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# Comparison of green and low-carbon development path between Yellow River Basin and Yangtze River Economic Belt--configuration analysis based on "two mountains theory"

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The integration of industrial ecology and ecological industrialization represents a critical mechanism for resolving the economy-ecology dichotomy in riverine systems, exemplifying the paradigm that "ecological assets translate to economic value." This investigation employs fuzzy-set Qualitative Comparative Analysis (fsQCA) to examine datasets from 18 provincial jurisdictions within the Yellow River Basin and Yangtze River Economic Belt, deconstructing the multifaceted determinants of sustainable development in these watersheds. Results demonstrate that industrial ecology and ecological industrialization exhibit "asymmetric complementarity," highlighting the necessity for multifactorial approaches to sustainable development rather than monofactorial interventions. The analysis further elucidates distinct developmental trajectories between watersheds: the Yellow River Basin manifests "industrial ecological compensation-driven" and "dual coupling upgrading" pathways, whereas the Yangtze River Economic Belt demonstrates "technological innovation breakthrough" and "system synergy symbiosis" modalities. Eco-industrialization emerges as a fundamental component in high-performance configurations across these watersheds, emphasizing the importance of ecological value transformation at various spatial scales. Through establishing an integrated "theory-method-evidence" framework, this study enhances the explanatory power of the "two-mountain theory" and provides theoretical underpinnings for evidence-based policy formulation in watershed management, offering strategic guidance for implementing contemporary ecological economic systems.

KEYWORDS

**green and low-carbon development, Yellow River Basin, Yangtze River Economic Belt, coordination of two modernizations, fuzzy set qualitative comparative analysis (fsQCA)**

## 1 Introduction

In the context of accelerating global climate governance restructuring and intensifying ecological crises, sustainable development paradigm transformation has emerged as a strategic international consensus. China, as the world's predominant coal consumer, confronts significant challenges in modernizing environmental governance capabilities while pursuing high-quality development objectives. Adhering to the "common but differentiated responsibilities" principle, the Chinese government has strategically established "dual carbon" targets (carbon peaking by 2030 and carbon neutrality by 2060), which addresses the "major power responsibility paradox" in environmental governance while signaling a systematic economic paradigm shift from "factor-driven" to "low-carbon locking" mechanisms (Chen L. et al., 2022). Notably, the imperative to achieve a green and low-carbon transformation must be acutely attuned to the realities of regional heterogeneity, a principle now recognized as global consensus. For instance, the European Union's recent "European Green Deal" articulates a vision of climate neutrality by 2050 and expressly underscores the necessity for member states to chart regionally differentiated green development trajectories in keeping with their distinct foundational conditions (European Commission, 2019). Within the EU's multi-tiered governance framework, member states have exhibited demonstrable heterogeneity in their respective transition pathways (Leipprand et al., 2020), offering valuable international experience for China's exploration of regionally differentiated transformation strategies. Focusing within China, the Yellow River Basin, serving as a national ecological security barrier, and the Yangtze River Economic Belt, functioning as an economic core region, demonstrate pronounced spatial heterogeneity in their transformation processes. Consequently, investigating the differentiated green transformation mechanisms in these critical regions provides a crucial analytical lens for evaluating the practical efficacy of the "Two Mountains Theory" implementation.

As two pivotal fluvial economic corridors in China, the eco-sustainable development of the Yellow River Basin and the Yangtze River Economic Belt holds profound implications for national and global environmental resilience. The Yellow River Basin, serving as the cradle of Chinese civilization, maintains ecological integrity that directly influences the nation's long-term development trajectory and cultural sustainability. Concurrently, the Yangtze River Economic Belt—traversing eastern, central, and western China across eleven administrative regions—represents one of China's most economically vibrant zones, where decarbonization efforts significantly impact regional development harmonization and national competitive advantage. These watersheds exhibit distinct characteristics regarding geomorphology, industrial advancement, and environmental governance frameworks, necessitating differentiated approaches to carbon mitigation and ecological modernization (Wei et al., 2022; Zhang and Zhang, 2020). Consequently, basin-specific pathways toward ecological transition warrant systematic investigation to optimize sustainability outcomes.

Extant literature has examined the green and low-carbon development trajectories of the Yellow River Basin and Yangtze River Economic Belt with varying emphases. The Yellow River Basin research prioritizes ecological remediation, water resource optimization, and industrial restructuring due to its inherent ecological fragility and hydrological constraints (Wang, 2020). Conversely, the Yangtze River Economic Belt, leveraging its strategic geographic positioning and abundant natural capital, has emerged as a critical catalyst for China's economic advancement. Recent implementation of the "joint protection without extensive development" paradigm has yielded significant ecological conservation outcomes and green industry proliferation in the region. Researchers have investigated sustainable development frameworks for the Yangtze River Economic Belt, exploring mechanisms for achieving economic-ecological synergies through policy innovations and technological advancements (Rao et al., 2022). Within this discourse, the "Two Mountains Theory" (lucid waters and lush mountains are invaluable assets) elucidates the dialectical relationship between environmental stewardship and economic prosperity, advocating for synchronized development of "industrial ecology and ecological industrialization" (Zhang and Bai, 2021; Xu et al., 2018). Guided by this theoretical framework, empirical investigations of eco-industrial integration in both watersheds have gained scholarly prominence (Ren and Tang, 2023; Feifei et al., 2024). At the international level, comparative investigations have illuminated the significance of regionally differentiated governance. Exemplified by the European Union, the European Green Deal has catalyzed cross-regional collaborative innovation, judicious resource management, and the sustainable industrial transition. The relevant literature systematically reviews the dynamics of green policy practice and governance across multi-regional landscapes (Olczyk and Kuc-Czarnecka, 2025; Bakkar et al., 2025). Moreover, Dupont et al. (2024) demonstrate that the success of intra-regional green transitions heavily depends on local developmental baselines, the practical enforceability of policies, and the efficacy of multi-actor collaborative mechanisms. Through the legislative suite "Fit for 55," the EU has promoted harmonized yet differentiated policy implementation that integrates fiscal transfers, technological support, and graduated regulatory instruments within a unified climate objective framework. These experiences provide instructive parallels for China as it seeks to foster multi-level coordination and institutional adaptation in vast regions such as the Yellow River Basin and the Yangtze River Economic Belt. Despite extensive research on individual basin development, comparative analyses remain insufficient. Particularly within the context of carbon neutrality objectives and the "Two Mountains Theory," identifying basin-specific green development pathways tailored to regional characteristics represents a critical research imperative.

Drawing upon the "Two Mountains Theory," this research establishes a dual-synergy framework examining the integration of industrial ecology and ecological industrialization for green and low-carbon development. Through comparative analysis of fluvial economic corridors in the Yellow River Basin and Yangtze River Economic Belt, we investigate: (1) the configurational development pathways of provincial eco-economic systems within these basins; (2) the necessity conditions of dual-modernization elements for regional sustainability transitions; and (3) optimal synergistic configurations for effective green development across diverse provincial contexts. This study contributes significantly by elucidating the theoretical underpinnings of the ecological-economic transformation paradigm, resolving the false dichotomy between environmental conservation and economic advancement through configurational analysis. Furthermore, it introduces an innovative research paradigm for sustainability transitions, emphasizing production relation transformations as the core mechanism, providing empirical evidence for regionally-differentiated policy formulation, and offering China-specific theoretical contributions to global sustainable development discourse.

# 2 Assessment of ecological sustainability and carbon mitigation trajectories in the Yellow River Basin and Yangtze River Economic corridor: a comparative analysis of current implementation status

## 2.1 Geomorphological heterogeneity and socioeconomic divergence patterns in the Yellow River fluvial economic corridor: current status and evolutionary trajectories

The Yellow River Basin exhibits concurrent ecological vulnerability and energy structure lock-in effects, creating distinctive constraints for its low-carbon transition trajectory (Jin et al., 2020). The basin's geomorphological fragility is evidenced by soil erosion affecting over one-third of its area, while *per capita* water resource availability remains significantly below national averages, exacerbating the tension between ecosystem carrying capacity and economic development imperatives. Concurrently, the region's carbon-intensive economic profile—characterized by fossil fuel dependence, disproportionate coal consumption, and concentration of energy-intensive sectors including chemical manufacturing and metallurgy—results in carbon intensity metrics that substantially exceed national benchmarks.

