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PARADIGM SHIFT IN CHINESE ENTREPRENEURSHIP UNDER THE GUIDANCE OF THE 15TH FIVE-YEAR PLAN: FROM MARKET-DRIVEN TO MISSION-DRIVEN

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Abstract: With the introduction of the 15th Five-Year Plan (FYP), China has set forth new expectations for entrepreneurship, signaling a shift beyond a purely market-driven orientation towards a more profound, mission-driven approach. Historically, market-driven entrepreneurship has played an indispensable role in promoting economic development and enhancing innovative capacity. However, in the new era, the limitations of this model have become increasingly apparent, necessitating a paradigm shift from market-driven to mission-driven entrepreneurship.The 15th FYP emphasizes that entrepreneurs should not only pursue economic returns but also undertake multiple missions, including advancing technological innovation, achieving green development, and safeguarding national security. This transformation represents a deepening of the understanding of the entrepreneur's role and an enrichment of the connotation of entrepreneursh ip. Therefore, this study aims to explore the new connotation, characteristics, and formation mechanisms of mission-driven entrepreneurship, analyzing its practical pathways within the context of the 15th FYP. The research objective is to construct an analytical framework to explain the dimensions and driving factors of mission-driven entrepreneurship. Through case studies, it will reveal how this spirit is embodied in actual business operations. The theoretical contribution of this research lies in enriching existing theories of entrepreneurship, particularly their application in the Chinese context, and providing theoretical support for understanding new trends in entrepreneurial spirit.Statistics show that entrepreneurship is crucial for enhancing a nation's innovative capacity. For instance, research indicates that mission-driven entrepreneurs are more inclined to invest in long-term R&D projects, which significantly drives technological innovation and industrial upgrading. Furthermore, amidst intensified global economic integration and competition, the transformation of entrepreneurship is of great significance for enhancing national competitiveness.Regarding core propositions, this study will explore the following key issues: first, the new requirements for entrepreneurship and their substance as proposed by the 15th FYP; second, the necessity of the paradigm shift from market-driven to mission-driven; and third, how to construct an analytical framework for mission-driven entrepreneurship and the theoretical and practical implications of this framework. Through an in-depth analysis of these issues, this study will provide a systematic understanding of this entrepreneurial transformation and offer policy recommendations.
Keywords: 15th Five-Year Plan (15th FYP); Entrepreneurship; Corporate innovation; Market-driven; High-quality development; New quality productive forces

1 INTRODUCTION

Market-driven entrepreneurship has historically served as a pivotal engine for economic growth, propelling the rapid development of social productive forces by stimulating market vitality and innovation momentum. However, with the deepening of economic globalization and profound structural changes within the domestic economy, the limitations of this paradigm have become increasingly palpable. Empirical evidence indicates that corporate behavior driven solely by the pursuit of economic metrics has, to a certain extent, resulted in resource mismatch and environmental degradation. Furthermore, in the face of intensifying international competition and external uncertainties, traditional entrepreneurship often falls short in terms of strategic vision and adaptive capacity. The promulgation of the "15th Five-Year Plan" signals a strategic paradigm shift in national development: a transition from a purely "market-driven" orientation to a "mission-driven" one. This transformation necessitates that entrepreneurs possess not only acute market insight but also a profound sense of mission to serve national strategies and shoulder social responsibilities. In this context, the role of the entrepreneur is evolving from a rational "economic actor" to a "strategic executor," requiring the alignment of individual interests with national imperatives to achieve high-quality development. Research suggests that mission-driven entrepreneurship is better positioned to meet national strategic demands, driving structural optimization and sustainable development through technological innovation and industrial upgrading. Guided by the "15th Five-Year Plan," entrepreneurs are endowed with new missions, such as fostering self-reliance and self-strengthening in science and technology, promoting green transition, and safeguarding national security. These mandates demand broader horizons, long-term vision, and robust strategic execution capabilities. In this new era, the evolution of the entrepreneurial role is reflected not only at the strategic level but also in the redefinition of the entrepreneurial spirit itself. Unlike traditional entrepreneurship, which emphasizes individual heroism and market competition, the new paradigm prioritizes collaboration, social value, and long-range planning. This shift is not only consistent with national strategic guidelines but is also an inevitable choice for adapting to economic globalization and social progress. In summary, the research problem is intrinsically linked to the contemporary context: the limitations of market-driven entrepreneurship call for a transformation of the entrepreneurial role, while the "15th Five-Year Plan" provides a clear path and objective for this transition. As strategic executors, entrepreneurs must continuously adapt to and lead new trends in economic development[1].

Against this strategic backdrop, investigating mission-driven entrepreneurship holds significant theoretical and practical value. Theoretically, constructing an analytical framework for mission-driven entrepreneurship deepens the understanding of the essence of entrepreneurship, particularly within the context of Chinese characteristics. By systematically analyzing its dimensions and structure, this study enriches the theoretical system of Chinese entrepreneurship, providing a foundation for future research. Practically, this study offers a reference for policy formulation and corporate strategy. Responding to the national deployment of "strengthening the principal position of enterprises in innovation," this research suggests how policy guidance and institutional design can stimulate the active role of entrepreneurs in innovation-driven development. By analyzing practices of mission fulfillment, it provides strategic guidance for corporate transformation and upgrading, facilitating the shift from market-driven to mission-driven models for sustainable development. Policy-wise, the value of this study lies in its in-depth interpretation of the entrepreneurial role shift under the "15th Five-Year Plan," offering theoretical support for government departments to formulate policies supporting corporate innovation. Clarifying the central role of entrepreneurs in technological innovation and their key function in implementing national strategies helps form a more effective policy environment, fostering synergistic development among enterprises, society, and the state. Additionally, through case studies, this research showcases successful practices in mission-driven strategies across different industries and scales, offering replicable models and paths. Comparative analysis reveals the challenges and opportunities inherent in this transition, providing empirical evidence for entrepreneurial strategic decision-making. In conclusion, this study not only expands the theoretical domain of entrepreneurship but also provides concrete operational suggestions and development directions at practical and policy levels, holding substantial theoretical and realistic significance for promoting the transformation and upgrading of entrepreneurship in China.This study aims to construct a theoretical framework and reveal the new requirements imposed on entrepreneurship by the "15th Five-Year Plan." Methodologically, this study employs textual analysis to meticulously interpret the text of the "15th Five-Year Plan," uncovering its role expectations and spiritual requirements for entrepreneurs. Furthermore, textual analysis is applied to analyze actual corporate cases to understand behavioral patterns and strategic choices in different contexts. The case study method focuses on the practical exploration of specific entrepreneurs; by selecting cases that are typical in terms of mission-driven orientation, this study aims to distill key factors for successful transformation and the challenges faced.

The structure of the remainder of this paper is organized as follows: First, the study clarifies the core concepts and dimensions of mission-driven entrepreneurship, defining the operationalization of "mission-driven" and distinguishing its boundaries from "market-driven" and "social-driven" models. On this basis, a multi-dimensional constitutive model is constructed, comprising the dimensions of strategic mission, organizational capability, and value creation. Next, the study explores the driving mechanisms and implementation paths, analyzing the roles of policy incentive mechanisms, entrepreneurial cognitive reconstruction, and organizational adaptation mechanisms. These analyses facilitate an understanding of the internal logic and external conditions of the transformation of entrepreneurship. In the specific analysis of the "15th Five-Year Plan" text, the study discusses the reshaping of the entrepreneurial role from the level of overall goals, and deeply interprets key task clauses, as well as relevant policy tools and support systems. In the case study section, the study selects two enterprises—one from the integrated circuit industry and another from the new energy system construction sector—to analyze their practices in responding to national strategies, adjusting organizational structures, determining R&D investments, and coping with market changes. Finally, the study discusses the challenges, dynamics, and institutional compatibility of the paradigm shift, proposing suggestions for optimizing the institutional environment, summarizing major research findings, and discussing theoretical contributions, policy implications, research limitations, and future prospects. Through these research methods and structural arrangements, this study aims to provide a comprehensive analytical perspective to deeply understand the transformation and development of mission-driven entrepreneurship under the guidance of the "15th Five-Year Plan."

2 FROM MARKET-DRIVEN TO MISSION-DRIVEN: THEORETICAL EVOLUTION AND LITERATURE REVIEW

2.1 Review of Research Related to the "15th Five-Year Plan"

Against the backdrop of the "15th Five-Year Plan," green transition and secure development have emerged as critical imperatives for corporate behavioral adjustment. Research indicates that as key entities in the implementation of national strategies, enterprises are undergoing a significant transformation in their behavioral patterns, a phenomenon that has garnered widespread academic attention. The following is a review of relevant literature.

In terms of green transition, research focuses on how enterprises respond to the national call for ecological civilization construction. Scholars have analyzed practical cases of corporate engagement in green technological innovation, cleaner production, and the circular economy. Statistical data reveals that since the implementation of the "15th Five-Year

Plan," the pace of corporate green transition has accelerated, with a large number of firms strategically laying out green industries to promote the optimization and upgrading of the industrial structure. However, enterprises face numerous challenges during this transition, such as technical barriers, financial constraints, and market risks.In the domain of secure development, research centers on how enterprises construct safety management systems to enhance the stability of industrial and supply chains. Findings suggest that enterprises play the role of "guardians of resilience" in the construction of the national security barrier. Under policy guidance, firms are required to not only focus on economic benefits but also strengthen their contributions to national security. For instance, some enterprises have enhanced their capacity to withstand external risks through strategies such as supply chain diversification and localization of production.

Current academic research has achieved preliminary results in the following aspects:

First, academic interpretations of the role positioning of enterprises within the planning text. These studies show that the status of enterprises in national strategy is becoming increasingly prominent. The Plan explicitly defines enterprises as the principal entities of technological innovation and key forces driving green transition and secure development. This role positioning provides a clear direction for corporate behavior.

Second, research progress on "self-reliance and self-strengthening in science and technology" and the enterprise as the main body of innovation[2]. This stream of literature reveals how firms enhance core competitiveness through technological innovation. For example, some enterprises have achieved breakthroughs in key core technologies through cooperation with national laboratories and Industry-University-Research (IUR) synergy.

Finally, preliminary discussions on the impact of green transition and secure development on corporate behavior. These studies point out the internal and external challenges faced by firms. The uncertainty of the external environment and the complexity of internal management impose higher requirements on enterprises. In the process of green transition, firms need not only technological innovation but also innovation in business models and organizational structures.

Despite these achievements, a gap remains in the research regarding the "Plan-Enterprise-Spirit" linkage mechanism. Future research should pay greater attention to how enterprises implement national strategies in actual operations and how to drive the transformation of corporate behavior through institutional innovation.

2.2 The Traditional Theoretical Trajectory of Entrepreneurship

The concept of market-driven entrepreneurship primarily revolves around the individual's ability to identify and exploit market opportunities. Within this traditional theoretical lineage, Joseph Schumpeter viewed the entrepreneur as the primary agent of innovation, emphasizing their role in disrupting old equilibriums and driving technological progress and industrial change (often referred to as creative destruction). Israel Kirzner, on the other hand, focused on the function of entrepreneurial alertness and opportunity discovery, arguing that entrepreneurs achieve efficient resource allocation through information processing and decision-making in the market process.

The characteristics of the market-driven paradigm are manifested in entrepreneurial behaviors that are largely guided by market signals and profit motives, with performance typically measured by the maximization of economic benefits. Research shows that under this paradigm, entrepreneurs have promoted the development and prosperity of the market economy through continuous innovation and risk-taking.In the Chinese context, research on the evolution of entrepreneurship emphasizes integration with national conditions. Since the Reform and Opening Up, market-driven entrepreneurship has played a vital role in propelling China's economic development. However, with the deepening of the market economy, the market-driven paradigm has also exposed certain limitations, such as excessive competition and resource misallocation.Regarding the performance of the market-driven paradigm, statistics indicate that entrepreneurship has achieved significant results in promoting employment, improving production efficiency, and driving technological innovation. Conversely, problems persist, such as entrepreneurs focusing excessively on short-term interests (myopia) while neglecting social responsibilities.Furthermore, the connotation of entrepreneurship under the market-driven paradigm emphasizes individualism and free competition. In contemporary China, however, with the adjustment of national strategies, entrepreneurship is gradually transitioning toward a mission-driven model, which places greater emphasis on serving the overall situation of national development and realizing social value.

In summary, while entrepreneurship under the traditional theoretical trajectory—with market drivers at its core—has promoted economic development to a certain extent, its connotation and performance are now facing new challenges and a demand for transformation[3].

Given the complexities inherent in the digital economy, establishing robust mechanisms for data element circulation is paramount. However, current practices are often hindered by significant theoretical and practical obstacles. To address these issues systematically, this study develops a comprehensive research structure grounded in high-level national strategic directives. Grounded in the spirit of the 4th Plenary Session of the 20th CPC Central Committee and the deployment of the "15th Five-Year Plan," we propose a holistic approach to designing governance rules. The following research framework (Figure 1) visually synthesizes the logical flow of this study, mapping the trajectory from macro-level guiding ideologies and identified challenges to specific governance goals and the tiered construction of concrete platform rules.

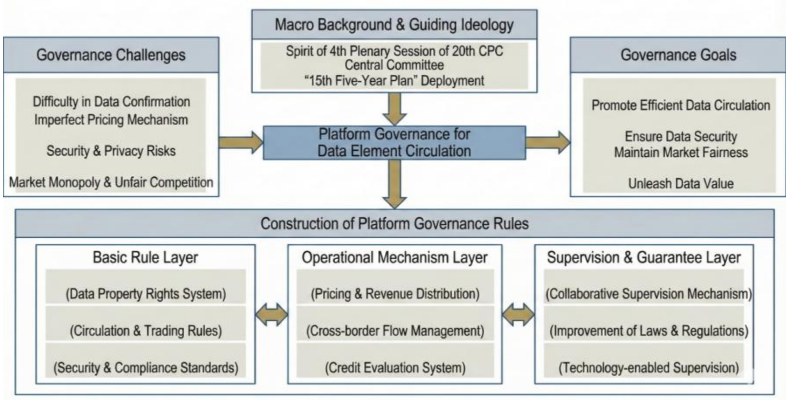

Figure 1 Research Framework for Platform Governance Rules of Data Element Circulation in the Digital Economy

This diagram illustrates the systemic approach adopted in this study. The framework is anchored at the top by the "Macro Background & Guiding Ideology," providing the strategic context derived from key national policies. This guidance directs the central focus on "Platform Governance for Data Element Circulation." The framework explicitly bridges the gap between current "Governance Challenges"—such as difficulties in data confirmation and security risks—shown on the left, and the desired "Governance Goals"—including efficient circulation and market fairness—shown on the right[4]. The core contribution is delineated in the bottom section, "Construction of Platform Governance Rules," which proposes a three-layered governance architecture: a "Basic Rule Layer" for foundational institutions, an "Operational Mechanism Layer" for managing transactions and flows, and a "Supervision & Guarantee Layer" to ensure enforcement and compliance through regulatory and technological means.

2.3 Frontier Exploration of Mission-Driven Entrepreneurship

In existing literature, research regarding the "Plan-Enterprise-Spirit" linkage mechanism remains in an exploratory stage. Although the "15th Five-Year Plan" imposes new requirements on entrepreneurship, the question of how to integrate national strategies with corporate practice—and subsequently internalize them into the entrepreneurial spirit—remains a subject necessitating urgent and in-depth investigation.Studies on social entrepreneurship, Benefit Corporations (B-Corps), and purpose-driven organizations offer fresh perspectives for understanding mission-driven entrepreneurship. Research indicates that social entrepreneurship, as an emerging corporate form, emphasizes that firms must pursue not only economic interests but also social and environmental benefits. B-Corps ensure comprehensive responsibility to stakeholders through legal structures, while purpose-driven organizations prioritize social purpose over profit maximization. These studies provide a theoretical basis for understanding how entrepreneurs can respond to national strategies and shoulder social responsibilities while pursuing economic efficiency.Literature regarding national strategy embedding and entrepreneurial responsibility reconstruction points out that in the new era, the entrepreneur's role is no longer merely that of a primary economic agent, but that of an executor and promoter of national strategies. In this process, the reconstruction of responsibility is paramount; entrepreneurs must transition from the traditional role of a rational "economic actor" to that of a "strategic executor" with a broad strategic vision.However, a significant gap persists in the research on the "Plan-Enterprise-Spirit" linkage mechanism. Specifically, a systematic theoretical framework has yet to be formed regarding how to effectively translate national strategies into an entrepreneur's internal mission drive, and how this translation process impacts corporate behavior and performance. Furthermore, at the policy level, existing research rarely touches upon how to construct an institutional environment that supports mission-driven entrepreneurship or how to guide entrepreneurial behavior through policy tools[5].

Statistical evidence suggests that with the deepening implementation of the "15th Five-Year Plan," an increasing number of enterprises are beginning to value the construction of mission-driven entrepreneurship. Nevertheless, the specific challenges and successful experiences encountered by these firms in practice, as well as how to elevate these experiences into theories with universal guiding significance, require further study. Therefore, exploring frontier issues in mission-driven entrepreneurship not only helps enrich relevant theoretical systems but also makes it possible to provide practical guidance for policymakers and enterprises.

2.4 Institutional Context: Construction of a Unified National Market

The construction of a unified national market serves as a foundational project for building a new development pattern with domestic circulation as the mainstay. With the deepening advancement of the unified national market, various institutional barriers are being progressively dismantled. This effectively facilitates the free flow and efficient allocation of factors such as commodities, services, and technology on a nationwide scale, thereby promoting the continuous expansion of domestic demand and the upgrading of domestic market forms.By standardizing market competition screening, encouraging technological innovation, and promoting consumption upgrading, the state fosters the agglomeration of economic factors toward high-efficiency and innovative industries. This further enhances the dynamic adaptability of the supply system to domestic demand, gradually forming a virtuous cycle where supply and demand mutually reinforce each other, and production and sales flow smoothly. On this basis, the resilience and vitality of the domestic circulation (internal cycle) are continuously strengthened[6]. This not only expands the strategic space for China's economic development but also lays a solid foundation for enhancing international competitiveness and coping with global uncertainties.Looking ahead, the in-depth advancement of the unified national market will further unleash domestic demand potential and enhance the efficacy of supply-demand linkages, injecting enduring momentum into high-quality economic development. Market integration promotes consumption upgrading and industrial modernization, driving robust growth in the domestic demand market. According to annual data published by the National Bureau of Statistics (as shown in Figure 2), total domestic consumption has witnessed sustained growth, rising from 28.66 trillion RMB in 2015 to 48.33 trillion RMB in 2024.

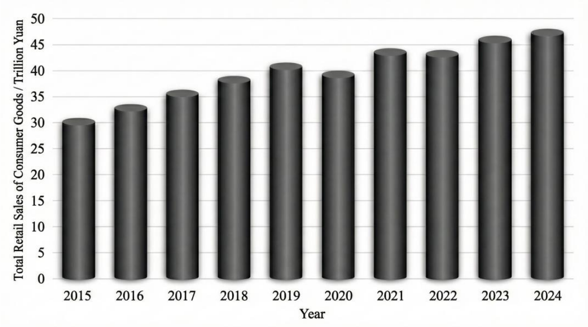

Figure 2 Total Retail Sales of Consumer Goods (2015–2024)

3 CONSTRUCTION OF THE THEORETICAL FRAMEWORK: DIMENSIONAL ANALYSIS OF MISSION-DRIVEN ENTREPRENEURSHIP

3.1 Resource Support for the Innovation Ecosystem: The Mechanism by Which Patient Capital Empowers New Quality Productive Forces

As China enters the "15th Five-Year Plan" period, Chinese modernization is advancing into a stage of in-depth development. The new round of technological revolution and industrial transformation is deepening, and global industrial and supply chains are accelerating their restructuring, exhibiting multi-dimensional trends toward localization, regionalization, and diversification. Chinese enterprises are transitioning from participants in low-end processing to important front-runners in high-end manufacturing and technological innovation. This shift imposes higher requirements on the structure of capital supply. As New Quality Productive Forces gradually become the core support for constructing national competitive advantages, financial capital must undergo a systemic transformation from a short-term arbitrage model to a long-term value orientation[7].

In this context, "patient capital" is regarded as a vital financial force capable of breaking through the short-term profit-seeking limitations of traditional capital and effectively supporting new quality productive forces. By comparison, "impatient capital" represents an acute manifestation of traditional capital; its allocation decisions prioritize financial returns and risk avoidance, thereby compressing the willingness to invest in high-risk, long-cycle projects such as R&D. Consequently, this suppresses the formation of endogenous corporate innovation capabilities and the stable evolution of technological progress paths to a certain extent.

In sharp contrast, patient capital possesses three key characteristics:Extensibility of Investment Horizon: It emphasizes the long-term nature of investment, refusing to treat short-term market fluctuations as exit signals[8]. Instead, it anchors itself to the enterprise's long-term strategic goals and innovation potential.Higher Risk Tolerance: It exhibits a particular preference for "hard-core" technology and disruptive innovation fields characterized by high market risks and long R&D cycles.Multi-dimensional Value Orientation: Beyond economic returns, it simultaneously embeds an evaluation system for market environment and social performance. By constructing a new mechanism of diversified equity investment and financing that matches the entire industrial and supply chain ecosystem, it deeply empowers the structural growth of enterprises.Under the guidance of the "15th Five-Year Plan" strategic goals, patient capital will become a key variable supporting private enterprises in accelerating digital-intelligent transformation and consolidating their technological foundations. It plays a significant role in elevating the participation level of enterprises in global value chains and cultivating world-class clusters of advanced manufacturing and high-end services (Figure 3).

In summary, the rise of patient capital not only provides the material basis for innovation but also calls for a new type of entrepreneurship that can balance long-term benefits with social responsibilities, setting the stage for the mission-driven dimensions discussed below.

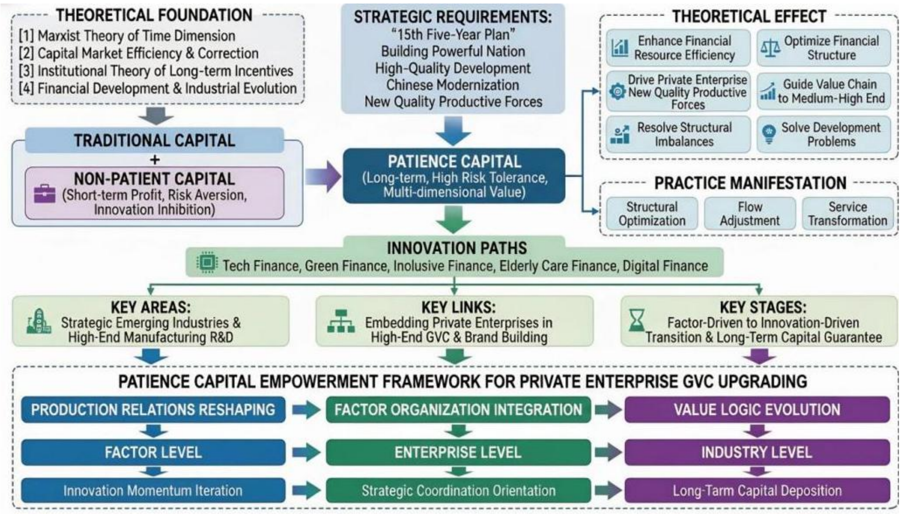

Figure 3 Connotation, Logic, and Pathways of Patient Capital Empowering the Global Value Chain Upgrading of Private Enterprises during the "15th Five-Year Plan" Period

3.2 The Context for Patient Capital Facilitating the Upgrading of Private Enterprises in Global Value Chains during the "15th Five-Year Plan"

The development of private enterprises constitutes a pivotal force in advancing Chinese modernization. Elevating their status and expanding their functions within the Global Value Chain (GVC) is becoming a critical pathway for enhancing national competitive advantages during the "15th Five-Year Plan" period. However, a stark mismatch exists between the financial support private enterprises receive from the capital market and their strategic status in the national economy and industrial development. Simultaneously, a structural contradiction persists between the long-term investment required for the industrial upgrading of private enterprises and the preference of traditional capital for rapid returns. This misalignment has long constrained private enterprises from ascending to the medium-to-high end of the GVC[7].

As a financial modality distinct from traditional capital, patient capital emphasizes long-term value creation. Through its stable investment mechanisms and value-added orientation, it effectively supports private enterprises in achieving sustained breakthroughs in R&D investment, technological accumulation, and brand building. Patient capital promotes the upgrading of private enterprises' value chains from multiple dimensions: macro-level scale expansion and quality improvement, meso-level regional synergy and industrial optimization, and micro-level technological innovation and global expansion. It provides solid capital support and institutional guarantees for embedding firms into the high-value-added links of the GVC.

Supported by various forms of medium-to-long-term capital, China's private enterprises have achieved significant scale and occupy a vital position in the national economy.

First, the scale of private enterprises serves as the foundation for market dominance. Data indicates a powerful momentum of expansion and resource carrying capacity:

The proportion of private enterprises in the total number of enterprises in China increased from 79.4% in 2012 to 92.3% in 2023, reaching 53 million entities.

The total operating revenue of the Top 500 Private Enterprises grew from 10.58 trillion RMB in 2012 to 41.91 trillion RMB in 2023.

The share of private enterprise imports and exports in China's total foreign trade value rose from 42.7% in 2019 to 55.5% in 2024 (Figure 4).

This expansion reflects the enhancement of the overall strength of private enterprises, laying a solid material foundation for acquiring larger market shares and stronger bargaining power in the GVC.

Second, the focus is on elevating development quality to create conditions for embedding into the high end of the value chain. Patient capital highlights a long-term value orientation, guiding private enterprises to transition toward high technology and high efficiency. It facilitates their climb toward the high end of the GVC, such as advanced manufacturing and R&D design[8].

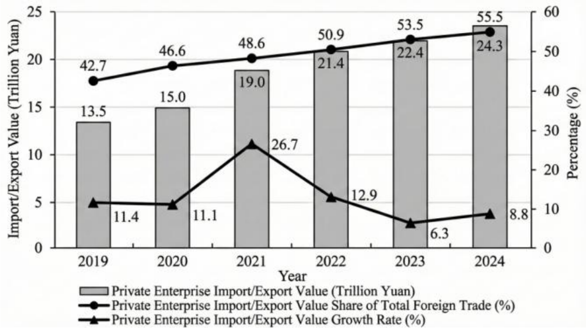

Figure 4 International Trade Participation of Chinese Private Enterprises (2019–2024)

Mission-Driven Entrepreneurship, as an emerging corporate development philosophy, centers on the tight integration of the entrepreneur's value commitment with national strategic orientation[9]. Here, this study first provides an operational definition of "mission-driven" and delineates its boundaries from "market-driven" and "social-driven" models."Mission-driven" refers to a paradigm where entrepreneurs, while adhering to national strategic guidance, integrate corporate development goals with national interests and social responsibilities to form a distinct value commitment. This commitment subsequently guides corporate decision-making and resource allocation. This driving mode transcends the traditional pursuit of profit maximization, emphasizing the unification of social benefits and national interests alongside the creation of economic value.Compared with the "Market-Driven" model, the mission-driven approach places greater emphasis on the entrepreneur's strategic vision and sense of responsibility[10].

Market-driven entrepreneurs typically base decisions on market signals and profit motives.

Mission-driven entrepreneurs, conversely, incorporate national strategic considerations on top of market mechanisms, pursuing long-term value and social contribution.

For example, in the face of the national strategy of "self-reliance and self-strengthening in science and technology," mission-driven entrepreneurs focus not only on market opportunities but are also devoted to achieving breakthroughs in key core technologies to support the nation's technological progress.

In the dimension of the "Social-Driven" model, mission-driven entrepreneurship also exhibits significant differences.Social-driven entrepreneurs primarily act in response to social problems and public needs.Mission-driven entrepreneurs go a step further by aligning corporate goals with national strategies, achieving a dual enhancement of economic and social benefits[11]. For instance, during the construction of a "Beautiful China," mission-driven entrepreneurs are not merely interested in the market potential of environmental products; they are committed to driving the green transition and promoting ecological civilization construction.

Research indicates that mission-driven entrepreneurship manifests unique characteristics in terms of organizational capability, value creation, and driving mechanisms:

Organizational Capability: These entrepreneurs prioritize the cultivation of capabilities for tackling key core technologies and constructing new industrial systems[12].

Value Creation: They pursue a "Triple Bottom Line" comprising economic performance, social benefits, and national interests.Driving Mechanisms: The transformation toward mission-driven entrepreneurship is propelled by the interplay of policy incentive mechanisms, entrepreneurial cognitive reconstruction, and organizational adaptation mechanisms.

In summary, the definition of mission-driven entrepreneurship embodies not only the elevation of the entrepreneur's individual value pursuit but also the manifestation of responsibility under national strategic guidance. By clarifying its boundaries with market-driven and social-driven models, this section lays the theoretical foundation for the subsequent exploration of its dimensional constitution and implementation paths[13].

3.3 Multi-Dimensional Constitutive Model

Within the dimensional analysis of mission-driven entrepreneurship, the value creation dimension constitutes one of the core elements. This dimension emphasizes a comprehensive value creation mode characterized by a "Triple Bottom Line," which balances the realization of social benefits and national interests while pursuing economic performance.

First, Economic Performance is the foundation for corporate survival and development, as well as a vital indicator of entrepreneurship. Under the mission-driven framework, entrepreneurs seek not merely profit maximization but focus on achieving sustainable development through innovation and efficiency improvements. Research indicates that long-term-oriented corporate strategies are more conducive to maintaining competitive advantages, thereby creating stable economic returns for shareholders, employees, and customers.

Second, Social Benefits are an integral component of mission-driven entrepreneurship. This involves environmental protection, the fulfillment of social responsibilities (CSR), and contributions to community development during corporate operations[13]. For instance, statistics show that by implementing green production processes and environmental measures, enterprises can not only reduce negative environmental impacts but also enhance corporate image and strengthen consumer brand loyalty.

Third, National Interests represent another crucial dimension of the entrepreneurial mission. At this level, entrepreneurs must actively respond to national strategies, drive breakthroughs in key core technologies, participate in major national science and technology projects, and assist in constructing the national security system. Such enterprises often gain advantages in resource allocation and market access under the support of national policies, achieving a benign interaction between corporate and national development.Specifically, the multi-dimensional constitutive model can be analyzed from the following three aspects:

Strategic Mission Dimension: Entrepreneurs must integrate national strategic orientation into the corporate mission. Guided by goals such as "self-reliance and self-strengthening in science and technology," "Beautiful China," and "national security," they establish long-term development objectives. In this dimension, entrepreneurial decision-making should revolve around how to embody the national will through corporate activities.

Organizational Capability Dimension: Enterprises must possess the capability to tackle key core technologies and construct a capability structure adapted to the new industrial system. This requires entrepreneurs to make continuous investments and optimizations in organizational architecture, talent cultivation, and technological innovation to ensure the enterprise maintains a leading position in fierce market competition[14].

Value Creation Dimension: While pursuing economic benefits, enterprises must emphasize the realization of social benefits and national interests. This requires entrepreneurs to comprehensively consider the balance of the "Triple Bottom Line" in business model design, resource allocation, and product development to achieve sustainable development.

In summary, the dimensional analysis of mission-driven entrepreneurship requires not only success in economic performance but also emphasizes contributions to social benefits and national interests[15]. This multi-dimensional constitutive model provides a clear development direction for entrepreneurs and offers a theoretical basis for policymakers to support corporate transformation. Although traditional market-driven entrepreneurship effectively promoted the enhancement of innovation capabilities and economic growth in historical stages, the limitations of its singular pursuit of economic returns have become increasingly prominent in the face of complex challenges in the new era.

The proposal of the "15th Five-Year Plan" serves not only as macro-guidance at the national strategic level but also profoundly constitutes the external institutional environment for reshaping Chinese entrepreneurship. It explicitly requires entrepreneurs to transcend traditional business logic and actively shoulder multiple strategic missions, such as driving technological innovation, realizing green development, and safeguarding national security[16]. To systematically and intuitively analyze this profound process of paradigm shift—and to clarify the core connotation, key dimensions, and internal driving mechanisms of entrepreneurship in the new era—this study constructs a comprehensive analytical framework. This framework aims to elucidate how Chinese entrepreneurship achieves a fundamental leap from "market-driven" to "mission-driven" under the guidance of national strategies (Figure 5).

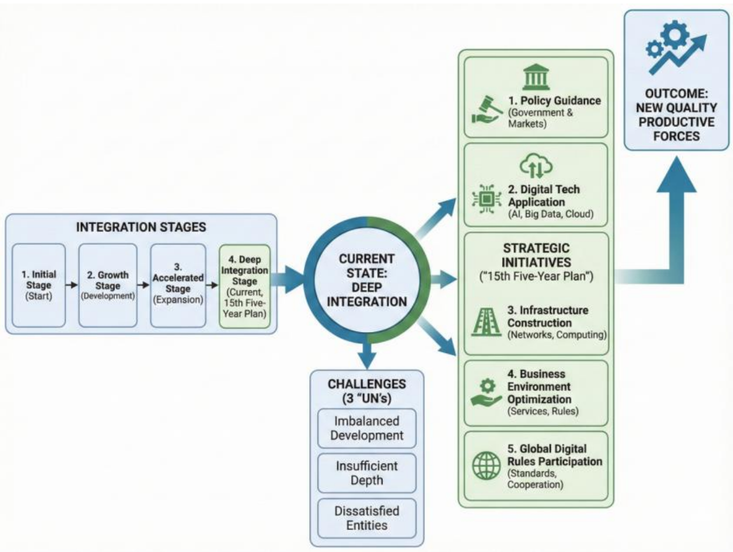

Figure 5 Analytical Framework for the Paradigm Shift of Entrepreneurship from Market-Driven to Mission-Driven under the Guidance of the "15th Five-Year Plan"

This analytical framework diagram clearly visualizes the dynamic trajectory and internal logic regarding the evolution of Chinese entrepreneurship.The left side of the figure illustrates the traditional market-driven paradigm, which prioritizes acquiring market competitive advantages and economic benefits through the enhancement of innovation capabilities.The transformation mechanism in the center highlights the guiding role of the "15th Five-Year Plan" as a critical institutional variable, which acts as a catalyst for the entire paradigm shift.The core section on the right detailedly deconstructs the multi-dimensional connotations of the new "mission-driven" paradigm: entrepreneurs are no longer merely "economic actors" but "strategic agents" shouldering responsibilities for self-reliance and self-strengthening in science and technology, green sustainable development, and national security. The evolutionary direction indicated by the arrows suggests that this transition toward a "mission-driven" model represents not merely a renewal of corporate philosophy, but provides crucial support for ultimately achieving the national macro-goals of High-Quality Development and cultivating New Quality Productive Forces. Overall, this figure reveals the inevitable trend of the deep integration between individual entrepreneurial goals and national strategic missions in the context of the new era[17].

3.4 Driving Mechanisms and Implementation Paths

The Organizational Adaptation Mechanism serves as the core link in realizing mission-driven entrepreneurship, involving the synergistic evolution of governance structure, incentive systems, and cultural shaping. Research indicates that during the transformation of entrepreneurship, the organizational adaptation mechanism acts as a bridge and a bond. The specific analysis is as follows:
First, the Governance Structure is the foundation of organizational adaptation. A governance structure that aligns with mission-driven entrepreneurship ensures consistency between the entrepreneur's decisions and the corporate mission.Entrepreneurs need to construct a system characterized by clear authority and responsibility and transparent decision-making. This enables the enterprise to respond rapidly to national strategies while maintaining decision-making flexibility and foresight.For example, establishing a specialized Strategic Committee strengthens the leading role of the entrepreneur in the decision-making process, helping to translate national strategic intent into concrete corporate actions.
Second, the Incentive System is a key element of the driving mechanism. Incentive systems must focus not only on short-term financial performance but, more importantly, on long-term value creation.In designing incentive schemes, entrepreneurs should integrate mission goals with personal development. Through equity-based incentives and long-term bonuses, entrepreneurs are encouraged to shoulder corresponding social responsibilities and national missions while pursuing economic benefits.Statistics show that enterprises adopting long-term incentive mechanisms witness significant improvements in both innovation capability and market competitiveness[18].
Third, Cultural Shaping is an indispensable component of organizational adaptation. Corporate culture acts as the carrier of entrepreneurship, influencing the behavioral patterns and values of internal members.Entrepreneurs need to foster a corporate culture anchored in innovation, mission, and responsibility through the propagation of ideas, behavioral norms, and institutional arrangements.
This culture stimulates employee enthusiasm and forms a shared value pursuit, thereby driving the enterprise's transition toward a mission-driven model.
Further Elaboration on Driving Mechanisms and Paths: Beyond the organizational level, the transformation is supported by external policies and internal cognitive shifts:Policy Incentive Mechanism (The Guiding Role): Planning guidance, institutional guarantees, and preferential resource allocation provide entrepreneurs with clear direction and necessary support. For instance, the government can incentivize enterprises to increase R&D investment and achieve breakthroughs in key core technologies through tax incentives and fiscal subsidies.Entrepreneurial Cognitive Reconstruction (The Psychological Foundation): The psychological shift from "profit maximization" to "mission internalization" requires entrepreneurs to possess a broader strategic vision and a heightened sense of social responsibility[19].This transformation involves a re-positioning of the entrepreneur's own role and a profound understanding of the relationship between the enterprise and the state.Conclusion on Synergistic Operation: The effective operation of the organizational adaptation mechanism relies on the synergy of governance structure, incentive systems, and cultural shaping.Optimization of the governance structure ensures the matching of decisions with the mission;Innovation in the incentive system stimulates the intrinsic motivation of entrepreneurs and employees;Cultural shaping provides sustained spiritual support.
In summary, by constructing effective policy incentive mechanisms, achieving entrepreneurial cognitive reconstruction, and promoting the synergistic evolution of organizational adaptation mechanisms, we can foster the formation and development of mission-driven entrepreneurship. This provides robust support for the successful implementation of China's "15th Five-Year Plan."

4 THE ORIENTATION TOWARD ENTREPRENEURSHIP TRANSFORMATION WITHIN THE TEXT OF THE "15TH FIVE-YEAR PLAN"

4.1 Reshaping the Entrepreneurial Role at the Level of Overall Goals

Under the guidance of the overall goals of the "15th Five-Year Plan," the role of the entrepreneur has undergone a profound reshaping.First, under the goal of "Self-reliance and Self-strengthening in Science and Technology," the entrepreneur is positioned as the main force of innovation. This role necessitates that entrepreneurs focus not only on their firm's technological development but also stand at the height of national strategy to drive technological innovation and realize the autonomy and controllability of industrial chains. In this process, entrepreneurs must possess strategic foresight and the courage to invest in core technology R&D to break through "stranglehold" (technological bottleneck) issues in key fields.Second, in the construction of a "Beautiful China," the entrepreneur assumes the role of a primary agent of responsibility for green transition. This reshaping implies that while pursuing economic benefits, entrepreneurs must simultaneously consider environmental protection and social responsibility. They are required to achieve a green and low-carbon transition in business models and operational processes, promoting sustainable corporate development and contributing to the construction of a clean, low-carbon energy system.Furthermore, in the construction of the "National Security Barrier," the entrepreneur is endowed with the functional requirement of being a "guardian of supply chain resilience." This requires that when facing external shocks and risks, entrepreneurs must maintain the stability and resilience of the industrial chain to ensure national economic security. By optimizing supply chain management and increasing the self-sufficiency rate of key components, entrepreneurs can enhance their capability to withstand external risks[19].

To realize the aforementioned role reshaping, entrepreneurs need to possess the following capabilities:Strategic Planning Capability: The ability to accurately grasp the direction of national strategies and tightly integrate corporate development strategies with overall national goals.Innovation Capability: The ability to sustain efforts in technological and business model innovation to drive corporate transformation and upgrading.Risk Management Capability: The ability to identify and cope with potential risks to guarantee steady corporate development.In practice, this role reshaping also faces numerous challenges. Key issues requiring in-depth consideration include: finding a balance between "market logic" and "mission logic"; weighing the short-term return requirements of capital markets against the long-term investment demands of national strategies; and coordinating the relationship between individual entrepreneurial rationality and national collective goals.

