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Green Finance and Manufacturing Transformation: A Coupling Approach to Sustainable Competitiveness

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Abstract
Green finance serves as a critical enabling instrument and resource-allocation mechanism, while the green transformation of the manufacturing industry constitutes both the core implementation domain and the ultimate objective of industrial upgrading. The effective coupling and coordinated development between these two dimensions represent a key pathway for achieving sustainable competitiveness. This study investigates how green finance develops in conjunction with the green transformation of manufacturing and examines whether the interaction between these two processes contributes to sustainable competitiveness. Using provincial-level data for 30 Chinese provinces over the 2011-2023 period, separate multidimensional indicator systems are developed to quantify green finance development and the green transformation of manufacturing. The empirical framework combines several complementary techniques: entropy-weighted TOPSIS for green finance assessment, a super-efficiency SBM model for manufacturing transformation, an improved coupling-coordination model for evaluating their interaction, Dagum Gini decomposition for regional disparities, and kernel density estimation for distributional dynamics. Sustainable competitiveness is represented by the degree of coordination between the two systems, reflecting the extent to which financial development and manufacturing transformation progress in a mutually compatible manner while supporting economic and environmental objectives. The empirical results reveal a general upward trajectory in coordination between green finance and manufacturing transformation, suggesting that their development has become increasingly synchronized across Chinese provinces. Despite this overall improvement, substantial spatial heterogeneity remains: provinces in the eastern region generally exhibit stronger coordination than those in the other regional groups. The study proposes policy recommendations to enhance alignment between green finance and industrial transformation, including developing innovation-driven financial instruments, strengthening policy coordination, and improving green financial market mechanisms.

Keywords: *green finance, green transformation, sustainable competitiveness, coupling*

JEL Classification: Q3, Q5, Q56

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1 INTRODUCTION

Growing climate pressures and increasingly binding resource and environmental constraints have placed the transition to environmentally sustainable development at the centre of economic and industrial policy agendas. Within this transition, sustainable competitiveness provides a useful perspective for assessing whether economies can maintain their productive and competitive capacity without undermining environmental quality or relying on inefficient

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patterns of resource use (Chen et al., 2024). Manufacturing occupies an important position in this process because it simultaneously influences productivity, employment, technological upgrading, resource consumption, and environmental pressures. At the same time, manufacturing models based on intensive resource and energy use are becoming increasingly difficult to sustain as environmental regulation strengthens and international production standards place greater emphasis on decarbonisation and resource efficiency (Han et al., 2022; Zhang & Bai, 2024).

Greening manufacturing requires simultaneous changes in production technologies, industrial processes, resource allocation, and the broader structure of industrial activity, many of which involve substantial and long-term investment. Such adjustments can be difficult to finance because environmental and technological projects frequently require large initial expenditures, generate returns only over extended horizons, and involve considerable technological and market uncertainty. In this context, green finance has emerged as a key enabling mechanism, facilitating the efficient allocation of financial resources towards environmentally sustainable activities. Through instruments such as green credit, green bonds, and carbon finance, green finance supports energy efficiency improvements, pollution reduction, and technological innovation, thereby contributing to both environmental performance and economic development (Chen et al., 2023; Khan et al., 2022).

Despite the growing body of literature on green finance and industrial transformation, existing studies predominantly focus on their direct effects on environmental outcomes, technological innovation, or economic growth. However, the systemic interaction between green finance and the green transformation of the manufacturing industry, particularly in the context of sustainable competitiveness, remains insufficiently explored. More importantly, prior research tends to treat competitiveness as a conceptual outcome rather than an empirically operationalised construct, leaving a gap in understanding how the alignment between financial mechanisms and industrial transformation translates into sustainable competitive capacity.

This gap limits the ability to empirically explain how sustainability-oriented financial and industrial policies contribute to sustainable competitiveness. To address this research gap, this study investigates how green finance develops in conjunction with the green transformation of manufacturing and examines whether the interaction between these two processes contributes to sustainable competitiveness. Specifically, the study investigates how the alignment between financial support systems and industrial transformation processes contributes to the formation of a more efficient, environmentally sustainable, and structurally balanced development trajectory.

Methodologically, the analysis covers 30 Chinese provinces from 2011 to 2023. Green finance is measured through an entropy-weighted TOPSIS index, while manufacturing transformation is evaluated using a super-efficiency SBM framework. Their interaction is then assessed through an improved coupling-coordination model, after which Dagum Gini decomposition and kernel density estimation are used to investigate regional inequality and distributional evolution. This study differs from closely related research in three important respects. The first contribution is to move beyond the predominantly one-way treatment of the finance–industry relationship by considering green finance and manufacturing transformation as interacting systems (Chen et al., 2023; Gao & Ma, 2024), whereas this study conceptualises green finance and manufacturing transformation as mutually interacting subsystems and evaluates the degree of their coordinated development. Second, while recent studies have applied coupling coordination approaches to green finance–environmental systems or technology–

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manufacturing transformation systems (Liu et al., 2025; Yang & Yongkang, 2026), this study specifically examines the financial–industrial nexus and interprets its coordination as an empirical proxy for sustainable competitiveness. This shifts the analytical focus from the coordination score itself to its economic meaning in terms of the alignment of financial resource allocation, manufacturing efficiency, and environmental performance. Third, building on the coupling assessment, the study employs Dagum Gini decomposition and kernel density estimation to examine the sources and dynamic evolution of regional disparities in the coordination between the financial and industrial subsystems underlying sustainable competitiveness. This analytical extension enables distinguishing whether observed disparities originate primarily within or between regions and tracing how the distribution of coordination levels changes over time. Taken together, these elements provide a distinct framework that links green finance and manufacturing transformation to sustainable competitiveness and reveals how both their coordination and regional imbalance evolve over time.

The empirical results indicate that the level of coupling and coordinated development between green finance and manufacturing transformation has steadily increased across China, reflecting a gradual strengthening of sustainable competitiveness driven by improved alignment between financial mechanisms and industrial transformation processes. Despite the overall progress, the results reveal pronounced spatial heterogeneity: coordination and competitive capacity are more developed in the eastern provinces, while the central, western, and northeastern regions remain at comparatively lower levels. The findings also reveal that interregional differences remain the primary source of overall inequality, highlighting the uneven distribution of financial and technological resources.

The paper proceeds with a review of the theoretical foundations and the proposed conceptual framework, followed by the description of the data and empirical strategy. The subsequent sections report and discuss the results, and the final section summarizes the main conclusions, policy implications, and study limitations

2 THEORETICAL BACKGROUND

2.1. Green finance

The transition towards a low-carbon economy increasingly depends on financial and policy arrangements that can reconcile economic development with constraints related to resources, pollution and ecological degradation. This represents an inherent requirement for establishing harmonious coexistence between humans and nature. To accelerate the comprehensive green transformation of economic and social development, various national guidelines and policies have been formulated to promote green development and transformation.

As environmental pollution has intensified, academic research has increasingly focused on the fields of green transformation and development, the natural environment, and green finance. One of the early attempts to connect financial activity with environmental objectives was provided by Salazar (1998), who discussed the integration of banking practices and environmental protection under the concept of “environmental finance.” Subsequently, the 2000 *American Traditional Dictionary* defined the specific concept of “green finance” and discussed in depth how financial instruments can contribute to environmental protection (Wang & Wang, 2021; Zhao et al., 2023). Labatt and White (2002) analysed green finance as a risk mitigation tool, emphasising its role in addressing worsening environmental risks.

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Further studies have examined green finance from the perspective of sustainable social development. For instance, Scholtens (2006) conceptualised green credit as both a financial innovation and an environmental protection innovation, suggesting that these dimensions complement each other in reducing the ecological and environmental pollution caused by economic activities. Yang et al. (2024) argued that for the green economy to progress rapidly, it is necessary to establish green financial centres, green credit, and green bonds, noting that China's green credit sector remains underdeveloped relative to that of other countries, and that banks should actively support green financing to increase the social value of enterprises.

Chin et al. (2024) identified the potential of green finance to improve banks' risk management, channel green funds into the economic system, and promote social progress alongside the green development of the financial system. Liu and Tang (2022) examined the moderating effect of green finance on carbon emissions, considering factors such as environmental technology innovation, environmental regulation intensity, cross-border trade activities, and economic growth in OECD member countries, and confirmed the synergistic relationship between green finance and ecological innovation in promoting sustainable development. Yue et al. (2024) further elaborated on the multiple functions of green finance, highlighting its role in providing capital support for ecological construction, improving environmental quality, and advancing green urbanisation. Financial engineering instruments within green finance systems play an important role in supporting environmental innovation management and improving the effectiveness of sustainability-oriented investment allocation mechanisms (Khalatur & Dubovych, 2022).

Existing scholarship has focused predominantly on the interrelations between green finance, economic growth, and green technological innovation, reflecting its significance as a strategic instrument for achieving sustainability objectives. Recent bibliometric evidence further confirms the rapidly growing global importance of green energy investment and green finance as key drivers of sustainability-oriented structural transformation and competitiveness across both developed and emerging economies (Kwilinski, 2024). Despite the extensive body of literature, most contributions examine green finance in isolation, focusing on its effects on environmental outcomes, innovation, or economic growth. However, limited attention has been paid to how green finance contributes to sustainable competitiveness, particularly through its interaction with industrial transformation processes. This highlights the need for a more integrated, system-level perspective on the role of green finance in shaping sustainable competitiveness.