Nevertheless, the basin is implementing a bifurcated approach to sustainability through the integration of industrial ecology and ecological industrialization paradigms. The region is capitalizing on renewable resource endowments in the "Shage Desert" ecoregion to establish multi-modal complementary energy infrastructure, increasing renewable energy capacity and facilitating inter-regional clean electricity transmission via ultra-high voltage corridors. Simultaneously, legacy industries are undergoing decarbonization through technological modernization, exemplified by the progressive adoption of advanced production methodologies in Shaanxi's coking sector. Furthermore, ecosystem service valuation mechanisms are being piloted basin-wide, with Inner Mongolia demonstrating asymmetric complementarity between desertification mitigation and photovoltaic deployment.

Despite these advancements, hydrological constraints and energy system inertia continue to impede transformation velocity, necessitating institutional innovation to overcome path dependencies and accelerate the transition toward eco-sustainable development.

## 2.2 Differentiation characteristics and development status of Yangtze River Economic Belt

The Yangtze River Economic Belt exhibits a fundamental contradiction between economic agglomeration and ecological vulnerability (Liu and Long, 2017). While generating nearly half of China's GDP, the region approaches critical environmental carrying capacity thresholds. Non-point source pollution is pervasive, with carbon emissions exceeding one-third of national totals. The basin's industrial composition demonstrates a "high value-added and high pollution coexistence" paradox: despite significant high-technology industrial presence, traditional carbon-intensive sectors like chemical manufacturing and steel production cluster along riparian corridors, creating spatial misalignment between ecological and economic imperatives. The region is undergoing accelerated green transformation through an integrated "institution-technology-market" governance framework. Policy interventions include coordinated financial support mechanisms from eight governmental departments, establishment of carbon and pollution rights trading platforms, and expansion of green finance instruments. Technologically, the region leverages the Yangtze River Delta innovation network, generating superior clean technology patent outputs compared to other regions, with progressive implementation of ultra-low emission retrofitting in steel and cement production facilities. Market mechanisms facilitate ecological value realization through diverse pathways, including Zhejiang Lishui forest carbon sequestration transactions and Hubei wetland ecological compensation schemes, enhancing ecological product value conversion efficiency. Nevertheless, deficiencies in regional collaborative governance persist, with upstream-downstream environmental regulatory asymmetries creating pollution displacement risks, necessitating strengthened coordination of pollution abatement and carbon reduction strategies at "watershed-urban agglomeration" scales.

# 3 Theoretical basis and research framework

The "Two Mountains Theory" (green waters and green mountains are golden mountains and silver mountains) is grounded in Marxist natural productivity theory, emphasizing the dialectical unity between ecological systems and economic development. Marx identified natural productive forces as the foundation and prerequisite for social productive forces, asserting that human societal survival and development are inseparable from nature's material provisions (Marx, 1975, p. 728). This theoretical framework has acquired contemporary significance in China's new era, providing scientific guidance for green development trajectories in the Yellow River Basin and Yangtze River Economic Belt. The critical pathway for operationalizing this theory lies in the synergistic development of industrial ecology and ecological industrialization (Zhang and Bai, 2021; Xu et al., 2018).

Industrial ecology emphasizes integrating green development principles into conventional industrial systems, minimizing resource consumption and environmental degradation through technological innovation and management optimization to achieve sustainable industrial development. Ecological industrialization transforms ecological assets into economic resources, cultivating green industries and generating novel economic growth vectors. Through the strategic integration of "two modernizations synergy," ecological resources and economic activities can be effectively harmonized to simultaneously protect environmental systems and sustain economic growth, establishing a national ecological civilization construction paradigm (Xiaojian et al., 2020). However, the specific mechanisms through which provinces within the Yellow River Basin and Yangtze River Economic Belt can advance green and low-carbon development via "two modernizations coordination" requires further scholarly examination.

## 3.1 "Two mountains theory," "two modernizations" and green and low-carbon development

The evolutionary trajectory of the "Two Mountains Theory" within social productive forces development profoundly embodies Marx's dialectical movement principles between natural productive forces and production relations. This development manifests in three distinct phases (Hu et al., 2019; Zhang and Bai, 2021): The initial phase exhibited natural productive forces alienation, with economic advancement predicated on ecological degradation. The conceptualization of "sacrificing green waters and green mountains for golden mountains and silver mountains" represented capital-logic-driven exploitation of natural forces, disregarding Marx's emphasis on natural productive forces' foundational role, resulting in significant ecological deterioration. Even industrial ecology initiatives during this period remained subordinate to natural factor commodification logic (O'Connor, 2003, p. 296); the second phase marked the rediscovery of natural productivity value, asserting that "green waters and green mountains are golden mountains and silver mountains," emphasizing the intrinsic economic value of ecological systems. High-quality environmental conditions became new means of production, with "ecological industrialization" transcending simplistic environmental materialization to achieve initial natural forces value marketization; the third phase represents natural productive forces liberation, pursuing "both green waters and green mountains, and golden and silver mountains" through balanced economic growth and ecological protection. The essence of "two modernizations coordination" constitutes creative advancement of Marx's "human-nature material transformation" theory, representing China's approach to achieving socialized reproduction of natural forces through production relations transformation, aligning with Marx's natural productivity theory on harmonious human-nature coexistence (Ye, 2020).

As a practical innovation at the intersection of Marxist natural productivity theory and the "Two Mountains Theory," the concept of "socialization of natural productive forces" is fundamentally concerned with transforming ecological resources from simple natural attributes into productive elements serving the collective progress of society, thus realizing the co-creation, co-governance, and shared enjoyment of ecological value. The realization mechanism comprises four key dimensions: First, clarifying ecological property rights through registration and value appraisal, thereby facilitating the transformation from "resource—asset—capital" (Foster, 1999); this enables the pricing and trading of ecological factors within the modern economic system. Second, establishing collaborative governance and benefit-sharing mechanisms whereby governments employ fiscal transfers, ecological compensation, and green taxation to mobilize participation from enterprises, communities, and rural households, fostering a landscape of multi-actor co-governance (Zhang et al., 2023; Verma et al., 2023). Third, refining mechanisms for market-based value realization, such as instituting ecological product certification standards and eco-system service payment schemes—including carbon sink trading and benefit-sharing in ecological tourism—to facilitate equitable circulation of ecological value (Chaplin-Kramer et al., 2019). Fourth, advancing the integration of green technologies and industries by harnessing the "dual engines" of industrial ecology and ecological industrialization, embedding green technological innovation in the construction of eco-industrial chains—such as eco-parks and green supply chains—to maximize the efficient transformation of natural productive forces (Wu and Gao, 2022). Through the synergistic interplay of institutional innovation, diversified stakeholder engagement, and market mechanisms, these four dimensions collectively channel ecological potential into a novel productive force propelling the region's green and low-carbon development.

### 3.1.1 Industrial ecology and green low carbon development

Industrial ecology conceptualizes harmonious industry-environment coexistence through enhanced resource utilization efficiency during industrial transformation and upgrading, emphasizing simultaneous economic advancement and ecological system protection to promote bidirectional economy-ecology coordination (Lu et al., 2012). Its core objective is repairing the "metabolic rift between humanity and nature" induced by capitalist industrialization, advocating human-nature coordinated development through rational natural productive forces allocation and production relations transformation. Industrial ecology reflects reciprocal interactions between industrial economic development and ecological environmental protection, exhibiting dual industrial economy and ecological economy attributes (Guo et al., 2019), providing theoretical foundations and practical pathways for green and low-carbon development in both major river basins. Industrial ecology reduces resource consumption and waste emissions through ecological design, cleaner production, and circular economy principles (Shi et al., 2013). For instance, watershed industrial production can minimize carbon footprints through production process optimization and material selection to reduce water and energy resource dependencies. Additionally, industrial ecology promotes resource efficiency and recycling while enhancing watershed ecological resilience. Through eco-industrial parks and green supply chains, enterprises can implement resource sharing and reuse, establishing "waste-as-resource" closed-loop economic systems (Bressanelli et al., 2022). This model simultaneously reduces environmental pollution while supporting watershed ecosystem functions and biodiversity conservation. Industrial ecology implementation effectively promotes rational resource utilization and environmental burden reduction, enhancing both economic and social benefits while facilitating green development model formation and ultimately advancing green and low-carbon economic transformation.