Research indicates that policy guidance and institutional guarantees play a critical role in this reshaping process. By perfecting relevant policies and regulations and constructing an institutional environment conducive to entrepreneurship, the state can help entrepreneurs better fulfill their missions and responsibilities in the new era. For instance, measures such as optimizing talent introduction and cultivation mechanisms, providing R&D funding support, and protecting intellectual property rights can stimulate entrepreneurial vitality.

In summary, the reshaping of the entrepreneurial role at the level of the "15th Five-Year Plan" overall goals is not only a necessity for corporate development but also an inevitable requirement for the implementation of national strategies. Entrepreneurs must play a key role in technological innovation, green transition, and supply chain resilience to contribute to national strategic goals. Simultaneously, the government and society should provide support to foster a new pattern of benign interaction characterized by "National Strategy—Corporate Mission—Market Vitality."

4.2 Deep Interpretation of Key Task Clauses

The text of the "15th Five-Year Plan" explicitly outlines multiple key tasks, which impose specific requirements on the transformation of entrepreneurship.

First, the clause on "Strengthening the Principal Position of Enterprises in Innovation" highlights the core role of firms in the national innovation system. The implementation path of this clause includes perfecting the corporate technological innovation system and promoting enterprises to become the principal entities in technological innovation decision-making, R&D investment, research organization, and result transformation. Research suggests that the policy implication here aims to stimulate entrepreneurial innovation momentum through institutional design, thereby enhancing corporate competitiveness.

Second, the clause on "Developing Future Industries" places new demands on entrepreneurs' foresight and risk-bearing capacities. In this context, entrepreneurs need to look beyond short-term market changes and possess a long-term vision to grasp future trends in industrial development. Statistics show that the development of emerging industries is often accompanied by immense uncertainty, which requires entrepreneurs to possess higher capabilities in risk identification and response within their strategic planning.

Third, under the context of the clause on "Coordinating Development and Security," systemic thinking and bottom-line awareness become keys to transformation. This clause requires enterprises to balance social stability and national security while pursuing economic benefits. In this process, entrepreneurs need to cultivate systemic thinking, considering corporate development within the broader picture of national development, and adhere to "bottom-line thinking" in business operations to prevent systemic risks.

To achieve the above transformation, the role of policy tools and support systems is indispensable. For example, the allocation of factors such as talent, capital, and data needs to be tilted toward mission-oriented enterprises. Through mechanism design, necessary resource support is provided to entrepreneurs. Meanwhile, the implementation of the Law on Promoting the Private Economy and policies safeguarding entrepreneurial rights can incentivize long-term investment and reduce the impact of uncertainty.

Moreover, case studies indicate that in fields such as integrated circuits and new energy, entrepreneurs have demonstrated active exploration in mission practice by responding to national strategies, adjusting organizational structures, and increasing R&D investment. These cases provide empirical evidence for understanding the transformation of entrepreneurship, revealing strategic choices and managerial wisdom during the transition.

In conclusion, the key task clauses in the "15th Five-Year Plan" text not only point out the direction for entrepreneurial transformation but also provide reference paths for policymakers. A deep interpretation of these clauses allows for a better grasp of the internal logic and implementation essentials of the paradigm shift in entrepreneurship.

4.3 Policy Tools and Support Systems

Under the guidance of the "15th Five-Year Plan," the construction of policy tools and support systems has become an important means to drive the transformation of entrepreneurship. The allocation of key factors such as talent, capital, and data is gradually being preferentially tilted toward mission-oriented enterprises, forming a relatively complete mechanism design.First, regarding Talent Policy: The state is strengthening the construction of the entrepreneurial workforce by optimizing talent cultivation and introduction mechanisms.For instance, the implementation of the "Great Country Craftsmen" (Master Craftsmen) training plan aims to enhance the innovation capability and international competitiveness of entrepreneurs and technical talents.Simultaneously, through high-level talent recruitment projects such as the "Thousand Talents Program," the state aims to attract global top-tier talents and high-level innovation teams, providing robust intellectual support for tackling key technological problems.Second, regarding Financial Policy (Capital): The state is constructing a diversified mechanism for science and technology investment, led by fiscal input and supported by financial markets.By establishing national-level funds—such as the Manufacturing Transformation and Upgrading Fund and the Strategic Emerging Industries Development Fund—the government leverages fiscal funds to guide social capital, particularly "patient capital," to flow into long-cycle, high-risk strategic fields.Concurrently, the deepening of inclusive tax incentives, such as the additional deduction of R&D expenses, effectively reduces the innovation costs and operational burdens for mission-oriented enterprises.Third, regarding Data Factor Policy: The policy focus lies in breaking information silos and promoting the development and utilization of public data resources.By accelerating the construction of fundamental data institutions, the state supports enterprises in undergoing digital transformation and intelligent upgrading. This empowers entrepreneurs to utilize data assets to optimize decision-making processes and enhance value creation capabilities.Finally, the Legal and Institutional Environment: This serves as the fundamental guarantee for the transformation of entrepreneurship.By strengthening whole-chain intellectual property protection and strictly cracking down on unfair competition, the state is committed to creating a fair, transparent, and predictable rule-of-law business environment.This not only secures innovation returns but also fosters a social atmosphere that "encourages innovation and tolerates failure" through the establishment of fault-tolerance and correction mechanisms. These measures aim to eliminate entrepreneurs' worries and strengthen their confidence in fulfilling national missions.

5 CASE STUDY: PRACTICAL EXPLORATION OF MISSION-DRIVEN ENTREPRENEURS

5.1 Case Selection Standards and Methodology

Selecting appropriate case subjects and employing a scientific methodology are paramount when conducting case studies on the practical exploration of mission-driven entrepreneurs. This study adheres to strict standards for case selection, with representativeness being the core criterion. Given the distinct national strategic orientation of the "15th Five-Year Plan," this study focuses on enterprises in the fields of "Key Core Technologies" and the "New Energy System." Entrepreneurs in these sectors face representative technical challenges and market transformations, effectively reflecting the core characteristics and transformation requirements of mission-driven entrepreneurship. Comparability serves as another critical criterion; by selecting enterprises across different industries, scales, and ownership structures for comparative analysis, this study reveals the commonalities and specificities of entrepreneurial transformation under varying backgrounds, thereby enhancing the comprehensiveness and depth of the research.

Regarding data collection, this study employs multi-source data triangulation, integrating corporate annual reports, interview records, policy documents, and third-party assessment reports. Annual reports provide official data on operations and finances, while interview records capture the entrepreneur's personalized understanding and strategic choices regarding mission practice. Policy documents and third-party reports further reveal the impact of the macro-policy environment on corporate behavior. Methodologically, this study adopts the Case Study Method, which is suitable for the in-depth exploration of specific phenomena. By detailing and analyzing the developmental history, strategic decisions, and organizational changes of the case enterprises, the internal mechanisms and dynamics of the transformation of entrepreneurship are unveiled. The analysis proceeds by first profiling the case enterprise's industry status and market environment, followed by a deep analysis of how entrepreneurs respond to national strategies through resource allocation. It then explores specific practices in organizational capability building and business model innovation, and concludes by distilling commonalities through comparative analysis to offer theoretical interpretations and strategic recommendations.

5.2 Case 1: Mission Practice of a Leading Enterprise in the Integrated Circuit Field

The mission practice of a leading enterprise in the Integrated Circuit (IC) field exemplifies the close integration of national strategy and corporate development. Actively responding to the "Self-reliance and Self-strengthening in Science and Technology" strategy, the enterprise has dedicated itself to breaking through "stranglehold" (technological bottleneck) technologies. To achieve this, the entrepreneur adopted a series of measures, including increasing R&D investment and introducing advanced international technologies and talents. By establishing an R&D platform supported by National Laboratories, the firm has significantly bolstered its innovation capacity. Statistics indicate that during the "15th Five-Year Plan" period, the ratio of R&D investment to operating revenue rose annually, reaching an industry-leading level. Furthermore, the enterprise actively engaged in Industry-University-Research (IUR) cooperation with domestic and foreign universities, promoting comprehensive technological innovation and industrial upgrading.

To better serve national strategies, the enterprise underwent profound changes in its organizational structure and decision-making logic regarding long-term R&D investment. The organization was restructured to establish specialized technology R&D centers and project management teams, forming an efficient technological innovation system. The entrepreneur's decision logic emphasizes long-term investment over short-term gains, manifested in sustained R&D on core technologies and talent cultivation, such as the implementation of the "Future Star" talent training plan. Crucially, the entrepreneur played a pivotal coordinating role in National Laboratory cooperation and IUR synergy. Acting as a bridge for multi-party cooperation, the entrepreneur successfully coordinated diverse resources to accelerate key technology projects, enabling them to reach advanced international levels ahead of schedule.

While responding to national strategies, the enterprise faced challenges in balancing R&D investment with economic efficiency and market competitiveness. Through optimizing resource allocation, improving management efficiency, and implementing differentiation strategies, the enterprise effectively addressed these challenges, achieving a 20% growth in market share during the "15th Five-Year Plan" period. Finally, the enterprise demonstrated a strong sense of social responsibility. Beyond technological breakthroughs, it played a significant role in driving industrial upgrading and regional economic development, for instance, by constructing industrial parks that boosted local employment and economic growth. In summary, the practice of this IC leader demonstrates that entrepreneurs play an irreplaceable role in serving national strategies, achieving technological breakthroughs, and contributing to national development through effective organizational adjustment and resource integration.

5.3 Case 2: Pioneer Enterprise in the Construction of the New Energy System

The construction of a New Energy System is a critical path for achieving sustainable development and a key area of global strategic layout. In this context, pioneer enterprises have demonstrated unique resilience management capabilities through their entrepreneurial strategic layout. Case studies indicate that these firms not only seek a balance between business model innovation and green technology implementation but also exhibit significant capabilities in coping with policy volatility and market uncertainty. The entrepreneur's strategic layout regarding "Dual Carbon Goals" and the "Clean and Low-carbon Energy System" reflects a profound understanding and active response to national strategies. By investing in the R&D and promotion of clean energy technologies—such as solar power, wind power, and electric vehicles—the pioneer enterprise optimized the energy structure and reduced carbon emissions. For example, through innovative energy management solutions, the firm achieved significant economic and environmental benefits while improving energy efficiency.

Business model innovation is central to this enterprise's competitiveness. The firm developed comprehensive energy services, such as Energy Performance Contracting (EPC), demand response, and Distributed Energy Resource (DER) management, providing one-stop solutions that improved customer satisfaction and generated stable revenue streams. In terms of green technology implementation, the enterprise adopted balanced strategies, promoting commercialization through partnerships with research institutions and long-term relationships with suppliers. Simultaneously, the enterprise focused on optimizing resource allocation and risk management through policy and market mechanisms, such as carbon trading and green credit.

Facing the challenges of policy volatility and market uncertainty, the enterprise demonstrated strong resilience management. This was achieved through a multi-pronged approach: employing diversified market strategies and product lines to mitigate business fluctuations; establishing flexible supply chains and inventory management mechanisms to cope with raw material uncertainty; and actively engaging in financial risk management through insurance and emergency funds. In conclusion, led by the entrepreneur, the pioneer enterprise successfully navigated challenges through effective strategic layout, business model innovation, and resilience management. These practices not only provide valuable experience for the development of the new energy industry but also offer a replicable model for other firms seeking to align with national strategic goals.

5.4 Case Comparison and Pattern Distillation

Following the in-depth independent case analyses of leading enterprises in the typical fields of Integrated Circuits and New Energy Systems, this study further conducts a cross-case comparative synthesis. The objective is to unveil the universal regularities and intrinsic logic governing the transition of entrepreneurship toward a "mission-driven" model across different contexts. Through a systematic review, we analyzed the divergence in strategic responses of the two types of enterprises against the macro-backdrop of the "15th Five-Year Plan." Furthermore, we identified commonalities in their pathways of organizational change, as well as the shared structural obstacles they face, such as short-term performance pressure and institutional friction. Based on this comparative analysis, the key factors driving successful transformation were distilled.To intuitively present this construction process—moving from empirical evidence to a theoretical model—the following figure systematically summarizes the complete mechanism and analytical framework for the transformation of mission-driven entrepreneurship. This figure clearly illustrates the logical chain of the research, originating from the policy background, proceeding through rigorous case verification and comparative synthesis, and ultimately culminating in the formation of the theoretical framework.

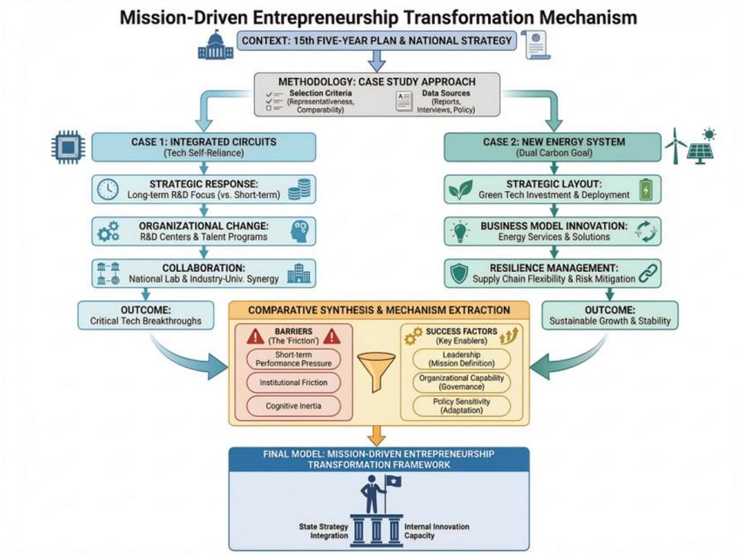

Figure 6 Transformation Mechanism and Analytical Framework of Mission-Driven Entrepreneurship Based on a Comparative Dual-Case Study

A comparative analysis of the two enterprises reveals the commonalities and heterogeneity of mission-driven entrepreneurship across different domains and contexts. Commonalities are manifested in the entrepreneurs' responsiveness to national strategic demands, adjustments in organizational architecture, and adaptability to external environmental changes. Differences, conversely, are reflected in how distinct industry characteristics influence strategic choices and execution pathways. Despite these variations, entrepreneurs universally face three structural obstacles.

First, short-term performance pressure constitutes a primary barrier. Against the backdrop of capital markets pursuing immediate returns, entrepreneurs often struggle to balance adherence to long-term strategies with meeting market expectations. For instance, the Integrated Circuit sector requires substantial long-term R&D investment to break through key technologies, which often conflicts with short-term financial metrics.Second, institutional friction represents a major challenge. Changes in the policy environment, regulatory uncertainty, and coordination issues between different policies can impact decision-making. In the New Energy sector, policy volatility directly affects business models, necessitating high flexibility from entrepreneurs.Third, cognitive inertia serves as a significant internal hurdle. Stakeholders accustomed to the traditional market-driven model may lack identification with the new mission-driven paradigm, requiring entrepreneurs to not only adjust structures but also guide a profound cognitive shift among employees.

Overcoming these obstacles relies on three key factors for successful transformation: Leadership, Organizational Capability, and Policy Sensitivity.Leadership is embodied in a profound understanding of national strategies and a clear definition of the corporate mission.

Organizational Capability is reflected in the ability to support long-term strategies through effective governance structures and incentive mechanisms.Policy Sensitivity is demonstrated by the ability to timely capture changes in policy orientation and make corresponding strategic adjustments.The comparative analysis indicates that successful entrepreneurs in both sectors exhibit shared characteristics: a deep recognition of national strategies, the construction of internal mechanisms for long-term R&D, and the establishment of Industry-University-Research (IUR) synergy with external institutions like National Laboratories. The interplay between these major obstacles and key success factors constitutes a holistic transformation model. This model emphasizes the core role of the entrepreneur while revealing the dynamic interaction between the external environment, internal capabilities, and individual traits. Distilling this model is significant for understanding the paradigm shift from "market-driven" to "mission-driven." Future research should further explore the deep-seated causes of these obstacles and investigate how policy design and corporate practice can better facilitate this critical transformation.

6 CHALLENGES, DYNAMICS, AND INSTITUTIONAL ADAPTATION OF THE PARADIGM SHIFT

6.1 Structural Contradictions in the Transformation Process

In the context of current economic transformation and development, the coordination between individual entrepreneurial rationality and national collective goals has emerged as a critical structural contradiction. An intrinsic tension exists between "market logic" and "mission logic," a tension that becomes particularly pronounced during the transformation of entrepreneurship. Market logic prioritizes efficiency and the maximization of personal interest, whereas mission logic focuses on national strategies and overall societal interests. This conflict manifests specifically as a mismatch between the short-term return requirements of capital markets and the long-term investment demands of national strategies. Investors typically seek to maximize returns within a short timeframe, which contradicts the long-term resource commitment required for strategic goals such as technological innovation and green transition.

Furthermore, the coordination dilemma is reflected in the institutional environment; in their pursuit of individual interests, entrepreneurs may encounter institutional friction and policy uncertainty, factors that constrain the pace of the shift toward a mission-driven model. For instance, a lack of clear property rights protection and a robust rule-of-law environment may cause entrepreneurs to be reserved when shouldering social responsibilities.

Empirical evidence suggests that enterprises successfully implementing national strategies are those that effectively reconcile market logic with mission logic, often exhibiting superior innovation capabilities and market competitiveness. Research indicates that these firms mitigate structural contradictions by constructing a harmonious corporate culture, optimizing incentive systems, and strengthening policy identification. The conflict between short-term capital pressures and long-term strategic investments also impacts entrepreneurial decision-making patterns. Entrepreneurs must balance economic benefits with social and national interests, making systemic thinking and "bottom-line awareness" crucial. Successful entrepreneurs can transcend the traditional profit-maximization framework to align corporate strategy with national strategy, achieving a harmony between individual rationality and collective goals. However, obstacles such as short-term performance pressure, institutional friction, and cognitive inertia remain. To overcome these, institutional optimization is required—such as perfecting the evaluation system for mission-oriented enterprises, constructing a "State-Enterprise-Society" synergistic responsibility-sharing mechanism, and strengthening legal safeguards to stabilize entrepreneurs' long-term expectations.

6.2 Core Driving Forces for Promoting Transformation

The endowment of national strategic legitimacy constitutes one of the core driving forces for the paradigm shift. Under the guidance of the "15th Five-Year Plan." Research shows that when entrepreneurs perceive the legitimacy and correctness of national strategies, they are more willing to commit resources to achieve these goals. Furthermore, the construction of a new type of government-business relationship provides entrepreneurs with a sense of institutional security and policy predictability. With the transformation of government functions and the strengthening of the rule of law, entrepreneurs feel supported and protected by the government while following market laws. This support, reflected in policy stability and the protection of legitimate rights, bolsters confidence in long-term investment and innovation.

Another intrinsic driver is the intergenerational shift in values and the endogenous awakening of a sense of mission among new-generation entrepreneurs. As the principal contradiction in society evolves and the economic development stage changes, entrepreneurs increasingly recognize that corporate social responsibility lies not only in pursuing economic benefits but also in serving national strategies and promoting social progress. This value shift injects new substance into entrepreneurship. Throughout this process, the leading role of national strategy cannot be overlooked; by setting clear goals—such as encouraging technological innovation and green development—the state guides entrepreneurs to align their strategies with national imperatives, forming a powerful combined force for transformation. Although challenges persist, such as the tension between market and mission logics, statistical evidence shows that enterprises capable of effectively integrating national strategies, market demands, and internal resources achieve significant results. The core dynamics of this transformation thus stem from the interplay of national strategic legitimacy, new government-business relations, and the endogenous awakening of the entrepreneurial mission.

6.3 Suggestions for Optimizing the Institutional Environment

Optimizing the institutional environment is a key external condition for realizing the paradigm shift in entrepreneurship. First, the evaluation and incentive system for mission-oriented enterprises must be perfected. Current systems often overemphasize short-term economic performance; therefore, a multi-dimensional evaluation system incorporating economic, social, and environmental indicators should be constructed. Measures such as special awards, tax incentives, and financing support should be utilized to incentivize long-term investment. Second, it is crucial to build a "State-Enterprise-Society" synergistic responsibility-sharing mechanism. The government must clearly define the national strategic role of enterprises while providing policy support; enterprises should actively respond to strategies and shoulder responsibilities; and society should promote mission fulfillment through public supervision. This synergy helps shift the focus from pure profit maximization to the realization of overall social interests.Third, strengthening legal safeguards and property rights protection is fundamental to stabilizing entrepreneurs' long-term expectations. A perfected rule-of-law environment is directly proportional to the vitality of entrepreneurship. Specific optimization pathways include: strengthening the legal system by enacting regulations relevant to entrepreneurship to adapt to new economic demands; improving judicial efficiency and fairness to reduce risks faced by entrepreneurs; and enhancing legal education to foster a social atmosphere that respects and protects entrepreneurship. Finally, policy tools must be employed flexibly and innovatively. Diverse and precise tools—such as policy-based lending, industrial funds, and risk compensation—can help entrepreneurs better adapt to market changes and national strategic needs, thereby reducing investment risks. In summary, through these institutional optimizations, powerful support can be provided for the growth of mission-driven entrepreneurship.

7 CONCLUSION

This study constructs a theoretical model of Mission-Driven Entrepreneurship against the backdrop of the "15th Five-Year Plan." It reveals that under national strategic guidance—such as self-reliance in science and technology and green development—entrepreneurs achieve a transformation from a purely market-driven model to a mission-driven one that balances economic, social, and national interests. This is accomplished through synergistic innovation across three dimensions: strategic mission, organizational capability, and value creation. Crucially, the study demonstrates how this new paradigm effectively reconciles the intrinsic tension between market logic and mission logic.By enriching the analytical framework of entrepreneurship with Chinese characteristics, this research not only offers theoretical contributions but also provides practical pathways. It proposes concrete recommendations, including perfecting evaluation and incentive systems, optimizing the rule-of-law business environment, and constructing a "State-Enterprise-Society" synergistic mechanism. These measures aim to foster a benign interaction pattern characterized by "National Strategy—Corporate Mission—Market Vitality."Addressing the current limitations regarding sample breadth and longitudinal data, future research should expand into quantitative measurement, long-term tracking, and cross-regional comparative studies. Such endeavors will further deepen the understanding of the dynamic evolutionary laws governing this critical transformation, providing sustained theoretical and practical support for China's high-quality development.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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FROM DUAL-CARBON MANAGEMENT TO GREEN INNOVATION: THE SYNERGISTIC PATHWAYS OF CARBON ACCOUNTING AND CARBON FOOTPRINT IN TECHNOLOGY ENTERPRISES

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Abstract: Under the national dual-carbon strategy, technology enterprises face increasing pressure to reduce carbon emissions resulting from intensive energy use, complex supply chains, and long product life cycles. Identifying effective pathways for achieving green innovation under carbon constraints has become an essential issue for sustainable corporate development. This study establishes a "dual-carbon management" theoretical framework that integrates organizational-level carbon accounting with product-level carbon footprint assessment. Drawing on existing literature, the study examines the roles of carbon accounting in carbon governance, strategic planning, and internal incentive mechanisms, as well as the contributions of carbon footprint analysis to life-cycle assessment, material optimization, and product Eco-design. It further explores the synergistic mechanisms between the two, including data complementary, governance alignment, strategic coordination, and value-chain integration. Based on these insights, the study proposes key principles for constructing green innovation paths, emphasizing data integrity, systemic thinking, innovation-oriented governance, life-cycle perspective, value-chain collaboration, and dynamic adjustment. A representative case of a technology enterprise is analyzed to illustrate how dual-carbon management supports the development of low-carbon technologies, process improvements, and green product innovation. The results show that carbon accounting provides a foundation for organizational carbon governance, while carbon footprint offers detailed life-cycle insights. The integration of these two mechanisms forms a multi-level system that enhances strategic decision-making, operational transformation, and supply-chain-wide collaboration. This study contributes theoretical insights and practical guidance for technology enterprises seeking green innovation pathways under carbon constraints.
Keywords: Carbon accounting; Carbon footprint; Green innovation; Technology enterprises; Dual-carbon management

1 INTRODUCTION

In the context of global climate governance and China's "dual-carbon" strategy, technology enterprises are facing unprecedented pressure to reduce carbon emissions while sustaining innovation-driven growth. As key actors in digitalization, advanced manufacturing, and high-tech industries, technology enterprises contribute significantly to carbon emissions through energy consumption, complex supply chains, and product life-cycle impacts. At the same time, they are also essential drivers of low-carbon technological transformation, green upgrading, and sustainable industrial development. Against this backdrop, exploring how internal carbon management mechanisms stimulate green innovation has become an urgent theoretical and practical issue.

Carbon accounting and carbon footprint—representing organizational-level and product-level carbon management, respectively—have emerged as crucial tools for strengthening corporate responses to environmental challenges. Carbon accounting provides systematic procedures for identifying, measuring, and reporting organizational greenhouse gas emissions, forming the foundation for corporate carbon governance, carbon disclosure, and strategic decision-making[1]. Carbon footprint analysis, grounded in life-cycle assessment, enables enterprises to quantify emissions throughout the entire value chain of products and services, thereby identifying emission hotspots, guiding technological improvement, and supporting green product development[2]. Although both mechanisms play important roles in low-carbon management, existing research tends to examine them independently, overlooking the potential synergistic effects between organizational carbon governance and product life-cycle carbon management.

At present, most studies on corporate green innovation emphasize external regulatory drivers, environmental policies, or market incentives, while relatively little attention has been paid to how internal carbon management systems jointly shape enterprises' innovation behaviors. For technology enterprises—characterized by rapid technological iteration, intensive knowledge production, and high sensitivity to environmental uncertainty—the combined application of carbon accounting and carbon footprint may form a "dual-carbon management system" that not only enhances data accuracy and transparency, but also embeds carbon constraints and environmental value into innovation processes. However, the internal logic, mechanisms, and pathways through which these two carbon management tools interact to promote green innovation remain insufficiently explored.

Therefore, this study aims to investigate the synergistic pathways through which carbon accounting and carbon footprint jointly influence green innovation in technology enterprises. Drawing on interdisciplinary perspectives from carbon accounting, sustainability management, and innovation theory, this research constructs a theoretical framework demonstrating how dual-level carbon management—organizational carbon governance and product life-cycle carbon management—shapes innovation motivation, capability formation, and strategic transformation. Specifically, the study examines the interaction between carbon accounting and carbon footprint, analyzes their integrated mechanisms in data governance, internal control, resource allocation, and value-chain collaboration, and identifies the pathways through which they stimulate green technological, managerial, and product innovation[3].

The significance of this research is threefold. Theoretically, it enriches the literature on corporate green innovation by introducing a dual-carbon management perspective and by clarifying the micro-level mechanisms underlying low-carbon innovation in technology enterprises. Practically, it provides guidance for technology enterprises to build comprehensive carbon management systems, optimize innovation strategies, and enhance competitiveness under carbon -constrained conditions. At the policy level, the research offers insights for improving carbon disclosure regulations, promoting life-cycle environmental governance, and accelerating the green transformation of high-tech industries.

2 LITERATURE REVIEW AND THEORETICAL BASIS

2.1 Carbon Accounting and Carbon Management

Carbon accounting has become a foundational component of corporate environmental management as global climate policies increasingly emphasize transparency, standardization, and accountability in greenhouse gas (GHG) reporting. Early studies on carbon accounting primarily focused on the development of measurement and reporting frameworks for organizational carbon emissions, with international standards such as the Greenhouse Gas Protocol and ISO 14064 providing structured guidance on defining emission boundaries, identifying emission sources, and quantifying direct and indirect emissions. This body of research established carbon accounting as a systematic approach to documenting corporate GHG emissions and supporting compliance with environmental regulations.

Over time, scholars expanded the focus of carbon accounting from narrow technical measurement to broader issues of governance, strategy, and performance management. In particular, the role of carbon accounting in enhancing information transparency, reducing environmental uncertainty, and supporting corporate decision-making has been well recognized. Research has shown that high-quality carbon accounting systems facilitate internal carbon budgeting, carbon performance evaluation, and the integration of carbon metrics into corporate financial and strategic planning[4]. Such developments signify a shift from carbon accounting as a reporting tool to carbon accounting as a strategic management instrument embedded within enterprise governance structures.

In addition to internal governance implications, carbon accounting has also been examined through the lens of external stakeholders. Studies demonstrate that accurate and credible carbon disclosure can reduce information asymmetry between firms and investors, enhance corporate reputation, and improve access to green finance. These findings underscore the significance of carbon information quality—driven by robust accounting practices—in shaping stakeholders' perceptions and influencing firms' environmental and financial outcomes[5].

Carbon management, as an extension of carbon accounting, encompasses organizational strategies, institutional arrangements, and operational practices that aim to monitor, control, and reduce carbon emissions. Research in this field highlights that effective carbon management requires not only accurate emissions data but also the establishment of internal carbon governance mechanisms, such as carbon performance indicators, carbon cost accounting, and internal carbon pricing systems. Scholars argue that these mechanisms help enterprises identify emission reduction opportunities, allocate resources toward low-carbon technologies, and embed environmental values into managerial decision-making processes[6]. As a result, carbon management is increasingly viewed as an integrated system linking measurement, governance, strategy, and performance.

Recent studies on carbon management especially emphasize its role in supporting corporate innovation. By internalizing carbon-related risks and costs, carbon management practices create incentives for firms to invest in energy efficiency, process optimization, and green technology development. For technology enterprises—characterized by rapid technological iteration and high resource intensity—carbon management serves not only as a compliance framework but also as a strategic driver of innovation capability and competitive advantage. However, existing research often treats carbon accounting and carbon management as separate constructs, lacking an integrated perspective on how carbon accounting practices contribute to the design, operation, and effectiveness of broader carbon management systems[7].

2.2 Carbon Footprint and Product Life-Cycle Carbon Management

Carbon footprint research, rooted in life-cycle assessment (LCA), has become an essential analytical approach for evaluating the environmental impact of products, services, and value-chain activities. Internationally, scholars have emphasized that carbon footprint assessment operationalizes sustainability principles by quantifying emissions across all stages of a product's life cycle—ranging from raw material extraction and manufacturing to transportation, usage, and end-of-life treatment[8]. Early studies predominantly focused on methodological refinement, including system boundary definition, emission factor selection, and allocation rules, establishing carbon footprint analysis as a standardized and scientifically grounded tool for product-level carbon quantification.

More recent research highlights the strategic implications of carbon footprint assessment in corporate environmental management. Scholars argue that carbon footprint results provide actionable insights for identifying high-emission processes, optimizing material choices, and redesigning production techniques. In manufacturing and technology-intensive industries, carbon footprint analysis enables firms to target emission hotspots and explore low-carbon technological alternatives, such as material substitution, renewable energy integration, and digital monitoring systems. This methodological evolution has expanded the application of carbon footprint from environmental accounting to product innovation, supply-chain optimization, and sustainability-driven decision-making[9].

In the context of corporate sustainability disclosure, carbon footprint has also become a key component of firms' environmental transparency initiatives. With the rise of consumer environmental awareness and green market differentiation, enterprises increasingly rely on product carbon footprint labels and third-party certifications to signal environmental responsibility and enhance brand competitiveness[10]. Studies show that carbon footprint information improves stakeholder trust, facilitates compliance with green procurement standards, and strengthens firms' positioning in low-carbon value chains. These developments mirror the function of high-quality teaching materials described in the template article, where standardized, comprehensible, and application-oriented materials serve as instruments for bridging institutional expectations and practical implementation[11].

However, much like the challenges identified in vocational textbook construction—such as outdated content, insufficient alignment with industry needs, and uneven digitalization—carbon footprint research and application also face limitations. Several studies point out that data availability, supply-chain transparency, and methodological inconsistencies hinder accurate product-level carbon assessment. Particularly in technology enterprises, where production systems are complex and globalized, obtaining reliable upstream and downstream emission data remains difficult. Moreover, the rapid pace of technological innovation often leads to mismatches between existing carbon footprint tools and emerging production processes. As a result, many firms struggle to systematically integrate carbon footprint results into product development, procurement management, and innovation planning.

To address these challenges, scholars increasingly advocate for digitalized, dynamic, and collaborative approaches to carbon footprint management. Emerging studies highlight the role of advanced technologies—such as big data analytics, IoT-based carbon monitoring, and blockchain-enabled supply-chain traceability—in enhancing carbon footprint accuracy, improving data integration, and facilitating multi-stakeholder collaboration. These approaches mirror the template's emphasis on the integration of digital tools, contextualized resources, and continuous updating mechanisms in building "gold textbooks," underscoring the importance of innovation, practicality, and adaptability in complex application scenarios.

2.3 Theoretical Framework for the Study

To support the analysis of how carbon accounting and carbon footprint jointly influence green innovation in technology enterprises, this study is grounded in three interrelated theoretical foundations. These theories provide conceptual guidance for understanding the mechanisms through which organizations internalize environmental information, allocate resources for innovation, and respond to institutional pressures. The selected theoretical perspectives—information asymmetry theory, resource-based view (RBV), and institutional theory—are summarized in Table 1.

Table 1 Theoretical Framework of the Study

Theory	Core Concepts	Application to This Study
Information Asymmetry Theory	Organizations and stakeholders possess unequal information; disclosure reduces uncertainty and enhances decision-making efficiency	Explains how carbon accounting and carbon footprint disclosure reduce environmental information gaps, enabling more accurate innovation decisions
Resource-Based View (RBV)	Firms gain competitive advantage by developing valuable, rare, and inimitable internal resources and capabilities	Provides a basis for viewing carbon data systems and carbon management capabilities as strategic resources that drive green innovation.
Institutional Theory	Organizations respond to regulatory, normative, and cognitive pressures by adopting legitimizing practices	Highlights how carbon accounting and carbon footprint practices evolve under regulatory and market pressures, influencing innovation strategies

The theoretical framework also serves as the foundation for constructing the study's overall analytical route. Drawing on these theoretical perspectives, this study examines how carbon accounting (organizational-level carbon governance) and carbon footprint (product-level life-cycle carbon management) interact to shape technology enterprises' innovation processes. The proposed research route integrates theoretical foundations, problem identification, mechanism analysis, and innovation pathway development—corresponding to the structural logic illustrated in the template's technical route diagram[12].

Specifically, information asymmetry theory supports the exploration of how enhanced carbon information quality improves transparency and reduces uncertainty in innovation decisions. The resource-based view provides the lens through which carbon data systems, carbon governance mechanisms, and life-cycle assessment capabilities are conceptualized as internal resources that strengthen firms' innovation capacities. Institutional theory helps explain why technology enterprises adopt carbon accounting and carbon footprint practices under external regulatory, normative, and market pressures, subsequently integrating these practices into their innovation strategies[13].

Taken together, these theories establish a coherent foundation for analyzing the synergistic role of carbon accounting and carbon footprint in promoting green innovation and guide the construction of the study's conceptual framework and analytical pathways.
This flowchart Figure 1 illustrates the complete research logic of the study, including problem identification, literature and theoretical foundation, dual-carbon mechanisms, green innovation path design, and final conclusions. Sub-nodes under each major stage clarify the analytical elements involved at each step of the research.

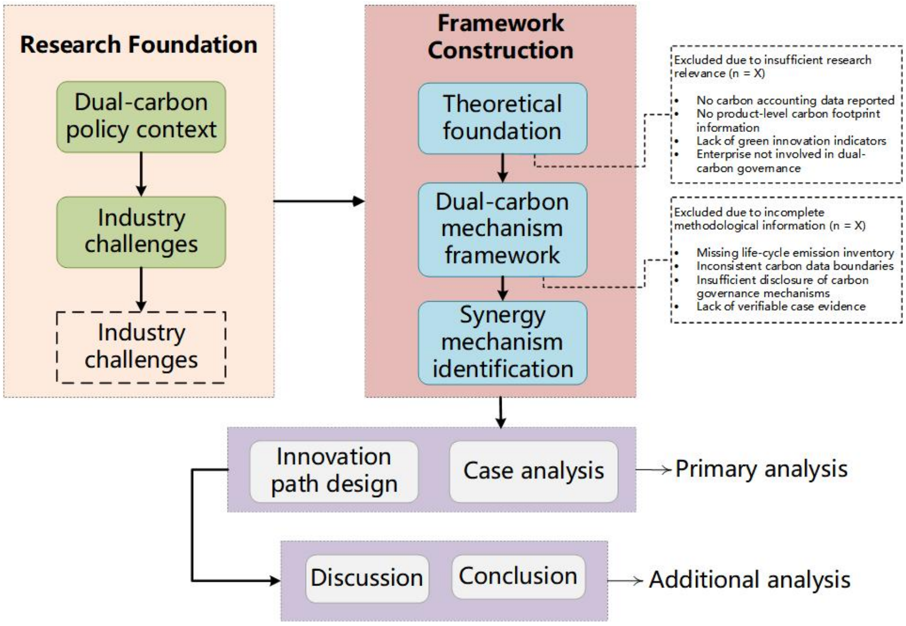

Figure 1 Technical Route of the Study

3 PATHWAYS OF DUAL-CARBON MANAGEMENT TO GREEN INNOVATION

3.1 The Role of Carbon Accounting in Enhancing Green Innovation

The foundation of dual-carbon management in technology enterprises lies in the establishment of a comprehensive and measurable carbon accounting system that reflects organizational-level carbon governance needs. Unlike traditional environmental accounting, which tends to focus on cost recognition or regulatory compliance, carbon accounting emphasizes the systematic identification, quantification, and reporting of greenhouse gas emissions across operational boundaries. For technology enterprises—whose operations involve energy-intensive data centers, complex manufacturing processes, and globalized supply chains—carbon accounting serves as a critical tool for understanding emission structures and managing environmental performance.
In recent years, the increasing stringency of national carbon regulations and the growing importance of green competitiveness have intensified the need for technology enterprises to develop accurate and standardized carbon accounting systems[1]. These systems not only document emission levels but also articulate carbon governance objectives that align with corporate strategies and societal expectations. Carbon accounting must integrate three core dimensions: carbon information accuracy, carbon governance capability, and carbon strategic integration[7]. Together, these dimensions determine whether carbon accounting can effectively support decision-making processes related to green innovation.
To illustrate this relationship more clearly, Table 2 summarizes the core dimensions of carbon accounting in technology enterprises and their implications for green innovation.

Table 2 Core Dimensions of Carbon Accounting and Their Implications for Green Innovation

Dimension	Definition	Relevance to Green Innovation
Carbon Information Accuracy	Precise measurement and reporting of Scope 1–3 emissions using standardized methods	Helps identify emission hotspots and guides targeted technological improvements
Carbon Governance Capability	Internal systems for carbon control, performance assessment, and compliance monitoring	Embeds carbon-reduction responsibilities into management processes, motivating internal innovation
Carbon Strategic Integration	Incorporation of carbon metrics into corporate strategy, investment, and R&D planning	Shapes long-term innovation priorities, supporting low-carbon technology development and deployment

As Table 2 indicates, carbon accounting forms the informational and organizational basis for supporting innovation-oriented environmental actions. When enterprises accurately identify the sources, intensity, and distribution of emissions across organizational units, they are better positioned to recognize areas requiring technological upgrading or process redesign.

Moreover, carbon accounting contributes to internal governance by embedding carbon performance metrics into management systems. Technology enterprises often operate within dynamic and data-driven environments; thus, the integration of carbon information into internal evaluation mechanisms enhances accountability and promotes innovation -oriented behavioral change. Through internal carbon pricing, carbon budgeting, and cross-departmental carbon performance assessments, enterprises convert carbon constraints into innovation incentives—particularly in areas such as energy-efficient computing, low-carbon materials, smart manufacturing, and circular product design.

