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Coupling characteristics between industrial linkage networks and carbon emission networks in Xi'an metropolitan areas

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Abstract: *Understanding the interplay between industrial linkages and carbon emissions is critical for regional low-carbon transitions, yet the structural coupling between economic networks and emission networks remains underexplored at the metropolitan scale. This study constructs industrial linkage and carbon emission networks for the Xi'an metropolitan area using city-level multi-regional input-output data and environmental extended input-output analysis. Complex network centrality measures and a coupling index are employed to identify key nodes and assess the matching relationship between industrial importance and carbon importance. Results show that the industrial network exhibits a core-periphery structure dominated by finance, business services, transportation, and chemical manufacturing, while the carbon network is centered on electricity/heat production, coal mining, transport, and energy-intensive manufacturing. The coupling analysis reveals 29 double-high nodes that simultaneously possess high industrial and carbon centrality, notably finance, transport, and electricity supply. These nodes act as critical conduits for both economic activities and emission diffusion, indicating that emission reduction policies should prioritize network-position-based interventions rather than relying solely on sectoral emission totals. The findings further reveal a spatial mismatch between economic benefits and carbon responsibilities across cities, with Xi'an concentrating high-value services while surrounding cities bear heavier energy-related emission pressures. This study provides a network-based framework for identifying synergistic emission mitigation targets and offers policy insights for optimizing industrial spatial layouts and promoting coordinated low-carbon development in metropolitan regions.*

Keywords: *Industrial linkage network, Carbon emission network, Coupling analysis, Xi'an metropolitan area, Input-output analysis, Complex network centrality*

1. Introduction

Against the background of global climate change and the continuous advancement of carbon reduction targets, achieving coordination between economic development and carbon emission control has become a critical issue for regional sustainable development[1]. Cities and metropolitan areas, as spatial units with high concentrations of population, industries, and energy consumption, are important carriers of economic activities and carbon emissions[2]. In recent years, with the acceleration of regional economic integration, complex industrial linkage networks have emerged within metropolitan areas, based on industrial division of labour, resource flows, and trade connections. Industrial chain synergy has promoted regional economic growth and resource allocation efficiency, but it has also led to the redistribution of energy consumption and carbon emissions among different cities and industries. Therefore, identifying the relationship between internal economic linkages and carbon emission transfers from the perspective of industrial chain connections is of great significance for optimising regional industrial layouts and promoting low-carbon transformation.

Traditional regional carbon emission research has mainly been based on production-side emission accounting methods, focusing on the total emissions, emission intensity, and influencing factors of different regions. However, as inter-regional industrial division deepens, the production process of products involves multiple regions and multiple industrial stages, and direct emissions from a single region cannot reflect the true carbon responsibility along the industrial chain. The multi-regional input-output model (MRIO) can describe input-output relationships between regions and industries, and combined with environmentally extended input-output analysis (EE-MRIO), it can identify embodied resource consumption and carbon emission transfers in economic activities[3][4]. Studies based on the MRIO model have been widely applied to measure inter-regional embodied carbon emissions, but existing research focuses more on emission scales, sources, and spatial transfer characteristics, while the role of industrial chain structure in shaping carbon emission networks remains insufficiently investigated[5].

An industrial chain is essentially a complex network composed of input-output relationships among different industrial entities. Complex network analysis can identify core nodes, key paths, and structural features of industrial systems from the perspectives of node relationships and network structure, providing a new analytical framework for studying regional industrial linkages[6][7]. Similarly, the transfer process of carbon emissions between industries and regions can be represented as a carbon emission network composed of emission sources, transmission paths, and affected entities[8]. The industrial network reflects the organizational structure of economic activities, while the carbon network reflects the environmental impacts behind economic linkages, and the two are inherently related. However, current studies usually analyse industrial linkage networks or carbon emission networks separately, lacking systematic research on their structural relationships and coupling mechanisms[9]. They cannot adequately explain which industrial nodes simultaneously possess high economic influence and carbon transmission effects, nor how industrial chain adjustments affect the spatial distribution of carbon emissions.

Metropolitan areas, as an important spatial scale linking urban economic activities, have strong industrial linkages and spatial proximity, making them suitable regional units for studying the coupling between industrial chains and carbon emissions[10]. The Xi'an metropolitan area, as a key economic region in western China, has developed an industrial system based on equipment manufacturing, electronic information, energy and chemical engineering, etc. Different cities are closely connected in terms of industrial division, energy supply, and product circulation, while also facing the pressure of coordinating industrial development and carbon reduction. Due to differences in development stages, industrial structures, and resource endowments among cities within the metropolitan area, industrial chain linkages may lead to the redistribution of carbon responsibilities and environmental pressures within the region. Therefore, studying the relationship between the industrial network and the carbon emission network in the Xi'an metropolitan area helps reveal the environmental effects of industrial synergy within the metropolitan area.