2.2. Green transformation of the manufacturing industry

Research on manufacturing transformation has developed along several related streams, with particular attention to digitalisation, environmental innovation and changes in production systems associated with sustainable development. Gereffi (1999) introduced the concept of manufacturing transformation, which he described as the transition from labour-intensive, low-value-added production to high-technology, high-value-added activities. Green transformation was further linked to the broader concept of the green economy through policy reforms aimed at reducing environmentally harmful subsidies and supporting sustainable development (OECD, 2005).

Subsequent studies have emphasised the role of technological innovation in enhancing the environmental performance of manufacturing while generating economic co-benefits (Liao & Drakeford, 2019). Empirical evidence further confirms that green innovation activities significantly improve firm-level performance through both market-driven and managerial

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mechanisms, reinforcing the role of innovation as a key driver of sustainability-oriented industrial transformation (Wagan et al., 2025). The green transformation of manufacturing has been conceptualised as an integrated model combining economic efficiency and environmental sustainability throughout the production process (Shan & Lili, 2023). In addition to technological upgrading, the success of sustainability-oriented industrial transformation is increasingly associated with the development of sustainability-related entrepreneurial attitudes and competencies, particularly among future economic actors in European transition economies (Titko et al., 2023b). From a measurement perspective, Chung et al. (1997) introduced the concept of green total factor productivity, which has been widely applied to assess transformation performance by incorporating undesirable outputs (Man et al., 2024). Other approaches include multidimensional index systems capturing environmental performance, production efficiency, and structural upgrading (Meng & Chi, 2018; Li & Bai, 2024; Si et al., 2024). However, much of the current literature has concentrated on productivity improvements and environmental outcomes, without explicitly linking green transformation processes to sustainable competitiveness. As a result, the role of manufacturing transformation as a driver of long-term competitive capacity remains insufficiently explored, particularly from a system-level perspective.

2.3. Green finance and the green transformation of the manufacturing industry

The relationship between finance and manufacturing transformation is particularly important because industrial greening depends on access to capital for technology renewal, cleaner production and environmental innovation. Evidence from E.U. countries further demonstrates that digital transformation processes, including the development of e-commerce ecosystems, support the achievement of sustainability-related development goals and strengthen the interaction between economic modernisation and environmental transition mechanisms (Kwilinski, 2023). The effective utilisation of financial instruments to address resource and environmental challenges is essential for the advancement of the renewable energy sector. He et al. (2019) demonstrated that financial system development positively affects industrial scale, structure, and technological progress, thereby influencing investment decisions and supporting green transformation. In contrast, traditional financial systems often prioritise short-term profitability, neglecting environmental considerations and constraining sustainable industrial development (Tamazian & Rao, 2010). Empirical studies further confirm that green finance promotes cleaner production and accelerates the transition of high-polluting enterprises towards more sustainable practices (Li et al., 2022). In addition, green finance has been shown to enhance technological innovation under environmental regulation, reinforcing the transformation process (Jiakui et al., 2023). Despite these findings, existing research predominantly focuses on the unidirectional impact of green finance on industrial transformation. The bidirectional and systemic interaction between green finance and manufacturing transformation, particularly in the context of sustainable competitiveness, remains insufficiently explored. This highlights the need for an integrated empirical framework capable of capturing their dynamic co-evolution and its implications for sustainable competitiveness.

2.4. Mechanism of coupling between green finance and the green transformation and development of the manufacturing industry

Within the context of pursuing sustainable development, system coupling serves as a theoretical mechanism for analysing the relationships between subsystems. In addition to financial and technological interactions, cross-country evidence suggests that institutional and cultural

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development factors significantly influence the achievement of sustainable development goals and shape the effectiveness of sustainability-oriented transformation processes, thereby strengthening the systemic foundations of sustainable competitiveness (Titko et al., 2023a). It reveals the internal dynamics of different subsystems through their interactions, mutual influences, and integration processes, ultimately leading to coevolution. The efficient coupling and coordinated development of these subsystems constitute a core pathway for achieving sustainable competitiveness, as they reflect the systemic alignment between financial resource allocation and industrial transformation processes, as illustrated in figure 1.

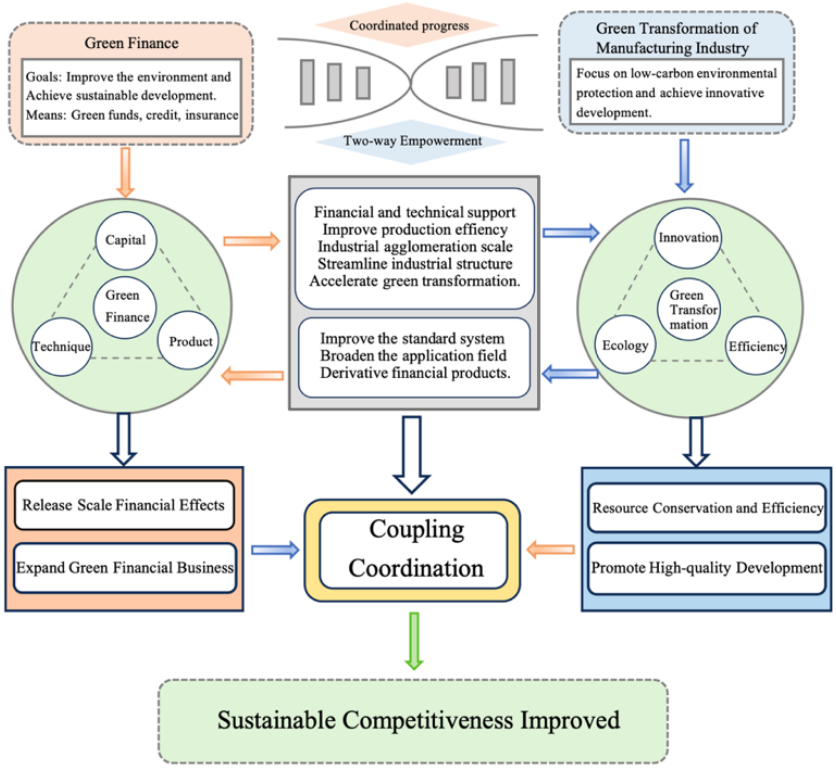


Fig. 1 – Coupling mechanism of green finance and the green transformation of manufacturing. Source: authors' conceptualisation based on the literature reviewed.

2.4.1. Mechanism of the effects of green finance on the green transformation and development of the manufacturing industry

Green finance encompasses financial arrangements that channel capital towards activities associated with environmental improvement, climate objectives and more efficient resource use (Tang et al., 2022). Its core is comprised of three primary elements: capital allocation, technological empowerment, and product innovation. Green finance enhances production efficiency through the provision of financial and technological support (Zhao et al., 2022; Zheng et al., 2022), unlocks the benefits of scale financing to foster industrial agglomeration, and improves resource allocation efficiency and industrial structure optimisation. Through their combined effects, these mechanisms support the transition of manufacturing towards greener development pathways and reinforce the competitive position of manufacturing enterprises.

Green finance provides financial and technological support to increase production efficiency. Through diversified capital formation and operational mechanisms, it directs the flow of social

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capital and technology towards the green transformation and development of the manufacturing industry. First, financial instruments such as green bonds, green funds, green credit, green insurance, and green equity investment provide low-cost financial support to manufacturing enterprises (Sartzetakis, 2021). This reduces financing thresholds, ensures operational efficiency and stability, enhances economic performance and market responsiveness, and thereby strengthens the competitiveness of enterprises within the economic dimension. Second, the collaborative system integrating green finance with supportive preferential policies effectively reduces innovation costs and risks, promoting extensive research, development, and the application of green production and recycling technologies. This enables high levels of efficiency, intelligence, and environmental performance throughout the production life cycle (Hao et al., 2025). Green finance also releases economies of scale and expands industrial agglomeration. By increasing the scale and density of manufacturing agglomeration, green finance and its derivative products and services guide governments, enterprises, and social organisations to create synergies in green, low-carbon, environmentally friendly, and efficient production sectors (Fu et al., 2023), thereby expanding agglomeration scales.

Furthermore, by optimising capital allocation structures, green finance facilitates in-depth cooperation among multiple entities focused on product innovation, technological research and development, and capacity enhancement, achieving synergistic linkages across upstream, midstream, and downstream segments to strengthen agglomeration density. Additionally, the external financial benefits generated by green finance-related products and services, including digital finance and inclusive finance (Hossain et al., 2024), support the establishment of a comprehensive, multilevel industrial agglomeration ecosystem. This ensures the structural stability and effective mechanisms for the green transformation and development of the manufacturing industry, maximising the diffusion and spillover of economic benefits derived from green finance. Green finance also improves resource allocation efficiency and optimises the industrial structure. It drives the transformation of traditional manufacturing from extensive to precision production, thereby advancing industrial transformation and optimisation (Ge et al., 2022). On the one hand, green finance enhances the cross-sector integration capabilities of manufacturing; promotes capital, technology, product, and talent flows into green production; effectively mitigates resource misallocation risk; and improves resource allocation efficiency (Zhou et al., 2024). On the other hand, green finance facilitates a more refined division of labour within the manufacturing industry, fostering new forms and attributes of industrial transformation and development. This promotes internal coordination and the orderly functioning of green transformation processes, enabling industrial structure upgrading, the rationalisation of industrial models, and the construction of a comprehensive industrial chain for the green transformation of the manufacturing industry.