Finally, carbon accounting plays a strategic role by linking carbon-related risks and opportunities with corporate development planning. As technology enterprises pursue competitiveness in global markets that increasingly value low-carbon products and green supply chains, the incorporation of carbon data into strategic decision-making helps firms allocate resources toward forward-looking innovation initiatives. These strategic initiatives may include R&D in alternative materials, green data-center technologies, product redesign for recyclability, or the adoption of new digital tools for carbon monitoring.

3.2 The Role of Carbon Footprint in Guiding Product and Technology Innovation

Carbon footprint analysis functions as a key component of product-level carbon management, enabling technology enterprises to examine the environmental impact of their products and processes throughout the entire life cycle. By quantifying emissions from raw material extraction, component manufacturing, assembly, distribution, use, and end-of-life treatment, carbon footprint provides a comprehensive perspective that connects low-carbon objectives with concrete technological and design decisions. This life-cycle approach is particularly important for technology enterprises, where complex supply chains, advanced materials, and energy-intensive operations contribute to diverse and distributed sources of carbon emissions.

Compared with organizational-level carbon accounting, which emphasizes overall emission inventories, carbon footprint offers detailed and location-specific insights. These granular measurements highlight emission hotspots across different stages of the product life cycle. This allows enterprises to identify which materials, processes, or suppliers contribute disproportionately to total emissions, thereby revealing opportunities for technological improvement and eco-design. As a result, carbon footprint acts both as a measurement tool and as an innovation guide, directing attention to the most impactful areas where low-carbon interventions can be effectively implemented[13].

The logical relationship between carbon footprint analysis and innovation can be described through a progression from life-cycle information to product redesign, process optimization, and evaluation-based decision-making. First, carbon footprint transforms abstract sustainability goals into concrete design requirements by identifying critical points where emissions are concentrated. Second, insights derived from life-cycle data stimulate technological improvements, such as adopting cleaner production methods, optimizing energy use, or integrating low-carbon materials. Third, carbon footprint metrics can be embedded into supplier selection, product benchmarking, and R&D evaluation systems to ensure that innovation aligns with long-term carbon reduction objectives[2,4,9].

These relationships can be summarized as follows in Table 3.

Table 3 Logical Relationship Between Carbon Footprint Analysis and Product/Technology Innovation

Relationship	Life-Cycle Carbon Insights	Innovation-Oriented Response
From Life-Cycle Goals to Design Choices	Identifies critical stages and emission hotspots in the product life cycle	Supports material substitution, low-carbon component selection, and eco-design integration
From Process Insights to Technological Upgrading	Reveals high-emission processes and operational inefficiencies	Encourages cleaner production, digital monitoring, and energy-efficient manufacturing
From Life-Cycle Metrics to Evaluation Systems	Provides measurable indicators for product and supplier assessment	Guides carbon-based procurement, supplier evaluation, and R&D performance management

As illustrated in Table 3, carbon footprint analysis connects environmental information with practical innovation mechanisms. When life-cycle carbon data are incorporated into the early stages of product development, enterprises can embed low-carbon considerations into design concepts, material selection, and structural decisions. This reduces the need for costly redesign later and supports the creation of inherently low-carbon products.

At the technological level, carbon footprint findings highlight opportunities for upgrading manufacturing processes. These improvements may involve more efficient energy systems, advanced automation, intelligent monitoring technologies, or redesigned workflows that minimize carbon-intensive inputs. Such process innovations not only reduce emissions but also enhance production efficiency, thereby improving overall competitiveness.

At the managerial level, carbon footprint metrics can be integrated into suppliers' carbon performance assessments, enabling enterprises to construct low-carbon supply chains. The availability of comparable, quantifiable data supports procurement decisions aligned with carbon reduction objectives, encouraging suppliers to adopt cleaner technologies and improve transparency.

3.3 Integration of Carbon Accounting and Carbon Footprint

The integration of carbon accounting and carbon footprint represents the core of a dual-level carbon management system that connects organizational governance with product life-cycle assessment. While carbon accounting provides an overall inventory of emissions at the enterprise level, carbon footprint supplies granular insights into carbon distribution along the value chain. When combined, these two mechanisms form a comprehensive structure that links carbon information, managerial control, and innovation-oriented actions in technology enterprises[3,14,15].

At the organizational level, carbon accounting establishes standardized procedures for measuring and reporting greenhouse gas emissions. This ensures that enterprises maintain an accurate understanding of carbon performance across business units, facilities, and operational boundaries. At the product and process level, carbon footprint analysis enables the identification of emission hotspots, revealing opportunities for material innovation, process optimization, and supply chain improvements. The integration of the two systems enables a more complete and dynamic representation of carbon emissions, reducing information fragmentation and enhancing the coherence of carbon management activities[12,13].

The relationship between carbon accounting and carbon footprint can be understood through their complementary roles in data governance, operational decision-making, and innovation management. Carbon accounting aggregates emission data from various activities and processes, forming a macro-level picture of corporate carbon performance. Carbon footprint, by contrast, offers micro-level evidence that can be traced to specific product components, processes, or suppliers. When integrated, macro-level data support strategic planning and resource allocation, while micro-level data guide technology choices and product development. This dual perspective creates a feedback loop in which organizational carbon information shapes product strategies and product-level findings inform corporate carbon governance.

The integrated functioning of carbon accounting and carbon footprint can be summarized as shown in Table 4.

Table 4 Integration of Carbon Accounting and Carbon Footprint

Integration Dimension	Role of Carbon Accounting	Role of Carbon Footprint	Expected Educational Outcomes
Data Complementarity	Provides enterprise-wide emission inventories	Offers detailed life-cycle emission data	Enhances accuracy of innovation decisions and prioritizes high-impact areas
Governance Alignment	Establishes internal carbon targets, budgeting, and oversight	Identifies product-level improvement opportunities	Strengthens consistency between strategic goals and technological innovation
Strategic Synergy	Incorporates carbon metrics into organizational planning	Guides low-carbon product redesign and technology choices	Enables alignment of long-term innovation roadmaps with carbon reduction goals
Value-Chain Integration	Supports carbon disclosure and supplier management	Traces emissions across upstream and downstream activities	Promotes collaborative green innovation across supply-chain partners

As shown in Table 4, the integration of carbon accounting and carbon footprint creates a multi-layered carbon management architecture that simultaneously supports strategic, managerial, and technological innovation. At the strategic level, decision-makers can allocate resources toward low-carbon technologies with greater precision. At the managerial level, internal governance structures become more responsive to product-level environmental data, reinforcing accountability and performance evaluation. At the operational level, engineers and designers obtain actionable insights to improve materials, processes, and components[12].

The combined application of these two mechanisms also promotes cross-departmental collaboration within technology enterprises. Carbon accounting often involves departments such as finance, operations, and corporate governance, whereas carbon footprint analysis engages product design, engineering, and supply-chain management. Their integration fosters interdepartmental communication and knowledge exchange, enabling firms to embed carbon considerations into all stages of technological development[8].

4 STRATEGIES FOR DEVELOPING DUAL-CARBON-BASED GREEN INNOVATION PATHS

4.1 Principles for Constructing Dual-Carbon-Based Green Innovation Paths

The development of effective green innovation paths in technology enterprises requires a systematic approach that integrates environmental objectives, organizational capabilities, and technological resources within a unified dual-carbon management framework. To ensure that carbon accounting and carbon footprint jointly support innovation-driven carbon reduction, several guiding principles must be established. These principles serve as the foundation for translating carbon data into innovation actions and for constructing long-term mechanisms that align enterprise development with low-carbon transformation.

4.1.1 Data integrity and traceability

Green innovation relies on accurate, consistent, and traceable carbon information. Technology enterprises typically operate complex production systems and multi-tier supply chains, making comprehensive carbon data essential for identifying emission sources and designing targeted innovations. Ensuring high-quality data requires the establishment of standardized measurement protocols, transparent data flows, and digital tools that integrate organizational carbon accounting with product-level carbon footprint analysis. Through robust data governance, enterprises can identify key emission hotspots, uncover innovation opportunities, and support evidence-based decision-making.

4.1.2 Integration of organizational and product-level carbon management

A second principle is the alignment of organizational carbon governance with product-level life-cycle carbon management. Organizational carbon accounting offers a strategic perspective, while product-level carbon footprint analysis provides detailed insights into materials, processes, and supply-chain impacts. Integrating these two dimensions ensures coherence between corporate carbon reduction goals and specific innovation activities. This integration also helps enterprises embed carbon considerations across departments—including design, engineering, procurement, and operations—thus supporting cross-functional collaboration and reducing the risk of fragmented or inconsistent innovation efforts.

4.1.3 Innovation-oriented carbon governance

For technology enterprises, carbon management should not be limited to compliance or reporting but should serve as a catalyst for innovation. Embedding carbon-related indicators into project evaluation, resource allocation, and internal performance assessment creates incentives for breakthrough technological solutions. This principle emphasizes the need to view carbon constraints as an opportunity for value creation rather than a limitation. By incorporating carbon metrics into strategic planning and R&D management, enterprises can establish forward-looking innovation pipelines aligned with environmental objectives.

4.1.4 Life-cycle perspective and systemic thinking

Green innovation requires moving beyond isolated technological improvements toward a comprehensive understanding of environmental impacts across the entire product life cycle. A life-cycle perspective encourages enterprises to consider upstream raw materials, manufacturing processes, logistics patterns, product use, and end-of-life disposal when designing low-carbon solutions. This systemic view helps avoid problem shifting—for instance, reducing emissions in one stage while unintentionally increasing them in another—and supports the development of balanced and sustainable innovation strategies.

4.1.5 Collaborative and value-chain-based development

Technology enterprises rarely operate independently; their innovation performance is shaped by suppliers, manufacturing partners, logistics providers, and end-users. Accordingly, effective green innovation paths must incorporate collaboration across the value chain. This includes sharing carbon data, aligning carbon reduction targets, and jointly developing low-carbon technologies or materials. Building a collaborative ecosystem promotes coordinated emission reductions and enhances the overall low-carbon competitiveness of the enterprise and its partners.

4.1.6 Dynamic improvement and adaptive adjustment

Given the rapid evolution of technologies, regulatory environments, and market expectations, green innovation paths must remain adaptable. Continuous monitoring, evaluation, and feedback mechanisms enable enterprises to refine carbon management practices and adjust innovation strategies. This principle supports dynamic improvement rather than static adherence to pre-established plans. Through iterative learning, enterprises can adapt to emerging challenges, integrate new technologies, and maintain alignment with long-term sustainability goals..

4.2 Framework and Key Characteristics of Dual-Carbon-Based Innovation Strategies

Building green innovation paths in technology enterprises requires not only a set of guiding principles but also a structured framework that links carbon management practices with innovation-oriented actions. A dual-carbon-based innovation framework integrates organizational-level carbon governance, product-level life-cycle carbon assessment, and value-chain collaboration into a coherent system that supports low-carbon technological advancement. This framework emphasizes the complementary roles of carbon accounting and carbon footprint analysis, positioning them as mutually reinforcing components that enhance strategic planning, operational transformation, and green technology development.

The framework consists of three interconnected layers:

1. Strategic Layer – embedding carbon objectives into enterprise-level strategies and long-term innovation planning;
2. Operational Layer – incorporating carbon data into processes, design activities, and managerial systems;
3. Collaborative Layer – extending carbon-oriented innovation across the supply chain and external partnerships.

These layers collectively enable enterprises to align environmental goals with technical capabilities and market demands. The key characteristics of dual-carbon-based innovation strategies are summarized in Table 5.

Table 5 Key Characteristics of Dual-Carbon-Based Innovation Strategies

Standard Dimension	Core Characteristics	Practical Approaches	Expected Impact
Strategic Integration	Incorporation of carbon goals into long-term innovation and development plans	Linking carbon metrics with corporate strategy, prioritizing low-carbon R&D agendas	Strengthened alignment between innovation direction and carbon reduction objectives
Data-Driven Transformation	Use of organizational and life-cycle carbon data to guide innovation	Integrating carbon accounting with carbon footprint insights; enabling digital carbon management platforms	More precise identification of innovation opportunities and emission hotspots
Process and Technology Enhancement	Continuous optimization of production processes and adoption of cleaner technologies	Implementing energy-efficient systems, advanced manufacturing, and digital monitoring tools	Reduced carbon intensity in operations and improved technological competitiveness
Product-Level Low-Carbon Design	Embedding carbon considerations into product design and material selection	Eco-design, low-carbon materials, modular structures, recyclable components	Development of low-carbon products with improved environmental performance
Supply-Chain Collaboration	Coordination with suppliers and partners to develop shared carbon reduction mechanisms	Carbon-based procurement systems, supplier carbon audits, co-development of low-carbon materials	Integrated emission reduction across the value chain and enhanced supply-chain resilience
Dynamic Evaluation and Adjustment	Continuous assessment of innovation progress and carbon performance	Establishing evaluation indicators, feedback loops, and iterative optimization mechanisms	Improved adaptability and consistency of innovation strategies over time

The framework emphasizes the interplay between strategic direction, technological execution, and value-chain engagement. At the strategic level, enterprises define long-term innovation trajectories informed by carbon reduction commitments. At the operational level, integrated carbon data systems guide the redesign of products, processes, and technologies. At the collaborative level, suppliers and partners are incorporated into shared carbon goals, ensuring that innovation does not remain siloed within the enterprise but extends to the broader ecosystem.

By incorporating these dimensions, the framework supports technology enterprises in achieving sustained green innovation that is both environmentally responsible and economically competitive. It highlights the need for coordination across organizational functions and emphasizes that effective carbon management requires simultaneous consideration of strategy, operations, and collaboration.

4.3 Case Analysis: A Representative Practice of Dual-Carbon-Based Innovation in a Technology Enterprise

To illustrate how the dual-carbon framework can be applied in practice, this section presents a representative example of how a technology enterprise integrates carbon accounting and carbon footprint analysis to support green innovation. Although the case is conceptualized rather than tied to a specific company, it reflects common practices observed in leading technology firms undergoing low-carbon transformation. The example demonstrates how enterprises can operationalize the principles and strategies described earlier and provides insight into the mechanisms through which dual-carbon management guides innovation activities.

4.3.1 Background of the enterprise

The case focuses on a medium-to-large technology enterprise engaged in smart device manufacturing, digital infrastructure, and component production. The company operates multiple production bases, maintains complex global supply chains, and invests heavily in research and development. As national regulations on carbon disclosure and carbon reduction became more stringent, the enterprise recognized the need to integrate environmental objectives with innovation strategies. To respond effectively, it established a dual-carbon management system consisting of organizational-level carbon accounting and product-level carbon footprint assessment.

4.3.2 Implementation practices

The enterprise initiated a multi-stage reform process that included data system development, internal governance restructuring, and product innovation driven by life-cycle insights. Key practices include:

4.3.2.1 Establishing a Digital Carbon Accounting System

The enterprise developed a unified digital platform to collect and manage carbon data across production facilities. The system standardized emission boundaries, automated data collection through IoT sensors, and consolidated Scope 1 to Scope 3 emission information. This centralized carbon inventory allowed managers to accurately identify major emission sources and set internal carbon targets aligned with the overall innovation strategy.

4.3.2.2 Conducting Life-Cycle Carbon Footprint Assessments

Parallel to organizational accounting, the enterprise launched a life-cycle carbon footprint project for its flagship hardware products. Through collaboration with suppliers, it gathered detailed material and process data covering upstream raw materials, manufacturing stages, logistics routes, product usage scenarios, and recycling processes. The results revealed that certain components—such as semiconductor modules and specialized composite materials—accounted for a disproportionate share of total emissions.

4.3.2.3 Linking Carbon Data with Innovation and R&D Planning
Findings from both accounting streams were integrated into the company's R&D decision-making system. The engineering division incorporated carbon footprint results into material selection and structural design reviews. At the same time, management used carbon accounting insights to prioritize investments in cleaner production technologies, including energy-efficient equipment, low-carbon surface treatment processes, and intelligent energy management systems.
4.3.2.4 Promoting Supplier Collaboration for Low-Carbon Materials
Recognizing the importance of upstream emissions, the enterprise worked closely with key suppliers to co-develop alternative materials with lower carbon intensities. Joint innovation initiatives focused on recyclable alloys, bio-based polymers, and high-efficiency electronic components. Supplier performance evaluations were updated to include carbon indicators, encouraging alignment across the supply chain.
4.3.2.5 Integrating Carbon Metrics into Product Evaluation and Market Strategy
To ensure consistency and accountability, the enterprise incorporated carbon indicators into product quality assessment, procurement rules, and internal performance reviews. Low-carbon product lines were highlighted in marketing strategies to strengthen brand competitiveness and meet customer expectations for environmentally responsible products.

5 DISCUSSION AND CONCLUSION

5.1 Discussion

This study investigates how carbon accounting and carbon footprint jointly contribute to the development of green innovation in technology enterprises. The findings presented in earlier chapters reveal that the integration of these two carbon management mechanisms forms a multidimensional framework that supports innovation at strategic, operational, and collaborative levels. The analysis highlights several theoretical and practical implications.
First, the study underscores the importance of integrating organizational and product-level carbon information. While carbon accounting provides a macro-level overview of enterprise emissions, carbon footprint offers micro-level, life-cycle-based insights. Their combination enables enterprises to develop a more accurate understanding of emission sources, revealing opportunities for technological upgrading, material substitution, and supply-chain optimization. This dual perspective strengthens decision-making by bridging corporate environmental objectives with actionable innovation strategies.
Second, the discussion emphasizes the central role of data governance in enabling effective dual-carbon management. High-quality carbon data allow enterprises to justify innovation investments, identify high-impact intervention points, and evaluate the effectiveness of technological improvements. The reliance on digital systems, such as carbon data platforms, IoT monitoring devices, and life-cycle databases, suggests that digitalization is not merely a supporting element but a fundamental driver of carbon-informed innovation.
Third, the analysis reveals how carbon governance mechanisms can act as internal sources of innovation incentives. By embedding carbon metrics into performance evaluations, budget allocation processes, and R&D planning, enterprises convert environmental constraints into opportunities for technological progress. This governance-driven innovation logic demonstrates that carbon management is not limited to compliance but can operate as a catalyst for organizational transformation and capability development.
Fourth, the study highlights the significance of value-chain collaboration in achieving systemic carbon reduction. Innovation activities that depend solely on internal processes may fail to capture upstream and downstream emission drivers. Effective dual-carbon management requires suppliers, partners, and customers to participate in coordinated innovation. The case analysis illustrates how supplier engagement in low-carbon materials development and carbon-based procurement standards can expand the scope and depth of innovation outcomes.
Finally, the study offers theoretical contributions by synthesizing insights from information asymmetry theory, resource -based view, and institutional theory. These theoretical perspectives help explain why enterprises invest in carbon information systems, how carbon management becomes a strategic resource, and under what institutional pressures enterprises adopt low-carbon innovation actions. The integration of these theories enriches understanding of dual-carbon-based innovation and provides an analytical foundation for future research.

5.2 Conclusion

This study explores the pathways through which carbon accounting and carbon footprint jointly drive green innovation in technology enterprises, proposing a dual-carbon framework that integrates organizational carbon governance with life-cycle carbon analysis. The findings indicate that:
1. Carbon accounting enhances innovation by providing enterprise-wide carbon inventories, strengthening internal governance, and embedding carbon considerations into strategic planning.
2. Carbon footprint analysis guides innovation by identifying life-cycle emission hotspots, informing eco-design, and supporting low-carbon process improvements.
3. The integration of carbon accounting and carbon footprint creates a comprehensive carbon management system that supports green innovation across strategic, operational, and collaborative dimensions.

4. A dual-carbon-based innovation pathway requires alignment of data integrity, carbon governance, technological upgrading, value-chain cooperation, and adaptive evaluation.

Taken together, these insights demonstrate that dual-carbon management is not merely a compliance mechanism but a powerful driver of long-term, capability-based environmental innovation. For technology enterprises, the adoption of integrated carbon management practices can strengthen competitiveness, support sustainability commitments, and accelerate the transition toward low-carbon development.

Future research may explore additional mechanisms, such as the role of carbon auditing, digital twin technologies, or industry-specific carbon innovation models, to further expand the theoretical and practical understanding of dual-carbon -driven innovation. As carbon regulation intensifies and markets increasingly value environmental performance, the strategic integration of carbon accounting and carbon footprint will become an essential pathway for technology enterprises seeking sustainable growth.

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BILATERAL DIPLOMATIC RELATIONS AND CROSS-BORDER M&AS: EVIDENCE FROM CHINA

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Abstract: Cross-border mergers and acquisitions (M&A) are one of the most important ways for countries to participate in the global economy. China's bilateral diplomatic relations with other countries are flawed and the data are mainly from the Chinese media, which may lead to omissions in diplomatic events, lack of objectivity and insufficient information, which may lead to miscalculations. Therefore, it is necessary to select a measure that reflects the high level of recognition between the two countries in international affairs or bilateral affairs. Using unbalanced panel data (including cross-border M&A data and United Nations General Assembly (UNGA) voting data) for 181 countries (or regions) from 1992-2017, the paper empirically examines the impact of bilateral diplomatic relations on China's cross-border M&A completion rate and its mechanism of action, by building an estimation model, mediation effect models, and conducting a robustness test. The mediating effect in the mechanism test finds that bilateral diplomatic relations affect the completion rate of cross-border M&As between Chinese and foreign firms through both formal (i.e., the signing of BITs and the establishment of bilateral partnerships) and informal mechanisms (i.e., exchanges among senior bilateral leaders and the establishment of Confucius Institutes). For formal institutions, bilateral diplomatic relations can increase the completion rate of cross-border M&As from and to China by facilitating the signing of BITs and the establishment of bilateral partnerships. For informal institutions, bilateral diplomatic relations increase the completion rate of cross-border M&As from and to China by facilitating exchanges between high-level leaders of the two countries and the establishment of Confucius Institutes. The results of the study show that bilateral diplomatic relations can help improve formal and informal systems to facilitate successful cross-border M&As, and the Chinese Government can draw on the successful experience of political diplomacy to create more opportunities for bilateral political, economic and cultural exchanges. In addition, both China and other countries can actively explore bilateral and multilateral cooperation mechanisms and promote the establishment or formulation of new cooperation rules and agreements.
Keywords: China; Cross-border mergers and acquisitions; Bilateral diplomatic relations; Mediating effect

1 INTRODUCTION

As the largest source of outward foreign direct investments (OFDI) from emerging economies, China has emerged as a leading global investor by proactively pursuing cross-border mergers and acquisitions (M&As). According to Thomson SDC statistics, the total amount of Chinese firms' cross-border M&As has increased from US $ 1.38 billion in 2002 to US $ 135.33 billion in 2016, increased by 98 times. But the failure rate of Chinese firms' cross-border M&As is also very high.

Existing literature indicates that the failure rate of cross-border M&As is very high, as firms confront "distance" such as institutional and cultural distance and the Liability of Foreignness [1]. Drawing on the institutional perspective, some studies consider the home-country institutional context and identify that government support also contribute to Chinese OFDI. Bilateral diplomatic relations establish a "bridge" between the host and the home country institution, creating a favorable political mutual trust and institutional ties for foreign firms to enter each others' market[2-4]. Apparently, government involvement gives cross-border firms a unique path in terms of international expansionThese limited studies highlight that bilateral diplomatic relations have become an important engine in promoting Chinese OFDI [5,6]. However, we are still unclear as to whether friendly bilateral diplomatic relations play a positive role in cross-border M&As and what is the mechanism.

In the existing researches, bilateral diplomatic relations between China and other countries are mainly measured by high-level leaders' mutual visits [7], bilateral partnership [8] and diplomatic relations between major powers [9]. However,these measures may be flawed. First, the number of high-level leaders' bilateral visits or diplomatic relation in major powers is limited, the duration is short. The concept of bilateral partnership is ambiguous and unclear [10] Second, the data is mainly obtained from Chinese media, which may cause the problem of omissions of diplomatic events. There may be lack of objectivity and insufficient information, which leads to misjudgment [11]. Therefore, it is necessary to choose a measure that is general, including most countries, and can reflect the high degree of recognition of the two countries in international affairs or bilateral affairs in order to better reflect the results of friendly diplomatic relations between the two countries.

At present, in the international political field, the United Nations voting data is used to reflect the foreign policy preferences of a country [12], and the foreign policy similarity between two countries can represent bilateral diplomatic relations between two countries[4,13]. China uses diplomacy tools to increase foreign policy similarity with other countries through the following channels. First, China use economic diplomacy to strengthen economic ties with many countries in the world, which can be further transformed into foreign policy similarity[2]. Second, outside the economic realm, soft power strategy is a comprehensive diplomatic tool which can facilitate bilateral relationship and recognition[14]. Third, China win other countries' support has been facilitated by a general shift from a "responsive" to a "proactive diplomacy," state and public diplomacy [15], expanding international influence and "generate bargaining leverage in its bilateral interactions" [16]. Strong political ties potentially further increase foreign policy similarity[17]. Thus, bilateral diplomatic relationship between China and other countries has close relationship with foreign policy similarity,foreign policy similarity is also a comprehensive representative of bilateral relationship.

Against this background, this study aims to investigate the impact of bilateral diplomatic relations on the completion of cross-border M&As from and to China and further examine the effect mechanism. The main contribution of the paper lies in the following ways. First, this paper focuses on the impact of bilateral diplomatic relations on the success rate of cross-border M&As from and to China. Existing literature has examined the impact of bilateral diplomatic relations on the total amount of trade or investment, instead of the success rate of investment. Diplomatic relations play important role in reducing investment risk for cross-border M&As,thus,it is necessary to see whether diplomatic relation have positive effect in reducing cross-border investment risk. However, endogenous problem may exist,that is whether cross-border M&As affect bilateral diplomatic relation, so we use GMM and IV method to solve this problem in the robustness test. Moreover, compared to the existing studies which mainly focus on the success rate of Chinese firms' cross-border M&As, we discuss the effect of bilateral diplomatic relations on the success rate of cross-border M&As both from and to China. Second, we further discuss the mechanism of the impact of bilateral diplomatic relations on the success rate of cross-border M&As, mainly from formal institution such as the signing of bilateral investment agreements and the establishment of partnerships, and informal institution such as the exchange of bilateral high-level leaders and the establishment of Confucius Institutes. Third, this paper adopts the foreign policy similarity data calculated based on the latest United Nations General Assembly(UNGA) voting data as a proxy of bilateral diplomatic relations friendliness between China and other countries[13]. Different from the previous measurement of diplomatic relations from Chinese perspective, the UNGA voting data offers the advantage that the data is available for all states in the international system and for a long time period, it also exhibits a higher level for variance than other foreign relations,thus contains more information on a nation's foreign policy interests[18], which can more objectively quantify the political relations between the two countries.

2 LITERATURE REVIEW AND HYPOTHESIS

2.1 Bilateral Diplomatic Relations and Cross-border M&As

Chinese firms are playing an increasingly important role in cross-border M&A market, but at the same time, the failure rate of cross-border M&A is still high [19]. Existing literature have studied the reasons for the failure of cross-border M&As,which indicate that institutional environment is one of the key factors. The host country's institutional environment has an important impact on corporate behaviour[20,21], since institutions can promote or restrict market transactions by reducing or increasing the transaction costs involved in corporate transactions. International firms need to obey the host country's institutional environment in order to establish legitimacy in the host country and help ensure subsequent business success[22]. In a host country with good institutional environment, the operating environment of the enterprise is better, and the transaction costs and uncertainty to gain profit are reduced, which is beneficial to corporate investment [6]. Secondly, institutional distance between the host country and the home country also affects firms' cross-border M&As. Research shows that the institutional distance between countries has a negative impact on the success rate of cross-border M&As[22]. Greater institutional distance indicates greater uncertainty and unfamiliarity with the local environment, thus increasing the cost of doing business in foreign countries for cross-border firms [23] and making it more difficult for firms to shift strategies and practices among affiliates, and gain legitimacy in foreign markets.

As the failure of cross-border M&As has caused many unnecessary losses to cross-border firms, it is also important for scholars to study what factors can reduce the negative effects of the institutional distance on multinational firms[5,24]. Although the existing studies point out that the institutional environment of the host country and the home country have an important impact on cross-border M & As, few studies consider the impact of the common linkage between the host and the home country on the internationalization of enterprises.In recent years, the internationalization of firms in emerging countries is still developing rapidly without "Ownership advantage". The motivation behind this behavior has aroused widespread concern in the academic, among which the bilateral diplomatic relation is one of the most important driving factors. Bilateral diplomatic relations establish a "bridge" between the host country and the home country institution. Most studies have proved that the friendly political relationship between the investing country and the host country is conducive to the development of OFDI[3,25]. The main theoretical analysis uses the transaction cost and agency theory to analyze the role of international political system and the relationship between countries. First, it is believed that institutional arrangements between countries can reduce uncertainty and help reduce the cost of legal transactions [26]. Friendly bilateral diplomatic relations can promote political mutual trust and reach consensus on cooperation[27], reducing the cost and uncertainty of legal transactions, and providing protection for enterprises' investment in the host country[28]. Moreover, bilateral diplomatic relations can form an external binding force on the host country's institutional risks, indirectly affect cross-border M&As and have some moderating effect on the inherent political, economic, and cultural institutional distances between two countries. On the one hand, when two countries have large institution differences, firms are not familiar with the local market, they encounter difficulties of information searching, communication and negotiation, and legal protection of M&As activities, which will lead to higher costs and greater uncertainty. On the other hand, large institution distance would cause cross-border firms to face difficulties in the internal and external legitimacy of the host country, and higher adaptation and coordination costs[29]. Friendly diplomatic relations are a higher-level institutional arrangement that is conducive to the creation and improvement of various other bilateral rules, which can guarantee the interests of investors, and also helps investors adapt to the host country institution[30]. Therefore, the institutional linkages created by bilateral diplomatic relations can compensate for the institution differences in host country, lower entry barriers for investors of the home country, enhance the legitimacy of investment, reduce the investment risks of multinational enterprises, and increase cross-border M&As' success rate. The hypothesis is proposed:

Hypothesis 1: Bilateral diplomatic relation has a positive impact on the completion rate of cross-border M&As from and to China.

2.2 The Influence Mechanism of Bilateral Diplomatic Relation on Cross-Border M&As

Based on the theory of realism in international relations, the diplomatic relation between the two countries is not only at the political level, but also affect the cooperation in economic and cultural aspects, which can help to create formal and informal institutions linkages between home and host countries. In an economy, there are formal and informal institutions that govern the economic behaviour of firms and the ways in which they interact[20,21]. Formal institutions refer to the rules, laws, and practices of a particular society; informal institutions refer to the implicit values and norms of culture, language, and society[22]. Institutional theory holds that there are significant differences of formal and informal institutions in various countries[31]. Differences of the formal institutions (laws, regulations, etc.) between the home country and the host country, as well as the informal institution (culturally driven), will affect several aspects of cross-border firms entering to overseas market, including the entering method, amount of M&A share, and success rate[21,32]. However, bilateral diplomatic relations can promote the establishment of formal and informal institutions and regulate the institution differences between two countries.

On the one hand, bilateral diplomatic relations will promote the establishment of formal institution between two countries, such as bilateral security alliances, bilateral partnerships or bilateral treaties[30]. Various uncertainties of economic exchanges between countries can be reduced through this relationship, which enhances bilateral trust so as to make it easier for the host country to accept foreign investment[33]. Secondly, the cost for firms to search for potential partners will be lower, because the information asymmetry problem will be alleviated[34]. Furthermore, the uncertainty of transactions can be minimized and the institution risk of investments in host country can be reduced, promoting the smooth development of bilateral economic cooperation. In reality, China responds to bilateral friendly diplomatic relations and joins some important international organizations mainly through establishing partnerships with other countries and signing bilateral investment agreements. On the one hand, partnership relation provides an institutionalized framework for bilateral relations. It is an independent and cooperative relationship between countries based on common interests, common actions, mutual complementarity, and common development. Under this framework, the bilateral relationship can further strengthen cooperation[35]. Studies have shown that bilateral partnerships can increase Chinese investment in host countries[36]. On the other hand, economic cooperation between the two countries will get promoted through bilateral friendly diplomatic relations. In order to obtain the legitimacy of foreign investment and regulate bilateral investment, the two countries will sign Bilateral Investment Treaties (BITs), which will effectively protect the property rights of foreign-owned enterprises in the host government, which brings an important practical impact. By protecting investment property rights and ensuring fair and preferential treatment of foreign investment, BITs have reduced the negotiation and transaction costs of individual firm, protected foreign investment, and promoted bilateral investment between signatory countries [28].

On the other hand, bilateral diplomatic relations will naturally evolve into informal institution, such as immigration resulted from close exchanges between the two countries [37]. It is mainly formed due to the close interaction between two countries, and finally promotes the convergence of bilateral values[30]. The two countries with informal institution enjoy similar languages, institutional structures, and business ideas, which can have a longer-term impact on economic exchanges[30]. In reality, China has established Confucius Institutes in other countries as a platform for bilateral cultural exchanges and Chinese learning, enabling bilateral countries to build bridges of non-governmental exchanges through non-governmental behavior, which is conducive to spreading bilateral cultural exchanges and language learning, and enhance the trust of the people of both countries, to strengthen cooperation between the two countries in various fields [38], thereby promoting the success of cross-border M&As.

Friendly diplomatic relations between two countries can promote more high-level leaders' exchange visits, which is also a form of informal institution. On the one hand, high-level mutual visits release signals of friendly relations between the two countries, enhance understanding, mutual trust and friendship between them, and reduce the security threats posed by political prejudice to corporate investment [39]. On the other hand, during high-level exchanges of visits, direct dialogue and political consultations are used to resolve possible differences in major bilateral interests, which enhances the ability and opportunities for negotiation, bargaining, and even rent-seeking activities, thereby increasing the possibility of economic transactions[33], increasing the confidence of enterprises in long-term investment in the host country, promoting enterprises to invest in the country[40], reducing the risk of enterprise investment and increasing the success rate of cross-border M&A. Thus, the hypothesis is proposed:

Hypothesis 2: Bilateral diplomatic relation influence the completion rate of Chinese cross-border M&As by promoting formal and informal institution linkages.

3 MODEL AND BASIC RESULTS

3.1 Data Sources

We use an unbalanced panel data of 181 countries (or regions) from 1992 to 2017 to empirically test the effect of bilateral diplomatic relations on the completion rate of cross-border M&As from and to China and the effect mechanism. The countries or regions of the sample come from World Bank WDI data.

The data of cross-border M&As comes from the Thomson SDC Platinum. We follow the following procedures in data processing for cross-border M&As. First, we choose China as the home country of the parent firms to get the data of cross-border M&As from China. Second, we choose China as the host country of the parent firms to get the data of cross-border M&As to China. Third, we stipulate that the acquirer is a corporate entity rather than an individual. Fourth, for cross-border M&As from China, we set that the target firm and its parent firm are not Chinese firms, while the parent company of the acquirer is in China, vice versa for cross-border M&As to China. Fifth, acquirers classified as financial firms according to *The Industry Classification Guidelines of Listed Companies*, issued by the CSRC, are excluded and the subject matter of the M&A event is the equity of the target firm, so as to avoid the impact of asset-acquisition events on the research.

The data of bilateral diplomatic relations mainly comes from the latest research of Bailey, Strezhnev & Voeten[4] by using the United Nation General Assembly (UNGA) voting data, which is processed with the Item Response Theory and Dynamic Ordinal Spatial Indicator Model to calculate the ideal point of each country's foreign policy. The ideal point is not binary data, but has specific scores, therefore, the absolute value of the difference between the ideal scores of each country can be used to denote the similarity of the two countries' foreign policy, we re-calculate foreign policy similarity between two countries as a proxy variable reflecting the degree of bilateral diplomatic relations between two countries[41].

3.2 Variables

3.2.1 Dependent variables

The dependent variable $M\&A_{it}$ indicates cross-border M&As in country "*i*" in year "*t*" from China to other countries or from other countries to China. In the database of Thomson SDC Platinum, for every M&A deal, we mainly consider two variables: announced deal and effective deal. Then, by summing up the cross-border M&As from China to a certain country and certain year, we can obtain variables such as the number of completed M&As deals, or the number of M&A announcements, the total value of completed M &As in one year and in one country. We make the same data processing for cross-border M&As from other countries to China.In this paper, we mainly use the number of completed cross-border M&As as a percentage of the number of announced cross-border M&As of country "*i*" in year "*t*" to represent the completion rate of cross-border M&As. In the robustness test, we also use the number of successful M&A cases.

3.2.2 Independent variables

Bilateral diplomatic relation ($forsimilar_{it}$) is the independent variable which indicates the degree of of bilateral diplomatic relation friendliness between China and country "*i*" in year "*t*". We define the variable of bilateral diplomatic relation on the basis of " Ideal Point" of Bailey, Strezhnev & Voeten[4] as $forsimilar = \frac{1}{\ln(|dforpoli - cdforpoli| + 1)}$. As there may $|dforpoli - cdforpoli| = 0$, it is necessary to add 1 and then take logarithm. Larger value of *forsimilar* means more friendly bilateral diplomatic relation.

3.2.3 Control variables

"X" represents control variables. According to Buckley et al.[42] and Kolstad and Wiig[43], three kinds of variables are controlled. The first variable reflects the situation of the host country, including: economic development (real per capita GDP, *lrpgdp*); the industrial structure of the host country (proportion of added value of secondary industry to GDP, *Rwg2*); the openness of the host country (total imports and exports as a proportion of GDP, *open*); the consumption structure of the host country (proportion of final consumption to GDP, *Rconsum*). The second variable reflects the situation of the home country, including: the economic development of the home country (logarithm of China's real GDP per capita, *clrpgdp*), the industrial structure of the home country (proportion of added value of China's secondary industry to GDP, *cRwg2*); the openness of the home country (proportion of total imports and exports to GDP, *copen*); the consumption structure of the home country (final consumption as a proportion of GDP, *cRconsum*). The third variable reflects the relationship between the host and home country, including the import and export relationship (proportion of the total import and export volume to China in the total import and export volume, *Reximc*), the logarithmic of geographical distance between the two capitals of the home and host country (*ldist*), and whether the host country borders China (if the country borders China's territory, it is assigned a value of 1, otherwise the value is 0, *conti*). In addition, we also control the year fixed effect and the individual fixed effect respectively in regression analysis.

4 EMPIRICAL METHODOLOGY

4.1 Model

This paper focuses on the impact of bilateral diplomatic relations on the completion rate of cross-border M&As from and to China. Referring to Gravity Model in international investment of Anderson &Van Wincoop[44] and studies of institutional influence on China's OFDI[42,45], we set the following estimation model:

$$M\&A_{it} = \beta_0 + \beta_1 forsimilar_{it} + X'\lambda + \alpha_i + \eta_t + \varepsilon_{it} \quad (1)$$

In model (1), i represents the country of cross-border M&As from or to China, and t represents the year. The coefficient $\beta 1$ measures the direction and intensity of the bilateral diplomatic relations on cross-border M&As from or to China.

4.2 Basic Results

Based on model (1), the panel data model is established to test the impact of bilateral diplomatic relations on the completion of cross-border M&As from and to China. Table 1 presents the results of basic regression and tables 2 to 4 show the results of different types of robustness tests.

