450.87	1182.38	1285.94	1045.05	771.57	547.14	1181.88
	Percentage	19.44%	15.84%	17.23%	14.00%	10.34%	7.33%	15.83%
	Cumulative Percentage	19.44%	35.28%	52.50%	66.50%	76.84%	84.17%	100.00%
2015	Emissions (10,000 tons)	1244.34	1096.14	1163.09	1004.27	773.17	566.87	1342.61
	Percentage	17.31%	15.24%	16.18%	13.97%	10.75%	7.88%	18.67%
	Cumulative Percentage	17.31%	32.55%	48.73	62.69%	73.44%	81.33%	100.00%
2017	Emissions (10,000 tons)	1366.95	1305.20	1302.05	1003.18	701.73	464.25	831.78
	Percentage	19.60%	18.71%	18.67%	14.38%	10.06%	6.66%	11.92%
	Cumulative Percentage	19.60%	38.31%	56.98%	71.36%	81.42%	88.08%	100.00%

As shown in Table 3 and Figure 7, although the upstream production chain could be extended indefinitely, indirect CH_4 emissions from household consumption are primarily concentrated in the first six production levels ($PL^{0\rightarrow5}$), accounting for 84.17%, 81.33%, and 88.08% of the total. The share of emissions from $PL^{6\rightarrow\infty}$ onwards is relatively small, and the rate of increase in emissions gradually decreases as the production level rises. Analysed at the industrial level, indirect CH_4 emissions from household consumption peak at PL^0. Across the $PL^{0\rightarrow3}$ stages, the proportions of these emissions consistently surpass 50%, standing at 66.50%, 62.69%, and 71.36%. This suggests that measures to cut household-driven indirect emissions should concentrate on the industrial chains embedded in $PL^{0\rightarrow3}$.

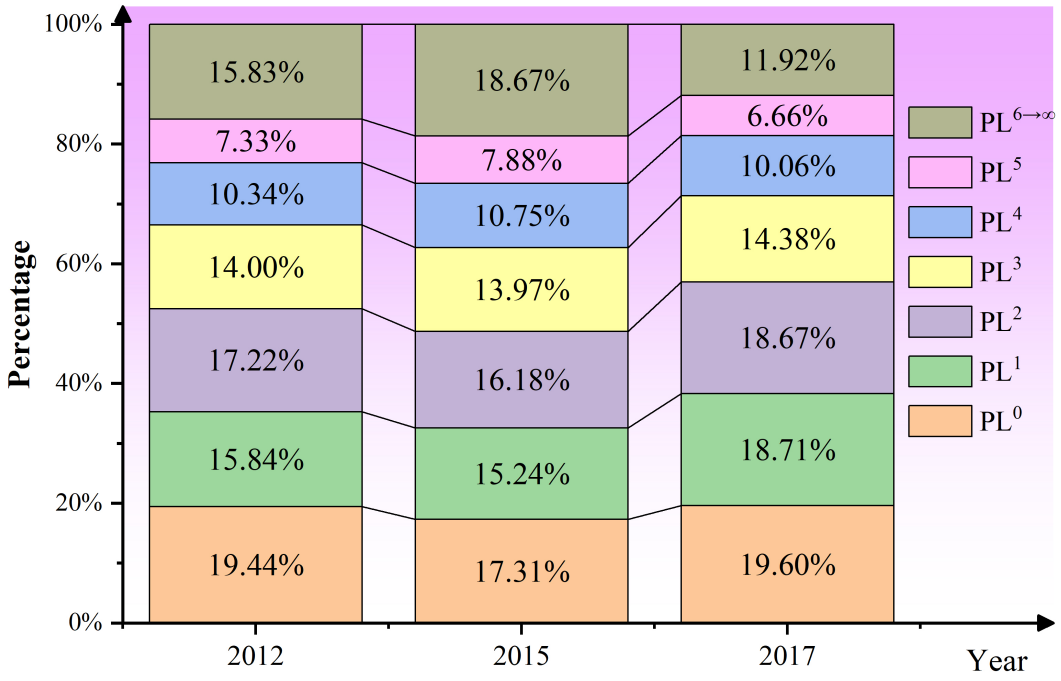

Figure 7. Indirect CH_4 emissions from household consumption across different industrial sectors in 2012, 2015, and 2017.