2.4.2. Mechanism of the effects of the green transformation and development of the manufacturing industry on green finance

As manufacturing moves away from resource-intensive production towards cleaner and more technologically advanced processes, the structure and scale of its financing needs also change (Peng et al., 2022). These changes stimulate demand for specialised financial products and encourage financial institutions to refine risk assessment, environmental standards and financing mechanisms for green industrial projects. The expansion of green finance business operations promotes product and service innovation. Within the context of the green transformation and development of the manufacturing industry, updates to industrial development models and the surge in development demand have broadened the application fields of green finance in terms of capital, technology, and products (Xu et al., 2025). The green

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and intelligent transformation of manufacturing has generated substantial demand for green projects, creating a large-scale market for derivative financial products and services and extending the scenarios in which green finance operates throughout the entire manufacturing transformation chain. Furthermore, the diversified demand for advanced technologies, products, and services arising from the green transformation of manufacturing (Yin et al., 2022) compels financial institutions to innovate more diverse and adaptable green financial products and services, establishing a dynamic matching mechanism between financial supply and industrial demand. Improving the standard system of green finance contributes to coordinated reductions in market risk. During the green transformation process, manufacturing enterprises reduce noncompliance risks, enhance environmental compliance, and improve information transparency by adopting green production standards. This provides financial institutions with reliable evaluation bases, thereby improving the accuracy and effectiveness of the green finance standard system. Additionally, the transformation and upgrading of the manufacturing industry enhances green financial infrastructure, facilitating two-way resource matching and information symmetry between green finance and manufacturing transformation. Improvements in the green transformation of manufacturing and related institutional mechanisms strengthen the stability and coherence of the coupling mechanisms between green finance and manufacturing development. This reduces policy, technological, and market risks during transformation and development processes (Sun et al., 2020) and enhances the stability of the coupling and coordination system between green finance and the green transformation of the manufacturing industry.

2.4.3. The coupling mechanism between green finance and the green transformation and development of the manufacturing industry

The two systems can therefore be viewed as mutually reinforcing: financial development supports industrial greening, while the expansion of green manufacturing creates additional demand and investment opportunities for green financial services. On the financial side, capital allocation and financing incentives can accelerate investment in cleaner technologies and more resource-efficient production processes (Gao & Ma, 2024). Conversely, the green transformation of manufacturing generates diverse application scenarios and value-creation opportunities for green financial instruments, such as green bonds, transition financing, and green insurance, reinforcing the resilience and development of the financial system. Both green finance and manufacturing transformation share green development as their common core. Their objectives are highly aligned, aiming to achieve sustainable economic growth alongside environmental improvement. From a technological perspective, the integration of green innovation enhances the effectiveness of this interaction and strengthens the foundations of sustainable competitiveness. From a resource allocation perspective, the efficient mobilisation and coordination of capital, technology, and production factors improve transformation outcomes and reinforce long-term competitive capacity. From an industrial perspective, the expansion of green financial instruments and the upgrading of manufacturing towards high-value, green, and integrated structures further deepen this interaction. The interaction between green finance and manufacturing transformation can be understood as a dynamic and mutually reinforcing system that shapes sustainable competitiveness. At the same time, the effectiveness of sustainability-oriented transformation processes also depends on the level of sustainability awareness among economic actors, which has been shown to influence behavioural readiness for implementing environmental innovation and green development strategies in transition economies (Veckalne et al., 2022). However, existing studies lack an integrated empirical framework capable of capturing this interaction and its implications for competitiveness. This

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study addresses this limitation by applying a coupling coordination approach, which enables the empirical operationalisation of sustainable competitiveness as an outcome of system-level alignment between financial and industrial subsystems.

3 RESEARCH OBJECTIVE, METHODOLOGY AND DATA

3.1. Data sources

The empirical sample is a balanced panel covering 30 provincial-level regions of China from 2011 through 2023. Tibet is not included in the sample because the required indicators are not available with sufficient continuity for the study period. The data used to construct the green finance index and to measure manufacturing green transformation were compiled from official statistical publications of the National Bureau of Statistics of China (2024), the Ministry of Ecology and Environment of the People's Republic of China (2024), and the China Stock Market & Accounting Research database (CSMAR, 2026). Missing data for individual years were supplemented via interpolation. The selected dataset ensures sufficient temporal and spatial coverage to capture both the evolution and regional heterogeneity of the interaction between green finance and manufacturing transformation.

3.2. Construction of the indicator system

The measurement framework was constructed to capture the principal financial mechanisms through which capital is mobilised, allocated, and redirected towards environmentally sustainable economic activities. Rather than representing green finance by a single financial indicator, the proposed framework distinguishes seven dimensions reflecting different functions of the green financial system (Table 1). Green credit captures the allocation of bank lending towards environmentally oriented projects, while green bonds represent the mobilisation of debt capital through capital markets. Green investment measures the scale of financial resources directed towards environmental pollution control, whereas green funds reflect the participation of institutional investment in financing green assets. Green insurance captures the financial management and transfer of environmental risks. Fiscal green support represents the role of public finance in directing resources towards environmental objectives, thereby complementing market-based sources of green capital. Finally, green rights capture the development of market-based mechanisms that assign economic value to environmental resources and externalities through transactions involving carbon-emission, energy-use, and pollution-emission rights. Taken together, these dimensions capture complementary credit-, investment-, insurance-, securities-, fiscal-, fund-, and market-based channels of green finance and therefore provide a broader representation of provincial green financial development than any individual financial indicator. The selection and operationalisation of the indicators are grounded in previous empirical approaches to green finance measurement (Wang et al., 2021; Zhang & Wang, 2021; He & Liu, 2023; Zhou et al., 2022). In this study, these indicators are aggregated using the entropy-weighted TOPSIS procedure to obtain a comparable provincial green finance score for 2011–2023.

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Tab. 1 – Indicator system for measuring green finance development. Source: authors' elaboration based on Wang et al. (2021), Zhang and Wang (2021), He and Liu (2023), and Zhou et al. (2022).

Green finance dimension	Direction	Data source
Green credit	+	CSMAR (2026)
Green investment	+	National Bureau of Statistics of China (2026); Ministry of Ecology and Environment of the People's Republic of China (2026)
Green insurance	+	CSMAR (2026)
Green bonds	+	CSMAR (2026)
Green fiscal support	+	National Bureau of Statistics of China (2026)
Green funds	+	CSMAR (2026)
Green rights	+	CSMAR (2026)

Manufacturing transformation is evaluated through an efficiency framework that relates desirable economic output to the production inputs employed and the environmental burdens generated in the production process. On this basis, the assessment framework is organised around three interrelated components: production resources, economic performance, and environmental burden. Production resources comprise capital, energy, and labour, thereby capturing the principal factor inputs required for industrial production. Economic performance is represented by secondary-industry value added and reflects the desirable economic return generated from these resources. Environmental burden captures the adverse consequences of industrial production and is represented by carbon dioxide emissions, industrial wastewater discharge, industrial sulphur dioxide emissions, industrial solid waste generation, and industrial smoke (dust) emissions. Within the Super-SBM model, production resources are specified as inputs, economic performance as the desirable output, and the measures of environmental burden as undesirable outputs. This structure enables the evaluation of manufacturing green transformation through the interrelationships among resource utilisation, economic value creation, and multiple dimensions of environmental pressure. The selection of the input and output variables follows established efficiency-based approaches to industrial green development (Zhai & An, 2020; Yin et al., 2022), while their operational definitions, measurement units, and statistical sources are reported in table 2.

Table 2 – Indicator framework for measuring green transformation in manufacturing. Source: authors' elaboration based on Zhai & An (2020) and Yin et al. (2022)

Model component	Variable	Measurement	Data source
Production resources	Capital	Fixed capital stock, 100 million yuan	National Bureau of Statistics of China (2026)
	Energy	Total industrial energy consumption, 10,000 tons	
	Labour	Manufacturing employment, persons	
Economic performance	Economic value creation	Value added of the secondary industry, 100 million yuan	
Environmental burden	Carbon emissions	CO_2 emissions, tons	
	Wastewater	Industrial wastewater discharge, 10,000 tons	

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	Sulphur dioxide	Industrial SO_2 emissions, 10,000 tons	Ministry of Ecology and Environment of the People's Republic of China (2026)
	Solid waste	General industrial solid waste, 10,000 tons	
	Smoke and dust	Industrial smoke (dust) emissions, 10,000 tons	

The selected indicators ensure a comprehensive assessment of both financial development and industrial transformation, forming the empirical basis for evaluating their interaction and its implications for sustainable competitiveness.

3.3. Operationalisation of sustainable competitiveness

In this study, sustainable competitiveness is operationalised as a system-level outcome reflecting the joint performance of financial and industrial subsystems. Given the multidimensional nature of competitiveness, it is not measured directly through a single indicator but is instead captured through the coupling coordination degree between green finance and manufacturing transformation. Specifically, the proposed framework integrates three key dimensions: (i) economic efficiency, measured by the super-efficiency SBM model; (ii) environmental performance, captured through undesirable outputs; and (iii) systemic alignment between financial and industrial processes, measured by the coupling coordination degree. Therefore, the coupling coordination degree (D) is interpreted as a proxy for sustainable competitiveness, reflecting the extent to which financial resource allocation and industrial transformation are effectively aligned to support long-term, environmentally sustainable economic performance.

3.4. Model setting

The empirical procedure begins with the construction of the provincial green finance index. Indicator weights are obtained objectively from the entropy method and are subsequently incorporated into the TOPSIS procedure to determine each province's relative position. Manufacturing green transformation is then measured through a super-efficiency SBM approach that accounts for both desired economic outcomes and environmental burdens. The resulting measures of the two subsystems provide the basis for estimating their degree of coordinated development, which is used in this study to represent sustainable competitiveness. The analysis is subsequently extended to the spatial dimension: the Dagum Gini decomposition identifies the sources of regional inequality, while kernel density estimation traces changes in the distribution of coordination levels over time.