Table 1 Regression Results of Model 1: The impact of Bilateral Diplomatic Relation on the Completion Rate of Cross-Border M&As Completion

	(1)	(2)	(3)	(4)	(5)	(6)
	Cross-border M&As from China			Cross-border M&As to China		
forsimilar	0.347***	0.361**	0.302**	0.101**	0.151**	0.295***
	(0.111)	(0.152)	(0.150)	(0.045)	(0.076)	(0.090)
lrpgdp		3.835***	3.762***		4.458***	4.091***
		(0.578)	(0.283)		(0.271)	(0.196)
Rwg2		-0.143***	-0.158***		-0.196***	-0.158***
		(0.053)	(0.026)		(0.027)	(0.019)
open		0.037**	-0.014		0.030***	-0.006
		(0.019)	(0.011)		(0.006)	(0.006)
Rconsum		0.132***	-0.041*		0.004	0.011
		(0.049)	(0.024)		(0.021)	(0.014)
Reximc		97.487	828.911***		323.374***	415.898***
		(382.869)	(277.200)		(112.720)	(116.918)
ldist			-3.373***			-5.536***
			(0.837)			(0.515)
conti			2.526			-2.155**
			(1.593)			(1.037)
clrpgdp			8.714**			-7.812***
			(4.029)			(2.613)
cRwg2			-1.531**			0.358
			(0.610)			(0.401)
copen			0.011			0.026
			(0.090)			(0.060)
cRconsum			-0.621			-1.016***
			(0.540)			(0.334)
Constant	5.036***	-29.289***	25.501	3.827***	-29.463***	95.552***
	(0.316)	(5.892)	(37.967)	(0.148)	(2.618)	(22.970)
Individual fixed effect	Y	Y	N	Y	Y	N
Year fixed effect	Y	Y	N	Y	Y	N
N	4261	2387	2379	4261	2387	2379
R^2	0.052	0.332	0.161	0.026	0.472	0.281

*Note: (1) ***, ** and * represent significance levels of 1%, 5% and 10% respectively; (2) The standard error is in the small brackets; (3) R^2, N represent goodness of fit and number of individuals respectively.*

In Table 1, the dependent variable of Columns (1)-(3) is the completion rate of cross-border M&As from China to other countries. In Column (1), there are no control variables, Column (2) adds variables reflecting the situation of host countries,we control both year fixed effect and individual fixed effect in Column (1)-(2). Column (3) adds variables reflecting the situation of China and the relationship between the host and the home country,which are geographical distance, whether or not there is a border, and doesn't control year and individual fixed effect. The dependent variable of Columns (4)-(6) is the completion rate of cross-border M&As from other countries to China. For the control variables,we take the same processing as Columns (1)-(3).

We mainly intend to study the coefficient of bilateral diplomatic relation (*forsimilar)*. In Columns (1)-(3), it can be seen that, when different dimensions of control variables are added, the coefficient is significantly positive at least 1%. This indicates that friendlier bilateral diplomatic relations significantly improve the completion rate of Chinese cross-border M&As. In Columns (4)-(5), it can be seen that, the coefficient is also significantly positive at least 1%, which indicates that friendlier bilateral diplomatic relation can significantly improve the completion rate of cross-border M&As to China. The results of the basic regression further verify that friendlier bilateral diplomatic relation can improve the completion rate of cross-border M&As.

4.3 Robustness Test

We conduct robustness tests regarding the regression of Table 1 in Tables 2-4. We use other control variables in the same way as the regression of Column (2) and Column (5) in Table1.

Table 2 Robustness Test: Replace the Dependent Variable

	(1)	(2)	(3)	(4)
	ln(1+ Number of successful M&A cases)			
	Cross-border M&As from China		Cross-border M&As from China	
forsimilar	0.004**	0.005**	0.003***	0.004**
	(0.002)	(0.002)	(0.001)	(0.002)
Constant	0.090***	-0.469***	0.135***	-0.577***
	(0.005)	(0.084)	(0.008)	(0.053)
Other control variables	N	Y	N	Y
Individual fixed effect	Y	Y	Y	Y
Year fixed effect	Y	Y	Y	Y
N	4261	2387	4261	2387
R^2	0.025	0.327	0.226	0.396

*Note: (1) ***, ** and * represent significance levels of 1%, 5% and 10% respectively; (2) The standard error is in the small brackets; (3) R^2, N represent goodness of fit and number of individuals respectively.*

First, in Table 2 we replaced the dependent variable by using the number of successful M&A cases,specifically ln (1+ number of successful M&A cases) as measure of the dependent variable. In Columns (1)-(2) is the the number of successful M&A cases of from China to other countries, Columns (3)-(4) is the the number of successful M&A cases of from other countries to China.The coefficient of (*forsimilar*) in Columns (1)-(2) are significantly positive at least at the level of 5%. The coefficient of (*forsimilar*) in Columns (3)-(4) are significantly positive at least at the level of 1%. The results show that even if the dependent variables are replaced, the conclusion of Table 1 still holds, that is, friendlier bilateral diplomatic relations significantly promotes cross-border M&As from and to China.

Table 3 Robustness Test: Replace the Independent Variable

	(1)	(2)	(3)	(4)
	Cross-border M&As from China		Cross-border M&As to China	
forsimilar2	10.560***	11.004***	3.207***	4.340***
	(2.346)	(2.479)	(0.893)	(1.284)
Constant	-0.108	-37.947***	2.214***	-33.313***
	(1.286)	(6.180)	(0.481)	(2.883)
Other control variables	N	Y	N	Y
Individual fixed effect	Y	Y	Y	Y
Year fixed effect	Y	Y	Y	Y
N	4287	2387	4287	2387
R^2	0.058	0.336	0.028	0.473

*Note: (1) ***, ** and * represent significance levels of 1%, 5% and 10% respectively; (2) The standard error is in the small brackets; (3) R^2, N represent goodness of fit and number of individuals respectively.*

Second, in Table 3 we replaced the independent variable by *forsimilar₂* which is defined as $forsimilar2 = \frac{1}{|dforpoli - cdforpoli| + 1}$. In Columns (1)-(2) is completion rate of cross-border M&As from China to other countries, Columns (3)-(4) is the completion rate of cross-border M&As of from other countries to China. The coefficient of ($forsimilar_2$) in Columns (1)-(4) are significantly positive at the level of 1%. The results show that even if the independent variables are replaced, the conclusion of Table 1 still holds, that is, friendlier bilateral diplomatic relations significantly promotes cross-border M&As from and to China.

Table 4 Robustness Test: Solving the Endogenous Problem

	(1)	(2)	(3)	(4)	(5)	(6)
	Cross-border M&As from China			Cross-border M&As to China		
VARIABLES	Fixed effect	System GMM	IV estimate	Fixed effect	System GMM	IV estimate
L.forsimilar	0.344**			0.202**		
	(0.158)			(0.080)		
forsimilar		0.122*	4.195***		0.103***	1.277**
		(0.070)	(1.215)		(0.031)	(0.523)
L.M&A		0.050***			-0.026***	
		(0.006)			(0.005)	
Constant	-29.570***		34.702	-29.527***		-3.825
	(6.144)		(31.738)	(2.678)		(17.014)
Individual fixed effect	Y	-	Y	Y	-	Y
Year fixed effect	Y	Y	Y	Y	Y	Y
N	2322	2324	2316	2316	2324	2316

*Note: (1) ***, ** and * represent significance levels of 1%, 5% and 10% respectively; (2) The standard error is in the small brackets; (3) N represent number of individuals respectively.*

Third, considering endogeneity, there may be reverse causality problem,that is, cross-border M&As may influence bilateral diplomatic relations. Based on established methods in the existing literature, we conduct a robustness test. First, we employ the lag term of bilateral diplomatic relation (*L.forsimilar*) as the independent variable. Second, we add the lag term of the completion rate of cross-border M&As (*L.M&A)* as the control variable, which is mainly concerned with the endogeneity problem caused by missing important variables, therefore, systematic GMM estimation method is adopted. Third, we use the lag term of bilateral diplomatic relation (*L.forsimilar*) as the instrumental variable of bilateral diplomatic relation of the current period. The results are shown in Table 4.

The dependent variable of Columns (1)-(3) is the completion rate of cross-border M&As from China to other countries. In Column (1), the lag term of bilateral diplomatic relation (*L.forsimilar*) is used as the independent variable, and the fixed-effect regression method is still adopted. The coefficient is significantly positive at the level of 5%. Column (2) adds the lag term of Chinese firms' cross-border M&As completion rate (L.M&A) as an independent variable. The coefficient of bilateral diplomatic relation is significantly positive at the 10% level. Column (3) uses the lag term of bilateral diplomatic relation (*L.forsimilar*) as the instrumental variable of the current period. The coefficient of bilateral diplomatic relation is also significantly positive at the level of 1%. The dependent variable of Columns (4)-(6) is the completion rate of cross-border M&As from other countries to China. We do the same regression as Columns (1)-(3). The coefficient of bilateral diplomatic relation is significantly positive at least at the 1% level. The above results indicate that friendlier bilateral diplomatic relation can improve cross-border M&As from and to China, which are consistent with the result of Table 1.

5 MECHANISM OF BILATERAL DIPLOMATIC RELATIONe ON CROSS-BORDER M&AS

5.1 Model

This section will examine the mechanism of bilateral diplomatic relation promoting the completion rate of cross-border M&As through both formal and informal institutions. Specifically, we use the mediation effect model as follows:

$$med_{it} = \alpha + \beta_1 forsimilar_{it} + X'\lambda + \varphi_i + \gamma_t + \mu_{it} \tag{2}$$

$$M\&A_{it} = \alpha_2 + \beta_2 forsimilar_{it} + \lambda med_{it} + X'\delta + \varphi_i + \gamma_t + \mu_{it} \tag{3}$$

In model (2)–(3), *med* is a mediation variable which is formal and informal institution. If the mediating effect holds, both conditions must be satisfied. First, β_1 is significant, that is, bilateral diplomatic relation has significant impact on the mediation variable. Second, λ is significant which indicates that there is mediating effect of bilateral diplomatic relation on cross-border M&As. If the above two conditions are satisfied, it can show that bilateral diplomatic relation can improve cross-border M&As through the mediation variables.

5.2 The Mediating Effect of Formal Institution

5.2.1 The mediating effect of Bilateral Investment Treaties (BITs)

BITs is officially signed between two countries to promote, encourage and protect or guarantee international private investment. We construct a dummy variable (*bit)* for BITs as mediation variable. If China signs BITs with a country (region) in a certain year, then *bit* of this year and the following years is assigned 1; otherwise, the value is 0.Table 5 presents the results.

Table 5 The Mediating Effect of Bilateral Investment Treaties(BITs)

	(1)	(3)	(4)

VARIABLES	*BITs(bit)*	Cross-border M&As from China	Cross-border M&As to China
forsimilar	0.005**	0.348**	0.145**
	(0.002)	(0.152)	(0.072)
bit		0.288**	0.335*
		(0.138)	(0.181)
Constant	-1.488***	-29.246***	-29.332***
	(0.205)	(5.847)	(2.660)
Other control variables	Y	Y	Y
Year fixed effect	Y	Y	Y
N	2387	2387	2387
R^2	0.119	0.332	0.472

*Note: (1) ***, ** and * represent significance levels of 1%, 5% and 10% respectively; (2) The standard error is in the small brackets; (3) R^2, N represent goodness of fit and number of individuals respectively.*

In Columns (1), the dependent variable is whether to sign BITs *(bit),* the coefficient of bilateral diplomatic relation (*forsimilar)* is significantly positive at the level of 5%; that is, friendlier bilateral diplomatic relation significantly promotes signing BITs between China and the certain country. Meanwhile, the dependent variables in Columns (2)–(3) are the completion rates of cross-border M&As from China and to China respectively.In Column (2)–(3) we take bilateral diplomatic relation and whether BITs are signed (*bit*) as the independent variable, the coefficients of bilateral diplomatic relation (*forsimilar)* are both significantly positive at the level of 5%, which shows that BITs can improve the success rates of cross-border M&As from and to China.

5.2.2 The mediating effect of bilateral partnership

Existing studies have shown that bilateral partnership can promote cross-border M&As, friendlier bilateral diplomatic relation means better mutual recognition between two countries, which can promote establishing bilateral partnership. Therefore, we take bilateral partnership as a mediation variable to test whether there is mediating effect. We construct a dummy variable of bilateral partnership (*parnter*), if China establish partnership with country *i* in year *t*, the value is 1, otherwise, it is 0. Table 6 shows the results.

Table 6 The Mediating Effect of Bilateral Partnerships

VARIABLES	(1) Bilateral partnership （*parnter*）	(2) Cross-border M&As from China	(3) Cross-border M&As to China
forsimilar	0.019***	0.307**	0.102**
	(0.004)	(0.150)	(0.048)
parnter		8.162***	1.915***
		(1.289)	(0.721)
Constant	-0.521***	-25.036***	-29.868***
	(0.116)	(6.013)	(2.604)
control variable	Y	Y	Y
Year fixed effect	Y	Y	Y
N	2387	2387	2387
R^2	0.478	0.351	0.474

*Note: (1) ***, ** and * represent significance levels of 1%, 5% and 10% respectively; (2) The standard error is in the small brackets; (3) R^2, N represent goodness of fit and number of individuals respectively.*

In Column(1), bilateral partnership is the dependent variable, the coefficient of bilateral diplomatic relation (*forsimilar)* is significantly positive at the level of 1%, indicating that friendlier bilateral diplomatic relation can promote establishing bilateral partnership. The dependent variables in Columns (2)–(3) are the completion rates of cross-border M&As from China and to China respectively. In Column (2)–(3) we take bilateral diplomatic relation and bilateral partnership as the independent variable, the coefficients of bilateral diplomatic relation (*forsimilar)* are both significantly positive at the level of 5%, which shows that the mediating effect of bilateral partnership holds, that is, friendlier bilateral diplomatic relation can improve the completion rate of cross-border M&As from and to China by promoting establishing bilateral partnership.

5.3 The mediating effect of informal institution

5.3.1. The mediating effect of bilateral high-level leaders' visits

We use bilateral high-level leaders' visits as a mediation variable to test whether bilateral high-level leaders' visits have mediating effect. Table 7 shows the regression results.

There are two kinds of bilateral leaders' visits. The first is Chinese national leaders' visits other countries, including the visits of the President of China, the Premier of China's State Council. The second is leaders of other countries who visit China, including Heads of State visiting China (found in the section on "China's Diplomatic Activities" in "China's Diplomacy"). This paper constructs the following dummy variables: The dummy variable of the Chinese President or Premier visiting foreign countries (*cy*), if the Chinese President or Premier visits a country in a certain year, the country will be assigned a value of 1 in that year, otherwise, the value is 0. The dummy variable of the heads of different countries visiting China(*wpy)*, if a head of country visits China in a certain year, the country has a value of 1 in the year otherwise, the value is 0.

Table 7 Mediating Effect of Bilateral High-Level Leaders' Visits

VARIABLES	(1) China's president or Premier's visit	(2) Foreign heads' visit	(3) Cross-border M&As from China	(4)	(5) Cross-border M&As to China	(6)
forsimilar	0.006**	0.009**	0.254*	0.253*	0.124**	0.114**
	(0.003)	(0.004)	(0.152)	(0.151)	(0.056)	(0.047)
cy			7.486***		3.722***	
			(1.414)		(0.869)	
wy				5.120***		1.967***
				(1.076)		(0.652)
Constant	-0.240	-0.865	-27.040***	-29.381***	-28.945***	-29.564***
	(0.700)	(0.543)	(5.715)	(5.856)	(2.580)	(2.608)
Other control variables	Y	Y	Y	Y	Y	Y
Year fixed effect	Y	Y	Y	Y	Y	Y
Individual fixed effect	Y	Y	Y	Y	Y	Y
N	2387	2387	2387	2387	2387	2387
R^2	0.094	0.146	0.346	0.342	0.478	0.474

*Note: (1) ***, ** and * represent significance levels of 1%, 5% and 10% respectively; (2) The standard error is in the small brackets; (3) R^2, N represent goodness of fit and number of individuals respectively.*

In Column (1)-(2), the dependent variables are bilateral high-level leaders' visits, the coefficient of bilateral diplomatic relation (*forsimilar)* is significantly positive at the level of 5%, indicating that friendlier bilateral diplomatic relations can significantly increase bilateral high-level leaders' visits, including China's leaders visiting other countries and other countries' leaders visiting China. In Column (3) - (4), the completion rate of Chinese firms' cross-border M&As is the dependent variable, and we add bilateral diplomatic relation and bilateral high-level leaders' visits including China's leaders visiting other countries and other countries' leaders visiting China respectively in the regression, and the coefficients of bilateral diplomatic relation (*forsimilar)* are both significantly positive at the level of 10%. In Column (5) - (6), the completion rate of cross-border M&As from other countries to China is the dependent variable, and we add bilateral diplomatic relation and bilateral high-level leaders' visits including China's leaders visiting other countries and other countries' leaders visiting China respectively in the regression, the coefficients of bilateral diplomatic relation (*forsimilar*) are both significantly positive at the level of 5%. The above results show that high-level leaders' visits have mediating effect, that is, friendlier bilateral diplomatic relation can improve the completion rate of cross-border M&As of Chinese firms by promoting mutual high-level leaders' visits.

5.3.2 The mediating effect of cultural exchanges

The friendly diplomatic relations between two countries can not only enhance political mutual trust, but also deepen the understanding and trust between the two peoples through official or unofficial cultural exchanges and improving the communication efficiency. We take the Confucius Institute as the proxy variable of cultural exchange and use it as the mediation variable to test whether friendly bilateral diplomatic relations affect the completion rate of cross-border M&As from ant to China through establishing Confucius Institutes.

We construct two major variables for Confucius Institute. First, the logarithm of the Confucius Institute stock (*lconfu_sto*), specifically, *lconfu_sto=ln* (*1+ Confucius Institute stocks*). Second, whether there is a Confucius Institute (*confu_d*), which is a dummy variable. If a host country has a Confucius Institute in a certain year, the value is 1; otherwise, the value is 0 (The Confucius Institute data comes from http://www.hanban.edu.cn/.).

Table 8 Mediating Effect of Cultural Exchanges

VARIABLES	(1) Logarithm of Confucius Institute	(2) Dummy variable of Confucius	(3) Cross-border M&As from China	(4)	(5) Cross-border M&As to China	(6)

	stock	Institute				
forsimilar	0.021***	0.023***	0.189*	0.141**	0.063**	0.092**
	(0.004)	(0.004)	(0.108)	(0.062)	(0.031)	(0.044)
lconfu_sto			8.778***		3.776***	
			(0.730)		(0.472)	
confu_d				9.416***		2.032***
				(1.016)		(0.604)
Constant	-1.485***	-0.592***	-16.249***	-23.714***	-26.331***	-28.980***
	(0.264)	(0.145)	(5.476)	(5.547)	(2.601)	(2.607)
Other control variables	Y	Y	Y	Y	Y	Y
Year fixed effect	Y	Y	Y	Y	Y	Y
Individual fixed effect	Y	Y	Y	Y	Y	Y
N	2387	2387	2387	2387	2387	2387
R^2	0.378	0.433	0.389	0.366	0.493	0.475

*Note: (1) ***, ** and * represent significance levels of 1%, 5% and 10% respectively; (2) The standard error is in the small brackets; (3) R^2, N represent goodness of fit and number of individuals respectively.*

In Columns (1)–(2) of Table 8,the dependent variables are the logarithm of Confucius Institute stock and the Confucius Institute dummy variable respectively. The coefficients of bilateral diplomatic relation (*forsimilar)* is significantly positive at least at the level of 1%, that is, friendlier bilateral diplomatic relation can significantly promote cultural exchanges between the two countries. In Column (3) - (4), the dependent variable is the completion rate of Chinese firms' cross-border M&As, and we add the logarithm of Confucius Institute stock and the Confucius Institute dummy variable respectively in the regression, and the coefficients of bilateral diplomatic relation (*forsimilar*) are both significantly positive at least at the level of 10%. In Column (5) - (6), the dependent variable is the completion rate of cross-border M&As from other countries to China, and we add the logarithm of Confucius Institute stock and the Confucius Institute dummy variable respectively in the regression, and the coefficients of bilateral diplomatic relation (*forsimilar*) are both significantly positive at the level of 5%. The results show that establishing Confucius Institute has mediating effect,that is, friendlier bilateral diplomatic relation can help promoting the establishment of the Confucius Institute, enhancing mutual culture communication, thus, and improves the completion rate of cross-border M&As from and to China.

6 CONCLUSION AND POLICY IMPLICATIONS

By acknowledging the growth of M&As both from and to China and the bilateral diplomatic relation as an important tool to establish a institution linkage between China and other countries,this study, drawing on institutional theory, investigates the impact of bilateral diplomatic relation on the completion rate of cross-border M&As both from China to other countries and from other countries to China. The results show that friendly bilateral diplomatic relation can significantly improve the completion rate of cross-border M&As from China to other countries and from other countries to China. The mechanism test found that bilateral diplomatic relations affect the completion rate of cross-border M&As from China to other countries and from other countries to China through formal and informal institutions. For the formal institution, bilateral diplomatic relations can improve the completion rate of cross-border M&As from and to China by promoting the signing of BITs and the establishment of bilateral partnerships. For the informal institution, bilateral diplomatic relations increase the completion rate of cross-border M&As from and to China by promoting exchanges of high-level bilateral leaders and the establishment of Confucius Institutes.

Our study generates practical implications for the promotion of M&As from China to other countries and from other countries to China. To enhance the success of cross-border M&As from and to China, the Chinese government can take advantage of the successful experience of political diplomacy in creating more opportunities for bilateral political,economic and culture communication to enable people with different institution to understand and trust each other and win public support for deepening bilateral and multilateral cooperation. Moreover, China and other countries can make endeavor to find effective channels to make linkages between countries. The mechanism test in the paper shows the bilateral diplomatic relations can help to improve formal and informal institutions to enhance the success of cross-border M&As from and to China. Therefore, both China and other countries can actively explore bilateral and multilateral cooperation mechanisms to promote the establishment or formulation of new cooperation rules and agreements, for example, by strengthening dialogue between leaders of countries, increasing cultural exchanges with countries around the world.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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DEVELOPMENT COUNTERMEASURES FOR THE CONSTRUCTION OF ZHENGZHOU NATIONAL LOGISTICS HUB

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Abstract: Under the new development paradigm, addressing the critical issue of the "Construction of Zhengzhou National Logistics Hub," this paper deeply analyzes the current status of logistics development in Zhengzhou, discusses the strategic significance of constructing the Zhengzhou National Logistics Hub, clarifies the strategic direction, and proposes implementation strategies for its construction.The construction of the Zhengzhou National Logistics Hub is an important part of the logistics network system construction. It is conducive to promoting logistics network construction, reducing total social logistics costs, improving logistics service levels and quality, optimizing the economic spatial layout and economic system construction of Zhengzhou and Henan Province, and promoting the rapid and healthy development of Zhengzhou's logistics industry and national economy.
Keywords: Logistics hub; Logistics industry; Regional logistics; Logistics development countermeasures

1 INTRODUCTION

A logistics hub is a cluster of logistics facilities and an organization center for logistics activities that centralizes functions such as cargo aggregation, storage, distribution, and transshipment. The National Logistics Hub serves as the core infrastructure of the logistics system. It is a comprehensive logistics hub characterized by broader regional radiation, stronger agglomeration effects, superior service functions, and higher operational efficiency, playing the role of a key node and backbone in the national logistics network. According to the national logistics hub layout and construction plan, Zhengzhou is designated to build four types of national logistics hubs: Land Port, Airport, Production Service, and Commerce & Trade Service. Therefore, it is necessary to conduct in-depth research on the construction of the Zhengzhou National Logistics Hub and propose corresponding construction and development strategies to enhance Zhengzhou's logistics service capabilities and promote the rapid and healthy development of its logistics industry and economy.

Currently, relevant research focuses mainly on the planning and construction of national logistics hubs, the development of logistics industry, and the hub economy. Research related to the planning and construction of national logistics hubs focuses on relevant countermeasures and suggestions. Jiang Chaofeng believes that national logistics hubs should have complete functions and advanced facilities, adapting to the development trends of economic structure and industrial layout as well as foreign trade needs[1]. Wang Ming proposed that the task of high-quality construction and development of national logistics hubs is to accelerate logistics transformation and upgrading and cultivate the logistics hub economy[2]. Xie Yurong proposed carrying out collaborative operations centered on national logistics hubs, building specialized logistics systems relying on them, and cultivating and developing the hub economy around them[3]. Wang Weilong have proposed a development strategy for national logistics hubs to support logistics cost reduction and efficiency improvement[4]. Anderluh studied logistics hub cities [5]. Some scholars have proposed development strategies for the logistics industry from the aspects of logistics parks, logistics information platforms, multimodal transport, green logistics, talent cultivation, and resource integration[6-9]. Research on the hub economy mainly focuses on urban hubs and regional economies. Zhang Guoqiang analyzed the development mechanism of hub economy[10].

However, current research lacks certain timeliness and specificity. Therefore, closely combining the current economic and spatiotemporal environment, and against the background of high-quality economic development, this paper proposes development countermeasures for the construction of the Zhengzhou National Logistics Hub to address this urgent issue.

2 CURRENT STATUS Of LOGISTICS INDUSTRY DEVELOPMENT IN ZHENGZHOU

2.1 Current Status of Freight Development

With the continuous development of Zhengzhou's economy, the growth rate of freight turnover in Zhengzhou has been significant in recent years. Zhengzhou's freight turnover increased from 68.05 billion ton-kilometers in 2019 to 860.75 billion ton-kilometers in 2023. The average growth rate of freight turnover in the past five years exceeded 5%. In 2023, Zhengzhou's freight volume reached 225.54 million tons..

2.2 Current Status of Aviation Logistics Development

Relying on Zhengzhou Xinzheng International Airport, Zhengzhou aviation logistics is positioned to build an international air cargo hub. Through rapid development in recent years, an international aviation logistics hub has been preliminarily established. Currently, Zhengzhou Airport's routes cover more than 100 cities in over 20 countries across Europe, North America, Asia, and Oceania. In 2023, the cargo and mail throughput of Zhengzhou Airport reached 607,700 tons. It has preliminarily built an international route network connecting the world's major aviation hubs and economies, forming an international freight development pattern featuring dual hubs, multiple nodes, multiple routes, and broad coverage.

2.3 Current Status of China-Europe Railway Express Development

In 2013, Henan Province launched the China-Europe Railway Express relying on the Zhengzhou Railway Port. Currently, the China-Europe Railway Express has built an international logistics corridor connecting Henan with Europe and Central Asia. In recent years, the Zhengzhou China-Europe Railway Express has developed rapidly in terms of the number of trips and freight volume. From 2020 to 2024, the number of trips increased from 1,100 to over 3,000, and the freight volume increased from over 90,000 TEUs to over 260,000 TEUs. Compared with China-Europe Railway Express services in other regions of China, Zhengzhou continues to maintain a leading position by virtue of its comprehensive strengths such as high total freight volume and a wide range of collection and distribution.

3 DEVELOPMENT STRATEGY AND SIGNIFICANCE Of ZHENGZHOU NATIONAL LOGISTICS HUB

3.1 Factors Influencing the Construction of Zhengzhou National Logistics Hub

As an important railway, aviation, and highway hub city in China, Zhengzhou has significant transportation and locational advantages. The China-Europe Railway Express has entered normalized operation, and high-speed railway construction is advancing rapidly. The highway network is developed, reaching all prefecture-level cities in the province within 3 hours. The 1.5-hour aviation circle of Zhengzhou Airport covers two-thirds of China's major cities. Zhengzhou possesses advantageous industries such as automobiles, equipment manufacturing, food, textiles and clothing, electronic information, cross-border e-commerce, and aviation logistics. In recent years, Zhengzhou has innovated cluster industry development and promoted the economic transformation and upgrading of industrial agglomeration areas, achieving remarkable results. Relying on the Zhengzhou Airport Economy Zone, high-end airport industries centered on aviation logistics, cross-border e-commerce, high-end manufacturing, and electronic information have developed rapidly.

Currently, Zhengzhou Airport has preliminarily been built into an international aviation logistics hub. However, compared with large international aviation hubs, there is still a large gap, especially in some logistics infrastructure. Some logistics enterprises in the Zhengzhou Airport area remain in the traditional freight stage, and new logistics technologies and management concepts have not yet been applied. The overall strength of logistics enterprises is not strong, logistics costs are relatively high, and high-end logistics talents are lacking. The construction of the Zhengzhou National Logistics Hub faces strong competition.

3.2 Development Strategy for Zhengzhou National Logistics Hub

Guided by the construction of Zhengzhou as a National Central City and the Central Plains Economic Zone, and in accordance with the requirements of high-quality economic development in Zhengzhou, the strategy takes the construction of the international logistics hub as an opportunity. Relying on the Zhengzhou International Aviation Hub and the Zhengzhou Airport Economy Zone, and based on Zhengzhou's rapid economic development and industrial layout, guided by regional logistics demand, the strategy aims to fully leverage Zhengzhou's advantages in location, transportation, policy, and industry. Following the principles of unified planning, rational layout, and phased implementation, Zhengzhou will build a National Logistics Hub. By constructing a modern logistics service system and a logistics information network platform, it aims to create a core node of the national logistics hub network. Through the successful operation of the Zhengzhou National Logistics Hub, effective allocation of logistics resources will be realized, and Zhengzhou's logistics service level will be further improved. The development of the logistics industry will drive the coordinated development of related industries such as equipment manufacturing, electronic information, cross-border e-commerce, food, and trade, providing strong support for the coordinated development of national logistics hubs in Henan Province and the construction of an efficient logistics service system in Henan.

3.3 Strategic Significance of Constructing Zhengzhou National Logistics Hub

The construction of the Zhengzhou National Logistics Hub is conducive to promoting the construction of Zhengzhou's logistics network and the integration of logistics resources, leveraging the synergistic effects of resources. It is conducive to the innovation of Zhengzhou's logistics industry management system and related logistics organization models. It helps reduce the total social logistics cost in Zhengzhou and improve the level and quality of logistics services, thereby further promoting the development and construction of the Zhengzhou Airport Economy Zone and the China (Henan) Pilot Free Trade Zone, and optimizing the economic spatial layout and economic system construction of Zhengzhou City and Henan Province.

4 IMPLEMENTATION STRATEGIES FOR THE CONSTRUCTION OF ZHENGZHOU NATIONAL LOGISTICS HUB

4.1 Strengthen the Development of Multimodal Transport

The construction of the Zhengzhou National Logistics Hub should rely on the Zhengzhou Aviation Hub to carry out related work, providing fast, convenient, and efficient logistics services such as direct air transport, transshipment, and cargo consolidation for the Zhengzhou Airport Comprehensive Experimental Zone and its radiating areas. At the same time, relying on the Zhengzhou Aviation Hub, multimodal transport services should be strengthened. Utilizing the transport capacity of international routes and the China-Europe Railway Express, transport modes should be innovated to reconstruct the logistics network between Europe and Southeast Asia and open up international multimodal transport routes.

Expand and densify the international passenger and freight route network. Expand the scale of air cargo to countries along the "Belt and Road," improve the layout of Zhengzhou Airport's international long-haul route network, and build an opening gateway for the central and western regions. Enhance the radiating power of the China-Europe Railway Express, open up new routes, and realize the coordinated and linked development of international freight trains. Strengthen docking with coastal port group companies, form specialized sea-rail intermodal transport companies, and solve the problem of bulk commodity exports for import and export enterprises in the province relying on highway transport to the sea. By building and reconstructing waterways, form an inland river water transport development pattern connecting the Huaihe River system, the Yangtze River system, and other water network areas to the sea, gradually expand the scale of ports, and leverage water transport channels to promote closer connections between the Central Plains Economic Zone and the Yangtze River Economic Belt, the Yangtze River Delta urban agglomeration, and the world economy.

4.2 Build and Improve the Logistics Network

In the dimension of logistics infrastructure, make full use of various logistics parks, logistics centers, railway freight yards, airport distribution centers, highway logistics bases, railway dedicated lines, various professional warehouses, multimodal transport facilities, bonded logistics centers, and other logistics infrastructure within the Zhengzhou city area. Through the Zhengzhou logistics infrastructure network, strengthen the interconnection of various logistics infrastructures and realize logistics resource sharing.

In the dimension of logistics organization, through various forms such as virtual organizations, strategic alliances, mergers and acquisitions, and capital cooperation, strengthen cooperation among logistics-related enterprises such as logistics enterprises, commercial enterprises, and production enterprises within Zhengzhou city. Realize complementary advantages, information exchange, and business synergy, guide the aggregation of Zhengzhou logistics resources, and realize the sharing and efficient utilization of Zhengzhou logistics resources.

In the dimension of logistics information, by building the Zhengzhou National Logistics Hub information network, integrate various logistics information of the Zhengzhou National Logistics Hub, realize the integration of various logistics information in Zhengzhou, effectively dock and match various logistics demands and resources, and realize rapid response to logistics demands and effective utilization of logistics resources in the Zhengzhou National Logistics Hub.

4.3 Create Professional Logistics Services

In recent years, Zhengzhou has innovated the development of industrial clusters and promoted the economic transformation and upgrading of industrial agglomeration areas, achieving remarkable results. Relying on the Zhengzhou Airport Economy Comprehensive Experimental Zone and the Henan Bonded Logistics Center, high-end airport industries centered on aviation logistics, cross-border e-commerce, high-end manufacturing, and electronic information have developed rapidly. Therefore, the construction of the Zhengzhou National Logistics Hub must leverage Zhengzhou's industrial advantages to create professional logistics services in areas such as cold chain logistics, e-commerce logistics, and aviation logistics.

In terms of cold chain logistics, guide relevant cold chain logistics facilities within Zhengzhou to gather towards the National Logistics Hub and promote the large-scale development of Zhengzhou cold chain logistics. Make full use of advanced technology to rationally plan and build cold chain logistics facilities such as three-dimensional cold storage and distribution cold storage, and encourage leading enterprises in cold chain logistics to carry out joint cold chain distribution. At the same time, vigorously develop railway refrigerated transport and refrigerated container multimodal transport. In addition, strengthen the construction of the Zhengzhou cold chain logistics information platform and strengthen the traceability of Zhengzhou cold chain logistics information to ensure cold chain food safety.

In terms of e-commerce logistics, relying on the Zhengzhou Airport Economy Comprehensive Experimental Zone, the Air Silk Road, and the China-Europe Railway Express, vigorously develop cross-border e-commerce logistics and build a cross-border e-commerce logistics system. Strengthen the construction of the Zhengzhou rural e-commerce logistics system and promote the efficient circulation of agricultural products within Zhengzhou. Increase the construction of various e-commerce logistics platforms in Zhengzhou and promote the interconnection of information between the Zhengzhou National Logistics Hub network and various Zhengzhou e-commerce networks.

In terms of aviation logistics, relying on the Zhengzhou Aviation Hub, innovate the aviation logistics service system and business models to provide logistics service support and efficient and convenient aviation logistics services for the Zhengzhou Airport Comprehensive Experimental Zone and its radiating areas, as well as for industries such as cold chain logistics, e-commerce logistics, equipment manufacturing, and electronic information within the radiation area of the Zhengzhou Aviation Logistics Hub.

4.4 Vigorously Develop International Logistics

Focus on promoting aviation hubs and railway hubs, improving the operation level of the China-Europe Railway Express, expanding sea-rail intermodal train routes, and forming a development pattern driven by both aviation ports and railway ports with the integration of logistics and industry. Establish land-based international hub ports, build warehousing and logistics bases for expressway freight hub distribution, and form open ports in the interior such as aviation, railway, and expressway ports. Construct the Henan Free Trade Pilot Zone at a high level, continue to deepen the construction of the service system, give play to the role of various ports, and build overseas warehouses and logistics distribution centers.

Accelerate the construction of a hub-and-spoke aviation logistics network and build the Zhengzhou International Aviation Logistics Center. Dock with aviation-preference product manufacturing enterprises and promote multinational companies to set up Asia-Pacific distribution centers in Zhengzhou. Promote internationally renowned air freight forwarders to set up regional express distribution centers, support international logistics integrators to carry out international transshipment at Zhengzhou Airport, and realize the consolidation and transshipment of international cargo between Europe, America, and the Asia-Pacific region at Zhengzhou Airport.

5 CONCLUSION

In recent years, the development trend of Zhengzhou's logistics industry has been good. The construction of the Zhengzhou National Logistics Hub is an important part of the construction of the logistics network system. It is conducive to promoting the construction of the logistics network, reducing total social logistics costs, improving the level and quality of logistics services, optimizing the economic spatial layout and economic system construction of Zhengzhou and Henan Province, and promoting the rapid and healthy development of Zhengzhou's logistics industry and national economy.

Through the construction of a modern logistics service system and a logistics information network platform, a core node of the national logistics hub network will be created. Through the operation of the Zhengzhou National Logistics Hub, the effective allocation of logistics resources will be realized, the level of logistics services will be improved, and the development of the logistics industry will drive the coordinated development of related industries such as equipment manufacturing, electronic information, cross-border e-commerce, and food, providing strong support for the construction of an efficient logistics service system in Henan Province. The construction of the Zhengzhou National Logistics Hub should be steadily advanced from the aspects of strengthening the development of multimodal transport, building and improving the logistics network, creating professional logistics services, and vigorously developing international logistics.

COMPETING INTERESTS

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THE DETECTION OF HOUSEHOLD ECONOMIC ANOMALIES BASED ON THE CFPS2022 DATABASE: AN EXAMPLE OF INCOME-CONSUMPTION DEVIATION PATTERN ANALYSIS

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Abstract: In recent years, China's household debt has witnessed explosive growth, increasing financial vulnerability and posing a potential threat to economic stability. Based on the China Family Tracking Survey 2022 database, this study innovatively synthesizes three algorithms, namely the statistically based 3-criteria, Isolation Forest, and Local Outlier Factor (LOF), to detect anomalies with higher accuracy, and further applies a variety of data analysis techniques, such as cluster analysis, association rule mining, and Random Forest algorithm, to conduct a systematic and in-depth study of household economic anomalies. We also utilize various data analysis techniques such as cluster analysis, association rule mining, and random forest algorithm to conduct a systematic and in-depth study of household economic anomalies. Consequently, the study proposes policy recommendations such as strengthening financial education, providing precise support, and establishing a risk warning mechanism. These measures are expected to assist high-risk households, foster healthy economic development, and contribute to national economic stability.
Keywords: Household economic anomalies; Anomaly detection; Optimal algorithm; Debt; Income-consumption deviation patterns

1 INTRODUCTION

The economic health of households is the micro-foundation of a country's economic stability. In recent years, the scale of household debt in China has shown explosive growth, with the debt/GDP ratio soaring from 33% in 2013 to 63% in 2023, far exceeding the average level of emerging economies, with the proportion of non-housing debt continuing to rise, and the growth rate of short-term debt such as credit cards and consumer loans reaching an annual average of 18.7%. Household financial vulnerability has increased significantly, with 10.2% of households having a debt-to-income ratio of more than 200%. Meanwhile, household debt is growing at varying rates globally, and for highly indebted households, the ratio is close to or even exceeds 10%. In order to provide debt risk screening tools for financial institutions and help the government pinpoint high-risk household groups, this paper uses the China Family Tracking Survey (CFPS) 2022 database, which covers microeconomic behavioral data of more than 16,000 households in 31 provinces and cities across the country, for outlier detection and a series of studies. Traditional studies often regard economic data outliers as noise disturbances and reject them outright. However, this study finds that outliers may reflect real economic risks (e.g., debt crises, income breaks), and the key information they contain has significant positive value for economic forecasting models.

Established studies reveal the complex heterogeneity of household economic behavior and its risk transmission mechanism. At the level of economic characteristics, Yang Simin et al. based on CHFS data confirmed that there is a significant regional differentiation of digitalization on household debt burden: the eastern part of the country deepens the debt pressure due to the penetration of consumer finance, while the western part of the country reduces the burden through inclusive finance [1]; Li Xinya et al. used CFPS panel data to find that aging weakens the consumption through the triple mechanism of rising savings, decreasing incomes, and inhibiting leverage, and leads to the crowding out of basic consumption by medical expenditure [2]; Zhou Li et al. constructed a model to prove that debt leverage has an inverted U-shaped nonlinear effect on economic vulnerability, and the external risk transfer mechanism is also inverted. Using CFPS panel data, Li Xinya et al. found that aging weakened consumption through the triple mechanism of rising savings, lower income and leverage suppression, and led to medical expenditure crowding out basic consumption; Zhou Li et al. constructed a model to prove that debt leverage has an inverted U-shaped nonlinear effect on economic vulnerability, and the "gas pedal effect" is significantly amplified by external shocks [3]; and Mian & Sufi further suggested that credit-driven household demand is the core transmission channel of economic fluctuations [4].