3.3.3. Sensitivity Analysis

(1) Sensitivity of direct emission intensity (S_t).

The study assessed the responsiveness of indirect CH_4 emissions from residential consumption to changes in direct emission intensity (t_i), and the findings are reported in Table 4. A sensitivity coefficient exceeding 0.01 implies that lowering the direct emission intensity of the corresponding sector offers high abatement effectiveness.

Table 4. Results of the 2017 Sensitivity Analysis.

Sector	S_t
S1	0.506
S2	0.351
S3	0.041
S37	0.102

As shown in Table 4, the direct emission intensities of four sectors are relatively sensitive to indirect CH_4 emissions from household consumption ($S_t > 0.01$). Among these, the sector of agricultural, forestry, livestock, and fishery products and services (S1) exhibits the highest sensitivity coefficient for CH_4 emissions, reaching 0.506. This implies that a 1% cut in the sector's direct emission intensity translates into a 0.506% decline in indirect CH_4 emissions from household consumption. This is followed by coal mining and beneficiation products (S2) and water, environmental, and public facility management (S37), with coefficients of 0.351 and 0.102. It is evident that the sectors with the highest sensitivity in direct emission intensity are primarily characterized by direct emissions. Therefore, reducing their direct emission intensity is the primary means of reducing indirect emissions from household consumption.

(2) Sensitivity of the direct consumption coefficient (S_α)

As shown in Equation (22), the direct consumption coefficient α_{ij} affects emissions only at higher industrial levels ($PL^{1\to\infty}$) and has no effect on the PL^0 level. The sensitivity index (S_α) of the direct consumption coefficient is crucial for identifying key emission reduction sectors and pathways in the $PL^{1\to\infty}$ tier. Therefore, this study further calculated the sensitivity of indirect CH_4 emissions from household consumption to the direct consumption coefficient α_{ij}. If the sensitivity coefficient exceeds 0.01, it indicates that upgrading the production technology in the industrial link from sector i to sector j yields high emission reduction efficiency. There are a total of 1764 industrial processes affecting indirect CH_4 emissions from household consumption, but only 43 of them are relatively sensitive (S_α>0.01). The S_α results for these 43 processes are shown in Figure 8.

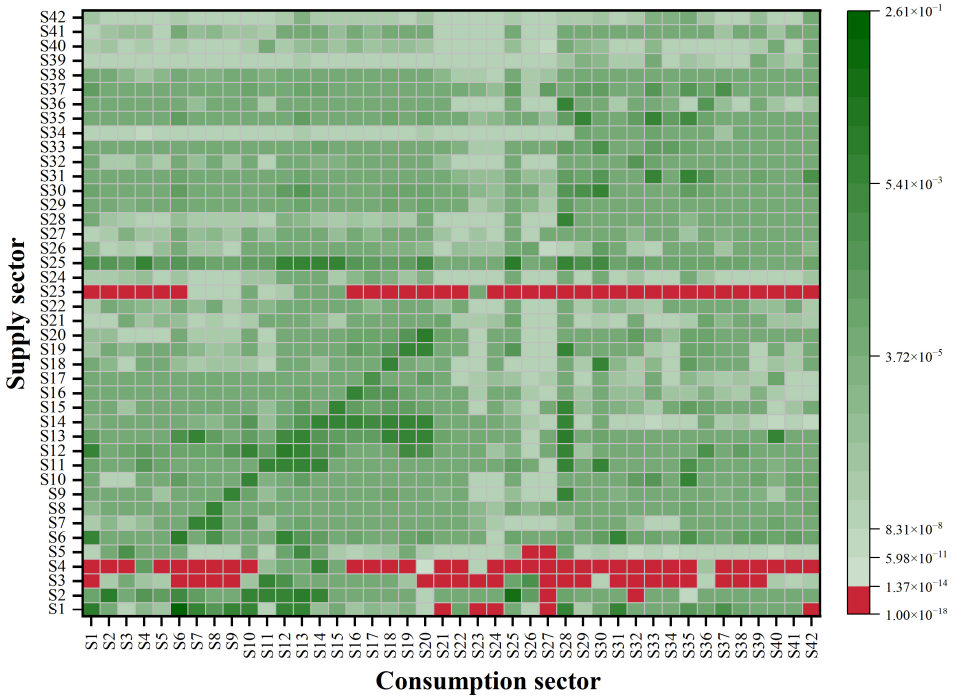

Figure 8. 2017 Sensitivity Analysis S_α Heat Map.