Based on this, this paper constructs an analytical framework for coupling the industrial linkage network and carbon emission network, using city-industry-scale multi-regional input-output data to study the industrial linkage structure and embodied carbon emission transfer characteristics of the Xi'an metropolitan area. First, based on input-output relationships, we build an industrial linkage network and analyse the internal industrial association structure and key node features. Second, we use the environmentally extended input-output model to calculate inter-industry embodied carbon flows and construct a carbon emission network. Finally, using network structure indicators and coupling analysis methods, we identify the correlation between the industrial network and the carbon network and the key industrial nodes. This study aims to reveal the transmission mechanism between economic activities and carbon emissions from the combined perspective of industrial linkages and environmental impacts, providing a theoretical basis for optimising regional industrial structures and formulating low-carbon development pathways.

2. Methodology

2.1. Study area and data

This study takes the Xi'an metropolitan area as the research object, and determines the scope according to the Xi'an Metropolitan Area Development Plan, including five cities: Xi'an, Xianyang, Baoji, Weinan, and Tongchuan. The Xi'an metropolitan area is an important component of the Guanzhong Plain urban agglomeration, playing a significant role in regional economic development, industrial synergy, and energy consumption systems. In recent years, with the deepening of industrial division within the metropolitan area, cities have formed close industrial linkage networks. At the same time, the growth of energy consumption and differences in industrial structures have led to increasingly complex spatial distributions and transfer relationships of carbon emissions. Therefore, selecting the Xi'an metropolitan area as the research object helps to reveal the coupling relationship between industrial linkages and carbon emissions from a regional network perspective.

The city-level input-output table and carbon emission data for 2017 used in this paper are sourced

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from the China Carbon Emission Database, covering 42 sectors including agriculture, mining, manufacturing, energy supply, construction, and services[11]. The input-output table can depict direct and indirect economic linkages among industrial sectors, providing basic data for constructing the industrial chain network. To eliminate the influence of scale differences among cities and industries on network structure analysis, we standardise industrial linkage intensities and carbon flows during network construction to ensure comparability among different nodes.

2.2. Industrial network construction

The industrial chain network can reflect the production linkages and value transfer relationships among industrial sectors within a region. Based on input-output theory, we construct an industrial linkage network, taking city-industry nodes as network nodes and input-output relationships as network edges. The input-output model is expressed as:

$$X = AX + Y \tag{1}$$

where X is the total output matrix, A is the direct consumption coefficient matrix, and Y is the final demand matrix. Further, we have:

$$X = (I - A)^{-1} + Y \tag{2}$$

Where$(\mathrm{I} - \mathrm{A})^{-1}$is the Leontief inverse matrix, reflecting the comprehensive impact of changes in final demand on the output of each industrial sector.

We use the industrial linkage strength in the Leontief inverse matrix as the edge weight of the industrial network. Specifically, we combine 42 industries with 5 cities to form 210 industrial nodes, constructing a weighted directed network matrix of size 210×210:

$$G_I = (V, E, W) \tag{3}$$

where V is the set of industrial nodes, E denotes industrial linkage relationships, and W represents the input-linkage intensity between industries. Through this method, we can characterise the production linkage structure among different cities and industries within the Xi'an metropolitan area, and further identify key nodes and core industries in the industrial chain.

2.3. Carbon network construction

The carbon emission network is used to describe the transfer relationships of embodied carbon emissions among industrial sectors during production activities. We employ the environmentally extended input-output model (EEIO) to calculate inter-industry embodied carbon flows. First, we calculate carbon emission intensity based on direct carbon emissions of each sector:

$$f_i = \frac{C_i}{X_i} \tag{4}$$

where C_i is the direct carbon emission of sector i, X_i is the total output of sector i, and f_i is the carbon emission per unit of output. We then construct a carbon intensity vector:

$$F = (f_1, f_2, \cdots, f_n) \tag{5}$$

Combined with the input-output model:

$$C = F(I - A)^{-1}Y \tag{6}$$

Based on inter-industry embodied carbon flow relationships, we construct the carbon emission network:

$$G_C = (V, E, W_C) \tag{7}$$

where the node set is consistent with the industrial network, and edge weights represent embodied carbon emission transfers between industrial sectors. Through carbon network analysis, we can identify key industries in regional carbon transmission and the diffusion paths of carbon emissions.

2.4. Network centrality analysis

To identify key nodes in both the industrial and carbon networks, we adopt complex network analysis methods, evaluating the importance of industrial nodes from three aspects: connection capacity, control ability, and network influence.