In terms of data foundation, Xie et al. systematically explain the concept of multi-level dynamic design of CFPS database, which links macro-environment and micro-behavior through the three-level structure of community-family-individual, and adopts multi-stage PPS sampling to adapt to the process of urbanization, which provides high-precision micro-evidence for tracking household changes in China [5].

Methodological advances provide key technical support for this paper: in the field of anomaly detection, Yi-Qing Liu et al. improved the LOF algorithm to achieve adaptive threshold optimization through Cornish-Fisher distribution correction, which significantly improves the real-time detection effectiveness; in cluster analysis, Yun Lu verifies the utility of K-means in managerial scenarios, and at the same time, points out that density-based (e.g., DBSCAN) and grid-based approaches can effectively overcome its spherical cluster limitation; in association rule mining, the TaperR algorithm proposed by Qiang Li significantly improves the efficiency of multidimensional rule mining through pruning strategy and threshold estimation mechanism. These results lay a methodological foundation for the fusion of multiple algorithms to detect household economic anomalies in this paper.

Although the existing literature has yielded fruitful results on micro household debt risk, consumption-income imbalances and anomaly detection methods, there are still some shortcomings:

Most studies reject extreme samples in CFPS/CHFS as "noise", ignoring the real risk signals they may contain; the existing literature often adopts traditional statistical thresholds (e.g., 3-Sigma) or a single machine-learning model, which makes it difficult to capture "global extremes", "local density anomalies", and "population anomalies" at the same time. "The existing literature often adopts traditional statistical thresholds (e.g., 3-Sigma) or a single machine learning model, making it difficult to simultaneously capture the multiple heterogeneity of "global extremes," "local density anomalies," and "group pattern anomalies. The four steps of clustering, anomaly detection, association rules and prediction models are usually carried out independently, without an integrated framework of "discovery-validation-warning", which leads to a lack of operational risk labels and thresholds for policy implementation.

To address the above gaps, this paper designs a closed-loop process of "clustering a priori, integrating anomalies, attributing rules, and robust prediction" based on CFPS2022, to systematically assess the household income-consumption deviation patterns, and to provide a new technical route and empirical evidence for accurately identifying the highly indebted and vulnerable groups.

2 MODEL BUILDING

2.1 Comparison between Statistically Based 3-Criteria, Isolation Forest and LOF

In this paper, three different anomaly detection algorithms as well as a combination of the three algorithms are used in order to select the optimal algorithm with higher accuracy, namely the statistically based 3-criteria, Isolation Forest and Local Outlier Factor (LOF) [6,7].

In order to quantify the impact of outliers on economic forecasting models, this paper evaluates and compares the performance of outlier detection algorithms by selecting the following metrics: precision rate and outlier cluster profile coefficient (a metric that evaluates the quality of clustering and measures the tightness and separateness of the clustering results). Subsequently, this paper uses the dataset containing outliers to train a linear regression model, constructs a baseline model to predict household consumption, removes samples detected as outliers from the dataset, retrains the linear regression model, and then compares the root-mean-square errors (RMSEs) of the two models in order to assess the effect of outliers on the predictive performance of the model.

2.2 Cluster Analysis, Random Forest Model and Apriori Algorithm on Anomaly Labeling

2.2.1 Cluster analysis

Cluster Analysis is an unsupervised learning method used to divide a set of objects into a number of "clusters" according to a certain similarity metric, so that objects within the same cluster are similar to each other, and objects between different clusters are more different.As shown in equation (4), data set $X=\{x_1,x_2,...,x_n\}$, n samples into K clusters $\{C_1,…,C_K\}$,The center of each cluster is μ_k .K-means clustering achieves classification by minimizing the Euclidean distance of each cluster in the dataset from the centroid value.

$$J(C,\mu)=\sum_{k=1}^{K}\sum_{x\in C_k}\|x-\mu_k\|^2 \tag{1}$$

In this study, k-means clustering is used to identify different patterns of household income-consumption relationships, to identify anomalous groups that significantly deviate from the main pattern, and to establish a deployable anomaly identification system. The clustering analysis verifies the existence of multiple patterns of "income-consumption deviation", identifies completely abnormal clusters that need to be prioritized for intervention, and provides a grouping framework for subsequent analysis. The clustering results are visualized by PCA dimensionality reduction.

2.2.2 Random forest model

Random Forest (Random Forest) is an integrated learning method, through Bagging (self-help aggregation) and the idea of random subspace, hundreds of decision trees packaged into a "forest", with collective voting (classification) or averaging (regression) to give the final prediction, both high accuracy, anti overfitting, easy parallelism and other advantages, is one of the most commonly used models in industry. It is one of the most commonly used models in the industry, with the advantages of high accuracy, overfitting resistance, and easy parallelism.where, for input x, the classification (majority voting) principle is shown in equation (5),and the T is the number of trees,H(x) is the final output of the random forest:

$$H(x)=mode\{h_1x,h_2x,...,h_Tx\} \tag{2}$$

In this paper, the Random Forest algorithm is used to assess the impact of debt indicators on household income and expenditure anomalies and to develop an automated detection tool. The model optimizes the hyperparameters by grid search, and the final setting is: n_estimators=200, max_depth=None, max_features='sqrt', min_samples_leaf=2, min_samples_split=2.

2.2.3 Apriori algorithm

Apriori algorithm is a classical data mining algorithm mainly used for association rule learning, i.e.[8], discovering relationships between variables from a large amount of data. The algorithm constructs association rules by iteratively identifying frequent itemsets. Frequent itemsets are those itemsets that occur more frequently than a set threshold (support) in a dataset. In the study of this paper, the goal of association rule mining is to discover patterns of associations between household economic characteristics, especially those associated with household economic anomalies.Where support is defined as shown in equation (6):

$$supp(A)=\frac{|\{T\epsilon D|A\subseteq T\}|}{|D|} \tag{3}$$

3 RESULTS AND ANALYSIS

3.1 The Conclusion of Comparison Between Statistically Based 3-Criteria, Isolation Forest and LOF

As shown in Figure 1, the number of anomalies detected by different methods varies, with the 3 method detecting the highest number of anomalies at 123 and the combined anomalies detecting the lowest number of anomalies at 54. As for the algorithm performance, regardless of any Top k level, the integrated anomaly detection method always performs the best in terms of accuracy rate, followed by the isolated forest model, which indicates that it is more accurate in identifying anomalous samples, which represents that the economic data usually contains a variety of anomalous patterns (e.g., extreme values, local anomalies, clustered anomalies), and it is difficult for a single method to cover them comprehensively.

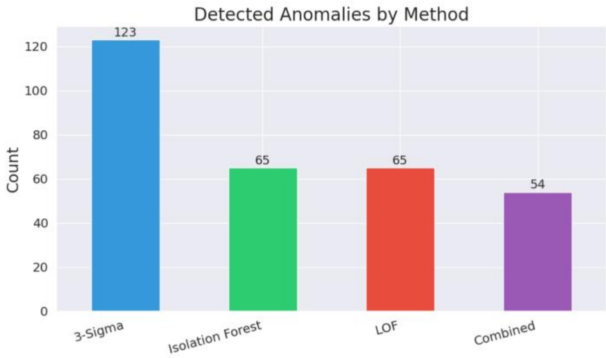

Figure 1 Number of Detections by Different Methods

3.2 The Conclusion of Cluster Analysis

This study uses cluster analysis to identify groups of households with different income-consumption characteristics, to detect outlier clusters, and to provide a grouping framework for subsequent analysis. The number of clusters is determined by the elbow method, which is selected based on the trend of the within-cluster sum of squares (WCSS) at different numbers of clusters. As shown in Figure 2, when the number of clusters is increased to 4, the decrease of WCSS slows down significantly, forming an "elbow" inflection point, indicating that 4 classes can avoid excessive clustering while maintaining intra-cluster tightness. This result is also verified by the contour coefficient and other indicators, and the number of clusters is finally determined to be 4.

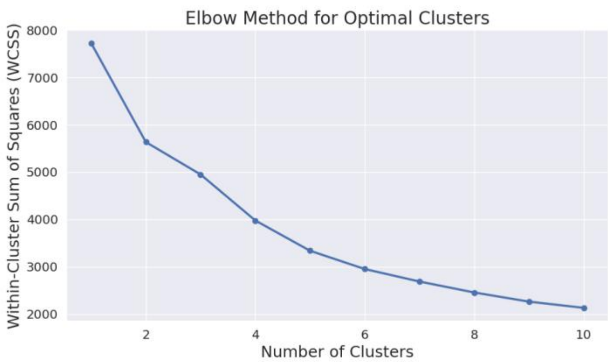

Figure 2 Elbow Method for Optimal Clusters

The clustering results show that the average profile coefficient of all samples is 0.2455, which is lower but still a better result in multiple clustering, indicating that the clustering effect is basically reasonable. As seen in Table 1, the proportion of abnormal samples in clustering group 2 is as high as 1.0, and the profile coefficient is the highest among the four groups, indicating that all the samples in this group are abnormal, and there may be highly abnormal household economic patterns that require in-depth attention. Although the proportion of abnormal samples in the remaining groups is lower, there are also abnormal samples of varying degrees, reflecting the fact that there is not a single pattern of household economic abnormality, but rather diversity and complexity. This distributional feature is even more intuitively demonstrated in Figure 3.

Subsequently, as shown in Figure 4, we calculate and present the distribution of several key variables for household economic data under different clusters. Taken together, Cluster 2 shows higher levels of total income, total consumption and disposable income per capita, but also higher levels of non-mortgage financial liabilities, suggesting that while this group is better off financially, they are also more indebted. Cluster 1 stands out in terms of total assets and household size, representing a group with more assets and larger households. Clusters 0 and 3 show low levels on most variables and may represent groups that are relatively less well-off but more economically stable. For cluster 2, which has an anomaly ratio of 1.0, both total household income and total consumption are significantly higher than the other clusters, which indicates that this group has higher economic capacity but also higher levels of consumption, signaling economic vulnerability for this group. More, we can find that Cluster 2 does not have the highest total assets, which may imply that the asset allocation of this group may not be sufficiently diversified or robust, and may be overly concentrated on certain risky assets, which may lead to a significant drop in asset values during market volatility. For this group, policymakers may need to pay attention to their economic vulnerability and provide appropriate financial education and counseling services to help them better manage their liabilities and assets. At the same time, the general public should be encouraged to form more prudent asset allocation and consumption habits to minimize the impact of economic volatility.

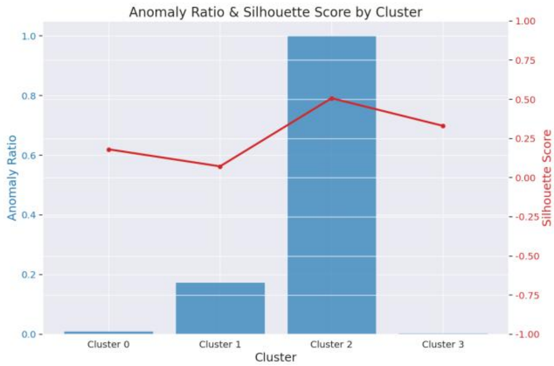

Figure 3 Elbow Method for Determining the Optimal Number of Clusters Figure

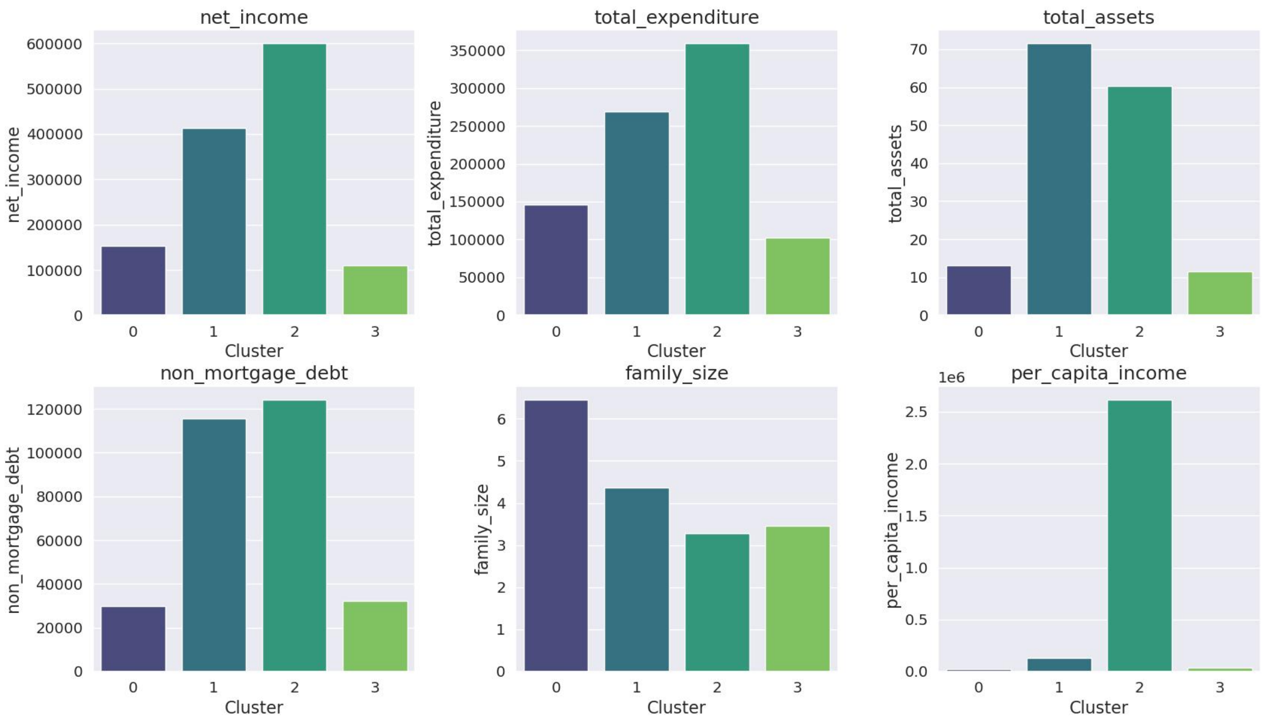

Figure 4 Six Distribution of Different Clusters of Key Variables

In this paper, Principal Component Analysis (PCA) is used to visualize the clustering results by dimensionality reduction. As shown in Figure 5, non_mortgage_debt (non-mortgage debt) is the most important feature, which is decisive for household economic anomalies; asset_debt_ratio (gearing) is the next most important, and together they constitute principal components 1 and 2. As seen in Figure 6, cluster 0 (purple) and cluster 3 (yellow) have concentrated and overlapping distributions, suggesting that the features are similar; cluster 1 (blue) has a dispersed distribution and a high degree of variability; cluster 2 (green) is isolated in the high value region and differs significantly from the other categories, corroborating the previous result of its anomaly ratio of 1.0 and further confirming the anomalous properties of the cluster.

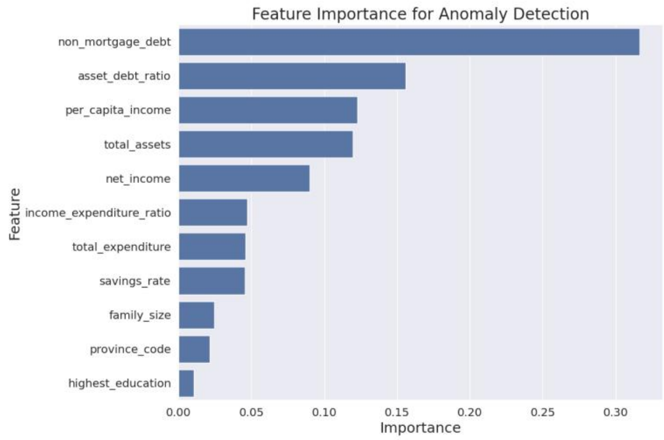

Figure 5 Importance Ranking Chart of Anomaly Detection Features

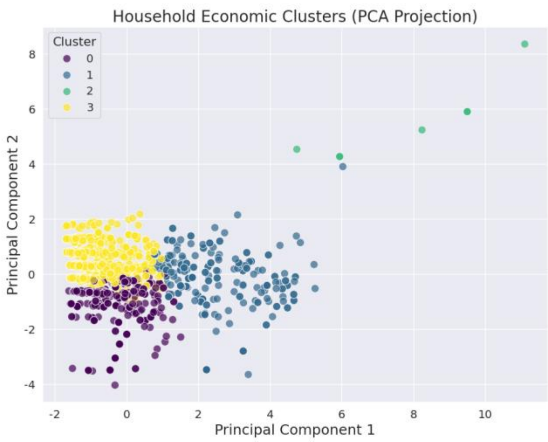

Figure 6 Household Economic Clustering Distribution Map (PCA Downscaling)

3.3 The Conclusion of Random Forest Model

The model achieves an accuracy of 0.9845 on the test set, as shown in Table 1, the model is very accurate in recognizing normal families (category 0), while the recognition of abnormal families (category 1) is relatively low but still has an acceptable accuracy. In the confusion matrix, it shows how the model predictions compare to the actual labels. For the prediction of normal families there were 245 families correctly predicted as normal (True Negative, True Negative) and 2 families incorrectly predicted as abnormal (False Positive, False Positive). While for the prediction of abnormal families there were 2 families incorrectly predicted as normal (False Negative, False Negative) and 9 families correctly predicted as abnormal (True Positive, True Positive).

This indicates that the model identifies normal families with high accuracy, but there is a small amount of underdetection of abnormal types. The F1 score of the five-fold cross-validation is 0.7983 (±0.0773), indicating that the model has good stability and generalization ability. The feature importance analysis re-validates non_mortgage_debt and asset_debt_ratio as the most critical abnormality identifiers, which is consistent with the PCA findings.

Table 1 Random Forest Model Performance Evaluation Form

Form	Precision	Recall	F1-Score	Support
0	0.99	0.99	0.99	247
1	0.82	0.82	0.82	11
accuracy	-	-	0.98	258
macro avg	0.91	0.91	0.91	258

Form	Precision	Recall	F1-Score	Support
weighted avg	0.98	0.98	0.98	258

3.4 The Conclusion of Apriori Algorithm

By using the Apriori algorithm, we achieved discretization of key features ranging from 2, 4 and found 119 anomaly-related rules, as shown in table 2, where we can observe the top 10 rules that are most relevant to household economic anomalies obtained from the association rule analysis, and the lift value of each rule. The lift value is a measure of the strength of the association between the antecedent and the consequent in a rule, and a lift value greater than 1 indicates a positive association, i.e., the occurrence of the antecedent increases the probability of the consequent. The lift of the first ten bars in the figure are all at high levels, indicating that the corresponding rules are strongly pointing to the absence of economic anomalies. Taken together, low indebtedness and maintaining a uniform level of income-expenditures is the key to the absence of economic anomalies. Conversely, households with high levels of debt and income-expenditure imbalances are more prone to economic anomalies, and policymakers need to focus on this group.

Table 2 Top 10 Rules Most Relevant to Family Economic Anomalies

Top 10 Rule	Lift value
Expense level = low => Asset level = low, Abnormal = normal, Income level = low	2.46
Income level = low => Asset level = low, Expense level = low, Abnormal = normal	2.46
Liability level = low, Asset level = very high => Abnormal = normal, Income level = very high	2.46
Liability level = low, Expense level = very high => Abnormal = normal, Income level = very high	2.48
Asset level = low, Expense level = low => Abnormal = normal, Income level = low	2.49
Household size group = large, Income level = very high => Abnormal = normal, Expense level = very high	2.53
Expense level = very high => Household size group = large, Abnormal = normal, Income level = very high	2.61
Expense level = very high => Asset level = very high, Abnormal = normal, Income level = very high	2.66
Asset level = very high, Expense level = very high => Abnormal = normal, Income level = very high	2.89
Income level = very high => Asset level = very high, Abnormal = normal, Expense level = very high	3.01

3.5 Data Preprocessing and Characteristic Equations

Data from the household economic module of the CFPS2022 database were selected for this study. The core variables include total household income (net_income), total_expenditure, total_assets, non-mortgage financial liabilities (non-mortgage_debt), family_size, and geography (province). These variables can provide basic data for subsequent anomaly detection and cluster analysis.

Subsequently, this paper uses Multiple Imputation (MIP) to deal with missing values to minimize the impact of missing values on the analysis results. The outliers were later smoothed using the Winsorization method.

For better anomaly detection and cluster analysis, the following economic characteristics are constructed in this paper:

As shown in equation (1), income_expenditure_ratio is the ratio of total household consumption to total household income, reflecting the consumption tendency of households:

$$income\_expenditure\_ratio=\frac{total\_expenditure}{net\_income} \tag{4}$$

As shown in equation (2), the asset_debt_ratio is the ratio of non-mortgage financial liabilities to total assets, reflecting the financial risk of households:

$$asset\_debt\_ratio=\frac{non\_mortgage\_debt}{total\_assets} \tag{5}$$

As shown in equation (3), per capita disposable income (per_capita_income) is the total income of the household divided by the size of the household, reflecting the per capita economic level of the household:

$$per\_capita\_income=\frac{net\_income}{family\_size} \tag{6}$$

In this paper, all numerical features are normalized. This step is particularly important for subsequent cluster analysis and anomaly detection algorithms, as many of them are sensitive to the scale of the data.

In order to evaluate the performance of the model, this paper further divides the dataset into a training set and a test set, where the former is used for model training and the latter is used for model evaluation. The dataset is divided using a stratified sampling approach to ensure that the proportion of each type of sample in the training and test sets is consistent with the original dataset.

3.6 Presentation and Analysis of Results

Based on the CFPS2022 data, this study reveals that household economic anomalies show concentrated characteristics of high debt, income and expenditure imbalance and unbalanced asset allocation, of which the level of non-mortgage debt and gearing are the core factors affecting stability.PCA clustering identifies the high-income and high-debt high-risk group (anomaly rate 100%), and the random forest model verifies the early warning value of the debt threshold (>83,000 RMB). The association rule then targeted the key trigger pattern of {high debt & low assets}→anomaly (lift=4.8). The model impact analysis confirms that the anomalous data only increase the prediction error by 7.18%, which highlights the robustness of the algorithm. The research results provide financial institutions and the government with a three-dimensional technical framework of "clustering and clustering - threshold warning - rule-based diagnosis", which can accurately identify high-risk families and formulate intervention strategies to help prevent and control family economic risks.

4 CONCLUSIONS AND OUTLOOK

Based on the CFPS2022 data, this paper focuses on solving the problem of "how to accurately identify household economic anomalies such as high indebtedness and imbalance of income and expenditure", and innovatively integrates 3-criteria, Isolated Forest and LOF, into a closed-loop framework of "clustering-integration-rule-prediction", and introduces Random Forest and Apriori algorithms for risk attribution. The three algorithms of 3σ, isolated forest and LOF are innovatively integrated into a "clustering-then integration-then rule-then prediction" closed-loop framework, and the random forest algorithm and Apriori algorithm are introduced to do risk attribution. The results show that the integration algorithm has the highest detection accuracy; PCA clustering locks a "high-income and high-debt" cluster with an anomaly rate of 100%, and non-mortgage debt ≥83,000 RMB becomes the risk threshold; the anomalous samples only increase the consumption prediction error by 7.18%, and at the same time, the model is tested to be robust. Moreover, we propose the following recommendations for profiling economically abnormal families: enhance financial education by providing financial guidance and counseling services to high-debt households, helping them optimize debt management and develop sound asset allocation and consumption habits; implement precise policy support by targeting high-risk household groups with necessary economic assistance and social aid based on research findings; establish an early warning mechanism for household economic risks through monitoring key indicators to promptly identify abnormal signs and take intervention measures; formulate regionally differentiated policies by considering provincial economic environments and household characteristics to design targeted interventions. This study verifies the effectiveness of multi-algorithm integration in detecting household economic anomalies, providing empirical evidence for relevant policies.

While this study demonstrates the feasibility of multi-algorithm fusion, future research can be expanded in several directions: data-wise, CFPS2022 cross-sectional data can be combined with tracking data from 2024 and 2026 to construct a panel anomaly series, introducing Hawkes process or Transformer time-series models to capture the impulse-persistence effects of household risk contagion[8]; methodology-wise, Gradient Boosting or TabNet models with Node-wise SHAP interpretation techniques can be tested to improve the explanatory power of nonlinear interactions and compare stability with the Random Forest results of this study; application-wise, the framework can be migrated to multi-country databases such as CHFS, PSID, and UKHLS to examine the cultural and economic system dependence of the "income-consumption bias" anomaly pattern, promoting international dialogue in household financial vulnerability research.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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NEW PRODUCTIVITY ENABLES HIGH QUALITY DIGITAL AGRICULTURE IN JILIN PROVINCE DEVELOPMENT LOGIC AND IMPLEMENTATION COUNTERMEASURES

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Abstract: As a pioneering model driving the transformation and upgrading of traditional agriculture, digital agriculture has long been prioritized by government authorities. The new quality productive forces, characterized by technological innovation, high efficiency, and superior quality, provide robust support for the high-quality development of digital agriculture. Under the impetus of these advanced productive forces, digital agriculture will fully embrace the development concepts of innovation, openness, coordination, green practices, and sharing, thereby comprehensively empowering the high-quality development of digital agriculture in Jilin Province. However, various challenges remain in the province that urgently require resolution. To achieve sustainable development in the new era, Jilin must focus on cultivating and advancing high-quality digital agriculture as its core objective, establishing distinctive local strategies for digital agricultural advancement.
Keywords: New quality productivity; Digital agriculture; High-quality development; Jilin province

1 INTRODUCTION

During the 2024 National Two Sessions, the leaders emphasized the imperative to prioritize high-quality development and cultivate new productive forces through localized approaches. This innovative concept, first proposed during his inspection tour in Heilongjiang Province, focuses on nurturing emerging and future industries as the cornerstone of new growth drivers. By prioritizing innovation-driven development, it breaks away from traditional economic growth models characterized by high-tech, efficient, and high-quality advanced productive forces that align with modern development philosophies. Currently, these new productive forces are reshaping industrial and service sectors while extending to agriculture and rural areas, injecting strong momentum into high-quality agricultural development. As an advanced form of agricultural development, digital agriculture serves as a crucial pathway for China's transition from a major agricultural country to a global leader in farming. Against the backdrop of Northeast China's comprehensive revitalization, exploring how new productive forces can empower digital agriculture has become particularly urgent, positioning it as both a new engine and enduring driving force for high-quality development. Therefore, thoroughly analyzing the essence and requirements of new productive forces, while examining Jilin Province's development logic and implementation strategies for high-quality digital agriculture, carries significant practical implications.

2 AN OVERVIEW OF NEW QUALITY PRODUCTIVITY AND HIGH-QUALITY DEVELOPMENT OF DIGITAL AGRICULTURE

2.1 Regarding New Quality Productivity

Regarding new-quality productive forces, internationally, Barro analyzed economic growth disparities across nations through cross-country data analysis[1], examining how government policies, market conditions, and initial economic states influence productivity and economic growth. Bloom explored the paradox of declining output per unit of input despite increased inputs[2], highlighting the urgent need to address traditional productive forces 'constraints on economic development. Domestically, scholars have approached this topic from multiple dimensions since its inception. On one hand, foundational discussions include Zhou Wen' s perspective that new-quality productive forces represent an organic integration of technological breakthroughs[3], economic advancement, and industrial upgrading, where innovations in key and disruptive technologies provide stronger impetus for productivity growth. Gao Fan expanded this concept by analyzing outcomes[4], production factors, factor combinations, industrial structures, and support mechanisms. On the other hand, researchers have developed empirical evaluation frameworks. Liu Jianhua established an integrated index system encompassing laborers, means of labor, and objects of labor[5], employing entropy methods and kernel density estimation techniques tailored to China's context. Furthermore, Guo Zhaoxian conducted applied research focusing on how new-quality productive forces drive modern industrial system construction[6].

2.2 Regarding the High-Quality Development of Digital Agriculture

Regarding the high-quality development of digital agriculture, since 1997, the academicians from the National Academy of Sciences and the National Academy of Engineering—the leading representatives in the U.S. scientific and engineering communities —were the first to introduce the innovative concept of "digital agriculture[7]." This concept integrates the essence of geospatial technology with information technology, marking the transformation of agriculture towards intensive and informatized directions. Subsequently, with deeper practical exploration and theoretical expansion, the field has continued to evolve.

The concept of "agriculture" has been further defined. Research by Seelan et al. established the foundation for a narrow interpretation of digital agriculture, defining it as smart agriculture. Alm. E. emphasized that the core of digital agriculture lies in agricultural digitization[9], encompassing technologies such as big data, Internet of Things (IoT), sensors, system integration, artificial intelligence, and blockchain. Eastwood characterized digital agriculture as utilizing sensors, machinery[10], drones, and satellites monitoring animals, soil, water, plants, and human activities to interpret historical data and predict future trends. Gunasekaran and Kamble further noted in their study that digital agriculture has evolved into a new agricultural paradigm integrating computer technology[11], Geographic Information Systems (GIS), and other modern technological tools for agricultural production.

Regarding the understanding of high-quality development, the "endogenous growth theory" represented by Romer's model and Lucas's model in the 1980s further explored socio-economic development patterns[12-13]. These theories identified endogenous technological progress as the decisive factor for sustained economic growth. Elena proposed that economic growth is an activity of continuous quantitative accumulation[14], ultimately achieving quality improvement in economic development. Meanwhile, Mlachila and others emphasized that high-quality growth encompasses the simultaneous rapid advancement of economic levels[15], people's income levels, and social welfare standards.

However, there remains no unified definition regarding the connotation of high-quality development in digital agriculture. In academic research, some scholars define it through pathways for achieving high-quality development, such as Du Jian who posits that high-quality development entails implementing new development concepts to achieve coordinated and sustainable growth[16]. Others explore how digital agriculture can attain high-quality development by integrating it with policy contexts, like Xia Yulin who emphasizes that rural revitalization requires digital infrastructure support and agricultural technological innovation[17]. Some researchers conduct empirical analyses using urban panel data, exemplified by Yao Wen who suggests strengthening infrastructure, enhancing informatization levels[18], leveraging market mechanisms, and promoting high-quality development in digital agriculture.

2.3 Regarding the Relationship Between New Quality Productivity and the High-Quality Development of Digital Agriculture

In the exploration of the connection between new-quality productivity and digital agriculture, academia remains in its early exploratory phase, demonstrating considerable depth yet to be fully uncovered. Most scholars currently focus on the correlation between new-quality productivity and high-quality agricultural development. For instance, Li Zicheng and colleagues conducted empirical analyses based on spatial spillover effects and threshold effects[19], concluding that new-quality productivity serves as a crucial driving force for advancing agricultural high-quality development. However, with deeper research, scholars have begun exploring from different perspectives. Wang Qinmei et al. [20], for example, observed that digital technologies can deeply permeate and reshape the intrinsic structures of agricultural laborers, farming tools, and agricultural production objects, giving birth to new-quality productivity in digital agriculture. This discovery opens up fresh exploration possibilities for the future development of agriculture.

2.4 The Value of New Quality Productivity Empowering the High-Quality Development of Digital Agriculture

Through literature review, it is found that although the academic community has achieved certain results in the high-quality development of new quality productivity and digital agriculture, the achievements on how new quality productivity can empower the high-quality development of digital agriculture are still insufficient. For instance: How can new-quality productivity drive the high-quality development of digital agriculture? What strategies should be implemented to propel the transition into a high-quality development phase?

The marginal contribution of this study can be summarized in three key aspects: First, focusing on Jilin Province as the primary research subject, we clarify the crucial role of new-quality productive forces by examining their development logic, core bottlenecks, and implementation strategies for empowering high-quality digital agriculture. Second, analyzing how these innovative productive forces—emerging from traditional growth models and aligning with high-quality development requirements—empower digital agriculture through new development concepts. Third, few scholars have analyzed the implementation strategies for promoting the high-quality development of digital agriculture through new quality productivity. This article takes Jilin Province as an example, aiming to enrich the achievements in this regard.

3 THE LOGIC OF NEW QUALITY PRODUCTIVITY ENABLING HIGH-QUALITY DEVELOPMENT OF DIGITAL AGRICULTURE

As an upgraded and transcended version of traditional productive forces, new-quality productivity represents a novel form of productivity driven by technological innovation, aligning with the requirements of high-quality development. High-quality development necessitates the support of new-quality productivity. Within this framework, the core strategic focus for advancing digital agriculture's high-quality development lies in comprehensive digital innovation across all agricultural sectors. This requires not only widespread dissemination of digital technologies in agriculture but also their deep integration and penetration to stimulate innovative vitality in agricultural production. The specific content includes five dimensions: digital infrastructure construction, transformation of production and operation models, paradigm shift in development concepts, restructuring of industrial organizations, and workforce skill upgrading [21]. Among these, infrastructure construction serves as the core support, forming an indispensable component of labor objects that lays the foundation for extensive digital technology application in agriculture. Subsequently, the transformation of industrial organization further propels digital agriculture's development. As another crucial element of labor objects, it optimizes and reorganizes agricultural industry chains, providing robust organizational guarantees for deep digital integration. Building on this foundation, the digital transformation of production and operation models becomes a key application of labor materials. The adoption of intelligent agricultural equipment and precision farming technologies directly enhances agricultural productivity and quality. Meanwhile, the paradigm shift in development concepts acts as spiritual guidance for laborers, emphasizing green development and sustainable concepts under digital leadership, thereby providing clear direction and momentum for digital agriculture. Finally, the transformation of labor skills has become a specific ability guarantee for the high-quality development of digital agriculture. As an important part of the labor force, it promotes the development of digital agriculture by cultivating the digital literacy and operational skills of high-quality agricultural talents.

The analysis demonstrates that the high-quality development of digital agriculture driven by new productive forces primarily stems from empowering agricultural digital transformation. This process involves reshaping three fundamental elements of agricultural production: labor objects, means of labor, and workforce. Through five dimensions—infrastructure, industrial organization, production operations, development philosophy, and workforce skills—the digitalization of agricultural labor objects, means of labor, and workforce is systematically categorized. By implementing innovative development concepts, this approach achieves "quantum optimization" of basic elements, "resonance coupling" in agro-industries, "energy-level leap" in production operations, "entropy-reduction restructuring" of cognitive patterns, and "field-magnetic field reshaping" of labor resources, ultimately realizing high-quality development in digital agriculture.

3.1 Scientific and Technological Innovation: Basic Element "Quantum Optimization"

As a key driver of new productive forces, technological innovation primarily relies on data resources. In advancing these capabilities, infrastructure development focuses on 5G and F5G all-optical networks, data centers, and other foundational projects. This involves optimizing the layout, structure, functionality, and system integration of digital and intelligent infrastructure while enhancing data resource consolidation and efficient circulation. Currently, the four pillars of digital agriculture infrastructure include smart farming equipment, agricultural IoT systems, big data platforms, and communication networks. With technological breakthroughs injecting momentum into new productive forces, digital agriculture infrastructure is undergoing fundamental transformation. First, "quantum enhancement" in smart farming equipment achieves performance breakthroughs and expanded operational boundaries. These devices are now deployed in cutting-edge agricultural zones. Driven by technological innovation, their algorithms and control systems have been optimized to improve precision in sowing uniformity, irrigation accuracy, and harvesting precision. Remote operations now transcend geographical limitations, enabling real-time responses even in challenging terrains and harsh climates, significantly expanding application scenarios. Second, "quantum enhancement" in agricultural IoT systems enables efficient data acquisition and analysis. The agricultural Internet of Things (IoT) is being increasingly integrated into farming processes. By utilizing diverse sensing devices to monitor and manage critical factors like farmland environments and crop growth, technological innovation in core data collection, processing, and sharing has optimized sensor network architectures and data transmission. This enables comprehensive and high-precision monitoring of key information such as soil moisture, crop status, and climate changes, significantly improving the accuracy and real-time responsiveness of agricultural data acquisition. Thirdly, the "quantum leap" in agricultural big data platforms has achieved both expanded application scope and enhanced data security. These platforms consolidate vast agricultural data resources, leveraging advanced data processing and analytics technologies to provide precise guidance and services for farming operations. Guided by technological innovation, their applications will transcend traditional agricultural management and extend into critical fields including agricultural product quality traceability, financial services, and rural e-commerce. Through blockchain and advanced encryption technologies, these systems ensure complete protection against illegal interference and data breaches during transmission, storage, and usage. Fourthly, the "quantum upgrade" in communication infrastructure has achieved deep integration of cutting-edge technologies. The leap from 2G to 5G has dramatically increased data transmission speeds, expanded network capacity, and reduced latency, providing robust support for real-time agricultural information exchange and efficient processing. Looking ahead, continuous technological empowerment will enable the convergence of 5G, satellite IoT, and other IoT technologies, forming a more comprehensive and multi-dimensional communication network system.

3.2 Open Cooperation: Resonance Coupling of Agriculture-Related Industries

The new productive forces driven by technological innovation can further propel industrial transformation and upgrading, breaking away from traditional economic growth models to achieve low energy consumption, high efficiency, and sustainability. Traditional agricultural industries are often confined to single production stages or specific sectors, making it difficult to transcend boundaries for optimal resource allocation and full realization of value potential. As the core concept, "resonance coupling" has become a key force in building an industrial ecosystem that connects various elements and drives cross-sector collaboration, serving as a crucial driver for agriculture's future development. The deep integration of digital agriculture with cutting-edge fields like information technology, biotechnology, and intelligent manufacturing will completely dismantle barriers in traditional industries, giving birth to a new industrial ecosystem characterized by diversified complementarity and collaborative innovation. Within this ecosystem, all industrial elements interdependently reinforce each other. Through the resonance coupling mechanism, not only is precise resource allocation achieved, but the breadth and depth of value extraction are also significantly enhanced.

3.3 Coordinated Development: "Energy Level Transition" of Production and Operation

The evolution from traditional to modern agriculture fundamentally represents the widespread adoption of scientific and technological advancements in farming. As conventional agricultural practices transition to modern models, their reliance on manual labor and experience often fails to meet the dynamic demands of contemporary markets. Digital agriculture leverages advanced data analytics and AI-driven decision-making to achieve precise control and scientific management of production processes. This technology empowers farmers to accurately track market trends and production patterns, enabling them to develop scientifically sound planting plans and marketing strategies that align with market realities.

Against this backdrop, the coordinated development philosophy guides agricultural production to achieve a "qualitative leap", transitioning from basic capabilities to advanced technological capabilities. This marks a fundamental transformation in agricultural production models. Farmers have shifted from relying on experience to depending on technology, while agricultural practices have evolved from extensive methods to intensive and precision-oriented approaches, achieving a qualitative leap in productivity. This transformation process not only focuses on improving production efficiency but also emphasizes close integration between agriculture and market demands, as well as synchronized optimization of ecological and economic benefits. Agricultural production can now respond more agilely to market changes, flexibly adjusting crop planting structures and sales strategies based on real-time market signals, ensuring precise alignment and efficient coordination between supply and demand.

3.4 Green development: "Entropy Reduction Reconstruction" of Thinking Mode

The cornerstone of new productive forces lies in technological innovation, with green development at its heart as the foundation of this scientific revolution. The concept of "entropy reduction restructuring" refers to harnessing technological advancement and digital transformation to eliminate inefficiencies, reduce waste, and optimize resource allocation in agricultural production systems, thereby achieving sustainable environmental outcomes. In contrast, traditional farming practices remain trapped in a vicious cycle of resource depletion, worsening pollution, and stagnant productivity growth. These entropy-increasing patterns have become major roadblocks to agricultural sustainability.