3.4.1. Entropy-weighted TOPSIS method

Following established applications of the entropy-weighted TOPSIS approach (Sun et al., 2017; Wang et al., 2021; Xueshan et al., 2025), the green finance index is constructed by combining entropy-based objective weighting with the TOPSIS ranking procedure. The method was selected because it enables the construction of a composite index while reducing subjectivity in indicator weighting. Unlike expert-based weighting schemes, entropy weights are derived from the degree of variation in the data, which is particularly appropriate for a multidimensional provincial panel dataset with heterogeneous indicators. Compared with PCA-based approaches, entropy-weighted TOPSIS preserves the interpretability of the original indicators and is better suited to ranking provincial performance when the objective is to evaluate relative development levels rather than to extract latent factors. The computational procedure follows the standard

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entropy-weighted TOPSIS framework, adapted here to the provincial green finance indicator system presented in table 1. The calculation procedure is as follows:

Step 1. Standardisation of data:

For forward indicators:

$$Y_{ij} = \frac{x_{ij} - minx_{ij}}{maxx_{ij} - minx_{ij}} \quad (1)$$

For negative indicators:

$$Y_{ij} = \frac{maxx_{ij} - x_{ij}}{maxx_{ij} - minx_{ij}} \quad (2)$$

where Y_{ij} is the standardised evaluation matrix and where $maxx_{ij}$ and $minx_{ij}$ denote the upper and lower values observed for the j-th indicator in year i, respectively.

Step 2. Weight calculation via the entropy method:

(1) Proportion of each indicator:

$$p_{ij} = x_{ij} / \sum_{i=1}^{n} x_{ij} \quad (3)$$

(2) Information entropy of each component:

$$e_j = -\frac{1}{ln\, n} \sum_{i=1}^{m} p_{ij}\, ln(p_{ij}) \quad (4)$$

(3) Coefficient of variation:

$$d_j = 1 - e_j \quad (5)$$

(4) Weight of each index:

$$w_j = d_j / \sum_{i=1}^{n} d_j \quad (6)$$

Step 3. Construction of the weighted standardised decision matrix

The standardised matrix $Y = (y_{ij})_{m\times n}$ is multiplied by the weight vector $W = (w_1, w_2, \ldots, w_n)$ to obtain the weighted standardised matrix $R_{m\times n} = (r_{ij})_{m\times n}$:

$$r_{ij} = \frac{Y_{ij}}{\sqrt{\sum_{i=1}^{m} y_{ij}^2}} \quad (7)$$

$$R_{ij} = w_j \times r_{ij} \quad (8)$$

Step 4. Determination of the optimal and worst solutions

Optimal solution vector:

$$F^+ = (f_1^+, f_2^+, \ldots\ldots, f_n^+) \quad (9)$$

Worst solution vector:

$$F^- = (f_1^-, f_2^-, \ldots\ldots, f_n^-) \quad (10)$$

$f_j^+ = max(f_{ij})$，$f_j^- = min(f_{ij})$，i=1，2，3.....m，j=1，2，3.....n.

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Step 5. Calculation of Euclidean distances to the ideal and negative-ideal solutions:

$$d_j^+ = \sqrt{\sum_{i=1}^{m}(f_j^+ - f_{ij})^2} \quad (11)$$

$$d_j^- = \sqrt{\sum_{i=1}^{m}(f_j^- - f_{ij})^2} \quad (12)$$

Step 6. Determination of the ideal-solution proximity score.

$$C = \frac{d_i^-}{d_i^+ + d_i^-} \quad (13)$$

3.4.2. Super-efficiency SBM model

Manufacturing green-transformation efficiency is estimated using a super-efficiency SBM specification, with each province-year observation treated as a decision-making unit. This method extends the traditional SBM model (Banker et al., 1984), which assigns an efficiency score of 1 to efficient DMUs but does not distinguish among them when the efficiency exceeds this value. For DMUs the efficiencies of which are less than 1, standard data envelopment analysis (DEA) deems them inefficient, whereas efficient DMUs remain incomparable. Tone (2002) extended the conventional SBM framework by introducing a super-efficiency specification that distinguishes efficient units located on the production frontier. Efficiency scores above unity provide the basis for ranking these units. The analytical setting comprises nDMUs, each described by m inputs $x_i(i = 1,2,\dots,m)$ and q outputs $y_r(r = 1,2,\dots,q)$. For the unit indexed by k, efficiency estimation follows the variable-returns-to-scale (VRS) assumption. The optimisation model is specified as follows:

$$\rho = min\frac{(1+\frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{ik}})}{(1-\frac{1}{s}\sum_{r=1}^{m}\frac{s_i^+}{y_{rk}})} \quad (14)$$

subject to:

$$\begin{cases} \sum_{j=1,j\neq k}^{n} x_{ij}\lambda_j - s_i^- \leq x_{ik} \\ \sum_{j=1,j\neq k}^{n} y_{rj}\lambda_j \geq y_{rk} \\ \lambda, s^-, s^+ \geq 0, i = 1,2\dots m;\ r = 1,2,\dots q;\ j = 1,2,\dots n;\ (j \neq k) \end{cases} \quad (15)$$

where ρ denotes the comprehensive efficiency of green transformation. Higher values of ρ indicate greater efficiency, whereas ρ<1 indicates that the DMU is not DEA efficient. The variables s^- refers to input slack and s^+ to output slack, whereas m and q specify the dimensions of the input and output sets.

The SBM results serve as the empirical representation of the green transformation subsystem in the subsequent coupling coordination analysis. This integration is conceptually coherent because the SBM model captures the efficiency of transforming production inputs into desirable economic outputs while accounting for undesirable environmental outputs. Therefore, it provides an appropriate efficiency-based measure of manufacturing green transformation for evaluating its alignment with the green finance subsystem.

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3.4.3. Improved coupling coordination model

After obtaining separate measures for the two subsystems, their degree of interaction is quantified using an improved coupling-coordination specification (Dong et al., 2023; Shen et al., 2018; Li et al., 2025). The model captures both the strength of interaction between the two systems and the extent to which their respective development levels remain balanced. This model reflects both the interdependence and the mutual constraints between systems. The degree of coordination characterises the extent of benign coupling within the interaction, thereby indicating the quality of the coordination. In this framework, the two subsystems are defined as the development level of green finance (U_1) and the level of green transformation of the manufacturing industry (U_2). The coupling degree C between the two subsystems is expressed as

$$C = \sqrt{\left[1 - \sqrt{(U_1 - U_2)^2}\right] \frac{min(U_1, U_2)}{max(U_1, U_2)}} \tag{16}$$

The coupling coefficient C ranges from 0 to 1, with higher values reflecting a stronger interaction between the two subsystems. However, this coefficient describes the intensity of their interdependence without accounting for the balance of their development. The coupling coordination degree D therefore complements this measure by incorporating the coordination dimension and is expressed as follows:

$$D = \sqrt{C \times T} \tag{17}$$

where T is a composite index of the two subsystems, defined as:

$$T = \alpha U_1 + \beta U_2 \, , \alpha + \beta = 1 \tag{18}$$

Both subsystems receive identical weights ($\alpha = \beta = 0.5$), reflecting the analytical assumption that neither green finance nor manufacturing transformation is given ex ante priority in determining overall coordination. Since the purpose of the model is to evaluate the balance and interaction between the two subsystems rather than to privilege one dimension over the other, equal weighting provides a neutral benchmark and is consistent with prior coupling coordination studies. This specification also avoids introducing additional subjectivity into the aggregation process.

Defined on the $[0, 1]$ scale, D reflects the extent of coordinated development between the two subsystems, increasing with greater coordination and decreasing as their developmental imbalance widens. The classification of the levels of coupling and coordination (Table 3) follows the criteria of Han et al. (2023).

Tab. 3 – Coordination level classification standards. Source: Adapted from Han et al. (2023).

Coordination type	Coupling coordination degree	Coupling Coordination Level
The dissonance phase	[0.0，0.1)	Extremely dysregulated
	[0.1，0.2)	Severe disorder
	[0.2，0.3)	Moderate dissonance
	[0.3，0.4)	Mild disorder
Transitional phase	[0.4，0.5)	On the verge of disorder
	[0.5，0.6)	Slight coordination
Coordination phase	[0.6，0.7)	Moderate coordination
	[0.7，0.8)	Relatively high

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		coordination
	[0.8，0.9)	High coordination
	[0.9，1.0]	Very high coordination

In this study, the coupling coordination degree (D) is interpreted as an empirical representation of sustainable competitiveness, as it reflects the degree of alignment between financial support mechanisms and industrial transformation processes.