(1) Degree centrality

Degree centrality measures the direct connection degree between a node and other nodes. For directed networks, we calculate out-degree and in-degree centrality separately:

$$D_i = \sum_j w_{ij} \tag{8}$$

where w_{ij} is the linkage strength between node *i* and node *j* . A higher degree centrality indicates closer connections with other industries.

(2) Betweenness centrality

Betweenness centrality measures the intermediary role of a node in network information transmission:

$$B_i = \sum_{s \neq i \neq t} \frac{\sigma_{st}(i)}{\sigma_{st}} \tag{9}$$

where σ_{st} is the number of shortest paths from node *s* to node *t* , and $\sigma_{st}(i)$ is the number of those paths passing through node i. Higher betweenness centrality indicates stronger control over network transmission.

(3) Eigenvector centrality

Eigenvector centrality considers the importance of a node's neighbouring nodes:

$$Ax = \beta x \tag{10}$$

where the importance of a node depends not only on its own number of connections but also on the importance of the nodes it connects to.

(4) PageRank centrality

PageRank is used to comprehensively evaluate the influence of a node in the overall network:

$$PR_i = \frac{1-d}{N} + d \sum_j \frac{PR_j}{L_j} \tag{11}$$

where *d* is the damping coefficient, and L_j is the number of connections of node *j*.

2.5. Network coupling analysis

To reveal the matching relationship between industrial economic linkages and carbon emission transfers, we further construct a coupling evaluation system for the industrial-carbon network. First, we standardise the centrality indicators of the industrial network and the carbon network, obtaining the Industrial Importance Index and Carbon Importance Index respectively. We adopt a comprehensive centrality evaluation method:

$$I_i = \sum_{k=1}^{m} \omega_k Z_{ik} \tag{12}$$

where Z_{ik} is the standardized value of the k-th centrality indicator, and ω_k is the indicator weight.

Further, we construct a node coupling index:

$$CCI_i = \sqrt{I_i \times C_i} \tag{13}$$

where CCI_i represents the industrial-carbon coupling level of node *i*. According to the relative levels of the Industrial Importance Index and Carbon Importance Index, we classify industrial nodes into four types:

(1) Double-high: high industrial importance and high carbon importance–priority optimisation nodes;

(2) Industry-core: high industrial importance but low carbon importance–green development support nodes;

(3) Carbon-core: low industrial importance but high carbon importance–emission reduction constraint nodes;

(4) Peripheral: low industrial importance and low carbon importance–limited overall network influence.

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Through this classification, we can identify the spatial matching relationship between industrial development and carbon emission pressure in the Xi'an metropolitan area from a network coupling perspective, providing a basis for subsequent low-carbon optimisation path design.

3. Results

3.1. Industrial linkage network characteristics

The industrial network density is 0.449, indicating that about 44.9% of potential industrial linkages have been formed, showing a relatively high level of inter-sector connections, which is consistent with structural features observed in other urban agglomerations in northern China[12], but there are still a certain number of unconnected relationships. The clustering coefficient of the industrial network is 0.804, suggesting that interconnected industrial sectors tend to form local clusters, with strong local organizational features, and resource sharing and input linkages mainly concentrate among local industrial groups. The average path length of the industrial network is 9.165, indicating that the transmission of industrial linkages requires passing through many intermediate nodes, so the overall connectivity efficiency is relatively limited, and industrial linkages still possess a certain hierarchical structure and transmission distance.

To identify the key industrial nodes in the Xi'an metropolitan area's industrial network, we construct the industrial linkage network based on input-output relationships and measure the importance of industrial nodes using degree centrality, betweenness centrality, closeness centrality, and eigenvector centrality.The main results of node centrality are presented in Table 1. The results show that the industrial network exhibits an obvious core-periphery structure, with a few industrial nodes playing crucial roles in network connection, resource allocation, and industrial transmission. Among them, Xi'an's financial industry, Xianyang's chemical products, Xi'an's leasing and business services, and Xi'an's transport, storage, and postal services have high comprehensive centrality, being the core nodes in the metropolitan area's industrial linkage network. In particular, the financial industry has the highest eigenvector centrality and Page Rank value, indicating that it maintains close ties with many important industrial sectors and possesses strong control ability in resource allocation and network organization.