### 3.1.2 Ecological industrialization and green and low-carbon development

Ecological industrialization, as a critical sustainable economic development pathway, aims to achieve synchronized ecological and economic benefit growth through ecological resource transformation into industrial economic activity (Ding et al., 2023). Its essence represents a historical exploration of Marx's "socialization of natural productive forces realization form." Its fundamental objective is transcending capitalism's paradoxical treatment of natural elements as both free exploitation objects and pollution repositories. This process transcends simple ecological resource commodification, constituting a natural force value formation revolution that reconstructs subject-object unity in human-nature interactions. This process involves ecological resource economization to realize ecological products or services market value, manifested through various industrialization forms including eco-agriculture, eco-industry, and eco-tourism (Cheng and Li, 2021; Chen, 2018). Ecological industrialization's core principle recognizes ecological resources as possessing both environmental protection functions and substantial economic potential. Through effective resource management and technological innovation, ecological resources transform into market-responsive products (Cheng and Li, 2021). This transformation enhances resource utilization efficiency while generating economic growth vectors. From market mechanism perspectives, ecological industrialization emphasizes ecological value conversion into economic benefits through robust market systems, promoting sustainable economic growth (Song and Du, 2024). Furthermore, within regionally differentiated ecological conditions, resource endowments, and industrial structures, locally-adapted ecological industry development facilitates regional economic complementarity and reduces development disparities. Consequently, ecological industrialization constitutes both a critical green and low-carbon development pathway and an essential mechanism for promoting coordinated regional development and ecological protection.

### 3.1.3 "Synergy between the two modernizations" and green and low-carbon development

Industrial ecology and ecological industrialization represent complementary dimensions of a unified challenge, with ecological industrialization predicated on industrial ecology, while industrial ecology establishes foundations for ecological industrialization (Gu, 2020). These approaches mutually reinforce through deep integration, constituting the practical implementation pathway for the "Two Mountains Theory," fully reflecting China's inherent requirements for simultaneous ecological protection and economic advancement (Chen, 2018). The essence of "two modernizations coordination" represents dialectical praxis of Marx's "socialized reproduction of natural productive forces," with its core addressing human-nature contradictions in capitalist industrialization through bidirectional natural force restoration and production relationship reconstruction. The industrial ecology-ecological industrialization synergy transcends simple complementarity, reflecting Marx's natural productivity theory unity. Industrial ecology reconstructs the "ecological environment as human inorganic body" integrity through natural forces recycling via clean production and waste recovery, while ecological industrialization realizes "nature-endowed use value" social expression through natural forces transformation including ecological product certification. These approaches integrate to form a closed-loop system from natural productivity material metabolism to value realization.

Furthermore, following Marx's assertion that "natural geographical differences determine labor division forms," the Yellow River Basin and Yangtze River Economic Belt should develop differentiated synergistic approaches (Marx and Engels, 1979, p. 334). Additionally, according to complex systems theory (Arthur, 2021), economic systems lack unique optimal equilibria, enabling different "bidirectional synergy" models to establish multiple green and low-carbon development pathways through diverse driving mechanisms. For instance, Qinghai Province, situated in the Yellow River's upper reaches and at the Three Rivers' source, possesses exceptional ecological advantages. Consequently, Qinghai should prioritize green energy development including solar and wind power generation, leveraging its distinctive natural landscapes and cultural heritage for ecological industry development, primarily adopting an "ecological industrialization-dominant, industrial ecology-supplementary" development pathway. Conversely, Jiangsu Province within the Yangtze River Economic Belt, located in an economically advanced region, possesses significant industrial structure upgrading advantages. Therefore, Jiangsu should facilitate traditional industry green and low-carbon transformation, emphasizing green and high-technology industry development, adopting an "industrial ecology-dominant, ecological industrialization-supplementary" development approach. Within this context, Yellow River Basin and Yangtze River Economic Belt provinces should utilize "two modernizations coordination" as their foundation, exploring regionally-appropriate green and low-carbon development pathways aligned with their specific ecological and economic characteristics.

## 3.2 Elements of "synergy of two modernizations" and green and low-carbon development

Previous "two modernizations synergy" research primarily analyzed its developmental trajectory and green and low-carbon development significance. These studies provide critical foundations for delineating "two modernizations synergy" element parameters (Furnari et al., 2021). Within industrial ecology, industrial economic development centers on industrial structure upgrading, reflecting industrial ecology's practical application in productivity dimensions. Ecological environmental protection corresponds to industrial ecology transformation in production relations dimensions through pollution prevention and ecological restoration implementation. Their interaction establishes production-ecology virtuous cycles. Within ecological industrialization, ecological agriculture industrialization focuses on natural resource development through organic cultivation, integrated planting, and recycling methodologies, highlighting ecological industrialization's resource transformation capabilities. Eco-industrialization emphasizes natural resource reorganization, utilizing green technologies including clean energy to reconfigure industrial metabolism processes, demonstrating ecological industrialization's system integration advantages. Together, these approaches construct ecological industrialization's global value chain.

### 3.2.1 Industrial economic development and green low-carbon development

Industrial economic development, as a modern economic system cornerstone, provides fundamental support for industrial ecological transformation while facilitating economic growth and social prosperity (Gereffi, 1999). Within this process, strategic industrial structure adjustment and upgrading constitute key green and low-carbon development pathways. Through green technology innovation and application, cleaner production implementation, and circular economy advancement, industrial economic development effectively reduces greenhouse gas emissions and resource consumption, promoting urban green economy intensive growth and sustainable development (Pang and Wang, 2023; Zeng et al., 2022).

### 3.2.2 Ecological environment protection and green low carbon development

Ecological environment protection encompasses maintaining and enhancing natural environmental quality through comprehensive measures safeguarding ecosystem health and biodiversity (Xin and Liu, 2022). Its core objectives include preventing environmental pollution, resource depletion, and ecological degradation, addressing both current environmental conditions and sustainable development imperatives, establishing necessary green and low-carbon development foundations (Wang, 2020). Robust ecological environments support renewable energy development and utilization while facilitating cleaner production technology application, reducing greenhouse gas emissions (Chen C. et al., 2022). Consequently, prioritizing ecological environment protection during industrial economic development represents a scholarly and practical consensus, constituting an inherent requirement for green and low-carbon economic advancement.

### 3.2.3 Industrialization of eco-agriculture and green and low-carbon development

Eco-agricultural industrialization represents advanced agricultural industrialization and innovative industrial chain models facilitating agricultural economy-natural ecosystem harmonious coexistence. Its essence lies in sustainable modern agricultural system construction through continuous rural industrial structure optimization (Shi, 2010). Through environmentally-compatible production methodologies and technical approaches, eco-agricultural industrialization enhances agricultural production efficiency while achieving resource utilization intensification and recycling, significantly improving agricultural ecological environment quality (Teng and Liu, 2024). This transformation generates rural economic value-added opportunities, substantially enhancing agricultural industry chain market competitiveness and promoting comprehensive rural economic development. Therefore, eco-agricultural industrialization constitutes both a critical rural revitalization pathway and an essential component advancing socioeconomic green and low-carbon development.

### 3.2.4 Eco-industrialization and green low-carbon development

Eco-industrialization emphasizes resource utilization efficiency, establishing sustainable industrial development systems through waste recycling and pollution emission minimization (Wang et al., 2019). Leveraging advanced technological support, eco-industrialization promotes digital economy-green manufacturing integration, facilitating ecological product industrialization transformation and injecting innovative momentum into economic growth (Liu et al., 2022). Additionally, eco-industrialization effectively reduces production process resource waste and environmental pollution, enabling enterprises to fulfill environmental responsibilities while securing economic benefits, enhancing market competitiveness and promoting regional economic sustainable development (Meng et al., 2023). Consequently, eco-industrialization represents both a necessary environmental challenge response and a critical green and low-carbon economic development pathway.

The systematic construction and internal dynamics of "two modernizations coordination" elements profoundly embody Marx's natural productive forces theory dialectical logic. From system coverage perspectives, industrial economic development and ecological environment protection evaluate industrial ecology processes bidirectionally from input and output dimensions: the former drives production mode transformation through green technology innovation, while the latter necessitates production relationship reconstruction through ecological carrying capacity constraints. Eco-agricultural industrialization and eco-industrial industrialization characterize ecological industrialization practices through spatial carrier and implementation form dimensions. The former establishes rural ecological value chains through natural force ecological development, while the latter reconfigures urban metabolic systems through natural force technological reorganization. These four elements comprehensively encompass the "natural force restoration-value transformation-spatial adaptation" collaborative chain. Therefore, utilizing industrial economic development, ecological environment protection, eco-agricultural industrialization, and eco-industrial industrialization as antecedent conditions, we construct a green and low-carbon development antecedent configuration analysis framework for the Yellow River Basin and Yangtze River Economic Belt, illustrated in Figure 1.