The "entropy reduction reconstruction" process manifests in two key aspects. First, it drives fundamental transformation in agricultural production methods. Traditional farming approaches often prioritized yield growth while neglecting quality and environmental balance. The new productive forces advocate a paradigm shift: ensuring stable grain production through green innovation technologies that maximize resource efficiency and minimize environmental impact, thereby achieving entropy reduction. Second, this paradigm shift propels digital agriculture to implement green "entropy reduction reconstruction". By leveraging computer systems, communication networks, and smart machinery, every link in the agricultural chain achieves precise control and significant enhancement in intelligence. This "intelligentization+" revolution reduces resource consumption and carbon emissions through precision fertilization, smart irrigation, and eco-friendly pest control measures, ultimately realizing a green transition in agricultural practices.

3.5 Shared Development: Labor Resources "Magnetic Field Remodeling"

The continuous leaps in technological innovation, the application of labor tools, and the expanding boundaries of labor objects all fundamentally rely on human effort. More crucially, the efficiency enhancement of labor tools and objects requires close collaboration with highly skilled workers to transform into tangible productivity. In this process, the high quality of workers serves as the core guarantee for new-quality productive forces. The transformation and upgrading of workforce skills lay a solid foundation for cultivating a high-caliber workforce. Particularly in the emerging field of digital agriculture, its essence lies in the close integration of digital technology and agricultural big data. This process essentially represents a profound and thorough "magnetic field restructuring" of traditional agricultural labor structures. It demands workers to achieve a leap from low-skilled to high-skilled status. This transition not only elevates individual value but also drives industry progress. The emergence of new-quality productive forces provides strong impetus for workforce skill transformation, with the ultimate goal of achieving shared development. While calling for more highly skilled professionals to join, it simultaneously guides labor migration toward digital agriculture, promoting skill structure optimization and upgrading. This ensures that the fruits of skill transformation benefit broader populations, thereby enhancing the overall workforce quality and technical proficiency across industries.

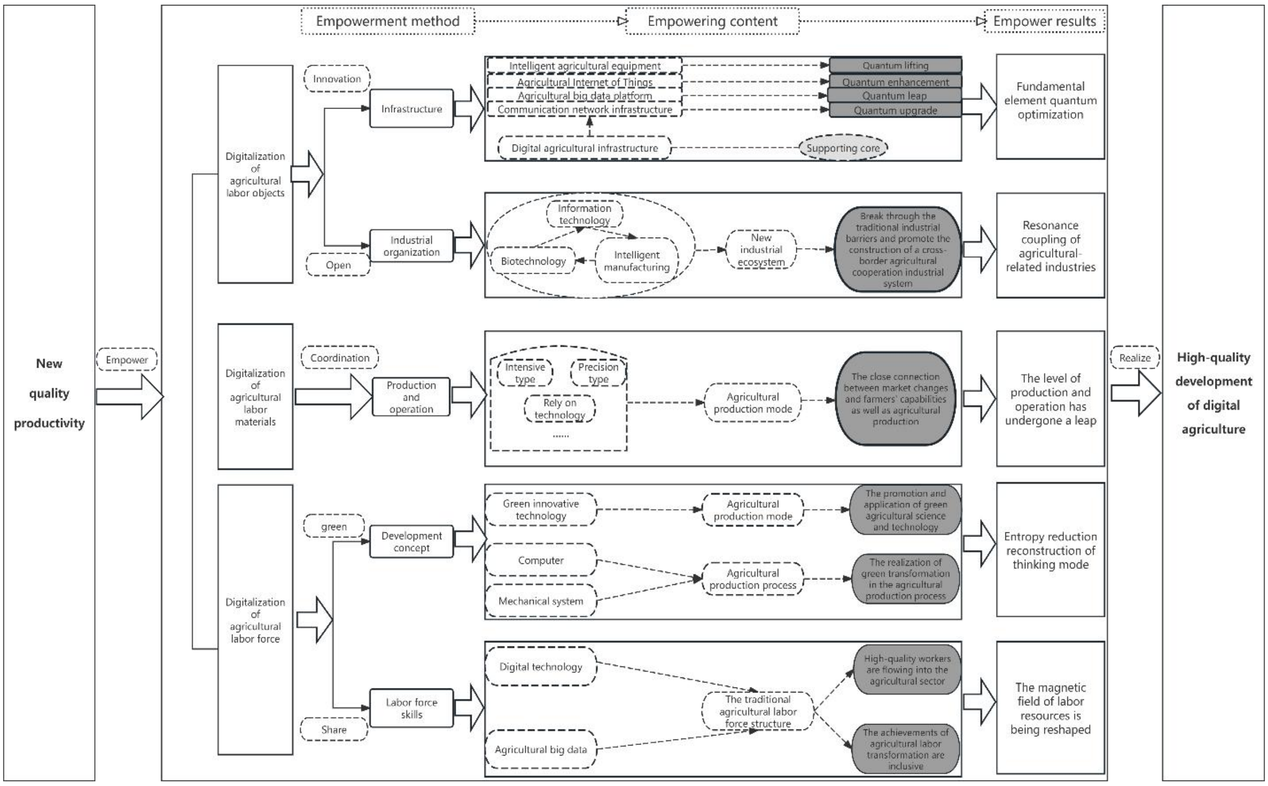


Figure 1 Logic Diagram of New Quality Productivity Empowering Digital Agriculture

4 CORE OBSTACLES TO THE HIGH-QUALITY DEVELOPMENT OF DIGITAL AGRICULTURE IN JILIN PROVINCE

As China advances its new productive forces strategy, Jilin Province—a vital hub for grain and agricultural products—must seize emerging opportunities in digital agriculture to establish a national benchmark. However, constrained by underdeveloped infrastructure and traditional farming practices, the province still faces multiple challenges in digital agriculture development. Developing localized strategies tailored to Jilin's unique conditions is crucial to achieve breakthroughs and leapfrog progress in this field.

4.1 Infrastructure Lagging Gap: Digital Connection Loosening

The development of digital infrastructure in Jilin Province is crucial, yet current progress reveals significant delays that starkly contrast with future expectations, primarily manifested through mismatches between existing facilities and actual needs. First, rural areas in Jilin lag significantly behind the national pace in communication network infrastructure adoption and upgrades. As of December 2023, while China's internet penetration rate reached 77.5%, rural coverage stood at merely 66.5%. In Jilin, only 370 out of 1,048 township-level administrative units achieved 5G network coverage in 2021, representing a mere 35.3% penetration rate. More critically, high-speed, stable communication networks remain inadequately deployed and underutilized in agriculture—a sector where such connectivity is essential for real-time data transmission and efficient processing. Second, the investment-to-output ratio of smart agricultural machinery in Jilin lags markedly. With total agricultural machinery power reaching 43.58 million kilowatts in 2022—accounting for just 3.94% of China's 1.106 billion kilowatts—this figure falls far below levels seen in agriculturally advanced regions. This indicates severe deficiencies in rural informatization infrastructure, leaving farmers unable to fully benefit from digital agricultural technologies. Third, the development of agricultural big data platforms and IoT systems requires further enhancement. Agricultural IoT in Jilin remains rudimentary, characterized by low intelligence levels and limited application scope. At the same time, the agricultural industry big data platform is also faced with the problem that data resources are scattered in different departments, enterprises and scientific research institutions, resulting in insufficient integration and sharing, difficult data acquisition, and thus affecting the application effect of the big data platform in the agricultural industry.

4.2 Industrial Structure Fragmentation: Unbalanced Development

The development of agricultural industrial chains has long been a critical challenge in Jilin Province's digital agriculture sector, significantly impacting farmers' income levels while invisibly constraining the industry's overall competitiveness and hindering its ability to stand out in fierce market competition. Three key issues require attention: First, uneven industrial development with sluggish growth in primary industries. In 2023, Jilin's primary industry added value reached 164.475 billion yuan, secondary industry 458.503 billion yuan, and tertiary industry 730.140 billion yuan. Despite rapid grain production growth, primary industry contributions accounted for merely 12.14% of total industrial output. Second, insufficient capabilities among agricultural enterprises. Only 57 enterprises were certified as provincial-level key agricultural leading enterprises in 2022—a stark contrast to Henan Province (319 certified enterprises) and Shandong Province (212 certified enterprises). Third, policy coordination challenges arise from differing interests and operational models between stakeholders and local governments. These discrepancies create regional cooperation barriers, information asymmetry undermines coordination across sectors, disrupts market dynamics, hinders information sharing, and ultimately restricts productive activities

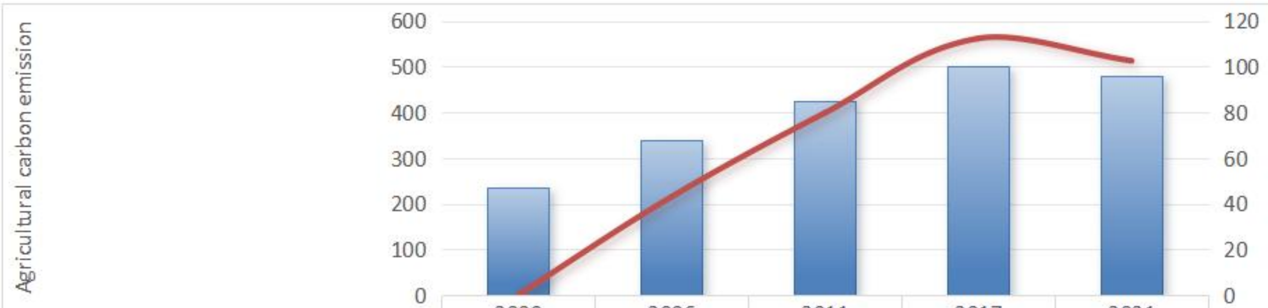
4.3 Traditional Agricultural System Dominates: The Rupture of The Coordination Mechanism between Business and Innovation

The integration of digital technology with agriculture can significantly enhance market transparency, boost agricultural productivity, and improve distribution efficiency. However, this digital transformation also imposes specific requirements on production capabilities and economic scale for agricultural operators [11]. In China's agricultural landscape, where 98% of farming households are small-scale farmers, the "large country with small-scale farming" phenomenon remains prevalent. Under these circumstances, Jilin Province still relies heavily on traditional agricultural models that depend on heavy manual labor and rudimentary machinery, resulting in low efficiency and poor adaptation to modern agricultural development needs.

With the continuous outflow of rural labor and accelerated population aging, the traditional farming system's heavy reliance on human labor has become unsustainable. Between 2014 and 2023, Jilin Province witnessed a significant decrease in rural population, dropping from 11.41 million to 8.25 million, accounting for 35.28% of the total population. Meanwhile, the elderly population surged from 3.02 million to 4.35 million (aged 65+), representing 18.63% of the total population. This labor-dependent model is becoming untenable. In 2022, Jilin Province planned to cultivate 25,000 high-quality farmers, yet this accounted for merely 3.31% of China's national initiative to train 753,900 skilled agricultural workers. Most farmers lack essential skills and knowledge to master modern farming techniques, hindering the establishment of integrated business-farming mechanisms. Compounded by deep-rooted traditional farming concepts, many farmers remain skeptical about modern technologies and prefer conventional cultivation methods. Under these circumstances, innovation in production models faces challenges, and the gap between traditional farming systems and modern agricultural development continues to widen.

4.4 Heavy Carbon Emission Load: Signs of Environmental Degradation are Prominent

The CPC Central Committee and the State Council emphasized in their "Strategic Guidelines on Revitalizing Northeast China and Other Old Industrial Bases" the importance of establishing a robust ecological security barrier in northern China and creating a green homeland with clear mountains, clean waters, and livable environments. The document stresses that environmental quality is closely tied to public welfare and serves as an essential component of livelihood protection. It advocates unwavering commitment to green development principles, calling for complete abandonment of any practices or models that harm natural ecosystems. The goal is to realize the vision of bluer skies, greener mountains, and clearer waters in Northeast China, ultimately building a sustainable region with harmonious ecology and improved living conditions. However, Jilin Province's traditional agricultural structure and production methods have led to significant environmental degradation. Carbon emissions from agriculture stand out as a prominent environmental issue. Since 2000, agricultural carbon emissions in Jilin have steadily increased from 2.3672 million tons to 5.0272 million tons in 2017, representing a peak growth rate of 112.37%. After a decline to 4.7952 million tons by 2021, emissions still rose by 102.6%, doubling the province's total carbon emissions over two decades [22]. Although emissions have slightly decreased in recent years, the overall increase remains substantial. If this trend continues, Jilin's ecosystem will struggle under such heavy pressure, potentially undermining agricultural foundations and jeopardizing regional ecological balance and sustainable development.



	2000	2006	2011	2017	2021
Agricultural carbon emissions（wt）	236.72	338.46	425.46	502.72	479.52
Growth rate（%）	0	42.97	79.73	112.37	102.6

Figure 2 Map of Agricultural Carbon Emissions in Jilin Province

4.5 Significant Dissipation of Human Resources: Market Supply and Demand Mismatch has Intensified

Jilin Province is grappling with a critical mismatch between its talent development mechanisms and rapidly expanding agricultural demands during its push for industrial growth. The first challenge lies in the disconnect between talent cultivation systems and fast-growing industry needs. Despite extensive training initiatives implemented across 50 cities and counties in 2022—encompassing 1,738 family farm operators, 1,376 farmer cooperative leaders, 425 agricultural service organization directors, 263 enterprise executives, 512 technical specialists, and 120 professional managers—all aimed at building a diversified and specialized agricultural workforce—the provincial government's work report reveals a striking contrast: while the number of farmer cooperatives surged to 81,000 and family farms reached 146,000 households, the demand for high-caliber professionals has skyrocketed. This surge coincides with the continuous expansion of agricultural bases and accelerated technological innovation, creating unprecedented pressure for skilled agricultural talent. The second issue stems from outdated recruitment strategies. Jilin's current talent acquisition policies lack flexibility and innovation, making them less attractive than their counterparts in more economically developed regions. Compounded by geographical constraints and economic disparities, the province struggles to retain top-tier professionals through conventional incentives alone.

5 NEW QUALITY PRODUCTIVITY ENABLES THE HIGH-QUALITY DEVELOPMENT STRATEGY OF DIGITAL AGRICULTURE IN JILIN PROVINCE

The deep integration of new productive forces in empowering digital agriculture is gradually demonstrating its strategic position as the core driver for high-quality agricultural development. This comprehensive empowerment provides robust support for Jilin Province to achieve its goal of becoming a leading agricultural province. Specifically, it manifests through multiple dimensions: building resilient infrastructure, developing diversified industrial ecosystems, nurturing new-generation agricultural innovators for the digital era, shaping green circular and low-carbon innovation ecosystems, and implementing targeted talent recruitment with regional collaboration. These efforts collectively propel the high-quality advancement of digital agriculture in Jilin Province.

5.1 Building a Resilient Development Framework for Infrastructure: Bridging the Gap

Establishing a resilient development framework for infrastructure is crucial for advancing digital agriculture modernization, narrowing the digital divide, and enhancing agricultural productivity and quality in Jilin Province. First, building a digital agriculture platform. By strategically increasing investment in intelligent agricultural machinery—particularly considering Jilin's northeastern location with extreme winter temperatures—farmers should prioritize cold-resistant equipment through low-freezing-point fuels, coolants, and insulation materials. Advanced technologies like autonomous driving and precision farming should be widely adopted to expand their applications. Policy incentives and fiscal subsidies will encourage farmers to adopt smart machinery while establishing agricultural equipment leasing and sharing systems to lower adoption barriers. Additionally, creating a unified agricultural big data platform will consolidate fragmented resources such as Jilin Statistical Yearbook and provincial agricultural data, enabling cross-system data sharing to support intelligent decision-making. Second, constructing a "Smart Network" for digital agriculture. To strengthen information accessibility, Jilin needs to accelerate rural communication infrastructure upgrades, especially 5G network coverage and high-speed broadband. Through IoT integration, deploying smart sensor networks will enable real-time monitoring of farmland conditions and crop growth, ensuring data accuracy and timeliness. Furthermore, deepening collaboration between IoT, big data, cloud computing, and AI technologies will create efficient communication networks, enabling smart interconnection and coordinated operations across agricultural equipment, ultimately forming a comprehensive smart agriculture ecosystem.

5.2 Developing Diversified Industrial Ecology: Restructuring the Pattern

The development of Jilin Province's diversified industrial ecosystem is primarily driven by the deepening integration and cross-sector collaboration within agricultural value chains. First, enhancing cross-regional cooperation in agricultural supply chains through establishing Northeast Asia agricultural cooperation platforms helps overcome limitations caused by the limited number of agribusiness enterprises. As a strategic hub in Northeast Asia, Jilin's unique geographical advantages enable it to break regional barriers through agricultural exhibitions and trade fairs. This facilitates strengthened agricultural exchanges with neighboring countries and regions, promotes trade cooperation, establishes collaborative mechanisms, and drives joint R&D efforts. Such initiatives achieve resource sharing and complementary advantages, thereby boosting the competitiveness and stability of the entire industrial chain while stimulating innovation across its upstream and downstream sectors. Second, leveraging its strengths in market intelligence and coordination, the Jilin provincial government has transformed traditional administrative functions into flexible industrial governance frameworks. This approach optimizes resource allocation and dynamic integration of production factors, strengthens policy support, funding mechanisms, interdepartmental coordination, supervision, and performance evaluation to eliminate institutional barriers in resource circulation.

5.3 Incubating New Agricultural Craftsmen in the Digital Era: Upgrading and Transformation

With the shrinking rural workforce in Jilin Province, it is imperative to transform labor-dependent agricultural practices and boost both crop yields and market sales. Two key strategies should be implemented: First, establishing a multi-dimensional cultivation framework to develop digitally savvy farmers who can mitigate the demographic decline. Provincial authorities should design specialized training programs leveraging resources from institutions like Jilin Agricultural University and Jilin Academy of Agricultural Sciences. These courses should cover core areas including modern farming techniques, business management, and marketing strategies, adopting a blended learning model that combines online instruction with hands-on field training. Customized services should address regional needs while enhancing farmers' proficiency in digital tools and platforms, improving their technical expertise, market insight, and innovative thinking to maximize training effectiveness. Second, restructuring agricultural operations to achieve seamless integration with market demands. As most regions adopt cutting-edge technologies like big data analytics, IoT, and AI, digitally literate farmers can master these innovations and effectively implement the "Internet + Agriculture" model. By expanding sales channels through e-commerce platforms and social media, they can break free from traditional limitations, build distinctive local brands, increase product value, and enhance market competitiveness. This deep integration of agriculture with e-commerce will help offset production and sales challenges caused by declining traditional farming populations.

5.4 Shaping a Green, Circular and Low-Carbon Innovation Ecosystem: Ecological Restoration

With the core focus on reducing agricultural chemical inputs, we aim to maximize synergistic effects in pollution and carbon reduction. From 2000 to 2021, agricultural carbon emissions in Jilin Province were primarily attributed to farmland utilization (72%), straw burning (23%), rice cultivation (4%), and livestock farming (1%) [28]. To advance decarbonization efforts, the province must develop region-specific strategies that align with local conditions, ensuring effective establishment of green circular and low-carbon innovation ecosystems. Firstly, cities with extensive cultivated land should prioritize the adoption of green agricultural technologies. Given that carbon emissions mainly stem from fertilizers, pesticides, plastic mulch, and machinery use, while straw burning and rice cultivation emissions correlate positively with land area, four regions—Changchun, Baicheng, Songyuan, and Siping—which account for 71% of the province's total arable land—should become key zones for green technology implementation. These areas could adopt advanced methods including biological control techniques, precision soil testing and formula fertilization systems, and eco-friendly pesticides. This will guide farmers to transition from traditional resource-intensive production models to environmentally sustainable practices, fostering the growth of organic and green agriculture. Secondly, comprehensive management of agricultural non-point source pollution requires establishing a deeply integrated circular symbiosis system that combines crop cultivation with livestock farming. Taking key livestock breeding zones such as Yanbian Yellow Cattle, East Feng County, and Shuangyang District's sika deer herds as examples, innovative closed-loop agricultural green ecosystems have been designed. Centered on efficient resource recycling, these systems achieve reduced agricultural waste and pollution-free processing. This approach effectively cuts carbon emissions and various pollutants at the source during farming processes, driving comprehensive pollution reduction and carbon mitigation in agriculture.

5.5 Targeted Talent Recruitment and Regional Progress: Gathering Talents

Jilin Province is currently formulating its "Talent Policy 4.0". Confronted with relatively lagging economic development, the province cannot solely rely on high salaries and abundant job opportunities to attract external talents. Therefore, the policy formulation should shift focus to deeply exploring and cultivating local talent resources. First, deepen local sentiment and precise positioning. By refining the talent classification system and comprehensively considering multiple factors such as origin, educational background, and career trajectory—such as whether candidates are locally born, educated locally, or remain after graduation—the province can accurately identify and nurture agricultural professionals with a sense of hometown belonging and mission. This reduces policy externalities and enhances talent identification and responsibility towards Jilin. Second, establish regional agricultural talent hubs. Jilin should actively strengthen cooperation with neighboring cities and regions like Shenyang, Dalian, and Harbin to jointly explore new pathways for coordinated regional agricultural talent development. Through sharing agricultural talent resources, technical expertise, and information networks, the province can break down geographical barriers, promote free flow and optimal allocation of agricultural talents and technologies, leverage its strengths, and create complementary win-win development patterns with partners.

6 CONCLUSION

In advancing high-quality digital agriculture development in Jilin Province, new productive forces serve as the core driving force. Through multidimensional advancements in technological innovation, open collaboration, coordinated development, green growth, and shared benefits, these efforts comprehensively enhance the overall efficiency and competitiveness of digital agriculture. Examining the current landscape of digital agriculture development in Jilin, it becomes evident that multiple challenges—such as lagging infrastructure construction, fragmented industrial structures, entrenched traditional farming systems, heavy carbon emission burdens, and significant talent drain—are becoming bottlenecks hindering further progress. To address these complex issues, Jilin should establish resilient infrastructure frameworks, develop diversified industrial ecosystems, cultivate new-generation digital-era agricultural artisans, build green circular and low-carbon innovation ecosystems, and implement targeted talent recruitment strategies for regional advancement. These measures will inject momentum into the province's digital agriculture development.

Looking ahead, agricultural research in Jilin Province should focus more on the in-depth exploration and efficient utilization of new quality productivity. Through scientific and rigorous methods and practices, we will thoroughly investigate the practical application effects of new quality productivity in agriculture and rural areas, so as to take more solid and powerful steps on the path of high-quality development of digital agriculture.

COMPETING INTERESTS

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A HOUSING PRICE PREDICTION MODEL BASED ON BACKPROPAGATION NEURAL NETWORK

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Abstract: The real estate industry serves as a crucial pillar of the national economy, playing an indispensable role in both national and local economic development. Analyzing and forecasting housing price trends can provide more reliable decision-making references for homebuyers, real estate agents, and market analysts. This study selects 150,000 data samples and addresses the complex non-linear characteristics of housing prices influenced by multiple factors by proposing a housing price prediction model based on a Backpropagation (BP) neural network. The model effectively simulates and predicts housing prices in the test set, achieving successful non-linear fitting,such as R is 0.8376, MAPE is 466873.78%%. This research not only offers a more reliable decision-making tool for homebuyers, real estate intermediaries, and market analysts but also provides a practical modeling approach for non-linear housing price prediction problems, thereby contributing positively to the rational development of the real estate market.
Keywords: BP neural network; House price forecast; Z-score standardization method; One-hot encoding; Trainlm algorithm

1 INTRODUCTION

With the rapid economic development and continuous improvement of living standards in China, the real estate industry has become a crucial pillar of the national economy, playing an indispensable role in both national and regional economic development. The rapid expansion of the real estate market has driven sustained increases in housing prices, consequently drawing growing attention to price trends[1]. However, due to factors such as supply-demand imbalances and information asymmetry, phenomena of excessively rapid or sustained price surges in commercial housing occasionally occur, influenced by complex and multifaceted factors. Internal determinants primarily include locational attributes, physical characteristics, and property rights considerations, while external factors encompass demographic elements, institutional policies, economic conditions, social influences, and international dimensions[2]. Therefore, establishing a rational and effective housing price prediction model can not only provide price references for both buyers and sellers but also offer a theoretical foundation for national policy formulation. This holds significant importance for curbing excessive housing prices and addressing socioeconomic challenges, making real estate price prediction a widely researched topic among scholars globally. The basic fundamental of BP neural network.
Existing traditional approaches include time series analysis[3], grey system prediction models[4], multiple linear regression models[5], and BP neural network models, among others. Zhou Liangjin and Zhao Mingyang developed a random forest model to predict and analyze second-hand housing prices in Shenzhen along with the degree of influence of various characteristic factors on housing prices[6]. Liu Hai employed a dual-chain genetic algorithm to optimize a BP neural network model for predicting second-hand housing prices in Hefei[7]. Ling Fei and Li Yanan adopted a housing price prediction model based on feature selection and ensemble learning[8]. However, most of these models are linear in nature, while housing price trends are complex and volatile, typically exhibiting non-linear fluctuations influenced by numerous factors. This fundamental mismatch often leads to significant prediction errors when applying traditional linear-based models to housing price forecasting.
Furthermore, housing prices are influenced by numerous factors. Sun Tingting and Shen Yi selected common characteristic factors affecting housing prices, such as Gross Domestic Product, total population, and per capita income, for analysis[9]. They constructed a BP neural network-based housing price prediction model to analyze and forecast price trends. In another study, Li Yuanyuan utilized housing listing profile data as novel indicators to develop a BP neural network prediction model. Through comparative analysis of prediction results, the study demonstrated the model's predictive accuracy and stability, while also revealing the unreasonableness of agency listing prices. The predictive outcomes contributed to reducing economic losses in the buyer's market. Similarly, Hu Rong identified eleven factors influencing commodity housing prices in the primary real estate market of Changsha's municipal districts[10].
The BP neural network demonstrates exceptional capability for nonlinear mapping, enabling relatively accurate predictions on new data without requiring explicit definition of functional relationships between input and output samples.Therefore, building upon existing research, this paper proposes an improved house price prediction model based on a BP neural network. For the price prediction task, the model systematically selects eight key features, including property type, geographical coordinates, and area size, balancing attribute comprehensiveness with data accessibility. It adopts a data preprocessing strategy combining Z-score normalization and one-hot encoding to effectively enhance training stability and convergence efficiency. A BP network structure with a single hidden layer is

constructed, utilizing the Trainlm algorithm suitable for medium-sized datasets as the training function. This approach ensures model fitting capability while controlling overfitting risks.This model is anticipated to significantly reduce prediction error margins and achieve improved accuracy compared to traditional linear models. Furthermore, it can process real estate price data from different regions and with varying feature dimensions, generating predictions that better align with actual market fluctuations, thereby providing more reliable decision support for homebuyers, real estate agencies, and market analysts.

2 THE ESTABLISHMENT OF BP MODEL

2.1 Fundamental Principles of Backpropagation Neural Networks

Artificial neural networks possess the capability to autonomously learn patterns from data, establishing complex relationships between inputs and outputs without requiring predefined mathematical equations. During the training process, these networks continuously optimize their internal parameters so that for any given input, the network's output approximates the desired values as closely as possible. As a typical architecture among neural networks, the Backpropagation (BP) neural network employs the error Backpropagation (BP) algorithm for training, with its core principle being the utilization of gradient descent to minimize the error between the network's output and the actual values.

The training process of the Backpropagation (BP) algorithm comprises two distinct phases: forward propagation of signals and backward propagation of errors. During the forward propagation phase, input data undergoes sequential processing through hidden layers, ultimately generating output results. Should discrepancies exist between the output and expected values, the Backpropagation (BP) process is initiated. This involves transmitting the error signal layer by layer from the output layer back to the input layer, while simultaneously adjusting the connection weights and thresholds of each layer according to their respective contributions to the overall error. Through multiple iterations, the network progressively optimizes its parameters until the error reaches an acceptable threshold.

In the context of housing price prediction, the model establishes predictive capabilities by learning the relationships between various features within historical housing data—such as the number of bathrooms, bedrooms, floor area, geographic coordinates, and property type—and their corresponding prices. Upon completion of training, the network can automatically generate predictions for new property listings that closely align with actual market prices, thereby providing valuable reference for housing price evaluation.

2.2 Establishment of the BP Model

2.2.1 Fundamental architecture of BP neural network

The fundamental architecture of the BP neural network comprises three distinct layers: the input layer, hidden layer(s), and output layer, as schematically illustrated in Figure 1.

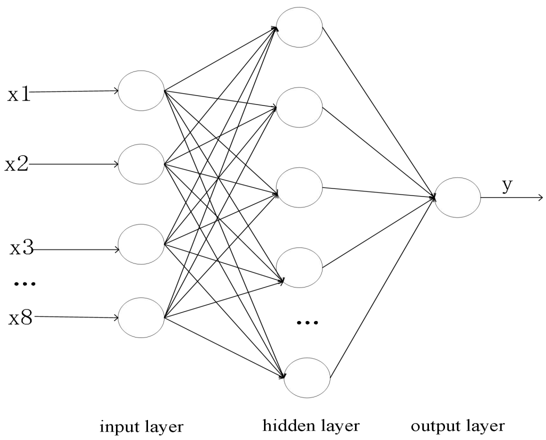

Figure 1 Neural Network Structure

2.2.2 Design of network topology architecture

The key features and their specific definitions are presented in Table 1.

Table 1 Feature Selection

Feature Name	Feature Description
Baths	Number of Bathrooms,indicates the completeness of housing facilities.
bedrooms	The number of bedrooms serves as a key indicator of a property's inherent potential for occupancy.
Area_in_Marla	Floor Area - Directly indicates the property's scale and serves as a primary determinant of housing price.

Feature Name	Feature Description
latitude	The geographic coordinates of a property are indicative of its locality, which encompasses factors such as transportation accessibility and the availability of surrounding amenities.
longitude	The geographic coordinates of a property are indicative of its locality, which encompasses factors such as transportation accessibility and the availability of surrounding amenities.
price	Property Price
Purpose	Transaction Purpose - Reflects the current condition of the property.
property_type	Housing prices vary significantly across different property types.

In the design of the neural network topology, the input layer consists of eight neurons, corresponding to the eight features in Table 1; this is followed by a single hidden layer comprising ten neurons; and the output layer contains a single neuron, which represents the predicted property price.

In the parameter configuration, the net.trainParam.lr is set to 0.01, the net.trainParam.epochs to 300, the net.trainParam.goal to 1e-5, and the net.trainFcn to trainlm.

For the activation functions, the hyperbolic tangent sigmoid function (tansig) is adopted in the hidden layer. This choice is motivated by the fact that housing prices can assume any positive real value without fixed bounds. The linear activation function (purelin) in the output layer preserves the numerical scale by directly outputting the weighted sum computed by the network, thereby accommodating the unbounded range of housing prices. The selection of tansig in the hidden layer introduces nonlinearity, enabling the network to capture complex nonlinear relationships between housing prices and features. Its saturation behavior under large inputs further contributes to forming smooth decision boundaries.

2.2.3 Model training process

The housing price prediction process commences with feature selection from the collected dataset, followed by data preprocessing and the construction of an initial BP neural network architecture. The network's weights and thresholds are subsequently initialized. Each data subset is utilized to train the BP neural network, during which training errors are computed. A conditional assessment is performed to determine whether the error meets the predefined criteria. If satisfied, the stabilized BP neural network is finalized and the process terminates; otherwise, the procedure returns to the weight and threshold initialization phase for iterative optimization. The detailed algorithm flowchart is presented in Figure 2.

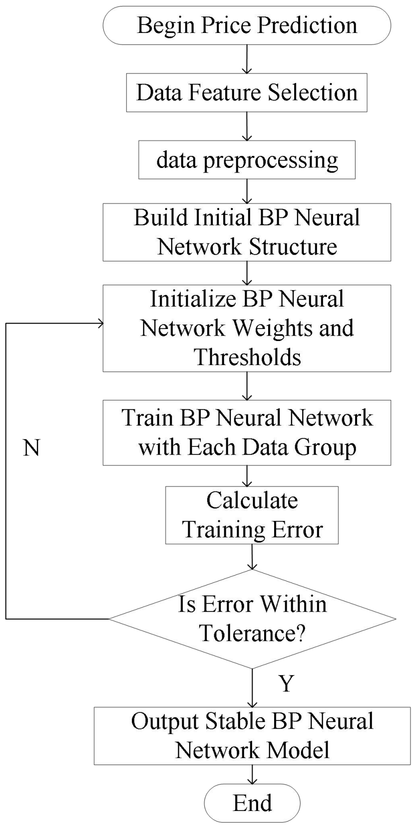

Figure 2 Algorithm Flowchart

Step1 Data Collection and Processing

The dataset comprises approximately 150,000 samples with eight feature vectors selected for modeling. During the data preprocessing phase, data integrity is first ensured through direct removal of rows containing missing values.

Categorical variables are then converted into numerical format using one-hot encoding to prevent erroneous ordinal interpretation. Subsequently, all numerical features and encoded categorical features are combined to form a complete feature matrix. Finally, z-score normalization is applied to eliminate scale disparities among different features, thereby providing uniformly-scaled input data for subsequent neural network training.

Step2 Architectural Process of the BP Neural Network

Based on the eight selected housing features, this study constructed a BP neural network with an 8-node input layer, 10-node hidden layer, and 1-node output layer. Through setting parameters such as learning rate and training epochs, and employing iterative training via error Backpropagation (BP), the model achieves accurate housing price predictions.

Step3 Initial Weights and Thresholds of the BP Neural Network

Network initialization serves as a preliminary step in the training process, which involves randomly generating weight matrices for the hidden and output layers along with threshold vectors. This establishes an initial parameter set for subsequent forward and backward propagation, enabling the iterative process to commence from a reasonable starting point.

Step4 The BP neural network was trained with each data set

The processed training set is utilized for network training, with the core process comprising both forward propagation of signals and backward propagation of errors. During forward propagation, input features are transmitted from the input layer to the hidden layer, processed through activation functions to compute hidden layer outputs. These outputs are subsequently passed to the output layer, where final predictions are generated through additional activation functions. In the Backpropagation (BP) phase, the error between predicted values and actual housing prices is first calculated. This error is then propagated backward from the output layer to the hidden layer and subsequently to the input layer using the chain rule of derivatives. The weights and thresholds are updated layer by layer, ultimately achieving the objective of iteratively reducing the prediction error.

Step5 Training Error Computation

During the training process, the Mean Squared Error (MSE) is calculated to quantify the average squared difference between predicted and actual values. As a commonly adopted error evaluation metric in regression tasks, the computation of this assessment indicator serves as a criterion for evaluating the final calculation of property prices.

Step6 Termination Condition Satisfaction

The training process terminates if either the training error falls below 1e-5 or the number of training epochs exceeds the maximum iteration threshold.

Step7 Output the stabilized BP neural network

Model Testing and Prediction: The test set that did not participate in training is fed into the model to obtain housing price prediction results.Performance Evaluation: A comprehensive performance evaluation is conducted using MSE, RMSE, and MAPE metrics.Result Visualization: The following visualizations are generated: BP NN: Predicted vs Actual, Residual Analysis, Actual vs Predicted, Regression Analysis, and Performance Plot.Output: The test results are systematically documented and presented.

3 SOLUTION OF THE MODEL

3.1 An Introduction to the Data

The dataset is sourced from an open-source real estate prediction dataset available on the CSDN website. This dataset encompasses diverse types of housing information, demonstrating high authenticity and reliability, making it suitable for training and validating real estate price prediction models.A total of 150,000 data samples were selected, incorporating eight characteristic factors influencing housing prices: baths, bedrooms, Area_in_Marla, latitude, longitude, price, property_type, and purpose. The feature selection demonstrates strong representativeness, with the data exhibiting highly non-linear mapping relationships, making it appropriate for modeling real estate price prediction problems.

For data preprocessing, missing values were first handled by removing incomplete records to ensure data integrity. Categorical variables such as property type and purpose were converted into numerical format using one-hot encoding. A feature matrix was subsequently constructed incorporating numerical attributes including the number of bathrooms, bedrooms, area, and geographical coordinates. Z-score normalization was then applied to standardize all input features and output targets to eliminate dimensional influences, while preserving standardization parameters for subsequent predictions. Finally, the dataset was partitioned into training and testing sets with an 80:20 ratio, providing cleansed, normalized, and uniformly formatted input data for subsequent BP neural network training.

The formula is as follows:

$$x' = \frac{x-\mu}{\sigma} \tag{1}$$

3.2 Evaluating Indicator

MSE, which stands for Mean Squared Error, is defined as the average of the squared differences between predicted and actual values. It is also known as the L2 Loss.

$$MSE = \frac{1}{n}\sum_{i=1}^{n}\left(y_{true}^{i} - y_{pred}^{i}\right)^{2} \tag{2}$$

MAE, which stands for Mean Absolute Error, is defined as the average of the absolute differences between predicted and actual values. It is also known as the L1 Loss.

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|y_{true}^{i} - y_{pred}^{i}\right| \tag{3}$$

RMSE, the Root Mean Squared Error, is defined as the square root of the MSE. It serves as a metric that quantifies the average difference between predicted and actual values. Similar to MSE, the RMSE's unit of measurement is identical to that of the original data, thereby facilitating a more intuitive interpretation.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_{true}^{i} - y_{pred}^{i})^{2}} \tag{4}$$

The correlation coefficient (R) is employed to quantify the strength of a linear relationship between variables and serves as a measure of the goodness-of-fit for a model. It provides an intuitive indication of the model's explanatory power and how closely it aligns with the observed data.

$$MAPE = \frac{1}{n}\sum\left|\frac{y_{true} - y_{pred}}{y_{true}}\right| * 100\% \tag{5}$$

The Mean Absolute Percentage Error (MAPE) offers the advantage of expressing the relative error between predicted and actual values in percentage terms, which prioritizes the analysis of relative errors and enhances comparability across prediction problems of different magnitudes. Furthermore, MAPE is widely employed in the financial sector for evaluating the performance of portfolio risk models. However, a notable limitation of MAPE is its susceptibility to division by zero when actual values approach zero, rendering the evaluation results invalid. Moreover, MAPE demonstrates heightened sensitivity to minor errors and may consequently amplify inaccuracies in samples with small actual values.

$$MAPE = \frac{1}{n}\sum\left|\frac{y_{true} - y_{pred}}{y_{true}}\right| * 100\% \tag{5}$$

3.3 Analysis of Model Solutions

The model solution is derived from a dataset of 150,000 real estate records through configured training parameters and evaluation metrics. Performance is assessed both quantitatively and visually, yielding the following results: MAE: 5,782,717.72, MSE: 406,391,669,110,579.31, RMSE: 20,159,158.44, MAPE: 466,873.78%, and R = 0.8376.The scatter plot of predicted versus actual prices (Figure 3) reveals that most predictions cluster around the actual values, though some deviation is observed in higher price ranges. Overall, the model demonstrates reasonable predictive accuracy for most properties but shows weaker mapping capability for high-value housing segments.Residual analysis (Figure 4) further indicates the model's limited capacity to capture underlying patterns in premium property data. The sample index variation plot (Figure 5) demonstrates generally close alignment between predicted and actual values despite occasional inverse fluctuations in certain data segments.Regression analysis (Figure 6) confirms strong positive linear correlation (R = 0.8376) between predicted outputs and actual targets, indicating effective training performance. The training performance plot (Figure 7) exhibits convergent behavior, achieving optimal performance after 300 epochs without premature convergence, confirming sufficient training cycles for model optimization.