Table 1: Top 20 nodes in industrial network centrality

City	Industry	Out-degree	In-degree	Betweenness	Closeness	Eigenvector	PageRank
Xi'an	Finance	6570463.82	2527260.65	0.34	1213.61	0.69	0.10
Xianyang	Chemical products	3480349.21	2875052.06	0.33	1204.35	0.05	0.03
Xi'an	Leasing and business services	3199056.99	2367768.84	0.10	1211.44	0.41	0.05
Xi'an	Transport, storage and postal	3467467.76	2340308.86	0.08	1210.39	0.28	0.04
Xi'an	Construction	174441.12	7905642.44	0.05	1155.57	0.01	0.00
Baoji	Metal smelting and rolling products	2857973.56	1708548.23	0.11	1182.96	0.01	0.01
Xi'an	Chemical products	2632804.42	1465901.93	0.10	1202.83	0.05	0.02
Xianyang	Non-metallic mineral products	2718605.65	1420443.19	0.13	1183.21	0.03	0.00

ISSN 2616-5783 Vol.9, Issue 7: 16-29, DOI: 10.25236/AJHSS.2026.090703

Xi'an	Real estate	1833411.47	1947925.80	0.02	1211.01	0.33	0.04
Weinan	Chemical products	1700135.62	1197677.45	0.11	1202.73	0.03	0.01
Xianyang	Agriculture, forestry, animal husbandry and fishery products and services	2050291.93	1040818.10	0.08	1202.51	0.04	0.01
Xianyang	Food and tobacco	1190633.58	2495382.08	0.06	1198.28	0.02	0.01
Weinan	Agriculture, forestry, animal husbandry and fishery products and services	1418381.91	909545.33	0.09	1200.45	0.02	0.01
Xi'an	Scientific research and technical services	1787405.27	2449032.79	0.03	1161.06	0.02	0.00
Xi'an	Electrical machinery and equipment	1480405.27	1414465.53	0.06	1188.35	0.04	0.01
Xianyang	Leasing and business services	1455631.42	1050600.92	0.03	1206.66	0.17	0.02
Baoji	Non-metallic mineral products	2044974.93	911600.32	0.06	1179.82	0.01	0.00
Baoji	Construction	74551.80	4439988.62	0.02	1067.69	0.00	0.00
Xianyang	Transport, storage and postal	1397095.50	772778.12	0.02	1205.24	0.09	0.02
Xi'an	Food and tobacco	883326.52	1731433.69	0.03	1200.60	0.02	0.01

From different centrality indicators, manufacturing sectors exhibit strong connective roles in the industrial network. In particular, chemical products appear as central nodes in multiple cities, and Xianyang's chemical products have a high betweenness centrality, indicating that this industry plays an important connection and transmission function among different industrial sectors. Manufacturing industries such as metal smelting and rolling, non-metallic mineral products, and electrical machinery also have high network centrality, reflecting that manufacturing remains an important carrier of industrial linkages and factor flows in the Xi'an metropolitan area. These industries not only support regional economic operations but may also become key links in embodied carbon emission transmission due to

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their high resource and energy inputs.

From the spatial distribution, Xi’an, Xianyang, and Baoji constitute the main core area of the industrial network, with a differentiated industrial division pattern. Xi’an’s core nodes are mainly concentrated in productive services such as finance, business services, transport, and scientific research and technical services, reflecting the leading role of the core city in resource allocation and innovation services. Xianyang's main network nodes are manufacturing like chemical products and non-metallic mineral products, undertaking industrial reception and manufacturing support functions. Baoji relies on metal processing and basic manufacturing industries to play a role in material supply and industrial chain supporting. Through industrial linkages, the different cities form a multi-level, multi-link industrial cooperation network.

The industrial network of the Xi’an metropolitan area shows a structural feature of core service-driven, manufacturing-supported, and multi-city synergy. The nodes with high centrality are not only key supports for regional industrial development but also important targets for subsequent analysis of carbon emission transmission and collaborative emission reduction. In the process of industrial low-carbon transformation, attention should be paid to high-linkage manufacturing industries such as chemical products, metal smelting and rolling, and non-metallic mineral products, as well as service sectors with strong network influence like finance and transport, to promote the overall green transformation of the industrial chain through key node regulation.

3.2. Carbon emission network characteristics

The carbon emission network density reaches 0.836, significantly higher than that of the industrial network, indicating that carbon emission coverage extends to most industrial nodes. This high connectivity pattern is also documented in provincial-level embodied carbon transfer networks across China[5]. The clustering coefficient is 0.914, reflecting a strong local clustering feature of carbon linkages, with high-emission industries forming a relatively tight association structure. The average path length of the carbon network is only 2.540, much lower than that of the industrial network, indicating that carbon emissions can propagate through fewer industrial linkages, with high overall connectivity efficiency and strong transmission capacity among industries.

The carbon network exhibits a clear concentration around core nodes, with the electricity and heat production and supply industry occupying an absolute dominant position. Xi’an, Xianyang, and Baoji’s electricity and heat production and supply sectors are respectively at the centre of the carbon network, with PageRank values of 0.103, 0.116, and 0.098, indicating that energy supply sectors have strong control over carbon emission transmission in the metropolitan area. As a key conversion and supply link, the electricity and heat industry connects energy inputs with downstream production activities, exerting significant influence on regional carbon formation.The centrality values for top- ranked nodes within the carbon emission network are summarised in Table 2.