## 4 Study design

### 4.1 Research methodology

Fuzzy set Qualitative Comparative Analysis (fsQCA) was employed to deconstruct the configurational effects of green and low-carbon development across the Yellow River Basin and Yangtze

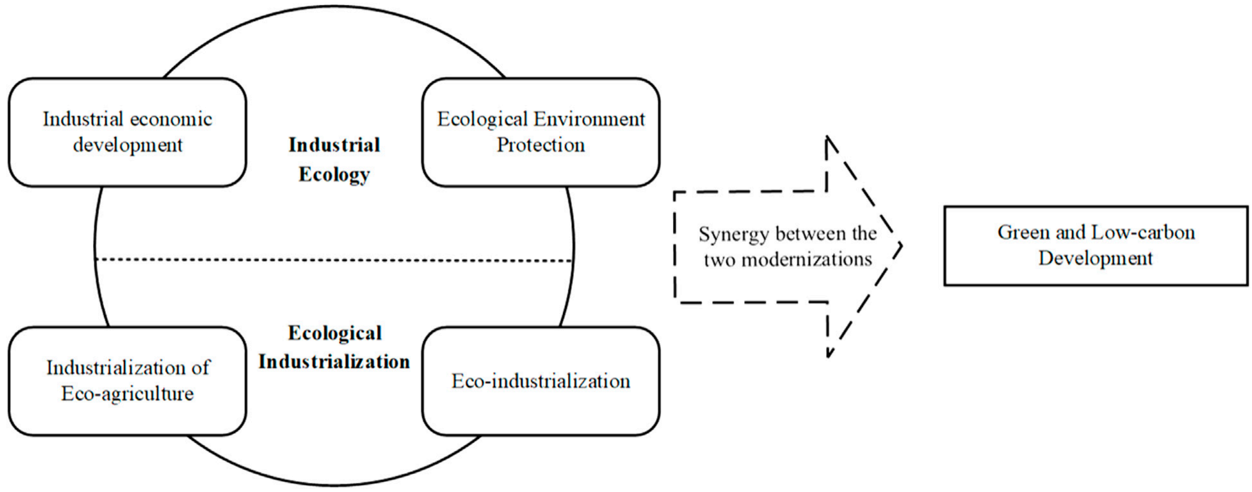


FIGURE 1
Theoretical architecture diagram.

River Economic Belt. This methodological approach, grounded in set theory and Boolean algebraic operations (Pappas and Woodside, 2021), elucidates concurrent causal mechanisms through multi-case comparison: initially, necessity analysis tests the universality of individual conditions, transcending the limitations of traditional regression analysis with its overreliance on independent effects (Schneider and Wagemann, 2012); subsequently, sufficiency analysis identifies multidimensional condition combinations, capturing alternative and complementary action pathways of "two-way synergy" elements (Misangyi et al., 2017). Compared to linear thinking paradigms, fsQCA offers methodological advantages in three dimensions: (1) addressing "multiple equifinality" issues, aligning with the multi-modal coexistence characteristics of riverine green and low-carbon development; (2) analyzing asymmetric interaction relationships between ecological industrialization and industrial ecology, revealing solution mechanisms for the "conservation-development" paradox; and (3) enabling "structure-process" bidimensional perspectives through configurational modeling, providing topological landscapes for differentiated policy design. Based on these advantages, this study constructs a novel framework that deconstructs the nested causal chains of high-performance pathways, offering mechanistic explanations for ecological value transformation challenges.

## 4.2 Study sample

In accordance with the Outline of Ecological Protection and High-quality Development Planning of the Yellow River Basin and the Territorial and Spatial Planning of the Yangtze River Economic Belt-Yangtze River Basin (2021–2035), the research encompasses nine provinces within the Yellow River Basin and 11 provinces within the Yangtze River Economic Belt as defined by these planning documents. However, Shanghai, as an international metropolis that has transitioned to post-industrialization with tertiary industry exceeding 70% of economic activity and carbon emission intensity merely one-third that of mid-Yangtze provinces, exhibits a fundamentally different low-carbon development trajectory compared to the high-carbon lock-in industrial transformation imperatives in the middle and upper Yangtze regions, and was therefore excluded from the analytical scope. Consequently, the final research sample comprises 18 provinces (autonomous regions and municipalities), as detailed in Table 1.

## 4.3 Variable measurements and data sources

### 4.3.1 Outcome variable

The critical determinants for regional green and low-carbon development lie in quality enhancement and consumption reduction. Following the objective requirements of green economic development, this study measures regional green and low-carbon development through two dimensions: green total factor productivity and carbon dioxide emission intensity (Xiaodan and Ning, 2024). Green total factor productivity is calculated using the GML index based on SBM distance function, wherein labor input is quantified by provincial end-year employment figures; capital input is measured through total fixed assets of above-designated-size industrial enterprises, calculated via perpetual inventory method with 2011 as the base period and a fixed capital depreciation rate of 9.6% (Jun et al., 2004); energy input represents total provincial energy consumption; expected output is measured by provincial real GDP; and unexpected output is quantified through provincial industrial sulfur dioxide emissions. Regional $CO_2$ emission intensity is calculated as the ratio of total $CO_2$ emissions to regional GDP.

### 4.3.2 Antecedent variables

1. Industrial Economic Development: This construct is comprehensively derived from four dimensions: industrialization development degree, industrial scale development level, industrial upgrading level, and industrial external dependence level (Guo et al., 2019). It is calculated using entropy-TOPSIS weighting methodology incorporating

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TABLE 1 Study sample.

| Basin | Provinces (autonomous regions and municipalities) |
|---|---|
| Yellow River Basin | Qinghai Province, Sichuan Province, Gansu Province, Ningxia Hui Autonomous Region, Inner Mongolia Autonomous Region, Shanxi Province, Shaanxi Province, Henan Province, Shandong Province |
| Yangtze River Economic Belt | Jiangsu Province, Zhejiang Province, Anhui Province, Jiangxi Province, Hubei Province, Hunan Province, Chongqing Province, Sichuan Province, Yunan Province, Guizhou Province |

TABLE 2 Variable definition and related index system.

| Variable type | Variable name | Measure |
|---|---|---|
| Outcome Variable | Green Low-carbon Development | SBM-GML method measurement |
| | | Total carbon dioxide emissions/gross regional product |
| Industrial Ecology | Industrial Economic Development | The ratio of secondary industry added value to tertiary industry added value |
| | | Total added value of secondary and tertiary industries |
| | | Ratio of total number of employees in information transmission, computer services and software and transportation, storage and postal services to total number of employees in manufacturing and mining industries |
| | | Per capita actual utilization of foreign capital |
| | Ecological Environment Protection | Per capita park green area |
| | | Per capita industrial sulfur dioxide emissions |
| | | Comprehensive utilization rate of general industrial solid waste |
| | | Energy consumption per unit GDP |
| Ecological Industrialization | Eco-Agricultural Industrialization | The added value of agriculture, forestry, animal husbandry, and fishery |
| | | The number of key rural tourism villages in China |
| | Eco-Industrialization | Industrial added value |

the ratio of secondary industry added value to tertiary industry added value, total added value of secondary and tertiary industries, industrial upgrading index, and *per capita* actual utilization of foreign capital.

2. Ecological Environment Protection: This construct is comprehensively derived from four dimensions: ecological environment protection level, ecological environment pollution pressure, ecological environment control response, and resource-environment utilization efficiency (Guo et al., 2019). It is calculated using entropy-TOPSIS weighting methodology incorporating *per capita* park green area, *per capita* industrial sulfur dioxide emissions, comprehensive utilization rate of general industrial solid waste, and energy consumption per unit GDP.
3. Eco-Agricultural Industrialization: This is calculated using entropy-TOPSIS weighting methodology incorporating the added value of agriculture, forestry, animal husbandry, and fishery, and the number of key rural tourism villages in China (Ren and Tang, 2023; Chen, 2019). Specifically, the number of nationally designated key rural tourism villages represents the total across four batches for each province. This integration not only reflects production efficiency and resource utilization improvements but also indicates ecological agriculture's diversity and resource integration capabilities, effectively representing eco-agricultural industrialization development.
4. Eco-Industrialization: This is measured by industrial added value (Ren and Tang, 2023). As a critical economic indicator of industrialization levels, industrial added value reflects both industrial production efficiency and benefits, while also indicating industry's contribution to green growth and sustainable development, effectively representing eco-industrialization development.