3.5. Dagum Gini coefficient decomposition method

Spatial inequality in coordination levels is examined with the Dagum Gini approach (Dagum, 1997), which allows overall inequality to be decomposed according to its regional sources. This method enables not only the measurement of overall inequality but also the decomposition of this inequality into meaningful components that reflect specific sources of disparity. Compared with alternative approaches, such as the Theil index, the coefficient of variation, or the standard Gini coefficient, the Dagum method provides a more detailed analysis by distinguishing differences within regions, between regions, and accounting for the overlap (or supervariable density) among distributions. This facilitates interpretation of both the magnitude of inequality and the contribution of each region to the total disparity. The Dagum approach separates total inequality into within-region variation (G_1), between-region variation (G_2), and transvariation intensity (G_3), yielding $G = G_1 + G_2 + G_3$. For the regional analysis, the 30 Chinese provinces are classified into four geographical groups: eastern, central, western, and northeastern China. Based on this regional structure, the aggregate Gini measure takes the following form:

$$G = \frac{\sum_{j=1}^{k}\sum_{h=1}^{k}\sum_{i=1}^{n_j}\sum_{r=1}^{n_h}|Y_{ji}-Y_{hr}|}{2n^2\bar{Y}} \tag{19}$$

$$G_{jj} = \frac{\frac{1}{2\bar{Y_j}}\sum_{i=1}^{n_j}\sum_{r=1}^{n_j}|Y_{ji}-Y_{jr}|}{n_j^2} \tag{20}$$

$$G_{jj} = \frac{\sum_{i=1}^{n_j}\sum_{r=1}^{n_h}|Y_{ji}-Y_{hr}|}{n_j n_h(\bar{Y_j}+\bar{Y_h})} \tag{21}$$

For the regional decomposition, the sample is partitioned into k regions comprising n provinces in total. Region j contains n_j provinces, and y_{ji} denotes the coupling coordination degree observed for province i within that region. The corresponding regional mean is denoted by $\bar{y}_j$, while $\bar{y}$ refers to the mean coupling coordination degree for the full provincial sample. Equations (20) and (21) quantify inequality within region j, G_{jj}, and between regions j and h, G_{jh}, respectively. Thus, the former captures dispersion among provinces belonging to the same region, whereas the latter measures the extent of distributional differences between provinces located in two different regions (Dagum, 1997). The following variables are defined:

$$P_j = \frac{n_j}{n} \tag{22}$$

$$S_j = \frac{n_j\bar{Y_J}}{n\bar{Y}} \tag{23}$$

$$M_{jh} = \int_0^{\infty} dF_j(Y)\int_0^{Y}(Y-x)dF_h(x) \tag{24}$$

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$$N_{jh} = \int_0^{\infty} dF_h(Y) \int_0^{Y} (Y - x) dF_j(x) \quad (25)$$

$$D_{jh} = \frac{M_{jh} - N_{jh}}{M_{jh} + N_{jh}} \quad (26)$$

For each pair of regions j and h, D_{jh} characterises the relative contribution of their distributional differences to regional inequality. The terms M_{jh} and N_{jh} are obtained from pairwise comparisons of provincial coupling coordination levels across the two regions. Specifically, M_{jh} is the expected positive difference associated with observations satisfying $Y_{ij} - Y_{hr} > 0$, whereas N_{jh} captures the expected difference in the reverse ordering, $Y_{hr} - Y_{ji} > 0$. The cumulative distributions of coupling coordination levels for regions $j$and $h$are represented by $F_j$and F_h. The Dagum decomposition then distinguishes three sources of spatial inequality within-region variation (G_w), net between-region disparity (G_{nb}), and transvariation intensity (G_t). Their mathematical expressions follow Dagum (1997):

$$G_w = \sum_{j=1}^{k} G_{jj} P_j S_j \quad (27)$$

$$G_{nb} = \sum_{j=2}^{k} \sum_{h=1}^{j-1} G_{jh} D_{jh} \left(P_j S_h + P_h S_j\right) \quad (28)$$

$$G_t = \sum_{j=2}^{k} \sum_{h=1}^{j-1} G_{jh} \left(P_j S_h + P_h S_j\right) (1 - D_{jh}) \quad (29)$$

where G_w represents the regional difference contribution; G_{nb} represents the contribution to the differences between regions; and G_t represents the transvariation component.

3.6. Kernel density estimation method

Changes in the distribution of provincial coordination scores over time are additionally explored using non-parametric kernel density estimation. This nonparametric technique estimates an unknown probability density function without imposing parametric assumptions, producing a smooth distribution that highlights multimodality, polarisation, and distributional dynamics (Wang et al., 2013). Compared with parametric approaches and histograms, kernel density estimation provides a more precise and detailed description of the distribution's location and shape and changes over time. Originally proposed by Rosenblatt (1956) and Parzen (1962), the method considers independent and identically distributed random variables $X_1, X_2, X_3, \ldots\ldots X_n$ with an unknown density function f(x). The kernel density estimator of f(x) is defined as follows:

$$f(x) = \frac{1}{Nh} \sum_{i=1}^{N} K\left(\frac{X_i - x}{h}\right) \quad (30)$$

where N denotes the sample size, h is the bandwidth controlling the smoothness of the estimate, and K(·) is the kernel function. The kernel function satisfies K(x)≥0 and $\int_{-\infty}^{+\infty} K（X） dx = 1$. The Gaussian kernel is defined as follows:

$$K(x) = \frac{1}{\sqrt{2\pi}} exp\left(-\frac{x^2}{2}\right) \quad (31)$$

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4 RESULTS AND DISCUSSION

4.1. Coupling coordination between green finance and manufacturing transformation

Figure 2 illustrates how the coordination between green finance and manufacturing green transformation evolved across the 30 Chinese provinces during 2011–2023, based on the improved coupling coordination framework.

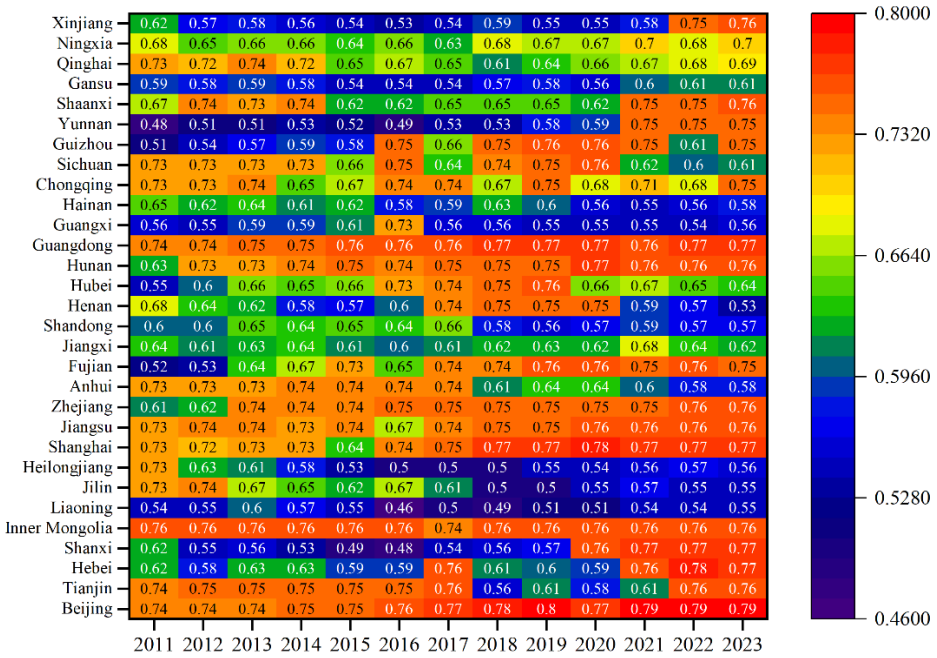


Fig. 2 – Coupling and coordination results of green finance and manufacturing transformation development in various provinces from 2011-2023. Source: own research.

Figure 2 shows that provincial coordination scores are generally concentrated between approximately 0.5 and 0.8 during the observation period. This indicates that the level of coupled and coordinated development between green finance and the green transformation of manufacturing has generally progressed from a state of barely coordinated development to moderately coordinated development over the observed period. However, certain provinces remain below the 0.5 threshold, such as Yunnan Province in 2011, Liaoning Province in 2016, and Shaanxi Province, which recorded a value of 0.48. These results suggest that these provinces remain in a state of barely coordinated development.

A broad improvement in coordination is observed after 2021, with rising values recorded for most provinces. This pattern reflects an increasingly close alignment between green finance development and manufacturing green transformation, although the magnitude of improvement differs across provinces. To explore this spatial heterogeneity, the provincial results are aggregated into four geographical regions (eastern, central, western, and northeastern). Figure 3 presents the resulting regional trajectories of coupling coordination.

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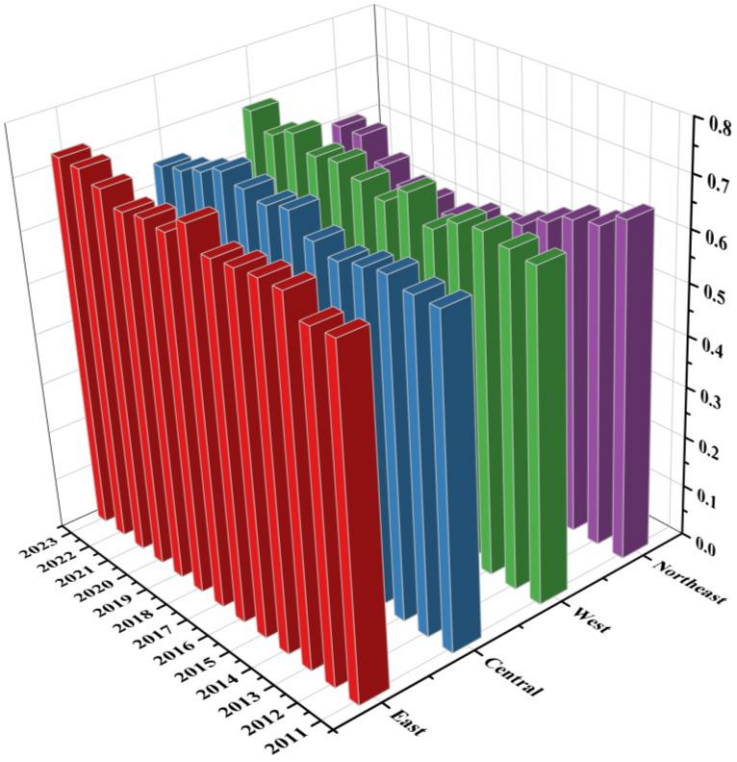


Fig. 3 – Coupling and coordination development trends of the four regions from 2011–2023.
Source: own research.