Table 2: Top 20 nodes in carbon emission network centrality

City	Industry	Out-degree	In-degree	Betweenness	Closeness	Eigenvector	PageRank
Xi'an	Electricity and heat production and supply	17022733.76	17123.22	0.38	0.45	0.92	0.10
Xianyang	Electricity and heat production and supply	7457092.29	50124.38	0.14	0.45	0.20	0.12
Baoji	Electricity and heat production and supply	6619252.60	87708.65	0.13	0.45	0.12	0.10
Xi'an	Transport,	685040.75	364975.35	0.73	0.45	0.07	0.03

ISSN 2616-5783 Vol.9, Issue 7: 16-29, DOI: 10.25236/AJHSS.2026.090703

	storage and postal						
Xi'an	Construction	1366.07	13281996.15	0.08	0.45	0.00	0.00
Xi'an	Finance	81161.32	453256.53	0.63	0.45	0.02	0.01
Xianyang	Coal mining and washing products	623870.16	7134.78	0.00	0.45	0.17	0.09
Baoji	Coal mining and washing products	710330.60	1398.81	0.00	0.45	0.18	0.08
Weinan	Electricity and heat production and supply	1070289.26	60758.67	0.15	0.45	0.05	0.04
Tongchuan	Electricity and heat production and supply	1152782.44	2460.18	0.11	0.45	0.01	0.04
Weinan	Transport, storage and postal	474014.89	57708.31	0.25	0.45	0.04	0.02
Baoji	Construction	691.89	5385162.78	0.08	0.45	0.00	0.00
Xi'an	Education	19256.45	1141427.58	0.30	0.45	0.00	0.00
Xi'an	Real estate	25936.48	3866143.08	0.13	0.45	0.00	0.00
Xianyang	Transport, storage and postal	455233.55	110572.23	0.21	0.45	0.04	0.01
Weinan	Coal mining and washing products	314932.45	2905.77	0.00	0.45	0.05	0.04
Xi'an	Metal smelting and rolling products	1885170.35	6076.50	0.00	0.45	0.05	0.02
Xianyang	Construction	745.84	2932781.69	0.01	0.45	0.00	0.00
Baoji	Transport, storage and postal	354474.59	130029.76	0.09	0.45	0.03	0.01
Xi'an	Non-metallic mineral products	3168679.03	21308.87	0.00	0.45	0.01	0.00

From the industry type perspective, the core nodes of the carbon network are mainly concentrated in energy supply, resource extraction, transport, and construction. The coal mining and washing products industry appears in the top 20 in Xianyang, Baoji, and Weinan, showing high eigenvector centrality and PageRank levels, indicating that coal resource supply is still a fundamental link in the formation and transmission of carbon emissions in the metropolitan area. Meanwhile, transport, storage, and postal services exhibit high centrality in multiple cities (Xi'an, Xianyang, Weinan, and Baoji), reflecting the important role of transport activities in spatial industrial linkages and energy consumption. In addition, high-energy-consuming industries such as construction, metal smelting and rolling, and non-metallic mineral products also have high network influence and are important carriers of carbon diffusion.

In terms of spatial distribution, Xi'an, Xianyang, and Baoji remain the main control areas of the carbon network, but their functional positions differ somewhat from those in the industrial network. Xi'an's carbon core nodes are mainly in electricity and heat supply, transport, construction, finance, and metal processing, reflecting the influence of the central city in energy consumption and economic agglomeration. Xianyang relies on electricity supply, coal mining, and transport to form a strong carbon transmission capacity, showing features of energy support and manufacturing support. Baoji mainly participates in carbon transmission through electricity supply, coal resources, construction, and transport. Meanwhile, Weinan and Tongchuan's electricity supply and coal industries enter the core node set, indicating that peripheral cities play important roles in energy supply and resource-based industries.

The carbon emission network of the Xi'an metropolitan area exhibits a structural feature dominated by the energy sector, supported by high-energy-consuming industries, and with multi-city collaborative transmission. Compared with industrial network centrality, the core nodes of the carbon network are more concentrated in energy production and resource-consuming sectors, suggesting a certain spatial mismatch between regional economic linkages and carbon emission transmission. Therefore, in the subsequent industrial-carbon coupling analysis, special attention should be given to key nodes such as electricity and heat production and supply, coal mining, transport, construction, and high-energy-consuming manufacturing, to reduce carbon network risks through energy structure optimization, industrial chain emission reduction, and cross-regional collaborative governance.