The study utilizes cross-sectional data from 2022, primarily because this year represents the concentrated policy effectiveness release period following the "dual carbon" targets announcement, enabling accurate capture of differential practice patterns in "two modernizations synergy" across the Yellow River Basin and Yangtze River Economic Belt. Data sources include the China Statistical Yearbook 2023, China Energy Statistical Yearbook 2023, and provincial statistical yearbooks for 2023 (containing 2022 data), supplemented by the CSMAR environmental governance module and official data from the Ministry of Culture and Tourism of the People's Republic of China, ensuring data timeliness and policy correspondence. The study variables are summarized in Table 2.

### 4.3.3 Variable calibration

In this study, we employed direct calibration techniques to conduct fuzzy-set calibration, uniformly assigning the thresholds for full membership, the crossover point, and full non-membership

TABLE 3 Calibration points of variables.

| Variables | Fuzzy set calibration | | | | | |
|---|---|---|---|---|---|---|
| | Yellow River Basin | | | Yangtze River Economic Belt | | |
| | Full membership | The crossover point | Full non-membership | Full membership | The crossover point | Full non-membership |
| Green Low-carbon Development | 0.372 | 0.347 | 0.166 | 0.477 | 0.440 | 0.425 |
| Industrial Economic Development | 0.509 | 0.488 | 0.472 | 0.498 | 0.481 | 0.464 |
| Ecological Environment Protection | 0.559 | 0.516 | 0.406 | 0.431 | 0.412 | 0.396 |
| Eco-Agricultural Industrialization | 0.793 | 0.426 | 0.326 | 0.818 | 0.668 | 0.612 |
| Eco-Industrialization | 16412.200 | 12758.600 | 3297.200 | 17262.775 | 14408.650 | 9149.575 |

TABLE 4 Necessity test for individual conditions of QCA method.

| Antecedent variables | Outcome variable | | | |
|---|---|---|---|---|
| | Yellow River Basin | | Yangtze River Economic Belt | |
| | High-level green and low-carbon development | Non-high green and low-carbon development | High-level green and low-carbon development | Non-high green and low-carbon development |
| High industrial Economic Development | 0.683 | 0.335 | 0.625 | 0.490 |
| Non-high industrial Economic Development | 0.366 | 0.706 | 0.461 | 0.592 |
| High cological Environment Protection | 0.410 | 0.563 | 0.437 | 0.576 |
| Non-high cological Environment Protection | 0.632 | 0.471 | 0.606 | 0.465 |
| High eco-Agricultural Industrialization | 0.720 | 0.327 | 0.565 | 0.443 |
| Non-high eco-Agricultural Industrialization | 0.351 | 0.733 | 0.492 | 0.612 |
| High ecological industrialization | 0.844 | 0.374 | 0.763 | 0.386 |
| Non-high ecological industrialization | 0.368 | 0.804 | 0.349 | 0.722 |

to the upper quartile (75th percentile), median (50th percentile), and lower quartile (25th percentile) of the full sample, respectively. This calibration strategy is grounded in two principal considerations: First, the direct calibration method, combined with standardized percentile thresholds, represents a widely adopted and methodologically robust approach within empirical fsQCA research, facilitating cross-case-group comparability and enjoying clear methodological precedent (Fiss, 2011; Greckhamer, 2016). Second, although the industrial structures of the Yellow River Basin and the Yangtze River Economic Belt exhibit certain differences, detailed analysis of the empirical distributions of each variable within both regions revealed a pronounced overlap in their core value ranges. Thus, employing full-sample percentiles as anchors not only ensures the consistency of the analytical framework but also safeguards the overall comparability of research findings across both river basins. This unified calibration scheme is therefore well-suited to the distributional characteristics of the study regions and the requirements of the fsQCA methodology, ensuring both rationality and operability. The specific calibration anchors for each variable are detailed in Table 3.

TABLE 5 Configuration analysis results.

| Region | Yellow River Basin | | | Yangtze River Economic Belt | | |
|---|---|---|---|---|---|---|
| Outcome variable | High-level green and low-carbon development | | Non-high green and low-carbon development | High-level green and low-carbon development | | Non-high green and low-carbon development |
| Antecedent Variables | H1a | H1b | NH1 | H2a | H2b | NH2 |
| Industrial Economic Development | | ● | ⊗ | ⊗ | ● | ⊗ |
| Ecological Environment Protection | ⊗ | ● | | ⊗ | ● | ● |
| Eco-Agricultural Industrialization | ● | ⊗ | ⊗ | ⊗ | ● | ⊗ |
| Eco-Industrialization | ● | ● | ⊗ | ● | ● | ⊗ |
| Consistency | 0.991 | 0.969 | 0.988 | 0.968 | 0.846 | 1.000 |
| Original coverage | 0.532 | 0.237 | 0.500 | 0.247 | 0.347 | 0.461 |
| Unique coverage | 0.476 | 0.180 | 0.500 | 0.227 | 0.327 | 0.461 |
| Overall consistency | 0.986 | | 0.988 | 0.895 | | 1.000 |
| Overall coverage | 0.712 | | 0.500 | 0.573 | | 0.461 |

Note: a. ● indicates the presence of a core condition, ⊗ indicates the absence of a core condition, ● indicates the presence of a marginal condition, ⊗ indicates the absence of a marginal condition, and blank spaces indicate optional variables. b. When performing "standard analysis" for high green low-carbon development in the Yellow River Basin, "~ecological environmental protection*ecological industrial development" and "industrial economic development*ecological industrial development" were selected as quality implication terms; when performing "standard analysis" for non-high green low-carbon development in the Yellow River Basin, "~industrial economic development*~ecological industrial development" was selected as the quality implication term. c. When performing "standard analysis" for high green low-carbon development in the Yangtze River Economic Belt, "~ecological agricultural industrialization*ecological industrial development" and "ecological environmental protection*ecological industrial development" were selected as quality implication terms; when performing "standard analysis" for non-high green low-carbon development in the Yangtze River Economic Belt, "~industrial economic development*~ecological industrial development" was selected as the quality implication term.

# 5 Results of analysis

## 5.1 Analysis of necessary conditions

The analysis initially investigates the necessary conditions for eco-sustainable development. As evidenced in Table 4, the necessity consistency coefficients for individual antecedent conditions fall below the 0.9 threshold. This indicates an absence of singular necessary determinants for green and low-carbon transformation in both the Yellow River Basin and Yangtze River Economic Belt fluvial economic corridors.

## 5.2 Configuration analysis

In light of the asymmetric causal relationships identified, this study employs fuzzy-set Qualitative Comparative Analysis (fsQCA) to examine the "dual synergy" configurations that promote high-level green and low-carbon development versus non-high-level green and low-carbon development across the Yellow River Basin and Yangtze River Economic Belt. Additionally, qualitative analysis and nomenclature are applied to the identified configurations to enhance conceptual understanding.

### 5.2.1 "Dual modernization synergy" configurations for high-level green and low-carbon development

The methodological parameters included a case frequency threshold of 1, original consistency threshold of 0.8, and adjusted PRI consistency threshold of 0.7 for configuration adequacy analysis (Pappas and Woodside, 2021; Du et al., 2022). Given the absence of scholarly consensus regarding the directional influence of "dual synergy" conditions, this study adopts a conservative approach to counterfactual analysis, positing that individual industrial ecology and ecological industrialization conditions may impact green and low-carbon development outcomes. Core and peripheral conditions for each solution were delineated by analyzing the nested relationships between intermediate and parsimonious solutions (Pappas and Woodside, 2021). As illustrated in Table 5, the analysis revealed two distinct "dual modernization synergy" configurations (H1a, H1b, H2a, H2b) for green and low-carbon development in each basin region, detailed as follows.