Figure 8 shows the S_α heatmap for the 2017 sensitivity analysis. As shown in Figure 8, the industrial sectors with the highest S_α values include: agricultural, forestry, livestock, and fishery products and services → food and tobacco (S1→S6, S_α = 0.261); coal mining and beneficiation products → non-metallic mineral products (S2→S13, S_α = 0.058) and coal mining and beneficiation products → electricity and heat production and supply (S2→S25, S_α = 0.140), and non-metallic mineral products → construction (S13→S28, S_α = 0.062) are the most sensitive industrial sectors to indirect CH_4 emissions from household consumption, with sensitivity coefficients all exceeding 0.05. This indicates that a 1% reduction in emissions from these sectors could reduce indirect methane emissions from household consumption by more than 0.05%. At the same time, the study found that the most sensitive inter-sectoral transactions include some self-supplying industrial sectors, such as agricultural, forestry, livestock, and fishery products and services → agricultural, forestry, livestock, and fishery products and services (S1→S1, S_α = 0.087), coal mining and beneficiation products → coal mining and beneficiation products (S2→S2, S_α = 0.067), food and tobacco → food and tobacco (S6→S6, S_α = 0.078), chemical products → chemical products (S12→S12, S_α = 0.063), and electricity and heat production and supply → electricity and heat production and supply (S25→S25, S_α = 0.062). These results align with earlier studies on carbon emissions.

(3) Sensitivity of household final consumption expenditure (S_y).

This study further estimated the sensitivity of indirect CH_4 emissions from household consumption to final consumption (y_i). If the sensitivity coefficient is greater than 0.01, it indicates that reducing consumption of products or services in this sector is a highly efficient means of reducing emissions. The findings are reported in Table 5.

Table 5. 2017 Sensitivity analysis results table.

Sector	S_y	Sector	S_y
S1	**0.158**	S19	0.019
S6	**0.172**	S20	0.029
S7	0.015	S25	0.011
S8	0.034	S28	**0.176**
S9	0.013	S30	0.014
S10	0.012	S31	0.026
S12	0.013	S36	0.013
S13	0.023	S37	**0.078**
S16	0.014	S39	0.010
S17	0.015	S40	0.028
S18	0.030	S42	0.019

Note: Numbers in bold indicate sensitivity coefficients greater than 0.05.

As shown in Table 5, household final consumption in 22 sectors is relatively sensitive to indirect CH_4 emissions ($S_y > 0.01$). Among these, household final consumption in the construction sector (S28) exhibits the highest sensitivity coefficient to CH_4 emissions ($S_y = 0.176$), followed by food and tobacco (S6) ($S_y = 0.172$). This clearly demonstrates that, with the acceleration of China's urbanization process and the improvement in the living standards of urban and rural residents, household consumption in the construction and food sectors has become a major driver of China's CH_4 emissions. In addition, the final demand sensitivity for agricultural, forestry, animal husbandry, and fishery products and services (S1) and for water conservancy, environmental protection, and public facility management (S37) is greater than 0.05.

3.3.4. Analysis of CH_4 Emission Reduction Pathways in China

Through the sensitivity analysis of the various components of the input-output model described above, this study has preliminarily identified the key sectors and pathways that individually meet the sensitivity criteria for each component. However, indirect CH_4 emissions from household consumption are determined jointly by direct emission intensity, final consumption, and inter-sectoral input coefficients. Therefore, to identify key emission reduction pathways, it is necessary to integrate the results of these three sensitivity analyses to provide policymakers with more targeted information.

In accordance with the design principles of the key emission reduction pathway identification framework, differentiated emission reduction measures should be adopted for the key pathways of different industrial levels. For critical pathways at the PL^0 level, emissions reductions are primarily achieved by lowering the direct emission intensity of the sector and reducing residents' consumption of the sector's products or services. Emissions reductions for critical pathways at higher industrial levels ($PL^{1\to3}$) focus on industrial linkages between different sectors (supply sectors → demand sectors), combining efforts to lower emission intensity in supply sectors with improvements in production efficiency in demand sectors.

(1) Key emission reduction pathways for indirect emissions from household consumption at the PL^0 level.