3.3. Coupling relationship between industrial and carbon networks

Based on the Industrial Importance Index and Carbon Importance Index, we construct a node coupling evaluation system and classify nodes into four types: Double-high, Industry-core, Carbon-core, and Peripheral. The results show that the industrial and carbon networks exhibit obvious spatial heterogeneity and node differentiation in the Xi'an metropolitan area, with 29 nodes simultaneously having high industrial and carbon importance, representing key nodes that require focused attention in regional industrial development and low-carbon transition. The quantity and proportion statistics for each coupling category are provided in Table 3.

Table 3: Statistics of node coupling types

Coupling type	Number of nodes	Proportion
Double-high	29	13.81%
Industry-core	27	12.86%
Carbon-core	3	1.43%
Peripheral	151	71.90%

Double-high nodes are mainly concentrated in energy supply, transport, high-energy-consuming manufacturing, and producer services. Among them, Xi'an's financial industry has the highest coupling index (CCI=0.56), indicating that although this sector has low direct carbon emissions, its core position in the industrial network and high carbon network relevance give it significant influence on regional industrial green transformation. In addition, Xi'an's transport, storage, and postal services (CCI=0.43), electricity and heat production and supply (CCI=0.32), construction (CCI=0.32), and Xianyang's electricity and heat production and supply (CCI=0.24) all show high coupling levels, indicating that energy supply, infrastructure, and production service sectors simultaneously bear the dual functions of industrial support and carbon transmission, making them priority regulation targets for collaborative emission reduction in the metropolitan area. Representative industrial nodes belonging to different coupling types are listed in Table 4.

ISSN 2616-5783 Vol.9, Issue 7: 16-29, DOI: 10.25236/AJHSS.2026.090703

Table 4: Representative industrial nodes of different coupling types

City	Industry	Industrial Importance	Carbon Importance	CCI	Type
Xi'an	Petroleum, coking and nuclear fuel processing	0.02	0.07	0.04	Carbon-core
Xi'an	Chemical products	0.32	0.03	0.10	Double-high
Xi'an	Non-metallic mineral products	0.08	0.07	0.07	Double-high
Xi'an	Electricity and heat production and supply	0.13	0.80	0.32	Double-high
Xi'an	Transport, storage and postal	0.43	0.42	0.43	Double-high
Xi'an	Finance	1.00	0.32	0.56	Double-high
Xianyang	Electricity and heat production and supply	0.10	0.54	0.24	Double-high

From the industry type perspective, Double-high nodes are mainly distributed in energy production sectors and resource-dependent manufacturing, including electricity and heat production, coal mining, chemical products, non-metallic mineral products, and metal smelting and rolling. These industries have strong connective capabilities in the industrial network and are also important channels for carbon transmission. For example, Xianyang’s chemical products, non-metallic mineral products, and coal mining all fall into the Double-high category, reflecting that traditional manufacturing supports the regional industrial system while also bearing significant carbon pressure. In contrast, some producer service nodes in Xi’an appear as industrial network cores and important carbon network connectors, reflecting the important role of modern services in industrial chain operation and carbon flow organisation.

The industrial-carbon network coupling in the Xi’an metropolitan area shows that core industrial nodes partially overlap with carbon nodes, but they are not completely consistent. Double-high nodes constitute the key breakthrough points for industrial green transformation, where priority should be given to energy structure optimisation, production process upgrading, and collaborative industrial chain emission reduction. Industry-core nodes mainly play roles in industrial support and value creation, and their indirect carbon emissions can be reduced through green finance, technological innovation, and supply chain management. Carbon-core nodes are few, mainly concentrated in energy-consuming sectors, and should be subject to targeted emission reduction constraints. This classification further reveals the coupling relationship between industrial development functions and carbon responsibilities, providing a basis for constructing differentiated low-carbon optimisation pathways.

4. Discussion

The carbon emission network exhibits higher network density and clustering coefficient than the industrial network, while its average path length is significantly lower, indicating that the carbon network has higher overall connectivity and stronger local clustering. In contrast, the industrial network shows strong local linkages but relatively low overall transmission efficiency, with industrial linkages still relying mainly on limited key paths for cross-industry transmission. These results suggest that the formation of industrial linkages does not fully correspond to the diffusion process of carbon linkages, and carbon emissions have stronger network transmission characteristics along the industrial chain. Therefore, in promoting industrial synergy and low-carbon transformation in the Xi’an metropolitan area, full consideration should be given to the structural differences between industrial linkages and carbon transmission, and collaborative governance should be strengthened among key industrial nodes and their upstream and downstream industries, to improve the overall efficiency of industrial chain optimisation and regional collaborative emission reduction.