#### 5.2.1.1 Industry-compensated collaborative pathway

Configuration H1a demonstrates that in the Yellow River Basin, a configuration characterized by high ecological industrialization and non-high ecological environmental protection as core conditions, with high ecological agricultural industrialization as a peripheral condition, can effectively generate high-level green and low-carbon development. This configuration reflects that despite insufficient prioritization of ecological protection in historical economic development, the implementation of high ecological industrialization has significantly mitigated carbon emissions and resource consumption through clean production technologies and renewable resource utilization, thereby promoting industrial sustainability. Additionally, while high ecological agricultural industrialization as a peripheral condition may contribute minimally to short-term economic growth, its synergistic interaction with industrialization facilitates optimal resource allocation, promotes agriculture-industry linkage development, and enhances the economy's green transformation capacity. This process ultimately establishes a virtuous cycle that advances green and low-carbon development in the Yellow River Basin, exemplifying economy-ecology coordinated development. Shaanxi Province stands as a paradigmatic exemplar of this "dual industrialization synergy" model. Leveraging policy innovation and technological advancement, the province has steadily advanced its transition toward green and low-carbon development. Core initiatives have included the vigorous promotion of traditional industrial upgrading, large-scale deployment of renewable energy (such as wind, photovoltaics, and biomass), and ambitious ecological restoration efforts since the implementation of the "Shaanxi Green and Low-Carbon Leading Action Plan" in 2021. The province has established numerous circular economy industrial parks and implemented over 300 green and low-carbon technological transformation projects across the industrial sector. These efforts have yielded tangible results: by the end of 2022, Shaanxi's installed capacity for renewable energy reached 17GW, marking a 26% increase from 2020; from 2020 to 2022, both GDP energy intensity and industrial carbon emissions declined steadily, ensuring robust progress towards energy saving and carbon reduction goals. As a synergistic support, Shaanxi has also actively fostered the development of ecological agriculture, emphasizing the construction of water-saving irrigation systems and organic agriculture demonstration zones. This coordinated advancement of industrial and agricultural ecological transformation has effectively promoted sustained improvements in regional green and low-carbon development, embodying the industry-compensated collaborative pathway explored in this paper.

#### 5.2.1.2 Dual-drive coupling upgrade pathway

Configuration H1b indicates that in the Yellow River Basin, a configuration featuring high industrial economic development and high ecological industrialization as core conditions, with high ecological environmental protection and non-high ecological agricultural industrialization as peripheral conditions, can fully generate high-level green and low-carbon development. This finding demonstrates that despite relatively low agricultural industrialization in certain regions, robust industrial economic development provides a solid economic foundation that facilitates technological innovation and industrial upgrading, thereby improving resource utilization efficiency and reducing per-unit carbon emissions. High ecological industrialization promotes green industrial transformation through cleaner production and circular economy principles, significantly reducing adverse environmental impacts. Simultaneously, high ecological environmental protection as a peripheral condition emphasizes the necessity of maintaining and restoring ecological systems during economic development to ensure ecosystem health and stability. Shanxi Province exemplifies this configuration, having actively diversified from a coal-dominated economy to a multi-pillar industrial structure featuring strategic emerging sectors such as new energy and advanced manufacturing. Through the implementation of the "Shanxi Green and Low-Carbon Development Action Plan (2021–2025)," the province has aggressively pursued coal substitution, industrial upgrading, and multibasin ecological restoration as key priorities. Remarkable achievements have materialized: by the end of 2022, Shanxi's installed wind and photovoltaic capacity soared to 40.5 GW, an increase of 45% over 2020 levels; the proportion of coal in overall energy consumption declined from 78% to 71%; flagship projects like the Taiyuan Green Manufacturing Cluster and wind-solar-storage integrated bases have achieved annual carbon dioxide reductions exceeding 10 million tons; and from 2020 to 2022, energy consumption per unit of GDP fell by 11.2%.This array of policy measures and outcomes robustly supports the core combination of high-quality industrial economic development and ecological industrialization, thereby illustrating the concrete mechanisms by which effective policy coordination propels industrial upgrading and low-carbon transition. As such, Shanxi serves as an exemplary case for ecological protection and high-quality development within the Yellow River Basin—embodying the dual-drive coupling upgrade configuration outlined in this study.

#### 5.2.1.3 Technology unipolar breakthrough pathway

Configuration H2a reveals that in the Yangtze River Economic Belt, a configuration with high ecological industrialization and non-high ecological agricultural industrialization as core conditions, accompanied by non-high industrial economic development and non-high ecological environmental protection as peripheral conditions, can effectively generate high-level green and low-carbon development. This finding indicates that high ecological industrialization significantly reduces resource consumption and environmental pollution through advanced clean production technologies and green management concepts, promoting industrial sustainability. Even within the context of suboptimal ecological agricultural industrialization, green transformation of the industrial sector can provide regional economic impetus. Furthermore, while non-high industrial economic development and non-high ecological environmental protection present certain challenges to green development, they do not fundamentally impede high ecological industrialization implementation. Conversely, industrialization's green transformation can provide necessary technical and financial support for ecological improvement, establishing beneficial interactions. Through the core function of high ecological industrialization, green and low-carbon development objectives remain achievable despite constraints in other conditions. Zhejiang Province exemplifies this configuration. Since the implementation of the "Zhejiang Carbon Peak Implementation Plan" in 2021, the province has launched over a hundred demonstration projects in green hydrogen energy and digital low-carbon manufacturing. Notably, the Hangzhou Asian Games low-carbon hydrogen demonstration project reduces carbon emissions by 860 tons annually, while from 2020 to 2022, the region's energy intensity decreased by approximately 9.5%. In 2022, the proportion of electricity generated from clean energy increased to 31%, a year-on-year rise of 4 percentage points; the number of green manufacturing enterprises continued to grow; and newly installed renewable energy capacity surpassed 10 GW. These flagship projects and quantifiable outcomes vividly illustrate the central and leading role of high ecological industrialization, aligning with the technology unipolar breakthrough pathway described in this study.

#### 5.2.1.4 Multidimensional collaborative symbiotic pathway

Configuration H2b demonstrates that in the Yangtze River Economic Belt, a configuration characterized by high ecological environmental protection and high ecological industrialization as core conditions, with high industrial economic development and high ecological agricultural industrialization as peripheral conditions, can fully generate high-level green and low-carbon development. This finding indicates that high ecological environmental protection establishes a favorable ecological foundation for industrial development while ensuring sustainable natural resource utilization. Through stringent environmental policy implementation, pollutant emissions can be effectively reduced, ecosystem health improved, and a conducive ecological environment created for economic activities. Moreover, ecological industrialization, through green technology integration and sustainable production models, ensures economic growth while minimizing resource consumption and environmental impacts. This industrialization model enhances industrial competitiveness while promoting resource efficiency and circular economy development. The presence of high industrial economic development and high ecological agricultural industrialization as peripheral conditions provides necessary economic support and market demand for core conditions, generating cross-industry synergies. Jiangsu and Hubei provinces exemplify this configuration. Jiangsu Province, for instance, has established a multidimensional green collaborative development framework rooted in ecological protection and advanced industrial ecology. Since 2021, Jiangsu has implemented the "Jiangsu Green and Low-Carbon Development Plan" alongside the most stringent ecological and environmental protection regimes, utilizing measures such as delimiting ecological redlines, tightening industrial regulations, and promoting renewable energy deployment. In 2022, the proportion of clean energy consumption rose to 28%, and energy intensity per unit GDP fell by 16% compared to 2020. Signature projects—such as the Nantong Renewable Hydrogen Carbon Emission Reduction Demonstration Zone—and Jiangsu's manufacturing industry, which has led the nation in the integration of informatization and industrialization for nine consecutive years, have significantly elevated ecological efficiency. Meanwhile, agricultural innovation pilot zones have driven comprehensive ecological upgrading across the entire agricultural value chain. Within the context of high industrial economic development and high ecological agricultural industrialization as peripheral conditions, this model generates cross-industry synergies and achieves advanced green and low-carbon development, consistent with the multidimensional collaborative symbiotic pathway.