Since emissions at the PL^0 level are determined by both the sector's direct emission intensity (t_i) and final demand (y_j) (as shown in Equation (22)), from the perspective of emission reduction efficiency, the key emission reduction pathways for this industrial level must satisfy the condition ($S_t > 0.01$) ∩ ($S_y > 0.01$). As shown in Tables 3 and 4, only two sectors meet this criterion: agricultural, forestry, livestock, and fishery products and services (S1) and water, environmental, and public facility management (S37). The emissions from these two key pathways together account for 97% of PL^0-level CH_4 emissions and align with China's current emission reduction priorities. This suggests that the critical path identification approach developed in this research offers a highly efficient means of curbing indirect CH_4 emissions at the PL^0 level.

Based on the design principles of the key emission reduction pathway identification framework, emission reductions in the PL^0 layer are primarily achieved by either reducing the sector's direct CH_4 emission intensity or decreasing household consumption of the sector's products or services. To further enhance the efficiency of emission reductions, the S_t and S_y values for each sector should also be compared. If $S_t > S_y$, reducing the sector's direct emission intensity is more effective for reducing overall carbon emissions. Conversely, reducing household final consumption yields better emission reduction results. Upon comparison, the S_t values for both sectors exceed their S_y values, indicating that reducing indirect emissions in these sectors is primarily achieved by lowering direct emission intensity. Specifically, the agriculture, forestry, animal husbandry, and fisheries products and services sector (S1) could reduce direct CH_4 emission intensity through measures such as optimizing ruminant feed and rearing practices, upgrading livestock manure treatment technologies, optimizing paddy field water and tillage management, and standardizing the treatment of agricultural waste (straw). Meanwhile, the Water, Environment, and Public Utilities Management sector (S37) could reduce direct CH_4 emissions by optimizing wastewater treatment processes, upgrading sludge anaerobic digestion and biogas utilization systems, and shifting waste management from a "landfill-centric" approach to one focused on "reduction and resource recovery".

(2) Key emission reduction pathways for indirect emissions from residential consumption in $PL^{1\to3}$.

Table 2 reveals that indirect CH_4 emissions from household consumption in China in 2017 were heavily concentrated in the $PL^{0\to3}$ layer, which accounted for 71% of the total. Therefore, indirect CH_4 emission reductions in the $PL^{1\to\infty}$ layer should primarily focus on the $PL^{1\to3}$ layer. Since emissions in the $PL^{1\to3}$ layer are determined by sectoral direct emission intensity (t_i), inter-sectoral input coefficients (α_{ij}), and final consumption (y_j), the key emission reduction pathways for this industrial layer must satisfy the conditions ($S_{t\text{ in the supply sector}} > 0.01$)∩($S_\alpha > 0.01$)∩($S_{y\text{ in the demand sector}} > 0.01$), meaning that S_t in the supply sector, S_y in the demand sector, and S_α in the industrial stage must all meet the sensitivity criteria simultaneously. Based on these

criteria, this study identified a total of 10 industrial stages that meet the sensitivity conditions. However, sensitivity analysis could only identify important emission stages within the $PL^{1\rightarrow3}$ layer. Theoretically, there are countless industrial pathways between the source and sink sectors of different industrial segments. Accordingly, the SPA approach is employed to dissect the emission pathways within key industrial sectors and to pinpoint the primary abatement routes based on the scale of emissions along each pathway. For the sake of analysis, this study presents only 13 pathways where individual emissions account for more than 1% of total emissions in the $PL^{1\rightarrow3}$ layer (as shown in Table 5), which collectively account for 40.4% of total emissions and are thus representative.

Table 6 shows the key pathways of indirect CH_4 emissions from household consumption (accounting for more than 1%). As shown in Table 6, there is a concentration of sectors in the $PL^{1\rightarrow3}$ key pathways. From the perspective of supply sectors, a total of 10 key pathways originate from agricultural, forestry, livestock, and fishery products and services (S1), collectively accounting for 35.54% of total emissions in the $PL^{1\rightarrow3}$ pathway. The primary downstream sectors include food and tobacco (S6), accommodation and food services (S31), textiles (S7), textiles, clothing, footwear, leather, down, and related products (S8), and construction (S28), while the remaining three pathways all originate from coal mining and beneficiation products (S2). It is evident that emissions reductions in key sectors such as agricultural, forestry, livestock, and fishery products and services (S1) and coal mining and beneficiation products (S2) not only directly reduce indirect CH_4 emissions from household consumption but also influence the progress toward achieving emissions reduction targets in other sectors.