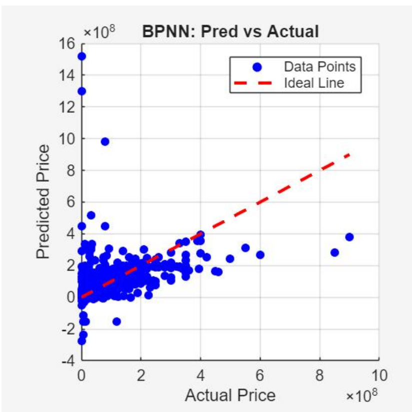

Figure 3 BP NN: Pred vs Actual

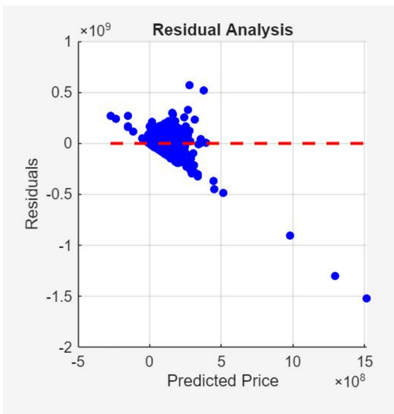

Figure 4 Residual Analysis

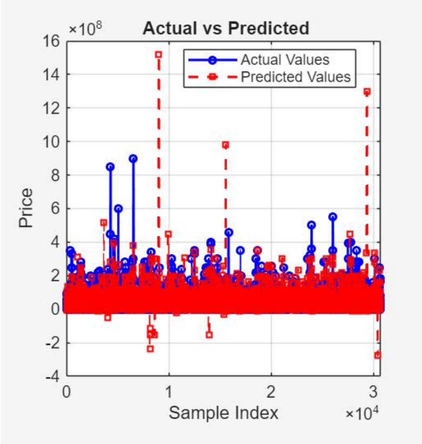

Figure 5 Actual VS Predicted

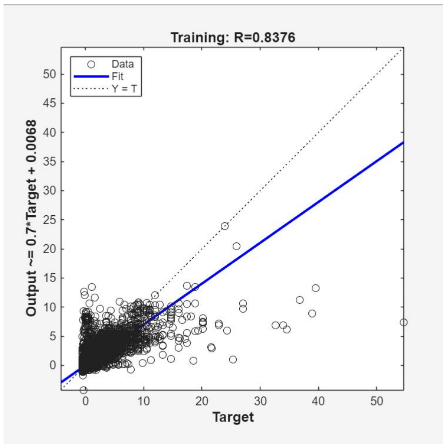

Figure 6 Regression

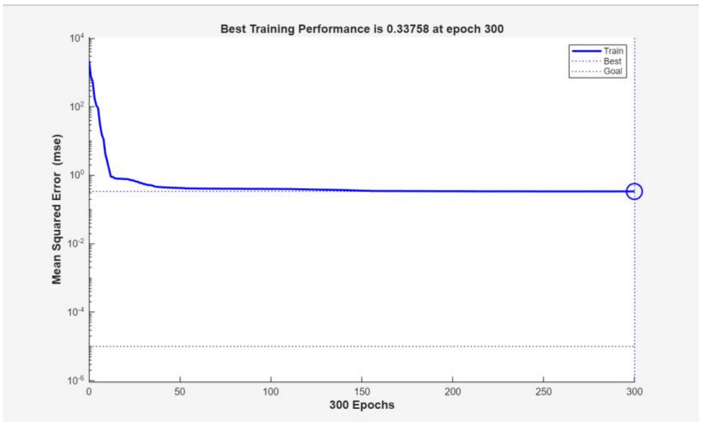

Figure 7 Performance

3.4 Conclusion of the Experimental Findings

The BP neural network-based housing price prediction model constructed in this study employs 8 input layer nodes, corresponding to the eight features influencing housing prices: baths, bedrooms, Area_in_Marla, latitude, longitude, price, property_type, and purpose. The network architecture consists of a single hidden layer with 10 neurons and an output layer containing one neuron, which generates the final price prediction.Comprehensive analysis of experimental visualization results indicates that the model demonstrates certain learning capabilities while possessing clear potential for improvement. The regression plot (Figure 6) reveals a strong linear correlation between predicted and actual values, suggesting the model has effectively captured primary data patterns. The training performance graph (Figure 7) confirms the effectiveness of the training process, showing stable convergence after approximately 300 epochs. However, both the scatter plot (Figure 3) and residual analysis (Figure 4) consistently demonstrate the model's inadequate predictive capability for high-end properties, exhibiting systematic underestimation. The sample index plot (Figure 5) further indicates that while prediction errors remain controllable for most samples, abnormal fluctuations persist in certain data segments.

In summary, the proposed BP neural network model successfully accomplishes basic housing price prediction tasks, yet requires optimization for handling extreme-value instances, particularly properties with exceptionally high or low prices. Regarding fitting effectiveness, generalization performance, and error metrics, the model demonstrates strong prediction stability for most properties, but shows significant errors in certain low and high-priced housing segments, indicating substantial potential for future optimization.

4 CONCLUSION

This paper proposes a house price prediction model based on a Backpropagation (BP) neural network, selecting multiple typical factors influencing price trends. The model fits historical housing price data using the BP neural network to forecast future price movements. In the specific implementation, eight housing features were preprocessed through standardization and one-hot encoding. A network structure was constructed and trained using the trainlm (Levenberg-Marquardt) algorithm for error Backpropagation (BP), ultimately achieving effective price prediction. Experimental results indicate that the model achieved an RMSE of 20,159,158.44, an MAE of 5,782,717.72, and a correlation coefficient (R) of 0.8376 on the test set, demonstrating its strong nonlinear fitting capability. In comparative experiments with traditional linear regression models (such as multiple linear regression) on the same dataset, the proposed model reduced RMSE by approximately 18.5% and MAE by approximately 21.3%, indicating a significant improvement in prediction accuracy and validating the advantage of the BP neural network in handling complex housing price data.However, the model still exhibits systematic bias in predicting high-end properties, with a notably high MAPE of 466,873.78%, indicating that its fitting capability in extreme price ranges requires further enhancement. Future research will focus on optimizing the network structure, incorporating attention mechanisms or ensemble learning methods, and enhancing the modeling of regional characteristics and market dynamics to improve prediction stability and generalization across all price ranges, particularly for high-value properties. In summary, the proposed BP neural network-based house price prediction model demonstrates satisfactory accuracy and practicality for conventional price ranges, providing reliable decision-making support for real estate market participants and offering a practical modeling approach for nonlinear house price prediction problems.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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THE IMPACT OF TWO-WAY FDI INTERACTIVE DEVELOPMENT ON CHINA'S DIGITAL ECONOMY

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Abstract: Distinct from the existing literature that predominantly focuses on the economic impact of either FDI or OFDI in isolation, this study examines the synergistic effects and coordinated development of two-way FDI on the digital economy across Chinese provincial regions. The findings reveal that the coordination of two-way FDI exerts a positive influence on the digital economy. This impact mechanism exhibits a distinct threshold effect, moderated by two key threshold variables: the level of local trade openness and the characteristics of the industrial structure. Notably, the facilitative effect of two-way FDI coordination is more pronounced within the Yangtze River Economic Belt, whereas in regions outside the Belt, it still contributes to the growth of the digital economy but with statistically weaker significance. This research not only offers policy implications for China's foreign trade and digital economic development but also elucidates the underlying mechanisms and threshold conditions involved. It provides valuable insights for regional economic and digital advancement in China, while also serving as an important supplement to the literature on two-way FDI.
Keywords: Foreign Direct Investment (FDI); Outward Foreign Direct Investment (OFDI); Digital economy; Threshold model

1 INTRODUCTION

Two-way FDI, which connects domestic and international markets and technologies, is increasingly recognized as a systemic enabler of China's digitalization and a strategic tool for overcoming development challenges. Rather than acting in isolation, IFDI and OFDI work together to promote corporate digital transformation through coordinated development [1]. IFDI offers domestic firms access to advanced digital technologies, managerial expertise, and global networks via spillover, demonstration, and competition effects [2,3]. Meanwhile, OFDI allows firms to integrate into global innovation hubs, acquire complementary knowledge and technologies, and enhance their talent base [4]. International experience also refines firms' digital transformation strategies through feedback mechanisms [5]. As a result, two-way FDI functions as a self-reinforcing digital engine: knowledge gained abroad strengthens domestic capabilities, which in turn encourages deeper outward investment [6]. This synergy fosters more comprehensive digital transformation at the firm level. Examining how two-way FDI collectively drives digital transformation is therefore of major theoretical and practical relevance, especially for understanding how firms in an open economy can accelerate digital upgrading, overcome resource constraints, and achieve technological leapfrogging.

The existing literature examines the individual roles of IFDI and OFDI, overlooking the significant impact of their coordinated development. More importantly, existing research predominantly focuses on the digital economy's influence over two-way FDI, paying scant attention to the inverse relationship. This paper makes a critical contribution to the literature by investigating the effect that coordinated two-way FDI exerts on the development of the digital economy.

2 THEORETICAL BACKGROUND AND HYPOTHESIS

IFDI generates forward technological spillovers, while OFDI facilitates reverse technology transfer [7]. IFDI and OFDI do not operate in isolation but exhibit synergistic coexistence. This two-way FDI interaction accelerates the digital transformation of China's industries, thereby optimizing the industrial structure, enhancing digital innovation capabilities, and promoting coordinated regional economic development. Furthermore, the coordinated development of two-way FDI significantly contributes to China's digital economy and high-quality development by leveraging technological spillover effects, intensifying market competition, and driving industrial upgrading [8]. Therefore, we hypothesize as follows:

Hypothesis 1. The coordinated development of two-way FDI exerts a positive promoting effect on the digital economy.

While existing literature often assumes a linear positive relationship between two-way FDI coordination and digital economy development, this study proposes a nonlinear relationship contingent on macroeconomic thresholds. Drawing on threshold effect theory, we argue that trade openness and industrial structure serve as critical threshold variables determining the actual impact. The positive effects of two-way FDI coordination become significantly stronger only after these variables surpass certain tipping points. Trade openness serves as a fundamental channel condition like low openness inhibits knowledge flows and technology spillovers, whereas high openness facilitates the cross-border exchange of digital technologies and innovative ideas, thereby amplifying the synergistic effects of FDI [9]. Similarly, industrial structure determines absorptive capacity for digital technologies. Traditional sector-dominated economies lack the foundation to assimilate advanced digital spillovers, whereas advanced industrial structures with greater shares of high-end services and manufacturing provide the necessary ecosystem for digital innovation, enabling regions to fully harness two-way FDI benefits [10]. Therefore, we hypothesize as follows:

Hypothesis 2. The promoting effect of two-way FDI coordination on the digital economy is subject to a threshold effect.

Two-way FDI facilitates the optimization of firms' locational advantages. Inward FDI drives host countries to enhance their digital infrastructure, increase the supply of digital talent, and refine digital governance policies. These improvements in the external environment reduce the institutional costs and technological barriers associated with digital transformation for domestic firms, thereby strengthening the locational attractiveness for digital investment within the home country. Concurrently, through OFDI, firms enter countries with advanced digital capabilities, gaining direct access to sophisticated digital industrial clusters, mature technology markets, and open innovation networks. This strategic locational embedding enables firms to acquire digital production factors at lower costs and subsequently transfer the knowledge and practices learned overseas back to their domestic operations, ultimately enhancing their overall digital efficiency [11]. Therefore, we hypothesize as follows:

Hypothesis 3. The promoting effect of two-way FDI coordinated development on the digital economy exhibits regional heterogeneity.

3 RESEARCH DESIGN

3.1 Baseline Model

To investigate the impact of two-way FDI coordinated development on the digital economy, this paper establishes the following baseline regression model:

$$lnDig_{it} = \mu_i + \beta_1 lnD_{it}(IO) + \beta_2 lnX_{it} + \sigma_i + \gamma_t + \varepsilon_{it} \tag{1}$$

Based on the results of the Hausman test, this paper employs a two-way fixed effects panel model for regression. In Equation (1), i denotes the Chinese province, t denotes the year, Dig_{it} represents the development level of the digital economy, $D_{it}(IO)$ represents the coordinated development level of two-way FDI, and X_{it} represents a set of control variables, namely trade openness $Open_{it}$, industrial structure Ind_{it}, level of government intervention Gov_{it}, financial development level Fin_{it}, and population quality Hrq_{it}. β_1 is the elasticity coefficient of the core explanatory variable: the coordinated development level of two-way FDI, β_2 represents the elasticity coefficients of the control variables, μ_i is the constant term, σ_i and γ_t represent the individual fixed effects and year fixed effects, respectively, and ε_{it} denotes the random error term.

This paper also employs two threshold models to investigate whether the impact of two-way FDI coordinated development on the digital economy exhibits a threshold effect.

$$\begin{gathered} lnDig_{it}=\mu_i+\beta_3 lnD_{it}(\mathrm{IO})I(lnOpen_{it}\leq\gamma) \\ +\beta_4 lnD_{it}(IO).I(lnOpen_{it}>\gamma)+\beta_5 X_{it}+\varepsilon_{it} \end{gathered} \tag{2}$$

$$\begin{gathered} lnDig_{it}=\mu_i+\beta_6 lnD_{it}(\mathrm{IO})I(lnInd_{it}\leq\gamma) \\ +\beta_7 lnD_{it}(IO).I(lnInd_{it}>\gamma)+\beta_8 X_{it}+\varepsilon_{it} \end{gathered} \tag{3}$$

Among these, trade openness $Open_{it}$ and industrial structure Ind_{it} serve as the threshold variables. $I(.)$ is an indicator function that takes the value of 1 when $q_{it} \leq \gamma$, and 0 otherwise. Here, γ represents the threshold value. The definitions of the remaining variables are consistent with those provided earlier.

3.2 Variables

Regarding the measurement the dependent variable Dig_{it}, this paper employs the entropy method to construct an index based on 19 secondary indicators across three dimensions for each Chinese province: digital infrastructure development, digital industrialization, and industrial digitalization [12,13]. To measure the core explanatory variable $D_{it}(IO)$, this paper adopts the physics-based capacity coupling model, consistent with mainstream literature and formalized in Equation (4).

$$C_{it}(IO)=\frac{IFDI_{it}*\ OFDI_{it}}{(\alpha IFDI_{it}+\beta OFDI_{it})^{\gamma}} \tag{4}$$

Here, both α and β are set to 0.5, γ is an adjustment coefficient, generally ranging between 2 and 5, and this study assigns it a value of 2. It is important to note that the coupling degree $C_{it}(IO)$ only reflects the intensity of interaction between systems, whereas the coordination degree can capture not only this interaction intensity but also the respective development levels of each system. Therefore, a coupling coordination development index is further introduced. The calculation formula for the Two-way FDI Coordination Development Index is as follows:

$$D_{it}(IO)=C_{it}(IO)*\left[\frac{IFDI_{it}+OFDI_{it}}{2}\right]^{\frac{1}{2}}=\left[\frac{IFDI_{it}*\ OFDI_{it}}{\frac{IFDI_{it}+OFDI_{it}}{2}}\right]^{\frac{1}{2}} \quad (5)$$

In the selection of control variables, this paper primarily adopts the following approach: Trade Openness $Open_{it}$: Measured as the ratio of a province's total import and export value to its GDP. Provinces with greater trade openness have better access to advanced foreign business models and digital management expertise, thereby fostering the development of their digital economy. Industrial Structure Ind_{it}: Measured as the ratio of the output value of the tertiary industry to that of the secondary industry within a province. The digital economy is inherently rooted in the tertiary sector. A more advanced industrial structure provides fertile ground for the digital economy to thrive. Government Intervention Gov_{it}: Measured as the ratio of a province's general public budget expenditure to the national GDP of that year. The government's sustained promotion of the digital strategy plays a direct and substantial role in driving the growth of the digital economy. Financial Development Level Fin_{it}: Measured as the ratio of the year-end loan balance of financial institutions in a province to its GDP. The development of the digital economy relies on a high level of financing. A robust financial environment is conducive to the growth of digital industries. Population Quality Hrq_{it}: Measured by the ratio of the number of people with higher education to the average years of schooling in a province. A high-quality talent pool provides the intellectual and technical support essential for the advancement of the digital economy.

4 RESEARCH AND DISCUSSION

4.1 Data Description

This study utilizes provincial-level data from China spanning the years 2011 to 2022 (excluding Tibet). The data are sourced from the National Bureau of Statistics of China, the China Statistical Yearbook, provincial statistical yearbooks, China Stock Market & Accounting Research Database (CSMAR), Chinese Research Data Services (CNRDS), the Ministry of Industry and Information Technology and the National Information Center's China Interprovincial Information Society Index. The descriptive statistics of the variables are presented in Table 1.

Table 1 Variable Table

		(1)	(2)	(3)	(4)	(5)
Variable type	**Variables**	**N**	**mean**	**sd**	**min**	**max**
Explained variable	$lnDig_{it}$	360	0.131	0.111	0.0145	0.702
Explanatory variable	$lnD_{it}(IO)$	360	11.69	8.423	0.0867	39.22
Control variable	$lnOpen_{it}$	360	0.248	0.270	0.00172	0.848
	$lnInd_{it}$	360	0.133	0.417	-0.658	1.667
	$lnGov_{it}$	360	0.0330	0.0158	0.00678	0.0868
	$lnFin_{it}$	360	1.510	0.443	0.670	2.770
	$lnHrq_{it}$	360	-1.975	0.413	-2.925	-0.683

4.2 Fixed Effects Regression

In Table 2, Column (1) presents the baseline regression results, while Column (2) introduces control variables based on this baseline. The results from both columns indicate that the coordinated development of two-way FDI promotes the digital economy, providing preliminary support for Hypothesis 1 of this study.

Table 2 Regression and Test Results

	(1)	(2)	(3)	(4)
	FE	**FE**	**GMM**	**Robust**
Variables	$lnDig_{it}$	$lnDig_{it}$	$lnDig_{it}$	$lnDig_{it}$
$lnD_{it}(IO)$	0.394***	0.062***	0.133***	
	(0.028)	(0.024)	(0.046)	
$l.\ lnDig_{it}$			0.082***	
			(0.018)	
$lnC_{it}(IO)$				0.031***
				(0.012)
$lnOpen_{it}$		0.164***	0.223***	0.164***

	(1)	(2)	(3)	(4)
	FE	**FE**	**GMM**	**Robust**
		(0.023)	(0.069)	(0.023)
$lnInd_{it}$		0.162***	0.061	0.162***
		(0.055)	(0.049)	(0.055)
$lnGov_{it}$		0.712***	0.572***	0.712***
		(0.037)	(0.077)	(0.037)
$lnHrq_{it}$		0.238***	0.248***	0.238***
		(0.061)	(0.054)	(0.061)
$lnFin_{it}$		0.274***	0.243*	0.275***
		(0.089)	(0.129)	(0.089)
Cons	-3.168***	0.814***	0.034	0.814***
	(0.065)	(0.202)	(0.088)	(0.202)
N	360	360	336	360
R^2	0.365	0.770	None	0.770

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

According to the regression results, without control variables, a 1% increase in the degree of two-way FDI coordination leads to a 0.394% rise in the development level of the digital economy. After including control variables, the coefficient decreases to 0.062%, which remains statistically significant at the 1% level. The coefficients of the control variable group are all positive and significant.

4.3 Endogeneity And Robustness Tests

To address endogeneity concerns, this study employs the Generalized Method of Moments (GMM) to estimate Equation (1). The GMM approach relies on moment conditions without requiring distributional assumptions, effectively handling endogeneity issues. Key diagnostic tests support the model validity: no significant AR (1) serial correlation was found, while AR (2) was significant. Both Sargan and Hansen test statistics met acceptable thresholds. These results confirm the validity of the instrumental variables, with the two-period lagged dependent variable treated as strictly exogenous. The GMM results in Table 2, column (3) show that two-way FDI coordination maintains a statistically significant positive effect at 5% level on digital economy development, confirming its promotive role.

To test the robustness of the findings, the regression is re-run by employing a different measure of the core explanatory variable. We substitute the coupling degree of two-way FDI $C_{it}(IO)$ for the coordinated development level $D_{it}(IO)$ in the regression. The results are presented in column (4) of Table 2. The results indicate that the variable continues to exert a positive influence on the digital economy at the 5% significance level. Specifically, a 1% increase in the two-way FDI coupling degree leads to a 0.031% rise in the digital economy, demonstrating the robustness of our empirical findings.

4.4 Threshold Effect Regression

Prior to conducting the threshold regression, we tested the statistical significance of the threshold effect. The results indicate that while the single-threshold hypothesis is not significant, the dual-threshold hypothesis is statistically significant $p<0.05$, confirming a dual-threshold effect. The testing procedure followed Hansen's method, employing 300 bootstrap replications and 300 grid searches, with data winsorized at the 1% level within threshold groups.

Table 3 Threshold and Heterogeneity Regressions

	(1)	(2)	(3)	(4)	(5)	(6)
	Th1	Th2	Rg1	Rg1	Rg2	Rg2
Variables	$lnDig_{it}$	$lnDig_{it}$	$lnDig_{it}$	$lnDig_{it}$	$lnDig_{it}$	$lnDig_{it}$
$lnD_{it}(IO)$			0.625***	0.094**	0.327***	0.029
			(0.043)	(0.041)	(0.037)	(0.030)
$lnOpen_{it}$		0.188***		0.111***		0.170***
		(0.022)		(0.027)		(0.030)
$lnInd_{it}$	0.051			-0.427***		0.309***
	(0.055)			(0.094)		(0.066)
$lnGov_{it}$	0.715***	0.691***		1.072***		0.700***

	(1)	(2)	(3)	(4)	(5)	(6)
	Th1	Th2	Rg1	Rg1	Rg2	Rg2
	(0.036)	(0.034)		(0.075)		(0.045)
$lnHrq_{it}$	0.185***	0.135**		0.446***		0.140*
	(0.061)	(0.060)		(0.090)		(0.082)
$lnFin_{it}$	0.241**	0.443***		0.504***		0.213
	(0.094)	(0.081)		(0.091)		(0.132)
$lnD_{it}(IO)0$	0.060	0.096***				
	(0.038)	(0.023)				
$lnD_{it}(IO)1$	0.214***	0.015				
	(0.030)	(0.023)				
$lnD_{it}(IO)2$	0.081***	0.237***				
	(0.022)	(0.031)				
Cons	0.254	0.496***	-3.713***	2.173***	-3.048***	0.683***
	(0.208)	(0.190)	(0.109)	(0.390)	(0.081)	(0.246)
N	360	360	132	132	228	228
R^2	0.782	0.807	0.642	0.905	0.263	0.753

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

The threshold regression results from Equations (2) and (3), presented in Columns (1) and (2) of Table 3, reveal that the effect of two-way FDI coordination on the digital economy is nonlinear and constrained by the level of trade openness $Open_{it}$. At a low level of trade openness, specifically at or below -3.0794, the coefficient for two-way FDI is an insignificant 0.060, indicating its promoting effect fails to materialize in a relatively closed economic environment. As trade openness increases to a moderate level between -3.0794 and -1.5844, the coefficient rises significantly to 0.214, marking a period of optimal synergy. However, when trade openness exceeds a high threshold of -1.5844, the promoting effect diminishes, with the coefficient declining to 0.081, though it remains statistically significant. These findings underscore that only through deep synergy between trade and two-way FDI policies can the composite driving effect on the digital economy be maximized.

Using industrial structure Ind_{it} as the threshold variable reveals two significant thresholds, 0.2793 and 1.0173, dividing the sample into three distinct regimes. At a low industrial structure level, specifically at or below 0.2793, two-way FDI exerts its strongest positive effect with a coefficient of 0.237. However, as industrial structure upgrades into the intermediate range between 0.2793 and 1.0173, the promoting effect not only diminishes but becomes statistically insignificant, indicating a structural bottleneck during this transitional phase. When industrial structure advances beyond 1.0173, where the tertiary sector becomes dominant, the positive effect of two-way FDI reemerges, registering a significant coefficient of 0.096, though weaker than in the initial stage. This nonlinear pattern underscores how industrial structure evolution shapes the investment environment, suggesting policies must align with specific developmental stages to maximize two-way FDI's digital economy benefits.

4.5 Heterogeneity Analysis

The sample is divided into the Yangtze River Economic Belt and non-YREB subgroups. YREB Regression results are reported in Columns (3)-(4) and (5)-(6) of Table 3 for the two regions, respectively. Without control variables, coordinated two-way FDI development shows a statistically significant positive impact in both regions, though the coefficient is larger for the YREB. This regional heterogeneity can be attributed to the YREB's superior digital infrastructure, more advanced industrial structure, and greater concentration of digital innovation talent. After including control variables, the effect remains significantly positive in the YREB but becomes statistically insignificant in the non-YREB. This suggests that in less developed non-YREB regions, the market environment is less mature, and the positive spillovers from two-way FDI are more dependent on macro-level factors rather than deep market-driven synergy. Therefore, for non-YREB regions, enhancing digital infrastructure, optimizing industrial structure, and improving the business environment are essential to unlocking the potential benefits of two-way FDI coordination.

5 CONCLUSION AND IMPLICATION

This study employs provincial-level data from China to examine the impact of coordinated two-way FDI development on the digital economy. The findings indicate that coordinated two-way FDI exerts a positive influence on the digital economy, with its effects varying according to local trade openness and industrial structure. Specifically, the promoting effect of two-way FDI is most pronounced when trade openness is at a moderate level -3.0794~-1.5844. When industrial structure serves as the threshold variable, the effect is significant at both low ≤ 0.2793 and high >1.0173

levels of industrial sophistication but encounters a structural bottleneck during the transitional phase 0.2793~1.0173. These results suggest that the effectiveness of two-way FDI is jointly shaped by external openness conditions and internal industrial structure. Furthermore, the positive impact of coordinated two-way FDI is more substantial in the YREB, whereas in non-YREB regions, this effect is less evident, largely due to underdeveloped digital infrastructure.

Therefore, this study proposes the following policy recommendations. First, integrate two-way FDI policies with the national innovation strategy. Local governments should coordinate inbound and outbound FDI to leverage external innovation resources. Second, align FDI policy with industrial digitalization. Given the threshold effect of industrial structure, policymakers should utilize tools like industrial guidance funds to attract digital-intensive FDI that matches local advantages. Finally, adopt regionally differentiated approaches. The Yangtze River Economic Belt should pursue higher-level opening-up in high-end manufacturing and digital services, while other regions should prioritize strengthening digital infrastructure, cultivating talent, and upgrading traditional industries to establish a foundation for two-way FDI synergy.

COMPETING INTERESTS

The author has no relevant financial or non-financial interests to disclose.

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THE IMPACT OF DIGITAL INCLUSIVE FINANCE ON URBAN INNOVATION AND ENTREPRENEURSHIP

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Abstract: Innovation and entrepreneurship are of great significance to enhance the overall national strength and promoting regional development. Promoting innovation and entrepreneurship is an inevitable requirement for China to enhance the internal driving force and high-quality economic development. Based on the panel data of 279 prefecture-level cities in China from 2011 to 2019, this paper constructs a fixed-effect model to verify the relationship between digital inclusive finance and urban innovation and entrepreneurship and its influence mechanism. The study found that digital inclusive finance can significantly affect the improvement of the level of urban innovation and entrepreneurship, and the conclusion is still valid after changing the measure of urban innovation and entrepreneurship and deleting the robustness test of the provincial capital cities. Secondly, through the construction of the intermediary effect model, it is found that digital inclusive finance promotes the level of urban innovation and entrepreneurship by improving the development level and marketization degree of the Internet.
Keywords: Panel data; Digital inclusive finance; Innovation and entrepreneurship; The intermediary effect

1 INTRODUCTION

1.1 Research Background and Significance

China's economy has entered an era of high-quality and healthy development, while also being at a crucial juncture of transitioning from old to new growth drivers. Economic growth is slowing, and the pandemic has created unavoidable downward pressure on the economy. As a new driving force for China's economic growth, developing innovation and entrepreneurship is an inevitable choice and requirement for enhancing the endogenous driving force of China's economy and promoting high-quality economic and social development. As early as 2014, Premier Li Keqiang called for "mass entrepreneurship and innovation" at the World Economic Forum, aiming to stimulate the passion for innovation and entrepreneurship across society, mobilize entrepreneurial vitality, and further enhance the driving force of economic development. In 2018, the State Council proposed to create an upgraded version of innovation and entrepreneurship, further stimulate the vitality of mass entrepreneurship and innovation, and promote high-quality development of mass entrepreneurship and innovation. The 14th Five-Year Plan and the 2035 Long-Term Goals Outline also clearly propose to promote the in-depth development of innovation and entrepreneurship and optimize the layout of demonstration bases for mass entrepreneurship and innovation. It is evident that China has always attached great importance to the role of innovation and entrepreneurship in economic growth and social development, and has consistently regarded innovation as one of the national development strategies.

With the deepening development of innovation strategies, promoting urban entrepreneurship and innovation faces greater challenges. Finance is a crucial supporting factor for innovation and entrepreneurship, and the government's emphasis on formulating and implementing policies and measures related to innovation and entrepreneurship is inseparable from the support of the financial industry. The "Plan for Promoting the Development of Inclusive Finance (2016-2020)" (hereinafter referred to as the "Plan") issued by the State Council has emphasized that actively promoting inclusive finance helps to foster "mass entrepreneurship and innovation." Since the implementation of the Plan, the breadth and quality of financial services have continuously improved, and the threshold for financial services has been continuously lowered. During the pandemic, it played a key role in controlling the spread of the epidemic, restoring economic and social development, and contributing to the fight against poverty. Against this backdrop, studying the impact and pathways of digital inclusive finance on urban innovation and entrepreneurship will help deepen the understanding of urban innovation and entrepreneurship, provide a reference for policy selection and implementation to improve the level of urban innovation and entrepreneurship, and have considerable theoretical value and practical significance for consolidating the theoretical foundation of urban innovation and entrepreneurship and promoting the high-quality and healthy development of my country's economy.

1.2 Related Concepts

1.2.1 Digital inclusive finance

In 2005, the United Nations proposed inclusive finance as a new financial development model. As a developing country, China also adopted this model in 2006, and formally proposed promoting inclusive finance in the "Decision of the CPC Central Committee on Several Major Issues Concerning Comprehensively Deepening Reform," issued at the end of 2013. In January 2016, the "Plan" also guided the development of inclusive finance to utilize innovative technologies such as the internet. Since the implementation of the "Plan, " coupled with the rapid development of information technologies such as cloud computing, big data, and blockchain, information technology and inclusive finance have accelerated their integration and innovation, giving rise to digital inclusive finance. In essence, digital inclusive finance represents a new stage in the development of inclusive finance. In 2019, the China Academy of Information and Communications Technology (CAICT) released the "White Paper on the Development of Digital Inclusive Finance (2019)," which explained that digital inclusive finance, under the condition of sustainable development with scientific cost control, uses various information and digital technologies to serve underserved urban and rural poor groups, as well as special groups in unfavorable geographical locations, providing more comprehensive, higher-quality, and lower-threshold financial services and products to micro and small enterprises.

1.2.2 Urban innovation and entrepreneurship

Urban innovation and entrepreneurship refers to pioneering entrepreneurial activities within a city that primarily rely on cutting-edge technologies, scientific knowledge, cultural heritage, and brand value as production factors. It focuses on innovation in one or more areas, such as product differentiation, technology application, service improvement, business models, management reform, organizational optimization, and marketing, emphasizing innovation, pioneering spirit, and originality. The level of urban innovation and entrepreneurship represents a city's development potential and competitiveness, and is a crucial indicator of whether a city can become an innovative city.

1.3 Research Framework and Content

First, this paper reviews relevant domestic and international literature, identifying both the achievements and shortcomings of research on digital inclusive finance and urban innovation and entrepreneurship. Second, it analyzes the impact mechanism of digital inclusive finance on urban innovation and entrepreneurship from a theoretical perspective and proposes research hypotheses. Third, using panel data from 279 prefecture-level cities in China as a sample, this paper empirically examines the relationship between digital inclusive finance and urban innovation and entrepreneurship, incorporating internet development level and marketization level as mediating variables into the mediation model to test the specific pathways through which digital inclusive finance affects urban innovation and entrepreneurship. Furthermore, the sample is divided by region to explore the heterogeneous impact of digital inclusive finance on urban innovation and entrepreneurship. Finally, the paper summarizes its research conclusions and proposes corresponding policy recommendations.

1.4 Innovations

This paper innovates in two aspects: From a research perspective, it explores the impact of digital inclusive finance on urban innovation and entrepreneurship from the perspectives of internet development level and marketization process, which helps enrich the theoretical framework of urban innovation and entrepreneurship. Regarding the selection of specific indicators, existing research on measuring the level of urban innovation and entrepreneurship still relies on relatively singular methods. Innovation provides the driving force for entrepreneurship, and entrepreneurship is the practical application of innovation; innovation and entrepreneurship are inherently complementary and interactive[1]. This paper fully considers the economic benefits brought about by the interaction mechanism between entrepreneurship and innovation, selecting a comprehensive evaluation index composed of technological big data and enterprise micro-level data to measure the level of urban innovation and entrepreneurship, hoping to better measure the quality of urban innovation and entrepreneurship output and identify market mechanisms.

2 LITERATURE REVIEW

The driving factors of innovation and entrepreneurship can be divided into two categories: external factors and internal factors. External factors mainly refer to environmental factors related to innovation and entrepreneurship, including industrial agglomeration, land resource allocation, and transportation infrastructure. Liu Maotao et al. found that the agglomeration of productive service industries has a particularly significant driving effect on urban innovation and entrepreneurship [2]. Mao Wenfeng et al. found from the perspective of land resource misallocation that it has a significant inhibitory effect on the quality of urban innovation and entrepreneurship [3]. Ji Yun et al. found that the opening of high-speed rail significantly affects the innovation vitality of large and medium-sized cities [4]. Internal factors mainly include human capital, technological innovation, and venture capital. Human capital is a key factor affecting innovation and entrepreneurship, and the optimal allocation of human capital and talent allocation can achieve the optimal scale of innovation. Liang Bang and Zhang Jianhua used data from prefecture-level cities in China to match data from the overall city level and found that digital inclusive finance can promote the improvement of urban innovation performance by promoting technological innovation [5]. In addition, L angeland et al. believed that innovation and entrepreneurship are also affected by venture capital [6].

Although China's digital inclusive finance development started late, the relevant research results are abundant. This paper focuses on the research on its effectiveness. A review of domestic and foreign literature reveals that the research on the effectiveness of digital inclusive finance is concentrated at both macro and micro levels. At the macro level, the research mainly focuses on its impact on industrial restructuring, urban-rural income gap, and economic output growth. Song Xiaoling et al. empirically found that digital inclusive finance significantly narrows the urban-rural income gap [7]. Wang Yongjing and Li Hui further found that the effective integration of digital inclusive finance and new urbanization will have a positive spatial spillover effect on the urban-rural income gap [8]. However, the academic community has not yet reached a consensus on whether digital inclusive finance can promote economic growth. Qian Haizhang et al. found that the development of digital finance significantly promotes economic growth[9], and Zhang Zhenhua et al. obtained the interaction effect between digital inclusive finance and fiscal expenditure through the system GMM method, which is conducive to the high-quality development of China's economy[10]. However, Arcand et al. found that when financial development reaches a certain threshold, it can even have a negative impact on economic output[11]; Ge Heping et al. constructed a dynamic panel threshold data model to confirm the nonlinear relationship between digital inclusive finance and industrial structure upgrading[12]; Yi Xin and Liu Fengliang believed that financial development can promote industrial structure transformation through technological innovation[13]. Research on the micro-level effects of digital inclusive finance mainly focuses on its impact on residents' consumption and enterprise technological innovation. Ren Rong et al. used provincial panel data to find that digital inclusive finance increases residents' consumption by alleviating liquidity constraints and reducing potential uncertainty[14]. Wu Qingtian et al. used data from A-share listed companies to verify that the market access efficiency of innovative achievements is a key mechanism by which digital inclusive finance affects enterprise technological innovation[15]. In summary, research on digital inclusive finance and urban innovation and entrepreneurship still lacks attention.

Based on the above, digital inclusive finance has always been a hot topic in academic research, but some shortcomings remain: research on its effectiveness focuses on the macro and micro levels, with few studies examining its driving effect on urban innovation and entrepreneurship at the meso level. Under the backdrop of the new normal of the economy, promoting urban innovation and entrepreneurship is both urgent and necessary. With the deepening development of the mass entrepreneurship and innovation strategy, exploring whether digital inclusive finance is conducive to the development of urban innovation and entrepreneurship has undeniable practical significance.

3 THEORETICAL ANALYSIS AND RESEARCH HYPOTHESES

3.1 Digital Inclusive Finance and Urban Innovation and Entrepreneurship

Digital inclusive finance plays a crucial role in innovation and entrepreneurship, and its impact can be divided into two aspects: its influence on innovation and its influence on entrepreneurship. Regarding entrepreneurship, most studies indicate that the development of digital inclusive finance significantly promotes entrepreneurship, and all three sub-dimensions of digital inclusive finance—coverage, usage, and the level of digital technology support services—can catalyze entrepreneurship [16]. In the early stages of entrepreneurship, businesses face many uncertainties and various risks of failure, while digital inclusive finance can provide stable financial support during the entrepreneurial development process, improving and safeguarding the financial environment for urban entrepreneurship. Feng Dawei et al. found that digital inclusive finance can expand access to financing by alleviating credit constraints and promote individual entrepreneurship by increasing financial participation[17].

At the innovation level, existing research has also demonstrated the crucial role of financial development in enhancing innovation levels [18-19]. Further analysis reveals that digital inclusive finance primarily promotes enterprise technological innovation by reducing financing constraints and costs [20-21], avoiding resource waste and moral hazard [22], and optimizing support conditions for enterprise technological innovation[23]. Furthermore, digital inclusive finance promotes regional innovation levels by improving regional credit resources and boosting resident consumption [24-25]. In summary, the development of digital inclusive finance primarily enhances urban innovation and entrepreneurship levels by improving the financing environment for innovation and entrepreneurship and by effectively supplementing traditional finance [26]. Therefore, this paper proposes the first hypothesis:

Hypothesis 1 : Improved digital financial inclusion will help urban innovation and entrepreneurship.

3.2 The Impact Mechanism of Digital Inclusive Finance on Urban Innovation and Entrepreneurship

Digital inclusive finance is the latest development of inclusive finance in the digital age. Relying on certain network platforms and information technology, it can reduce the cost of information collection and processing for innovative and entrepreneurial entities, thus alleviating information asymmetry and enhancing their confidence in innovation and entrepreneurship. When the level of urban internet development is relatively weak, it is usually constrained by technological limitations, resulting in a weaker impact of digital inclusive finance on urban innovation and entrepreneurship. As the level of internet development improves, the service scope and reach of digital inclusive finance will be further extended, leading to a more significant driving effect on urban innovation and entrepreneurship. Zhan Yong and Xu Leshowed that digital inclusive finance belongs to the "Internet + finance industry," improving information transparency and accelerating the flow of funds, thereby reducing entrepreneurial risks and increasing the likelihood of entrepreneurship[27]. Huang et al. also found that digital inclusive finance can utilize internet technology to improve the efficiency of loan approval by financial institutions, thereby promoting innovation and entrepreneurship[28].

From the perspective of market integration, digital inclusive finance can break down spatial and temporal barriers, promoting the free flow of factors such as capital and knowledge among capital markets [29], thereby creating a fair and equitable market environment for innovation and entrepreneurship. Furthermore, with market development, information transparency is increasing, regulatory systems and legal frameworks are becoming more complete and robust, intellectual property rights are being more effectively protected, and market competition is becoming increasingly fair and transparent, creating a favorable atmosphere for innovation and entrepreneurship and stimulating the enthusiasm for innovation and entrepreneurship in cities. Based on the above analysis, the following hypotheses are proposed:

Hypothesis 2: Digital inclusive finance can promote urban innovation and entrepreneurship by improving the level of internet development.

Hypothesis 3 : Digital inclusive finance can promote the improvement of urban innovation and entrepreneurship by improving the level of marketization.