### 5.2.2 "Dual-oriented synergy" configurations for non-high green and low-carbon development

This study also examines the "dual synergy" configurations associated with non-high green and low-carbon development in both river basins, identifying two distinct configurations. Configuration NH1 demonstrates that green and low-carbon development cannot be effectively promoted without high industrial economic development, high ecological industrialization, and high ecological agricultural industrialization. Configuration NH2 indicates that even with high ecological environmental protection, green and low-carbon

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**TABLE 6** Robustness test results (PRI consistency threshold = 0.65).

| Region | Yellow River Basin | | | Yangtze River Economic Belt | | |
|---|---|---|---|---|---|---|
| Outcome variable | High-level green and low-carbon development | | Non-high green and low-carbon development | High-level green and low-carbon development | | Non-high green and low-carbon development |
| Antecedent Variables | H1a | H1b | NH1 | H2a | H2b | NH2 |
| Industrial Economic Development | | ● | ⊗ | ⊗ | ● | ⊗ |
| Ecological Environment Protection | ⊗ | ● | | ⊗ | ● | ● |
| Eco-Agricultural Industrialization | ● | ⊗ | ⊗ | ⊗ | ● | ⊗ |
| Eco-Industrialization | ● | ● | ⊗ | ● | ● | ⊗ |
| Consistency | 0.991 | 0.969 | 0.988 | 0.968 | 0.846 | 1.000 |
| Original coverage | 0.532 | 0.237 | 0.500 | 0.247 | 0.347 | 0.461 |
| Unique coverage | 0.476 | 0.180 | 0.500 | 0.227 | 0.327 | 0.461 |
| Overall consistency | 0.986 | | 0.988 | 0.895 | | 1.000 |
| Overall coverage | 0.712 | | 0.500 | 0.573 | | 0.461 |

Note: a. ● indicates the presence of a core condition, ⊗ indicates the absence of a core condition, ● indicates the presence of a marginal condition, ⊗ indicates the absence of a marginal condition, and blank spaces indicate optional variables. b. When performing "standard analysis" for high green low-carbon development in the Yellow River Basin, "~ecological environmental protection*ecological industrial development" and "industrial economic development*ecological industrial development" were selected as quality implication terms; when performing "standard analysis" for non-high green low-carbon development in the Yellow River Basin, "~industrial economic development*~ecological industrial development" was selected as the quality implication term. c. When performing "standard analysis" for high green low-carbon development in the Yangtze River Economic Belt, "~ecological agricultural industrialization*ecological industrial development" and "ecological environmental protection*ecological industrial development" were selected as quality implication terms; when performing "standard analysis" for non-high green low-carbon development in the Yangtze River Economic Belt, "~industrial economic development*~ecological industrial development" was selected as the quality implication term.

**TABLE 7** Robustness test results (case frequency threshold increased from 1 to 2).

| Region | Yellow river basin | | Yangtze river economic belt | |
|---|---|---|---|---|
| Outcome variable | High-level green and low-carbon development | Non-high green and low-carbon development | High-level green and low-carbon development | Non-high green and low-carbon development |
| Antecedent Variables | H1 | NH1 | H2 | NH2 |
| Industrial Economic Development | ● | ⊗ | ● | ⊗ |
| Ecological Environment Protection | ⊗ | ⊗ | ● | ● |
| Eco-Agricultural Industrialization | ● | ⊗ | ● | ⊗ |
| Eco-Industrialization | ● | ⊗ | ● | ⊗ |
| Consistency | 0.986 | 0.984 | 0.846 | 1.000 |
| Original coverage | 0.341 | 0.371 | 0.347 | 0.461 |
| Unique coverage | 0.341 | 0.371 | 0.347 | 0.461 |
| Overall consistency | 0.986 | 0.984 | 0.846 | 1.000 |
| Overall coverage | 0.341 | 0.371 | 0.347 | 0.461 |

Note: a. ● indicates the presence of a core condition, ⊗ indicates the absence of a core condition, ● indicates the presence of a marginal condition, ⊗ indicates the absence of a marginal condition, and blank spaces indicate optional variables. b. When performing "standard analysis" for high green low-carbon development in the Yellow River Basin, "ecological industrial development" was selected as quality implication terms; when performing "standard analysis" for non-high green low-carbon development in the Yellow River Basin, "~ecological industrial development" was selected as the quality implication term. c. When performing "standard analysis" for high green low-carbon development in the Yangtze River Economic Belt, "ecological environmental protection*ecological industrial development" was selected as quality implication terms; when performing "standard analysis" for non-high green low-carbon development in the Yangtze River Economic Belt, "~ecological industrial development" was selected as the quality implication term.

development remains unattainable without high industrial economic development, high ecological industrialization, and high ecological agricultural industrialization. This phenomenon can be attributed to several factors: First, industrial economic development constitutes the foundation for technological innovation and optimal resource allocation; without high-level industrial economic development, necessary funding and technical support for green technology research, development, and application remain insufficient, constraining green and low-carbon transformation. Second, ecological industrialization and ecological agricultural industrialization represent critical pathways for resource efficiency and environmentally-friendly production; their absence prevents effective reduction of resource consumption and environmental pollution throughout production and consumption processes, impeding green and low-carbon objective achievement. Finally, although high ecological environmental protection can enhance ecological conditions, its impact remains limited without industrial economic development and ecological industrialization, failing to generate effective economic drivers. Therefore, across both the Yellow River Basin and Yangtze River Economic Belt, authentic green and low-carbon development necessitates the integrated action of industrial ecology and ecological industrialization.

## 5.3 Robustness assessment

To assess the robustness of the green and low-carbon development configurational results for the Yellow River Basin and the Yangtze River Economic Belt (Du et al., 2022), we first reduced the PRI (Proportional Reduction in Inconsistency) threshold from 0.7 to 0.65. As shown in Table 6, the resulting configurations remained highly consistent with the original configurations. Next, we increased the case frequency threshold from 1 to 2. As illustrated in Table 7, the resulting configurations were essentially subsets of the original ones. In accordance with the methodological standards of Qualitative Comparative Analysis (QCA) (Fiss, 2011; Greckhamer, 2016), adjusting the PRI consistency threshold and the case frequency threshold provides a rigorous test of the robustness and stability of the principal pathways. The results indicate that the main configurations identified in this study remain highly consistent under both more lenient and more stringent parameter conditions, further affirming the robustness of the green and low-carbon development configurations across the Yellow River Basin and the Yangtze River Economic Belt.

## 5.4 Sensitivity analysis with one-year lag

This study utilizes cross-sectional data from 2022, as the "dual carbon" (carbon peaking and carbon neutrality) goals were proposed in China in September 2020, followed by an intensive stage of policy formulation and implementation in 2021. During 2021–2022, all provinces (including autonomous regions and municipalities) successively issued specific action plans, pilot schemes, and assessment measures. Therefore, analyzing 2022 data effectively captures the interim outcomes of the dual

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**TABLE 8** Sensitivity analysis results.

| Region | Yellow River Basin | | | Yangtze River Economic Belt | | |
|---|---|---|---|---|---|---|
| Outcome variable | High-level green and low-carbon development | | Non-high green and low-carbon development | High-level green and low-carbon development | | Non-high green and low-carbon development |
| Antecedent Variables | H1a | H1b | NH1 | H2a | H2b | NH2 |
| Industrial Economic Development | ● | ● | ⊗ | ⊗ | ● | ⊗ |
| Ecological Environment Protection | ⊗ | ● | | ⊗ | ● | ● |
| Eco-Agricultural Industrialization | ● | ⊗ | ⊗ | ⊗ | ● | ⊗ |
| Eco-Industrialization | ● | ● | ⊗ | ● | ● | ⊗ |
| Consistency | 0.995 | 0.979 | 0.985 | 0.940 | 0.982 | 0.972 |
| Original coverage | 0.530 | 0.239 | 0.657 | 0.225 | 0.225 | 0.471 |
| Unique coverage | 0.466 | 0.176 | 0.657 | 0.213 | 0.213 | 0.471 |
| Overall consistency | 0.993 | | 0.985 | 0.968 | | 0.972 |
| Overall coverage | 0.705 | | 0.657 | 0.439 | | 0.471 |

Note: a. ● indicates the presence of a core condition, ⊗ indicates the absence of a core condition, ● indicates the presence of a marginal condition, ⊗ indicates the absence of a marginal condition, and blank spaces indicate optional variables. b. When performing “standard analysis” for high green low-carbon development in the Yellow River Basin, “~ecological environmental protection*ecological industrial development” was selected as quality implication terms. c. When performing “standard analysis” for high green low-carbon development in the Yangtze River Economic Belt, “~ecological agricultural industrialization*ecological industrial development” was selected as quality implication terms; when performing “standard analysis” for non-high green low-carbon development in the Yangtze River Economic Belt, “~industrial economic development*~ecological industrial development” was selected as the quality implication term.

carbon policy. However, as policy implementation typically follows a cycle of project approval, investment, construction, and commissioning, the results of green performance tend to become pronounced in the following year. To capture this policy time lag, this study anchors the antecedent conditions in the year of intensive policy introduction (2021) and sets the outcome variable during the period when policy effects are more prominent (2022), thus constructing a "T-1 → T" lagged cross-sectional model. This approach, within the framework of cross-sectional data, aims to simulate to the greatest extent possible the logic of a lagged panel data test. As shown in Table 8, the configurational results with a 1-year lag demonstrate that the core pathways for both the Yellow River Basin and the Yangtze River Economic Belt remain highly stable, while both coverage and consistency improve, further verifying the delayed manifestation of policy effects.