Table 6. Key pathways of indirect CH_4 emissions from residential consumption in $PL^{1\rightarrow3}$ (accounting for more than 1%).

Rank	Pathways	Emissions (10,000 tons)	Share/%	Industry Level
1	S1→S6	666.47	18.46	1
2	S1→S6→S6	142.32	3.94	2
3	S1→S1	113.95	3.16	1
4	S2→S13→S28	91.49	2.53	2
5	S1→S1→S6	88.87	2.46	2
6	S1→S6→S31	53.92	1.49	2
7	S1→S28	49.89	1.38	1
8	S1→S31	48.16	1.33	1
9	S1→S7→S8	45.60	1.26	2
10	S2→S14→S28	44.10	1.22	2
11	S2→S25	40.14	1.11	1
12	S1→S13→S28	37.46	1.04	2
13	S1→S7	36.37	1.01	1

3.4. Limitations

This study has made some progress by integrating methods such as the multi-region input-output model, industry-level decomposition, structural path analysis, and sensitivity analysis. However, due to constraints related to data availability, methodological assumptions, and the scope of the study, this research has several limitations. First, the multi-region input-output tables used in this study are based on 2017 data. These are the most recent publicly available MRIO tables for China's 31 provinces and regions. Currently publicly available provincial MRIO tables primarily cover the years 2010, 2012, 2015, and 2017. Consequently, this study cannot directly reflect the dynamic changes in interprovincial trade structures and industrial linkages after 2017. Future research should focus on the latest MRIO data released by official statistical agencies and, when data conditions permit, advance the base year of analysis. Second, this study used default emission factors provided by the IPCC for CH_4 emissions accounting, without performing parameter localization adjustments based on the resource endowments and agricultural production conditions of different provinces. Future research should advance the regional localization of emission factors and establish differentiated sets of emission factor parameters based on measured data from each province. Third, this study focused on three major categories of anthropogenic CH_4 emission sources: energy activities, waste and wastewater, and agricultural activities. Although these sources account for 93.8% of the national total, a small number of emission sources remain excluded from the accounting scope, such as biomass burning and land-use change. Additionally, this study excluded the impact of export trade; its conclusions primarily reflect emission shifts within China's domestic regional division of labor and cannot directly explain CH_4 emission shifts resulting from China's integration into global supply chains. Future research should further expand the accounting boundaries and incorporate international trade data to comprehensively characterize the global-local interlinkages of China's CH_4 emissions.

4. Conclusions and Recommendations

4.*1. Conclusions*

A methane emissions accounting framework was constructed in this study to quantify CH_4 emissions for 31 Chinese provinces over the 2012–2022 period. It analyzed the spatiotemporal distribution characteristics of provincial CH_4 emissions during this period and further integrated methods such as multi-region input-output modeling, sectoral decomposition, structural path analysis, and sensitivity analysis to investigate the transfer characteristics of CH_4 embedded in interprovincial trade in China. quantified indirect CH_4 emissions from Chinese household consumption, and identified key sectors and pathways for emission reductions at different industrial levels. This study yields the following principal findings:

(1) Analysis of spatiotemporal characteristics indicates that China's total CH_4 emissions from 2012 to 2022 followed a fluctuating trend of "first declining, then rising," increasing from 58.6299 million metric tons to 64.4081 million metric tons, with an average annual growth rate of 0.89%. Specifically, CH_4 emissions from energy activities were primarily concentrated in resource-rich provinces such as Shanxi, Inner Mongolia, and Shaanxi. CH_4 emissions from waste and wastewater were mainly concentrated in economically developed regions such as Beijing and Shanghai and CH_4 emissions from agricultural activities were primarily concentrated in provinces such as Tibet and Hunan.

(2) Analysis of the patterns of emission shifts indicates that interprovincial trade has a significant impact on China's CH_4 emissions. Provinces with net inflows are predominantly located in central and western China and tend to have a higher proportion of energy-related industries or agriculture and animal husbandry. Provinces with net outflows are predominantly located in the southeastern coastal regions and tend to be economically more developed, with industrial structures dominated by high-value-added industries. Overall, CH_4 emissions exhibit a shift pattern from east to west and from coastal to inland regions.