There are clear regional differences in the coupling coordination levels across the four regions (Figure 3), with all values exceeding 0.5. This indicates that the coupling coordination relationship has generally progressed from a stage of barely coordinated development to primary coordination. However, development remains highly uneven across regions. Specifically, the eastern region presents significantly higher coupling coordination levels than the other three regions do, with an increasing trend observed from 2011–2023. This can be attributed to the region's strong economic foundation, advanced financial market development, and high levels of industrial technological innovation, particularly in the eastern coastal areas, which collectively foster a favourable environment for coupling coordination and form a pattern of positive interaction.

In contrast, the central region experienced an initial increase in coupling coordination, followed by a gradual decline after 2020. This pattern may be explained by the central region's active undertaking of industrial transfers from the east, supported by its strategic location connecting eastern and western China, as well as by policies promoting the rise of the central region. Local governments have also strengthened support for green finance and industrial transformation and upgrading, thereby enhancing coupling coordination. However, after 2020, particularly owing to the impacts of the COVID-19 pandemic and accelerated adjustments in global supply chains, many industries in the central region faced transformation pressures and risks of relocation, contributing to the observed decline.

The western region has demonstrated slow growth in coupling coordination, primarily benefiting from national strategies such as western development and rural revitalisation, which have provided policy preferences for green finance and infrastructure development.

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Nevertheless, the region's relatively weak economic foundation and resource-based industrial structure limit the endogenous driving forces for green transformation, resulting in only modest increases in coupling coordination levels.

In the northeastern region, coupling coordination initially declined but has shown signs of recovery in recent years. The initial decline can be attributed to the high concentration of traditional heavy industries and a relatively narrow industrial structure, which hindered coupling coordination. However, with the implementation of national policies promoting comprehensive revitalisation in Northeast China, there has been increased emphasis on industrial structure adjustment and the exploration of green financial models suited to old industrial bases, including support for equipment renewal and energy-saving transformations. Additionally, progress in the development of emerging industries in some cities has contributed to the gradual rebound in coupling coordination between green finance and the green transformation of manufacturing.

4.2. Interval difference and decomposition

Regional heterogeneity is examined by dividing the provincial sample into four geographical groups: eastern, central, western, and northeastern China. The analysis covers 30 provinces, with Tibet, Hong Kong, Macao, and Taiwan outside the sample. The Dagum Gini coefficient method, which uses formulas (19) to (25), was applied to examine regional disparities and decompose the sources of these differences. The results are presented below.

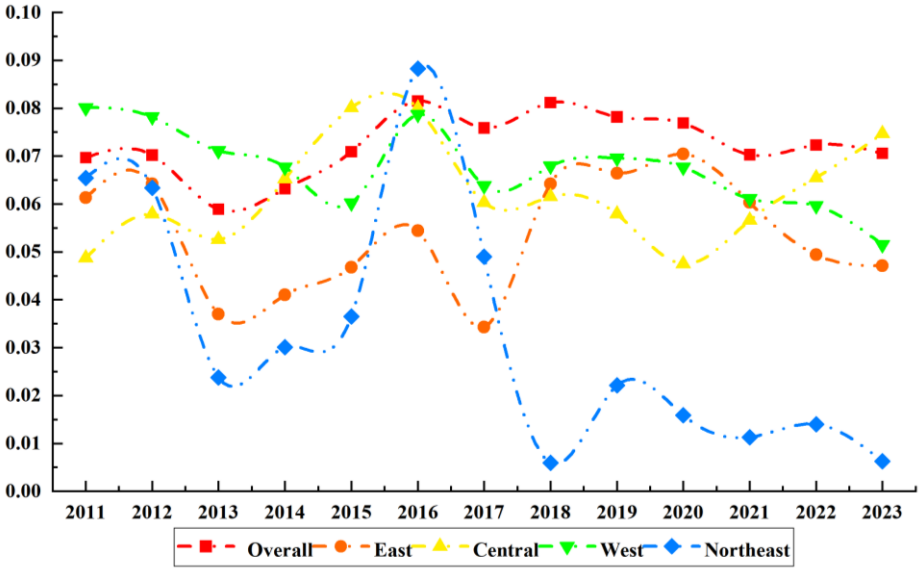


Fig. 4 – Coupling and coordination of the trend of Gini coefficient changes in green finance and green transformation of the manufacturing industry across the country and regions.
Source: own research.

The Dagum Gini estimates in Figure 4 indicate a non-linear evolution of spatial inequality: dispersion in provincial coordination levels rises during the earlier part of the period and subsequently declines. The decline in the later years therefore points to a gradual convergence in coordination levels across provinces, although differences remain evident.

Specifically, the average Gini coefficients for coupling and coordinated development across the four major regions from 2011–2023 follow the pattern west (0.067) > central (0.062) > east

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(0.054) > northeast (0.033). This suggests that the western region experiences relatively severe unevenness in coupling development. The eastern and central regions broadly follow the national pattern of inequality. Northeastern China exhibits a distinct trajectory, with its Gini coefficient declining markedly after 2016 and remaining below the levels recorded for the other regions. The observed decline points to a gradual convergence in coupling coordination levels among northeastern province

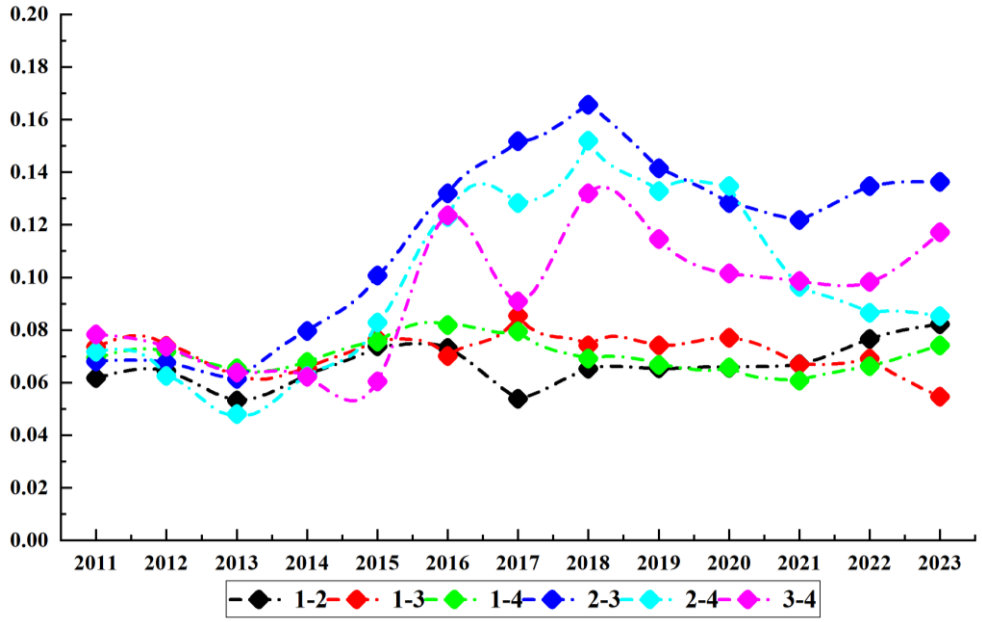


Fig. 5 –Trend of changes in the interregional Gini coefficients for the coupling coordination between green finance and the green transformation of manufacturing. Source: own research. Note: 1-East; 2-Central; 3-West; 4-Northeast

Figure 5 reveals substantial heterogeneity in the evolution of interregional disparities. The East–Central (1–2), East–West (1–3), and West–Northeast (3–4) pairs generally remain at comparatively low levels, although their trajectories fluctuate over time. In contrast, disparities increase markedly for the East–Northeast (1–4) and Central–West (2–3) pairs after 2015, with both reaching their highest levels around 2018. These differences subsequently narrow, particularly for the Central–West pair, whereas the East–Northeast disparity remains relatively pronounced toward the end of the study period.

In contrast, the difference between the central and western regions has reached its largest value, indicating an expanding disparity. This widening difference may be attributed to the central region being in a critical period of industrial transformation and upgrading, with its economic vitality enhanced through the undertaking of industries transferred from the eastern region. In comparison, the western region continues to have a relatively narrow industrial structure characterised by a dependence on resource-based industries, limited marketisation, and insufficient endogenous growth momentum. These factors have resulted in differentiated economic development speeds and varying levels of coupling coordination between the central and western regions.

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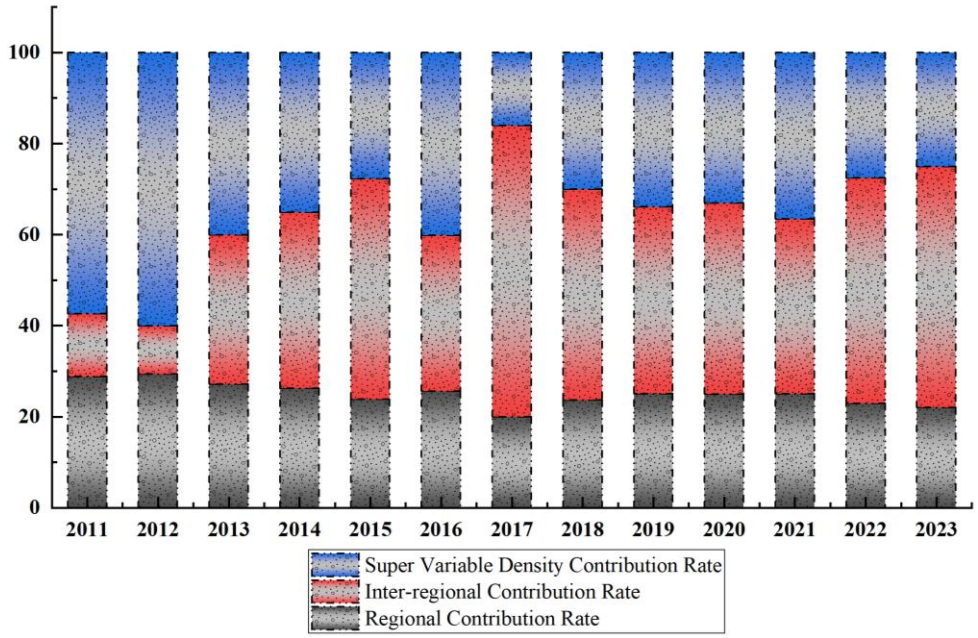


Fig. 6 – Composition of the source of the difference between the Gini coefficients of green and green transformation and the development of manufacturing industries in various regions. Source: own research.