Both the industrial network and the carbon network exhibit a core-periphery structure, but the core nodes of the two networks are not completely consistent, reflecting structural differences between economic linkages and environmental pressures. The core nodes of the industrial network are mainly concentrated in finance, business services, transport, and some manufacturing sectors, reflecting the important role of modern services and producer services in resource allocation, industrial organisation, and value creation. In contrast, the carbon network is dominated by energy-dependent industries such as electricity and heat production, coal mining, and high-energy-consuming manufacturing, indicating that energy input and production stages remain the main sources of regional carbon emissions. This difference suggests that regional economic network centrality does not necessarily correspond to carbon centrality, and the functional positioning of industrial sectors in the economic system differs significantly from their environmental impact mechanisms. On the one hand, sectors like finance and technical services have low direct emissions but influence a wide range of production activities through capital allocation, technology diffusion, and supply chain organisation, exerting indirect effects on regional carbon emissions. On the other hand, energy supply and resource processing industries, being at the upstream of the industrial chain, can diffuse their carbon emissions to many downstream sectors through input-output relationships, forming network propagation effects. Therefore, analysing the relationship between industrial development and carbon emissions from a network perspective helps break through traditional single-industry emission accounting and more accurately identify key influential nodes in regional low-carbon transition.

The industrial-carbon coupling results reveal the dual attributes of key industrial nodes between economic development and environmental constraints. Among them, Double-high nodes simultaneously possess high industrial and carbon importance, being the core links affecting regional industrial operation and carbon diffusion. These nodes are mainly concentrated in electricity and heat production, chemical products, non-metallic mineral products, metal smelting, and transport, and their common feature is strong connectivity in the industrial linkage network and significant energy consumption and carbon transmission functions. Traditional emission reduction research usually determines governance targets based on direct emission scales, but network analysis shows that the environmental impact of an industrial node depends not only on its own emission level but also on its position in the industrial network. Nodes in key network positions, even if their own emissions are not the highest, may generate large systemic effects through industrial linkages. Therefore, identifying key nodes based on network centrality can further improve the precision and effectiveness of emission reduction policies. At the metropolitan scale, prioritising the regulation of Double-high nodes can not only reduce their own carbon pressure but also drive synergistic emission reduction among upstream and downstream sectors through industrial chain transmission, achieving a shift from single-industry governance to network-based governance.

The study finds that the internal industrial division pattern of the Xi'an metropolitan area has a significant impact on the spatial distribution of carbon emissions. As the core city, Xi'an's industrial network centrality is mainly concentrated in finance, business services, scientific research and technical services, and transport, reflecting resource allocation, innovation-driven, and comprehensive service functions. In contrast, cities like Xianyang and Baoji assume more functions of energy supply, resource processing, and manufacturing support, showing higher influence in the carbon network. This functional division improves industrial collaboration efficiency within the metropolitan area, but may also cause a mismatch between economic benefits and carbon responsibilities – the core city gathers more high-value-added links, while energy consumption and resource processing are more distributed in peripheral areas, causing some cities to bear higher environmental pressure. From a sustainable development perspective, carbon emissions within a metropolitan area are not a problem of a single city or a single industry, but rather the result of the joint action of industrial chain spatial layout and regional division. Therefore, future research and governance practices should start from the overall network structure of the metropolitan area, pay attention to the carbon responsibility transmission mechanisms behind industrial linkages, and strengthen technology diffusion, industrial synergy, and energy optimisation between core and peripheral cities, achieving a dynamic balance between industrial value creation and carbon responsibility.

5. Policy implications

Based on input-output analysis and complex network theory, this paper constructs the industrial linkage network and carbon emission network of the Xi'an metropolitan area, analyses the characteristics of industrial association structure and carbon transmission from the perspectives of network centrality and node coupling, and reveals the intrinsic relationship between economic linkages and environmental pressures. The main conclusions are as follows:

First, the industrial network of the Xi'an metropolitan area shows an obvious core-periphery structure, with a few key industrial nodes playing a dominant role in regional industrial linkages. Industries such as finance, leasing and business services, transport, and chemical products have high network centrality and are important nodes for promoting industrial factor flows and collaborative development. In terms of spatial distribution, Xi'an mainly undertakes resource allocation, innovation services, and

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comprehensive support functions, while Xianyang and Baoji form the industrial chain support system through manufacturing processing and basic industries, jointly constituting a multi-level industrial cooperation network.

Second, the carbon emission network exhibits a more pronounced energy-dependence feature, with core nodes mainly concentrated in electricity and heat production, coal mining, transport, and high-energy-consuming manufacturing. Compared with the industrial network, the carbon network has stronger upstream control characteristics, with energy supply and resource processing industries transmitting carbon pressure to other sectors through input-output relationships. Therefore, regional carbon governance cannot only focus on terminal emission sectors, but should fully consider key transmission nodes in the industrial network.