# 6 Conclusion and discussion

## 6.1 Theoretical findings

Employing the "Two Mountains Theory" conceptual framework, this study empirically validates the scientific basis and practical rationality of China's differentiated eco-economic policies through fuzzy-set Qualitative Comparative Analysis (fsQCA) of green and low-carbon development configurations in the Yellow River Basin and Yangtze River Economic Belt. Our findings provide theoretical substantiation for the strategic orientation of "classified policy and systematic governance" across these two critical watersheds.

First, the "non-single necessity" principle confirms the scientific validity of policy synergy logic. Our analysis demonstrates that isolated factors such as industrial economic advancement or ecological protection do not constitute necessary conditions for green and low-carbon development, methodologically refuting both the "pollute first, remediate later" paradigm and purely "ecological preservation" approaches. This empirically validates the dialectical unity between economy and ecology central to the "Two Mountains Theory" (Huang et al., 2024). The transformation of development paradigms requires coordinated integration of industrial ecology and ecological industrialization. These findings substantiate China's policy framework of "systematic governance of mountains, rivers, forests, fields, lakes, and grasslands," highlighting the necessity of transcending sectoral fragmentation through cross-domain coordination mechanisms to activate natural productivity's systemic benefits.

Second, the "differentiated configuration pathways" support regionally tailored policy approaches. The four distinct high-performance green and low-carbon development configurations identified not only demonstrate the rationality of China's "basin-specific governance" strategy but also reveal the dynamic adaptation mechanisms between policy instruments and regional endowments (Mengzhi et al., 2023). Yellow River Basin configurations emphasize industrial-ecological feedback loops, aligning with the "industrial upgrading to support ecological security" pathway outlined in the Yellow River Basin Ecological Protection and High-quality Development Planning framework. Conversely, Yangtze River Economic Belt configurations prioritize "technology-driven coordination," validating the strategic logic of addressing environmental carrying capacity constraints through industrial technological revolution as articulated in the Special Implementation Plan for Green Development of the Yangtze River Economic Belt.

Third, the "pivotal function of eco-industrialization" underscores policy targeting efficacy. Our findings indicate that neither economic development in isolation nor environmental protection alone can achieve green and low-carbon economic transformation. Only through synergistic interaction between these domains can sustainable development materialize (Liu et al., 2025). Comparative analysis of high-performing versus non-high-performing configurations reveals eco-industrialization as the critical determinant, validating China's policy prioritization of "industrial green revolution" within its national carbon neutrality strategy.

## 6.2 Policy implications

Based on our empirical findings, we propose the following recommendations for advancing green and low-carbon development through "dual modernization synergy":

First, establish a "Two Mountains" value transformation system with robust eco-economic synergy mechanisms. Focusing on the value realization pathway from "green waters and green mountains" to "mountains of gold and silver," policymakers must transcend single-instrument limitations to develop comprehensive institutional frameworks spanning "protection-restoration-transformation" continuums. In the Yellow River Basin, it is essential to refine the marketization mechanisms for ecological products—for instance, by advancing the "ecological banking" model. Under this approach, local governments may authorize specialized agencies to act as operational entities, establishing unified systems for the accounting, registration, and registration of ecological resource assets. This facilitates the centralized collection, consolidation, and large-scale integration of dispersed resources such as water-conserving forests, wetlands, and farmland soil carbon sequestration, ultimately converting them into tradable assets and directly actualizing the transformation of "green waters and green mountains" into "mountains of gold and silver." For the Yangtze River Economic Belt, green financial innovation should be further promoted through the establishment of dedicated "Two Mountains Transformation Funds." Adopting a "government-guided, market-driven" model, these funds would be seeded with allocations from provincial finance authorities and leverage additional capital from banks, insurance companies, and industrial investors. The fund's regulations should specify investment priorities, define concessional loan rates or equity return thresholds, and establish robust mechanisms for project screening, risk assessment, and post-investment management. These measures would enable the provision of low-interest loans to ecological industrial parks and organic agricultural bases, guiding private capital toward the industrialization of ecological assets.

Second, implement geographically differentiated, context-specific pathways adhering to spatial adaptation principles. In the Yellow River Basin, an "ecological restoration-driven" strategy must be adopted, advancing an institutional linkage between ecological restoration responsibilities and industrial development rights as delineated in the Yellow River Basin Ecological Protection and High-Quality Development Plan. Specifically, enterprises occupying ecological spaces would be required to assume corresponding off-site restoration obligations or invest in ecological restoration projects to secure industrial development quotas—thus resolving the binary tension between ecological preservation and economic stability through innovative "industry-fostering-ecology" mechanisms. For the Yangtze River Economic Belt, a "technology innovation-led" trajectory should be prioritized. This entails piloting "ecological innovation alliances" in economically advanced regions such as Jiangsu and Zhejiang, leveraging the existing platform and resources of the Yangtze River Delta G60 Science and Technology Innovation Corridor. Under government leadership, alliance charters and collaborative rules would be instituted, member rights and responsibilities clarified, and low-carbon technology joint laboratories or innovation centers established as operational entities. With clearly defined technological objectives and incentive mechanisms for achievement commercialization, such frameworks would foster virtuous cycles wherein ecological constraints effectively propel industrial upgrading.

Third, prioritize ecological industrialization as the catalytic nexus for "Two Mountains" synergistic endogenous development. Given eco-industrialization's core function identified in our analysis, institutional bottlenecks require targeted intervention: In the Yellow River Basin, establish a comprehensive negative list, rigorously enforcing prohibitions on high water-consuming and high-emission projects, complemented by the implementation of joint project access review mechanisms and online supervision platforms. Simultaneously, introduce positive incentive structures—offering clearly delineated preferential policies for green industries such as wind and solar power, including incentives like discounted land use, priority grid access for green electricity, provincial fiscal subsidies proportional to fixed-asset investments, and streamlined approval processes. For the Yangtze River Economic Belt, reinforce the synergy between technology and industry by supporting the development of green manufacturing demonstration projects, such as "industrial brains and future factories." Harness the Internet of Things and big data to optimize resource and energy management, thus driving the deep integration of the digital economy with ecological industries and nurturing a new, "eco-friendly" productivity paradigm. At the same time, a robust and enduring ecological compensation mechanism must be established, instituting cross-provincial horizontal compensation systems whereby downstream provinces compensate upstream regions for ecological protection costs in proportion to water usage, thereby operationalizing the "beneficiary pays" principle.

### 6.3 Theoretical contributions

The "Two Mountains Theory" represents a significant conceptual framework for understanding the synergistic relationship between economic development and ecological security. Our findings offer several substantive theoretical contributions to both this framework and regional green development scholarship.

First, we deepen "Two Mountains Theory" conceptualization. While previous literature often treats this framework as policy discourse, our analysis demonstrates that the transformation from "green waters and mountains" to "mountains of gold and silver" transcends simple ecological resource commodification, instead representing social reproduction of natural productivity through production relation reconfiguration and technological pathway innovation. Our findings establish that industrial ecology-ecological industrialization synergy follows the dialectical movement principle of "natural productivity duality": industrial ecology restores natural system cycles fragmented by capital accumulation, while ecological industrialization constructs social channels for natural capital value realization. This provides dynamic analytical tools for "Two Mountains Theory" and resolves the theoretical binary opposition between protection and development.

Second, we advance paradigmatic innovation in green and low-carbon development theory. While numerous studies focus on technological innovation or policy instruments, our research reveals that green and low-carbon development fundamentally depends on production relation transformation rather than merely technological advancement, providing a production-relations theoretical interface for green transition research. Furthermore, the identified "industry-feeding-ecology" pathway in the Yellow River Basin and "technology-driven synergy" in the Yangtze River Economic Belt represent contemporary manifestations of the principle that "differentiated natural conditions determine labor division forms." This framework transcends traditional "factor-stacking" regional development theories and provides spatial foundations for differentiated low-carbon policy design.

## Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

## Author contributions

BJ: Writing - review and editing. JC: Writing - review and editing. HJ: Writing - original draft, Writing - review and editing. TJ: Writing - original draft, Writing - review and editing.

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## Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2025.1644348/full#supplementary-material

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