Figure 6 shows a pronounced shift in the composition of spatial inequality over the study period. The share attributable to between-region disparities rises from 13.77% in 2011 to 53.02% in 2023, becoming the dominant component of inequality in coupling coordination across the four regions. The within-region component occupies an intermediate position and varies less markedly than the other two components. By contrast, transvariation intensity follows a downward trajectory, with its contribution falling from 57.35% to 24.98% over the same period.

4.3. Nuclear density estimation analysis

Figure 7(a) illustrates the distribution dynamics of the coupled and coordinated development between green finance and the green transformation of manufacturing at the national level. The movement of the curve's centre reveals that the centre of the distribution curve has continuously shifted to the right, indicating an overall increase in the coupling coordination level between green finance and manufacturing transformation. The height of the main peak initially tends to increase, whereas its width gradually decreases. Towards the end of the observation period, a tail phenomenon emerges, with an increase in the tail width, suggesting that although the coupling coordination development is generally improving nationwide, disparities at the lower end of the distribution remain.

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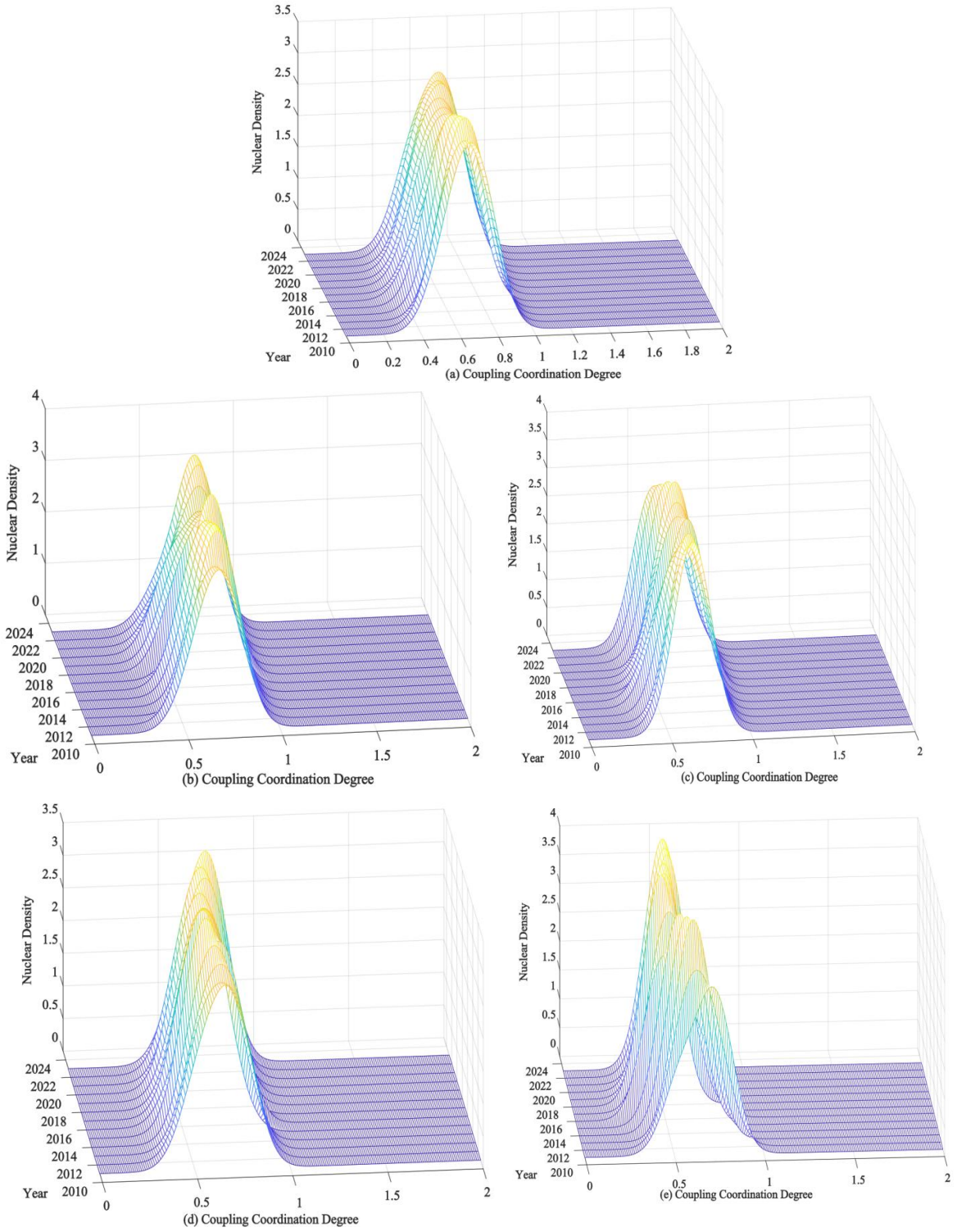


Fig. 7 –Dynamic evolution trends of the level of coupled and coordinated development in the country and four regions from 2011–2023. Source: own research.
Note: a-National; b-East; c-central; d-western; e-Northeast

Figures 7(b), 7(c), 7(d), and 7(e) illustrate the distribution dynamics of the coupled and coordinated development between green finance and the green transformation of manufacturing

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in the four regions. In the eastern region, the centre of the distribution curve shifts to the right, accompanied by a right-tail phenomenon, indicating an overall improvement in the level of coupled and coordinated development. From 2011–2023, the main peak exhibited a "rise–decline–rise" pattern, with the peak width gradually narrowing. This suggests that intraregional disparities are continuously diminishing. Although a tailing phenomenon is present, its extent is decreasing, indicating a narrowing of absolute differences within the region. In the central region, the distribution curve also shifts to the right. The main peak initially rises and then declines, with regional disparities showing a "narrowing–widening–narrowing" pattern, suggesting fluctuating intraregional differences in coupling coordination levels over time. For the western region, the centre of the distribution curve shifts to the right, and the main peak demonstrates a consistent upwards trend, maintaining a single peak without evidence of polarisation. This indicates that the level of coupled and coordinated development between green finance and the green transformation of manufacturing is gradually improving in this region. In the northeastern region, the distribution curve also shifts to the right, with the main peak showing an increasing trend. However, the persistent presence of side peaks indicates regional polarisation, suggesting that the gap between high-level and low-level areas in terms of coupling coordination is widening.

5 DISCUSSION

The empirical results of the study provide important evidence on the systemic interaction between green finance and the green transformation of the manufacturing industry and their joint role in shaping sustainable competitiveness. Unlike previous studies that primarily examine the direct environmental or technological effects of green finance, the present analysis interprets the coupling coordination degree between financial and industrial subsystems as an operational proxy for sustainable competitiveness. This approach enables a more integrated understanding of how financial resource allocation mechanisms and industrial transformation processes jointly contribute to long-term development capacity within a sustainability-oriented economic framework.

The results indicate that the coupling coordination level between green finance and the green transformation of the manufacturing industry increased steadily across Chinese provinces between 2011 and 2023. This trend reflects a gradual strengthening of the alignment between financial support systems and industrial transformation processes, suggesting that green finance is increasingly functioning as a structural driver of sustainability-oriented industrial upgrading rather than merely as a complementary policy instrument.

These findings are consistent with prior empirical research demonstrating that green finance supports technological innovation, improves environmental performance, and promotes structural upgrading in manufacturing systems (Chen et al., 2023; Jiakui et al., 2023; Gao & Ma, 2024). However, the present study extends this literature by demonstrating that these effects operate through a coordinated interaction mechanism between financial and industrial subsystems. In this context, sustainable competitiveness emerges not as a direct outcome of individual policy tools but as the result of systemic alignment between capital allocation efficiency, environmental performance improvement, and industrial restructuring processes.
By interpreting the coupling coordination degree as an empirical representation of sustainable competitiveness, this study contributes to the competitiveness literature, where sustainability-

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oriented competitiveness has often remained conceptually defined but insufficiently operationalised. The results therefore provide empirical support for the argument that sustainable competitiveness should be understood as a dynamic system-level outcome reflecting coordinated development between economic and environmental transformation mechanisms rather than isolated sectoral progress.
A key finding of the analysis concerns the presence of substantial regional disparities in the coupling coordination levels across China. The eastern region consistently demonstrates higher levels of coordinated development than the central, western, and northeastern regions, reflecting differences in financial market maturity, industrial structure upgrading capacity, and technological innovation intensity.