(3) Analysis of indirect emissions indicates that in 2017, indirect CH_4 emissions from household consumption in China totaled 69.7514 million metric tons, primarily originating from four sectors: construction (S28), food and tobacco (S6), agricultural, forestry, livestock, and fishery products and services (S1), and water, environmental, and public infrastructure management (S37). These emissions were mainly concentrated in the first four industrial levels (PL^0~PL^3).

(4) Analysis of emission reduction pathways indicates that, at the sector 0 level, key pathways for indirect CH_4 emissions from household consumption involve two sectors: agricultural, forestry, livestock, and fishery products and services (S1) and water management, environmental protection, and public facilities management (S37). At the sectoral levels 1-3, the study identified 10 key emission reduction pathways and found that these pathways exhibit a distinct "sectoral aggregation" phenomenon. When formulating emission reduction measures, prioritizing specific key sectors could facilitate CH_4 emission reductions across the entire industrial chain.

4.*2. Recommendations*

In light of the empirical results presented above, this study puts forward the following policy proposals aimed at provincial methane mitigation.

(1) Implement tailored measures to establish a differentiated regional emissions reduction policy framework. Resource-dependent provinces like Shanxi and Inner Mongolia should leverage elevated CCER prices to stimulate large-scale extraction of coal mine methane, while simultaneously boosting investment in the development and deployment of crucial energy-conservation and emission-mitigation technologies, thereby balancing abatement goals with market stability. In megacities (Beijing, Shanghai, etc.), strengthen tiered management of landfill gas, implement mandatory CCER disclosure for incineration plants processing over 3000 tons per day, and innovate "municipal bonds + green credit" to support distributed biogas projects. Agriculture-dominated provinces such as Tibet and Hunan should center their efforts on the "S6 Agricultural Inclusive Finance" initiative, implementing subsidies for water-saving irrigation in rice farming and "livestock methane-CCER" ecological compensation in pastoral areas, while establishing an agricultural emissions reduction quality traceability system using blockchain technology.

(2) Spatial coordination: Innovate cross-regional compensation and cost-sharing mechanisms. In line with the "common but differentiated responsibilities" principle in emissions reduction, provinces should bear responsibility for emissions originating from both production and consumption activities. This study proposes establishing an "East-West CCER Trading Alliance" to prioritize the inclusion of western agricultural emission reduction projects in the eastern carbon market, allowing high-emission provinces to fulfill a certain

percentage of their quotas by purchasing western credits. This study also recommends piloting an "upstream livestock emission reduction—downstream industrial compensation" scheme in the Yangtze River Economic Belt, using satellite remote sensing to quantify the cross-regional impact of rice-related methane emissions, and establishing an emissions trading market among Hunan, Jiangxi, and Hubei provinces. This study recommends promoting technologies such as coalbed methane power generation in the Beijing-Tianjin-Hebei and Yangtze River Delta regions, and providing additional quota incentives for cross-regional joint projects. It further recommends establishing a dedicated methane emission reduction fund to provide technical renovation subsidies to resource-based provinces and offer interest-free loans to agricultural cooperatives.

(3) Focus on key areas and prioritize collaborative emission reductions across critical sectors and pathways. Indirect CH_4 emissions from household consumption are concentrated in a few key sectors and pathways. Conducting in-depth research on these areas could enhance the effectiveness and precision of emission reduction measures. At the sectoral level (Level 0), emissions reductions are primarily achieved by lowering direct emissions intensity within sectors, such as promoting the application and dissemination of innovative emission reduction technologies and management practices. At higher industrial levels, the focus should shift to collaborative emissions reductions across sectors. Potential approaches include reducing food waste in food production, the restaurant industry, and the textile sector, as well as substituting coal combustion with coal mine gas in cement and lime production.

Author Contributions

Conceptualization, Y.W.; Data curation, Y.W.; Formal analysis, T.H.; Funding acquisition, Q.M.; Investigation, Y.W. and T.H.; Methodology, Y.W. and T.H.; Project administration, Y.W.; Resources, Y.W. and M.Q.; Software, Y.W. and T.H.; Supervision, Y.W., T.H. and Q.M.; Validation, Q.M. and X.W.; Visualization, Y.W. and M.Q.; Roles/Writing—original draft, Y.W., T.H. and M.Q.; Writing—review & editing, Y.W., T.H., X.W., L.J. and X.G. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The authors declare that they have no conflict of interests.

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Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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