Third, the coupling analysis of the industrial-carbon network shows obvious structural heterogeneity between economic linkages and carbon pressure. Double-high nodes simultaneously have high industrial importance and carbon influence, and are the priority targets for low-carbon transformation in the metropolitan area. Industry-core nodes embody industrial development and value creation functions, while Carbon-core nodes reflect the special influence of certain industries in the carbon network. This indicates that identifying key nodes based on network coupling can effectively compensate for the shortcomings of traditional emission-scale-based decision-making, providing a new analytical perspective for regional precise emission reduction.

Based on the above findings, this paper proposes the following policy implications:

(1) Strengthen key node identification and implement targeted industrial emission reduction strategies.

The study finds that Double-high nodes simultaneously have high industrial importance and carbon influence, serving as key links connecting economic activities and carbon transmission. Therefore, the Xi’an metropolitan area should break through the traditional governance model based on total industry emissions, incorporate industrial network position into the emission reduction decision-making system, and implement precise regulation on industries with high betweenness centrality and network influence. For Double-high industries such as electricity and heat production, chemical products, non-metallic mineral products, and metal smelting, priority should be given to improving energy efficiency, green transformation of production processes, and collaborative emission reduction along the industrial chain, fully leveraging the network diffusion effects of key node reduction. At the same time, for Industry-core nodes such as finance and scientific research and technical services, their advantages in resource allocation and technology diffusion should be used to guide green investment and low-carbon technology innovation, forming a synergistic optimisation pattern of economic and carbon networks.

(2) Promote low-carbon transformation of the energy system to reduce the transmission pressure of the carbon network.

The carbon network analysis shows that the electricity and heat production and supply industry is the core node of carbon transmission in the metropolitan area, and energy system optimisation is a key breakthrough for regional emission reduction. Therefore, the energy structure should be accelerated, increasing the share of renewable energy, and promoting the transformation of traditional energy supply systems towards clean and intelligent directions. At the same time, collaborative management between energy supply sectors and key energy-consuming industries should be strengthened, reducing carbon emissions per unit of output through improved energy efficiency, waste heat utilisation, and cascade energy use. In addition, a coordination mechanism between energy production and industrial layout should be established to avoid further concentration of energy demand and carbon pressure due to the expansion of high-energy-consuming industries.

(3) Optimise the metropolitan area’s industrial division to promote the coordinated matching of economic benefits and carbon responsibilities.

The study finds that Xi’an, Xianyang, and Baoji play different roles in the industrial and carbon networks, forming a spatial division pattern where the core city leads services and peripheral cities support manufacturing. This division improves regional industrial collaboration efficiency, but may cause a mismatch between economic value creation and carbon responsibility. Therefore, the internal industrial layout of the metropolitan area should be further optimised to promote a more reasonable industrial division system. Xi’an should leverage its innovation resources and service advantages to strengthen green technology R&D, financial support, and industrial organisation functions. Manufacturing cities like Xianyang and Baoji should accelerate the green upgrading of traditional industries, improving resource efficiency and industrial added value. At the same time, a cross-regional carbon coordination mechanism should be established, incorporating industrial chain linkages and carbon responsibilities into the regional governance system, and avoiding the spatial transfer of carbon emissions through industrial relocation.

(4) Promote green restructuring of the industrial chain and facilitate the upgrade of traditional industries towards low-carbon and high-value-added directions.

The industrial network analysis shows that manufacturing remains an important foundation for industrial linkages and a significant source of carbon pressure in the metropolitan area. Therefore, future industrial optimisation should not simply weaken traditional manufacturing, but promote industrial chain restructuring through green technology innovation. On the one hand, digital, intelligent, and green transformation should be promoted in advantageous industries such as chemical products, equipment manufacturing, and material processing to improve production process energy efficiency. On the other hand, green supply chain construction should be strengthened, extending carbon management from individual enterprises to upstream and downstream associated enterprises, achieving full-chain low-carbon management. In addition, relying on Xi'an's scientific research and innovation advantages, green technology achievements should be transferred to industrial bases in Xianyang and Baoji, enhancing the overall industrial green competitiveness of the metropolitan area.

(5) Build a multi-stakeholder collaborative governance system to achieve holistic low-carbon development of the metropolitan area.

Since industrial and carbon networks have obvious cross-regional transmission characteristics, governance by a single city cannot effectively address carbon emission issues at the metropolitan scale. Therefore, a multi-stakeholder collaborative governance system involving governments, enterprises, and research institutions should be established. At the regional level, coordination among industrial planning, energy planning, and carbon management policies in the Xi'an metropolitan area should be strengthened, promoting a unified low-carbon development goal. At the industrial level, cross-regional green cooperation among enterprises should be encouraged to achieve technology sharing, resource circulation, and industrial synergy. At the technical level, relying on universities and research institutions, an industrial carbon monitoring and assessment platform should be established to enable dynamic identification of key industrial nodes and carbon flow paths.

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