These results confirm earlier research indicating that regions with stronger financial infrastructure and innovation ecosystems exhibit higher levels of green transformation efficiency and environmental performance improvement (Zhang & Wang, 2021; Yue et al., 2024). However, the present study further demonstrates that interregional differences represent the dominant source of inequality in coupling coordination levels, as revealed by the Dagum Gini coefficient decomposition. This finding suggests that structural disparities between regions, rather than variations within regions, constitute the primary constraint on the balanced development of sustainable competitiveness across the national economic system.
The persistence of these spatial differences highlights the importance of institutional coordination capacity and differentiated regional policy frameworks in shaping transformation outcomes. In particular, the results indicate that provinces with stronger integration between financial innovation mechanisms and industrial upgrading strategies are more capable of achieving coordinated sustainability transitions. Conversely, regions characterised by resource-dependent industrial structures and relatively underdeveloped financial systems face greater challenges in achieving effective alignment between financial and industrial subsystems.
Although the empirical analysis focuses on provincial-level data from China, the observed interaction between green finance and manufacturing transformation reflects patterns consistent with international evidence on sustainability-oriented industrial development. Studies conducted in OECD countries demonstrate that green finance instruments, including green bonds and environmental credit mechanisms, play a critical role in facilitating industrial decarbonisation and technological upgrading processes (Sartzetakis, 2021; Liu & Tang, 2022). Similarly, research on European economies shows that financial system development contributes significantly to improving resource allocation efficiency and supporting green innovation diffusion within manufacturing sectors. Sustainability-oriented innovation dynamics have also been observed in Central European economies, where the implementation of environmental principles supports sectoral transformation processes and strengthens the competitiveness of regional economic systems under green transition conditions (Vargova & Matusikova, 2025).

In particular, recent empirical evidence from E.U. countries confirms that digital transformation processes, including the development of e-commerce ecosystems, contribute to achieving sustainability-related development goals and strengthening competitiveness within sustainability transition frameworks (Kwilinski, 2023).

At the same time, the transformation trajectory identified in the Chinese context differs from those observed in many advanced economies due to the stronger role of policy-guided financial coordination mechanisms. Whereas sustainability transitions in the European Union are largely

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driven by market-based financial instruments combined with regulatory frameworks such as the E.U. taxonomy and green investment strategies, China's transformation process reflects a hybrid model integrating state-led financial coordination with market-oriented instruments. This institutional configuration helps explain both the rapid improvement in coupling coordination levels and the persistence of regional disparities identified in the empirical analysis.

Despite these institutional differences, the results confirm that the coordinated interaction between green finance and manufacturing transformation represents a universal mechanism supporting sustainability-oriented competitiveness across both developed and emerging economies. The Chinese experience therefore provides important empirical evidence for understanding how large transition economies can strengthen sustainable competitiveness through integrated financial–industrial policy frameworks.

This study contributes to the emerging literature on sustainable competitiveness by providing an empirical framework capable of capturing the interaction between financial development and industrial transformation processes. Previous research has frequently conceptualised sustainable competitiveness as a multidimensional construct integrating economic performance, environmental sustainability, and institutional quality. However, empirical measurement approaches have remained limited.

By operationalising sustainable competitiveness through the coupling coordination degree between green finance and manufacturing transformation subsystems, this study demonstrates that competitiveness can be interpreted as the outcome of coordinated system-level interactions rather than as a static indicator of economic performance. This interpretation supports the view that sustainability transitions should be analysed as dynamic processes shaped by the interaction between financial systems, technological change, and industrial restructuring mechanisms.

Furthermore, the results highlight that improving the efficiency of green financial resource allocation alone is insufficient to ensure sustainable competitiveness unless it is accompanied by parallel progress in industrial transformation capacity. The formation of sustainability-oriented competitive advantages therefore depends on the synchronisation of financial and industrial development trajectories.

From a policy perspective, the results suggest that strengthening the coordination between green finance systems and manufacturing transformation strategies represents a critical pathway for enhancing sustainable competitiveness. In particular, the findings indicate that improving financial infrastructure in less-developed regions, promoting innovation-oriented financial instruments, and strengthening institutional coordination mechanisms between financial regulators and industrial policy authorities can accelerate transformation processes.

The study demonstrates that the effectiveness of green finance depends not only on the scale of financial resources allocated to environmental objectives but also on the degree of alignment between financial systems and industrial transformation priorities. This insight is particularly relevant for emerging economies seeking to accelerate sustainability transitions while maintaining industrial competitiveness, as well as for advanced economies aiming to strengthen the resilience of their manufacturing sectors under increasingly stringent environmental constraints. The results confirm that coordinated development between green finance and manufacturing transformation constitutes a key mechanism supporting sustainable competitiveness within the global transition towards environmentally sustainable economic systems.

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6 CONCLUSION

On the basis of panel data from 30 provinces in China from 2011–2023, an evaluation index system for green finance and green transformation of the manufacturing industry was constructed. The entropy-weighted TOPSIS method, superefficiency SBM model, improved coupling coordination model, Dagum Gini coefficient decomposition method, and kernel density estimation method were used to explore the level of green finance and green transformation of the manufacturing industry, further calculate the level of coupled and coordinated development between the two, and analyse the differentiation of their development via the Dagum Gini coefficient. Then, the evolution trend of the coupling coordination development level in different regions was analysed, and a three-dimensional kernel density map was produced. The conclusions obtained from the research are as follows:

- The level of green finance and green transformation of the manufacturing industry in the 30 provinces of China gradually increased from 2011 to 2023.
- The level of coupled and coordinated development between green finance and manufacturing green transformation also showed a growth trend, with the coupling coordination levels in the eastern, central, western and northeast regions increasing annually.
- The Gini coefficient for the coupled and coordinated development of green finance and green transformation of the manufacturing industry initially increased but then decreased, with average values across the four regions showing the following trend: west (0.067) > central (0.062) > east (0.054) > northeast (0.033).
- The proportions of intraregional, interregional, and transvariation intensity differences fluctuated over time, with interregional differences being the main source of coupling coordination disparities between green finance and green transformation of the manufacturing industry in China's four major economic regions.
- The coupled and coordinated development levels of green finance and manufacturing green transformation showed an upwards trend both nationally and in the four major regions, although with some fluctuations. Among these, no polarisation trends were observed in the eastern, central, or western regions, whereas the northeast region showed a clear polarisation trend.

To improve the level of coupled and coordinated development between green finance and the green transformation of manufacturing, the following countermeasures and suggestions are further proposed:

1. In addition to innovation-driven development, green financial products and green financial service methods should be actively innovated, a multilevel green financial service system should be built, and targeted support for the green and low-carbon transformation and development of manufacturing should be provided. First, with innovation as the core driving force, methods for innovating green financial products and services should be actively explored, diversified green financial derivatives should be developed, and a comprehensive green financial service system that includes green credit, green funds, green bonds, and green insurance should be built. Second, they should adhere to the integration of education, science and technology, and talent; strengthen talent cultivation and social cooperation; deepen multiparty collaboration; and enhance core innovation and competitiveness. In-depth cooperation between financial institutions and governments, universities, and social organisations should be strengthened to improve the green technology innovation capabilities of the manufacturing industry; resource allocation efficiency through policy guidance, market cultivation, technological innovation, talent introduction, and results transformation should be

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optimised; precise support throughout the entire process of green transformation and development in the manufacturing industry should be provided; and the vitality of green transformation and development should be continuously injected.

2. A comprehensive policy support system should be built, policy orientation should be optimised, consistency, differentiation, and effectiveness of policy measures should be ensured, and policy coordination should be strengthened to enhance the coupling between green finance and the green transformation of the manufacturing industry. First, it is essential to fully understand the inherent integration of green finance with the green transformation of the manufacturing industry. In line with the core objectives of simultaneously promoting pollution reduction, green expansion, and efficiency improvement, support for green finance within manufacturing transformation and development should be increased. Financial institutions should be guided to focus on green and efficient production sectors within manufacturing while strengthening the coordination and alignment between green finance policies and manufacturing transformation and development policies to ensure a coherent direction. Second, attention should be given to regional differences in policy demands, with policies and regulations formulated according to local economic conditions, industrial structures, and development statuses, targeting key areas and improving the overall policy system accordingly. Finally, policy incentives and constraint mechanisms for green finance and the green transformation of the manufacturing industry should be established and enhanced. This includes comprehensively employing fiscal measures, taxes, subsidies, and rewards to create an intelligent and efficient dynamic evaluation and risk control mechanism, thereby ensuring the effectiveness of policy formulation and implementation.

3. The system and mechanisms of the green finance market should be improved, and a favourable market environment should be created. On the one hand, it is necessary to fully leverage the decisive role of the market in resource allocation, optimise the flow of factors, and guide resources towards green, intelligent, and high-end production sectors. Efforts should focus on establishing markets for carbon emission rights and green bonds, building a multilevel and broad green financial product market system, and ensuring smooth capital flow channels. On the other hand, market-oriented incentive and constraint mechanisms should be established and improved to guide financial institutions, government departments, and social organisations to actively participate in the entire green production process, achieving mutually beneficial outcomes for both the economy and the environment. In addition, market supervision and management should be strengthened to build a scientific and effective green financial market system. This includes enhancing the oversight of both the financial and manufacturing markets; establishing a shared information platform for green finance and manufacturing transformation and development; ensuring the openness and transparency of market information; and creating a fair, open, competitive, and orderly market environment. These measures enhance the confidence of market entities and promote the sustainable development of both the green finance market and the manufacturing green transformation market.

Despite the contributions of this study, several limitations should be acknowledged. First, the analysis is conducted at the provincial level, which provides a comprehensive macro-level perspective but may not fully capture micro-level dynamics of firms and industries. Second, the study focuses on the Chinese context, which may limit the generalisability of the findings to other institutional and economic environments. Future research could extend this study in several directions. First, incorporating firm-level or industry-level data could provide deeper insights into the micro-foundations of sustainable competitiveness. Second, comparative cross-country analyses may help to validate the applicability of the findings in different institutional

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settings. Third, future studies may explore dynamic and spatial modelling approaches to better capture the evolving, interconnected nature of green finance and industrial transformation.

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