4 RESEARCH DESIGN

4.1 Econometric Model Setting

Based on the above theoretical analysis, in order to empirically test the hypotheses proposed in this paper, the following static panel benchmark model is constructed:

$$inn_{i,t}=\beta_0+\beta_1 ifi_{i,t}+\beta_2 X_{i,t}+\lambda_i+\mu_t+\varepsilon_{i,t} \quad (1)$$

In the formula, the subscripts i and t represent an individual city and the corresponding year, respectively. The dependent variable inn is the level of innovation and entrepreneurship in the city, the independent variable ifi is the level of digital inclusive finance, and X is a series of control variables that affect the innovation and entrepreneurship in the city, including the level of economic development, the level of financial development, the level of fiscal expenditure, the level of industrial structure, the intensity of scientific research expenditure, etc., λ_i representing the fixed effect of the individual city, μ_t representing the fixed effect of the city over time, and $\varepsilon_{i,t}$ representing the random disturbance term.

4.2 Variable Measurement and Explanation

4.2.1 Dependent variable: urban innovation and entrepreneurship (inn)

Most scholars consider indicators of urban innovation and entrepreneurship from the perspective of a single dimension of innovation or entrepreneurship, neglecting the complementary relationship between the two. This paper draws on the research approach of Liu Maotao et al. and uses the "Langrun Longxin China Regional Innovation and Entrepreneurship Index 2019" from the National School of Development at Peking University to calculate a comprehensive evaluation index by weighting the secondary indicators proportionally to measure the level of urban innovation and entrepreneurship[2]. Table 1 shows the evaluation system and weighting ratio of this index.

Table 1 Innovation and Entrepreneurship Quality Evaluation Index System

Primary indicators	Secondary indicators	Weighting percentage
New Enterprise	Number of newly registered enterprises	20
Attracting foreign investment	The number of new foreign corporate investments	15
Attracting venture capital	The amount of new venture capital	25
	Number of newly granted invention patents	12.5
Number of patents granted	Number of newly published utility model patents	7.5
	The number of newly published design patents	5
Number of trademark registrations	Number of newly registered trademarks	15

4.2.2 Explanatory variable: digital inclusive finance index (ifi)

This paper utilizes data on inclusive finance released by the Institute of Digital Finance at Peking University and selects a general indicator for digital inclusive finance as the explanatory variable. This indicator system, a result of joint research between the Institute of Digital Finance at Peking University and Ant Financial, is based on traditional methods of measuring inclusive finance while incorporating advancements in digital technology. It has been widely applied in existing academic research on inclusive finance. This index encompasses the coverage, depth of use, digitalization level of inclusive finance, and various types of financial services within the depth of digital finance applications, including payment, credit, lending, and investment. A higher index indicates better development of digital inclusive finance within a region.

4.2.3 Control variables

(1) Economic development level (lngdp): The level of innovation and entrepreneurship in a city is closely related to the level of economic development in that city. The higher the level of economic development in a region, the more favorable the macro environment for innovation and entrepreneurship will be, and the more conducive it will be to stimulating innovation and entrepreneurship in the city[30].

(2) Financial Development Level (FIN): A sound internal financial mechanism can disperse or reduce various risks faced by enterprises and boost their confidence in innovation and entrepreneurship[31] The more perfect a region's financial system is, the better its financial development level is, and the more conducive it is to innovation and entrepreneurship. This paper uses the ratio of outstanding loans of financial institutions to GDP as a representative of

the financial development level.
(3) Fiscal expenditure level (gov) : As an important supporter and participant in urban innovation and entrepreneurship, the government provides important guarantees for the development of innovation and entrepreneurship activities. This paper uses local government general budget expenditure to represent the fiscal expenditure level.
(4) Industrial Structure Level (is): A reasonable industrial structure provides an important source of motivation for urban innovation and entrepreneurship. The higher the degree of industrialization and modernization, the more developed the secondary and tertiary industries are. This paper uses the proportion of the total amount of the secondary and tertiary industries to GDP to represent the industrial structure level.
(5) Research and development expenditure level (rd): Government subsidies are beneficial to the innovation efficiency of enterprises, both before and after the event [32]. This paper uses the proportion of government science and technology research and development expenditure to the general budget expenditure of the government to represent this.

4.2.4 Mediating variable M

(1) Internet development level (net)
Currently, there are three main methods used in research to measure the level of internet development: the number of internet users, internet industry revenue, and internet penetration rate. Based on data availability, this paper adopts the approach of most scholars, using internet penetration rate as a proxy variable for the level of internet development, specifically represented by the number of broadband internet users divided by the year-end registered population of the city.
(2) Level of marketization (mar)
The Fan Gang Marketization Index was used as a proxy variable for the level of marketization (Table 2).

Table 2 Variable Definition and Description

type	Variable name	Variable symbol	Indicator Explanation
Explanatory variable	Urban Innovation and Entrepreneurship	inn	Langrun Longxin China Regional Innovation and Entrepreneurship Index Weighting
Explanatory variables	Digital Inclusive Finance	ifi	Peking University Digital Inclusive Finance Index
control variables	Economic development level	lngdp	Logarithm of GDP per capita
	Financial development level	fin	Financial institutions' loan balance / GDP
	Industrial structure level	Is	Total output of secondary and tertiary industries / GDP
	Fiscal expenditure level	gov	Local government general budget expenditure
	Research expenditure intensity	rd	Government science spending / GDP
Mediator variables	Internet development level	net	Number of broadband internet users / City's year-end registered population
	Marketization	mar	Fan Gang Marketization Index

4.3 Data Sources and Processing

Based on existing research and data availability, this paper selects panel data from 279 prefecture-level cities in China for basic research. After removing city samples with significant variable omissions, a final total of 2204 observations were obtained. The digital inclusive finance related index comes from the Digital Finance Research Center of Peking University, and the urban entrepreneurship and innovation index comes from the Langrun Longxin Regional Innovation and Entrepreneurship Index of the National School of Development at Peking University. Control variables are from the *China Urban Database*, *China Urban Statistical Yearbook*, and *China Statistical Yearbook*, with some missing data sourced from the statistical yearbooks of the corresponding provinces. Mediating variables are from relevant years in the *Statistical Report on Internet Development in China* and the Fan Gang Marketization Index.
Table 3 presents descriptive statistics of the relevant variables in this paper, showcasing the general outline of the sample data. It can be seen that the data dimensions are relatively consistent, providing a data foundation for further analysis. Furthermore, the table reveals significant differences in the development level of digital inclusive finance and the vitality of innovation and entrepreneurship across different regions.

Table 3 Descriptive Statistics of Variables

variable	Sample size	average value	Standard deviation	Minimum value	Maximum value
inn	2,541	51.70	25.15	3.285	100
ifi	2,540	164.4	65.21	17.02	321.6
lngdp	2,524	15.41	0.831	12.66	18.84
fin	2,532	1.159	1.005	0.132	16.74
gov	2,533	0.253	0.284	0.0154	6.041
rd	2,531	314.1	382.0	12.82	6,310

is	2,215	0.878	0.0766	0.501	1.000
mar	2,507	11.48	2.103	4.960	17.47
net	2,459	0.222	0.182	0.01	1.890

5 EMPIRICAL ANALYSIS

5.1 Benchmark Regression

This paper uses Stata 16.0 software for hypothesis testing and regression analysis of the model. The estimation results are shown in Table 4. The regression results show that the regression coefficient measuring digital inclusive finance (ifi) is positive and reaches a statistical significance level of 1%, indicating that digital inclusive finance is an important driving force for urban innovation and entrepreneurship. Therefore, hypothesis 1 is verified. Regarding control variables, the regression results of the three variables—urban economic development level (lngdp), R&D expenditure intensity (rd), and industrial structure level (is)—are highly significant and positively correlated with urban innovation and entrepreneurship (Inn). The regression result for financial development level (fin) is also relatively significant. Higher regional economic development and financial development levels, better industrial structure, and greater government R & D expenditure intensity all reflect a favorable economic environment. This also indicates that a better economic environment is conducive to stimulating urban innovation and entrepreneurship vitality and improving the quality of innovation and entrepreneurship, which is consistent with the expected conjecture of this paper. However, it can be seen that the relationship between the level of fiscal expenditure and urban innovation and entrepreneurship is negative, contrary to expectations. This may be because the incentive effect of government expenditure on the innovation capabilities of enterprises at different stages of their life cycle varies. Government subsidies have an inverted U-shaped relationship with enterprise innovation and entrepreneurship [33]. When government subsidies for innovation and entrepreneurship reach their maximum value, the incentive effect may be squeezed out as incentive input increases. In addition, government expenditure encompasses multiple aspects, and its specific impact on urban innovation and entrepreneurship requires a process. For example, the proportion of government investment in scientific research is needed to accurately grasp the government's support for innovation and entrepreneurship.

Table 4 Model Estimation Results

variable	(1)	(2)	(3)	(4)
ifi	0.021***	0.021***	0.021***	0.025***
	(4.55)	(4.57)	(4.57)	(5.01)
lngdp	5.685***	5.726***	5.513***	5.289***
	(6.18)	(6.20)	(6.12)	(4.95)
fin	0.051	0.172	0.131	0.608*
	(0.47)	(0.59)	(0.46)	(1.70)
gov		-0.511	-1.132	-0.125
		(-0.46)	(-1.18)	(-0.07)
rd			0.001**	0.002**
			(2.07)	(2.08)
is				32.887***
				(2.73)
Constant	-32.521**	-33.135**	-30.044**	-55.374***
	(-2.40)	(-2.44)	(-2.27)	(-3.67)
Individual fixed effects	have	have	have	have
Year fixed effect	have	have	have	have
N	2516	2510	2509	2204
id	284	284	284	279
R 2	0.048	0.049	0.051	0.073

Note: The values in parentheses are statistical measures, *** p<0.01, ** p<0.05, * p<0.1.

5.2 Robustness Test

Two types of robustness tests were conducted on the regression results in Table 4, and Table 5 shows the results of these two robustness tests. First, a robustness test was performed by replacing the weighted innovation and entrepreneurship index in the baseline regression with the unit area index of urban innovation and entrepreneurship as the measure of the dependent variable. Second, a second regression test was conducted after removing 28 resource-rich and economically developed provincial capitals from the sample. The results show that the results remain robust regardless of whether the dependent variable was changed or the influence of provincial capitals was removed.

Table 5 Robustness Test Results

variable	Change the explained variable	Excluding provincial capitals
ifi	0.016***	0.026***
	(4.90)	(4.93)
lngdp	3.333***	5.685***
	(4.43)	(4.91)
fin	0.490**	0.517
	(1.97)	(1.31)
gov	-0.694	1.633
	(-0.57)	(1.34)
rd	0.001**	0.002**
	(2.11)	(1.98)
is	22.829***	30.769**
	(2.65)	(2.48)
Constant	-17.403*	-62.627***
	(-1.67)	(-4.00)
Individual fixed effects	have	have
Year fixed effect	have	have
N	2204	1980
R 2	0.0749	0.0720

Note: The values in parentheses are statistical measures, *** p<0.01, ** p<0.05, * p<0.1.

5.3 Mediation Effect Analysis

Following the analysis of the relationship and impact between digital inclusive finance and urban innovation and entrepreneurship, this paper further employs a mediation effect model, using the level of internet development and marketization as mediating variables to examine the specific pathways through which digital inclusive finance influences urban innovation and entrepreneurship. Drawing on the mediation effect model established by Baron and Kenny (1986) and Wen et al. (2014), where M represents the two mediating variables in this paper, the mediation effect model is as follows[34]:

$$inn_{i,t}=\theta_1+cifi_{i,t}+\lambda X_{i,t}+\mu_{i,t} \quad (2)$$

$$M_{i,t}=\theta_2+aifi_{i,t}+\lambda X_{i,t}+\mu_{i,t} \quad (3)$$

$$inn_{i,t}=\theta_3+c'ifi_{i,t}+bM_{i,t}+\lambda X_{i,t}+\mu_{i,t} \quad (4)$$

This paper refers to Wen Zhonglin and Ye Baojuan (2014) to test the mediation effect using stepwise regression[35]. The stepwise regression logic consists of three steps: First, test the coefficient c of equation (2), that is, the overall effect of the independent variable ifi on the dependent variable inn. If the coefficient c is significant, it is rejected. Second, test the coefficient a of equation (3), that is, the effect of the independent variable H_0： c=0ifi on the mediating variable M, that is, test the effect of the independent variable ifi on the marketization level mar and the Internet development level net. Third, after controlling for the mediating variable M, test the coefficients and coefficient b of equation (c'4). If the coefficient a is significant, it is rejected, and if the coefficient b is also rejected, the mediation effect is significant. If the coefficients c and a and b are significant and H_0： a=0c' not significant, then there is a complete mediation effect; otherwise, it is a partial mediation effect. Table 6-7 shows the estimation results of the mediation effect.

As shown in columns (1) to (3) of Table 6, when the level of marketization is the mediating variable, digital inclusive finance and innovation and entrepreneurship are highly significantly positively correlated, and digital inclusive finance also shows a significant positive correlation with the level of marketization. When the marketization index is controlled as the mediating variable, the regression coefficient of digital inclusive finance is still significant, indicating that there is a partial mediating effect.

Table 6 The Mediating Effect of Marketization Level

variable	(1)	(2)	(3)
ifi	0.085***	0.017***	0.073***
	(11.32)	(30.47)	(8.39)

mar			0.567**
			(2.09)
Constant	37.806***	8.720***	33.541***
	(28.62)	(89.58)	(12.36)
N	2540	2507	2507
R 2	0.0477	0.270	0.0477
F	128.2	928.3	63.7

Note: The values in parentheses are statistical measures, *** p<0.01, ** p<0.05, * p<0.1.

Further analysis of columns (1) to (3) in Table 7 shows that when the level of internet development is the mediating variable, digital inclusive finance is highly significantly positively correlated with both the level of innovation and entrepreneurship and the level of internet development. When the influence of the three factors is controlled for by the level of internet development, the regression coefficient of digital inclusive finance is no longer significant, indicating that the level of internet development has a complete mediating effect. Furthermore, referring to the Sobel test conducted by Wen Zhonglin et al. on the two mediating effects, the results show that the Sobel test p-values for both the level of internet development and the level of marketization are below 0.05, indicating the existence of a mediating effect. Moreover, the proportion of the level of internet development in the total effect is higher than that of the level of marketization, indicating that the mediating effect of the level of internet development is more significant, consistent with the results of the stepwise regression test. Therefore, hypotheses 2 and 3 are verified.

Table 7 The Mediating Effect of Internet Development Level

variable	(1)	(2)	(3)
ifi	0.085***	0.001***	- 0.003
	(11.32)	(29.56)	(-0.39)
net			60.646***
			(20.63)
Constant	37.806***	-0.014*	33.541***
	(28.62)	(-1.67)	(12.36)
N	2540	2459	2459
R 2	0.0477	0.262	0.187
F	128.2	874.1	283.0

Note: The values in parentheses are statistical measures, *** p<0.01, ** p<0.05, * p<0.1.

5.4 Heterogeneity Analysis

This paper divides the sample into eastern, central and western regions according to administrative geographical areas for heterogeneity analysis, and attempts to explore the heterogeneous effects of digital inclusive finance on urban innovation and entrepreneurship in different regions. It is hoped that the research conclusions will provide ideas for implementing relevant policies according to local conditions.

Table 8 Subsample Regression Results

variable	(1) Eastern	(2) Central	(3) Western
ifi	-0.013*	0.014	0.038***
	(-1.79)	(1.18)	(5.24)
lngdp	3.590**	-1.441	8.602***
	(2.44)	(-0.73)	(5.05)
fin	-4.088**	0.361	1.451***
	(-2.43)	(0.80)	(4.55)
gov	11.741	-0.542	-1.610
	(0.80)	(-0.34)	(-0.20)
rd	0.002	0.001**	0.004
	(1.06)	(2.29)	(1.44)
is	57.543**	26.036	10.721
	(2.40)	(1.05)	(0.61)

Constant	-40.876	35.961	-88.873***
	(-1.58)	(1.16)	(-3.75)
Individual fixed effects	have	have	have
Year fixed effect	have	have	have
N	885	841	478
R 2	0.0987	0.126	0.0131

Note: The values in parentheses are statistical measures, *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

As shown in Table 8, in the more economically developed eastern region, the regression coefficient of digital inclusive finance is significantly negative; the regression coefficient in the central region begins to turn positive; and the regression coefficient in the western region not only meets expectations but also reaches a significance level of 10 %. This indicates that the role of digital inclusive finance in promoting urban innovation and entrepreneurship is gradually increasing in the eastern, central, and western regions, especially in the relatively underdeveloped western region where the effect is most obvious.

6 RESEARCH CONCLUSIONS AND RECOMMENDATIONS

This paper examines the impact of digital inclusive finance on urban innovation and entrepreneurship based on panel data from 279 prefecture -level cities in China from 2011 to 2019, using internet penetration rate and marketization level as mediating variables. The results show that: First, the development of digital inclusive finance can significantly improve the level of urban innovation and entrepreneurship. This conclusion remains robust even after changing the measurement method of the explained variable and excluding provincial capitals. Second, this paper attempts to test the specific pathways through which digital inclusive finance affects urban innovation and entrepreneurship by constructing a mediation effect model. The test results show that digital inclusive finance improves the level of urban innovation and entrepreneurship by increasing internet development and marketization. Finally, regional heterogeneity analysis reveals that the promoting effect of digital inclusive finance on urban innovation and entrepreneurship varies across different regions of China, with a greater effect in central and western China. Based on these findings, the following policy recommendations are proposed:

First, we must continue to steadily advance the development of digital inclusive finance, increase the coverage of basic financial services, fully leverage and realize the comparative advantages of digital inclusive finance and traditional finance, and promote healthy competition and complementarity between the two. Research has found that urban innovation and entrepreneurship are also influenced by various factors such as the level of economic development, financial development, and industrial structure. Therefore, it is also necessary to improve the financial regulatory system, enhance the comprehensive service capabilities of digital finance, promote industrial optimization and upgrading, increase investment in scientific research and incentives for scientific and technological innovation, and improve policies and mechanisms for the transformation of scientific and technological innovation achievements, thereby improving the output level and quality of innovation and entrepreneurship.

Second, strengthen the construction of network information service infrastructure in the financial industry. Despite the rapid development of the internet in the digital economy era, it is still necessary to strengthen and optimize network infrastructure, continue to improve internet penetration, and further extend the reach of digital inclusive finance. Efforts should be made to lower the barriers to information access and reduce the costs of information verification for various urban innovation and entrepreneurship entities, thereby mitigating the risks of information asymmetry. In short, we must continue to leverage the maximum advantages of the integration of inclusive finance and digital information technology to support urban innovation and entrepreneurship.

Third, we must accelerate the marketization process and create a favorable market environment. We should continue to promote the positive role of digital inclusive finance in improving the marketization of innovation and entrepreneurship, stimulating the innovation and entrepreneurship vitality of enterprises and individuals. The government should respect the dominant position of the market, further streamline administration and delegate power, reduce excessive intervention in the economy, allow all sectors to develop according to their own laws, and let market competition achieve survival of the fittest, thereby driving innovation and entrepreneurship. We should improve relevant laws, regulations, and systems, strengthen effective market supervision, and provide institutional guarantees for the effective flow of resources.

Fourth, digital inclusive finance has a regionally heterogeneous effect on innovation and entrepreneurship across different regions. Governments should formulate differentiated development strategies for inclusive finance based on the actual development of digital inclusive finance in different regions. For the economically developed eastern regions with a high level of digital inclusive finance development, the development of digital inclusive finance should continue to be steadily promoted. However, for the central and western regions, where digital inclusive finance development is relatively lagging, but where its role in promoting urban innovation and entrepreneurship is most significant, governments should increase incentives through mechanisms and policies, formulate guidelines that align with local development, and ensure that digital inclusive finance leverages its inclusive characteristics to better promote the integration of digital inclusive finance with innovation and entrepreneurship, thereby fostering high-quality and healthy development across all regions of the country.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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IMPACT OF DIGITAL ECONOMY DEVELOPMENT ON POLLUTION REDUCTION AND CARBON REDUCTION

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Abstract: Exploring the impact and spatiotemporal characteristics of the digital economy on pollution and carbon reduction is of great significance in the context of the "dual carbon" goal and The digital economy is advancing at a fast pace. Currently, China is facing the dual task of reducing pollution and carbon emissions, and the "technological dividend" of the digital economy provides a new path for achieving environmental governance goals. However, there are still shortcomings in the systematic analysis of the spatial spillover effects, regional adaptation differences, and dynamic mechanisms of pollution and carbon reduction in the digital economy, which urgently require in-depth research from a multidimensional perspective. This study comprehensively utilized entropy weight method, benchmark regression model, mediation effect model, spatial-Durbin-model (SDM), spatiotemporal-geographically-weighted-regression (GTWR), and graph attention network (GAT) to construct a research framework covering impact effect assessment, mechanism identification, and spatiotemporal dynamic analysis. Firstly, This study utilized the entropy weight method for quantifying the development degree of the digital economy, and conducted an analysis on the spatiotemporal features of both pollutant emission intensity and carbon intensity of emissions, the fundamental correlation between the digital economy and environmental performance is revealed; Secondly, through the application of a fixed effects model, the digital economy exerts a direct influence on achieving the twin goals of reducing pollution and carbon emissions, and identifying indirect paths such as industrial structure upgrading, technological progress, and green finance through a mediation effect model; Finally, using spatial econometric models and GAT models, analyze the spatial dependence, regional heterogeneity, and the digital economy’s emission reduction effects: Spatiotemporal dynamic evolution characteristics.
Keywords: Digital economy; Pollution reduction and carbon reduction; Spatial effects; Spatiotemporal heterogeneity; Intermediary mechanisms

1 INTRODUCTION

Faced with the requirements of pollution reduction and carbon emission reduction in the new stage, the influence of the digital economy on pollution reduction and carbon emission reduction has increasingly grown into a key concern within academic circles. Research on how the development of the digital economy affects pollution control and carbon emission reduction primarily covers the following four dimensions: firstly, the measurement of the level of digital economy development. Previous studies have often used methods such as factor analysis, entropy method, and B-team method, coupled with the construction of an evaluation indicator system, to measure the level of development of the digital economy[1]. After considering the necessary conditions for the development of the digital economy, the construction and development process of the digital industry, the degree of digital transformation of traditional industries, and the extensive impact of the digital economy on various aspects of society, The Academy of Information and Communications Technology of China has proposed a comprehensive measurement standard - the Digital Economy Index[2-5]. In addition to constructing an evaluation index system, some scholars focus more on quantifying the causal effects between variables and calculating the level of China's digital economy development through methods such as BEA [6-7]. The second is the research on the influencing factors of digital economy on pollutant emissions and carbon emissions. The relationship between the digital economy and environmental pollution is gradually emerging. Based on spatial econometric models, projection pursuit models, and fixed effects models, empirical research has been conducted by scholars to explore the inhibitory role of digital economy development level in three major pollutant emissions[8-9].To investigate how regional carbon emissions are affected by the digital economy, researchers performed in-depth analysis with panel data and revealed that the digital economy notably increases aggregate carbon emissions but diminishes carbon emission intensity [10-12]. The third is the study of the influence mechanism of the digital economy on pollutant emissions and carbon emissions. The research on the impact mechanism of digital economy on carbon emissions continues to deepen, mainly expanding the understanding of its mechanism from the perspectives of technological progress and energy utilization efficiency. However, there is relatively little research on the impact mechanism of the digital economy on pollutant emissions, and the depth is somewhat insufficient. Most scholars consider pollutant reduction, ecological environment improvement, and ecological efficiency enhancement as the main characteristics [13-14]. Another category is the exploration of spatial heterogeneity regarding the role of the digital economy in pollutant and carbon emissions. A number of scholars adopt spatial econometric analytical approaches, including QAP regression and the spatial Durbin model to explore regional linkage relationships and spatiotemporal heterogeneity analysis[15-18]. Research has found that per capita GDP level, geographical proximity, technological innovation level, and informatization level all have a significant positive impact on the spatial correlation between pollutant emissions and carbon emissions [19-22].

The existing literature on pollution reduction and carbon reduction in the digital economy has achieved significant results in terms of measurement methods, spatiotemporal evolution characteristics, and exploration of influencing factors. However, there are shortcomings in the analysis of spatiotemporal heterogeneity and spatial effects. The majority of researches have not comprehensively examined spatiotemporal heterogeneity, nor have they separated the spatial spillover effects and local impacts arising from the digital economy's pollution and carbon reduction.Drawing on panel data from 30 Chinese provinces spanning 2011 to 2021, this study employs the entropy weight method to quantify the development level of the digital economy. It uncovers disparities in the spatial distribution of the digital economy via visualization techniques, while leveraging the Spatio-Temporal-Geographically-Weighted-Regression (GTWR) model and Spatial-Durbin-Model (SDM) to analyze the spatiotemporal heterogeneity and dynamic shifts in how the digital economy influences pollution and carbon reduction. Additionally, the mediation effect model is utilized to examine the mechanisms through which the digital economy impacts carbon and pollutant emissions, focusing on channels such as technological advancement, industrial structure upgrading, and green finance indicators.

2 EMPIRICAL ANALYSIS AND VERIFICATION OF THE IMPACT OF PROVINCIAL DIGITAL ECONOMY ON POLLUTION REDUCTION AND CARBON REDUCTION

2.1 Analysis of Benchmark Regression Model Results

Firstly, to guard against estimation inaccuracies caused by multicollinearity, the variance inflation factor (VIF) test is implemented alongside the least squares method for every explanatory variable. According to Table 1, the VIF values of all explanatory variables are less than 10, which can rule out serious multicollinearity issues between explanatory variables.

Table 1 Variance Inflation Factor Test

Variable	VIF	1/VIF
DIG	5.408	0.184
ED	5.087	0.196
FDI	1.228	0.814
PD	1.418	0.705
ECI	1.048	0.954
Average VIF	2.837	

After F-test and Hausman test, this article ultimately chose the fixed-effects model for analysis. According to Table 2, the development of digital economy can significantly reduce the pollutant emission intensity and carbon emission intensity of each province, and the R2 model shows robust regression results. Each unit increase in the digital economy is associated with an average reduction of 0.2575 units in pollutant emission intensity and 0.2773 units in carbon emission intensity. This empirical outcome provides solid support for the validation of Hypothesis H1.

Economic development standards and population density exert a suppressive impact on both pollutant intensity and carbon emission intensity. With the improvement of economic development level, agglomeration effect promotes efficient allocation of resources and intensive utilization of public facilities (such as centralized heating and sewage treatment), reducing dispersed emissions; The increasing of population density is accompanied by the process of urbanization, and the promotion of green planning, low-carbon buildings, and renewable energy further reduces emission intensity.

The per capita energy consumption is significantly positively correlated with two types of intensity. The energy structure and high energy consumption production mode dominated by coal in our country directly lead to an increase in pollutant and carbon emission intensity, reflecting the pressure of high pollution production mode on the environment. Pollutant emission intensity is subject to a restraining effect from foreign investment, demonstrating its positive effect in reducing pollution by promoting industrial upgrading and the application of environmental protection technologies, effectively controlling pollutant emissions.

Table 2 Benchmark Regression Results

Variable	C	P
DIG	-0.2773*** （0.0287）	-0.2575*** （0.0430）
ED	-0.0441 （0.0300）	-0.1375*** （0.0448）
PD	-1.927*** （0.2320）	-1.7247*** （0.3466）
ECI	0.4467*** （0.2320）	0.0064 （0.1253）
FDI	-0.0188 （0.0121）	-0.0576*** （0.0181）
R2	0.7720	0.6981

Note: The parentheses indicate standard errors；*P<0.10,**P<0.05,***P<0.01

2.2 Endogeneity Test

To ensure the accuracy of the empirical analysis results, this article uses the instrumental variable method for endogeneity testing to minimize the impact of these potential issues on the research conclusions.

The research selects the Internet broadband access rate of each province and city in 2012 as the tool variable of the digital economy. First, as the early core infrastructure, its popularity level directly determines the subsequent development of the Internet, which can be regarded as a measure of the historical development of the digital economy; Secondly, there is no direct causal relationship between this indicator and the intensity of pollutants and carbon emissions, which satisfies the condition of exogeneity of instrumental variables. In order to adapt to the panel data, further construct the interaction term between this indicator and the Internet penetration rate lagging one year as a tool variable. This method, while increasing the time dimension of data, captures the dynamic correlation of infrastructure penetration through interaction design to more accurately reflect the development characteristics of the digital economy, and uses the two-stage least square method (2SLS) for estimation.

As shown in Table 3,through instrumental variable regression, it is observed that the regression coefficient corresponding to the digital economy achieves significance at the 1% statistical level. Such a result demonstrates that the digital economy continues to exert a significant inhibitory effect on pollutant emission intensity and carbon emission intensity, without being compromised by endogeneity-related biases.The RKF test result exceeds the 10% critical threshold specified for the weak identification test.This outcome verifies the validity of the instrumental variable selected in this study and confirms the absence of issues related to weak instrumental variables.

Table 3 Results of Endogeneity Test Regression

	Phase One Return to the Digital Economy	Two-stage regression P	C
DIG		-0.4918*** （0.0509）	-0.3043*** （0.0355）
instrumental variable（IV）	0.2069*** （0.0302）		
RKF inspection		93.4300	
R^2		0.2443	0.2031

Note: The parentheses indicate standard errors；*P<0.10,**P<0.05,***P<0.01

2.3 Robustness Test

2.3.1. Exclude special samples

Considering the administrative specificity of municipalities directly under the central government, they have advantages in policy support and resource allocation, which may interfere with the robustness of research conclusions. To ensure the reliability of the research results, this study excluded Beijing, Tianjin, Shanghai, and Chongqing from the sample and re estimated the remaining samples to eliminate the influence of administrative specificity and more accurately analyze the development trend of non municipalities directly under the central government.

2.3.2. Shorten time window

In 2020, the global COVID-19 epidemic will break out, which is set to have a marked effect on the evolution of the digital economy and related industries and will affect pollutant emissions and carbon emissions. Such factors may interfere with the reliability of research conclusions. To test the stability of the model, this study excluded data from the special year of 2020, in order to weaken the impact of abnormal data caused by the epidemic on the research results.

The robustness test results for the exclusion of special samples are provided in column (1) of Table 4, and those for the shortened time window are listed in column (2) of Table 4. The findings indicate that after removing special samples and narrowing the time frame, both pollutant emission intensity and carbon emission intensity are continuously positively affected by the digital economy in terms of reduction.

Table 4 Robustness Test Table

Variable	(1) Exclude special samples		(2) Shorten Time Window	
	P	C	P	C
DIG	-0.2724*** （0.0303）	-0.3048*** （0.0303）	-0.2597*** （0.0418）	-0.3016*** （0.0294）
ED	-0.1036** （0.0462）	-0.0137 （0.0307）	-0.1332*** （0.0428）	-0.0331 （0.0302）
PD	-1.8017*** （0.3510）	-1.8961*** （0.2333）	-1.6623*** （0.3425）	-1.7961*** （0.2415）
ECI	-0.0320 （0.1337）	0.4716*** （0.0888）	-0.0209 （0.1252）	0.3824*** （0.0883）
FDI	-0.0518*** （0.0183）	-0.0066 （0.0122）	-0.0589*** （0.0173）	-0.0234* （0.0122）

R^2	0.7094	0.8940	0.7222	0.8642

2.4 Mechanism Verification of the Impact of Provincial Digital Economy on Pollution Reduction and Carbon Reduction

2.4.1 Inspection of advanced industrial structure mechanism

According to Table 5, firstly, the level of digital economy development significantly promotes the upgrading of industrial structure (7.364), while the upgrading of industrial structure reduces the intensity of pollutant emissions (-1.351) and carbon emissions (-0.210), confirming H2a.

Secondly, the digital economy shows a weak positive impact on pollutant emission intensity (with a coefficient of 1.123), but it exerts a significant inhibitory effect on carbon emission intensity (-1.245), highlighting its positive function in promoting carbon reduction.

Thirdly, in terms of controlling variables, economic development significantly reduces pollutant emissions and has a slight positive impact on carbon emissions; Population density has a slight positive impact on both types of emission intensity; The energy consumption intensity significantly inhibits industrial structure upgrading and pollutant emissions (-0.413, -1.192), but significantly promotes carbon emissions (1.668); Foreign investment significantly reduces pollutant emissions (-77.570) and has a slight negative impact on carbon emissions (-0.094).

Table 5 Regression Results of Intermediate Effects of Advanced Industrial Structure

variable	（1） IS	（2） P	（3） C
DIG	7.364*** -15.197	1.123* (1.098)**	-1.245** (-2.153)**
ED	-0.000*** (-16.711)	-0.000** (-2.496)	0.000* (0.567)**
PD	0.000*** -4.608	0.000** (1.314)**	0.000* (0.786)**
ECI	-0.413*** (-5.645)	-1.192** (-2.337)**	1.668*** -13.824
FDI	-0.95* (-0.605)**	-77.570*** (-7.431)	-0.094* (-0.038)**
IS		-1.351*** (-3.602)	-0.210** (-2.119)**
constant term	1.579*** （-16.534）	19.777*** （-22.776）	0.341** （-1.662）**
N	330	330	330
R2	0.589	0.296	0.55
F	90.034	27.895	62.375

Note: The parentheses indicate standard errors；*P<0.10,**P<0.05,***P<0.01

2.4.2 Testing the mechanism of technological progress

According to Table 6, the digital economy significantly promotes technological progress (8.256), and technological progress can significantly reduce pollutants (0.000) and carbon emission intensity (0.000). The digital economy exerts a significant inhibitory effect on both types of emission intensity, with the impact coefficients being -10.567 and -1.125 respectively.

When the digital economy and technological progress are both introduced into the model, their coefficients retain significance, indicating that technological progress operates as a partial mediating factor in the influence exerted by the digital economy on emission intensity and corroborating the H2b hypothesis.

Table 6 Regression Results of Mediating Effects of Technological Progress

variable	（1） TD	（2） P	（3） C
DIG	8.256* (16.51)	-10.567** (-2.894)**	-1.125** (-2.678)**
ED	3.273*** -14.305	0.000* (2.496)	0.000*** (4.109)
PD	-14.731*** (-3.340)	-0.001** (-1.827)**	0.000* (0.786)
ECI	13559.850* (1.703)	-0.736** (-1.488)**	1.761*** （-15.183）
FDI	40545.009* （0.237）	-76.591*** (-7.247)	0.13* （0.052）
TD		0.000** （2.153)	0.000* (1.987)
constant term	-8.90e+04***	18.312***	-0.055

	(-8.562)	（25.636）	(-0.331)
N	330	330	330
R2	0.904	0.278	0.526
F	588.715	20.069	57.913

Note: The parentheses indicate standard errors；*P<0.10,**P<0.05,***P<0.01

2.4.3 Verification of the green finance index mechanism

According to Table 7, the digital economy exerts a significant promotional effect on the advancement of green finance, with a coefficient of 2.156. Meanwhile, green finance demonstrates a notable negative impact on both pollutant emission intensity (with a coefficient of -0.397) and carbon emission intensity (with a coefficient of -1.252), which indicates that green finance is capable of lowering these two types of emission intensity.

Pollutant emission intensity (-6.608) and carbon emission intensity (-2.309) are still influenced by the digital economy in terms of reduction, and both influences reach statistical significance. Overall, the digital economy exerts an indirect promotion effect on emission reduction by virtue of its direct impact and the boosting of green finance, validating H2c.

Table 7 Regression Results of Green Finance Index

variable	（1） GF	（2） P	（3） C
DIG	2.156*	-6.608**	-2.309***
	(3.214)	(-2.010)	(-3.050)
ED	0.000*	0.000*	0.000***
	(2.496)	(2.496)	(4.109)
PD	-0.001*	-0.001*	0.000*
	(-2.191)	(-2.191)	(0.786)
ECI	-0.156***	-0.572*	1.941***
	(-10.438)	(-1.488)	(15.183)
FDI	-1.110***	-75.846***	1.474*
	(-3.456)	(-6.993)	(0.052)
GF		-0.397*	-1.252***
		(2.153)	(1.987)
constant term	0.425***	17.474***	-0.487**
	-21.73	-17.046	(-2.064)
N	330	330	330
R2	0.476	0.335	0.55
F	57.075	27.895	62.735

Note: The parentheses indicate standard errors；*P<0.10,**P<0.05,***P<0.01

3 SPATIAL EFFECT ANALYSIS OF PROVINCIAL DIGITAL ECONOMY ON POLLUTION REDUCTION AND CARBON REDUCTION

3.1 Global Moran Index Test

This article uses ArcGIS 10.8 software to conduct spatial autocorrelation tests on provincial pollutant emission intensity, carbon emission intensity, and digital economy development level. Moran's index is utilized to test whether spatial autocorrelation exists among various regions. The range of Moran's I values is (-1,1). When Moran's I > 0, this denotes that spatial positive autocorrelation exists, and when Moran's I<0, it indicates the existence of spatial negative autocorrelation.

Table 8 Global Moran Index Test Table

year	P Moran’s I	C Moran’s I	DIG Moran’s I
2011	0.3626***	0.0384	0.0724
2012	0.3057**	0.0290**	0.0753
2013	0.2860***	0.0277*	0.0658*
2014	0.2524***	0.0214**	0.0594**
2015	0.2262***	0.0371*	0.0464**
2016	0.2182***	0.0393*	0.0614**
2017	0.4050***	0.0485**	0.0586*
2018	0.5571***	0.0531***	0.0390*

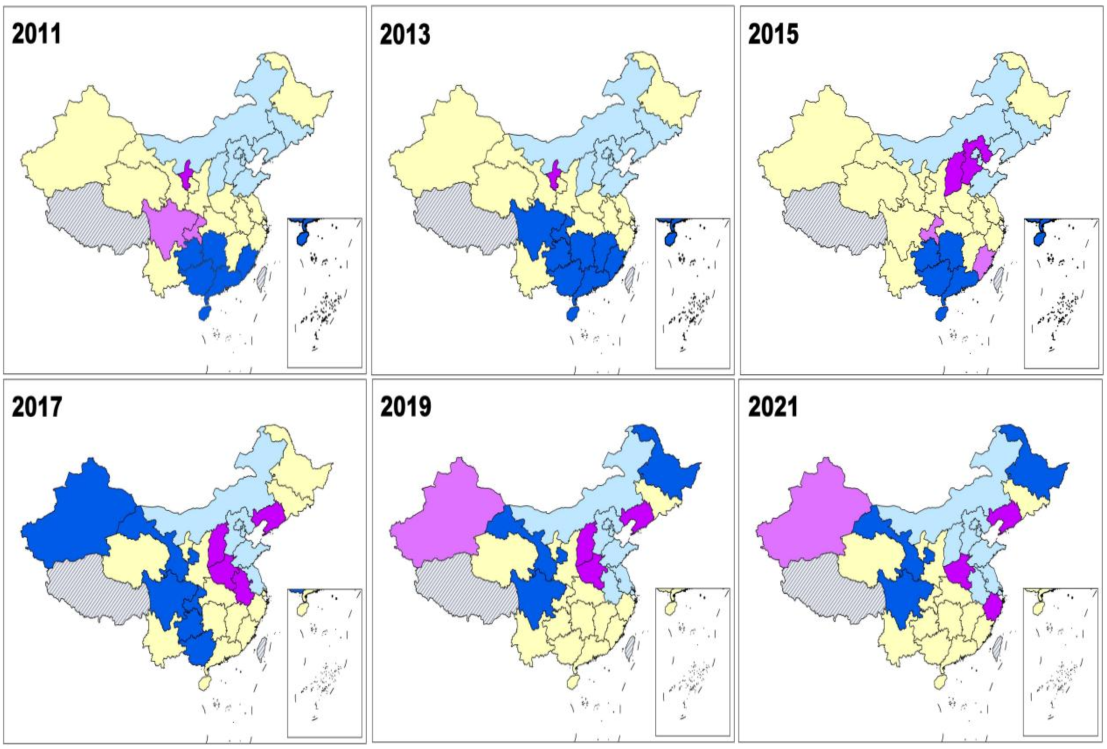
2019	0.5381***	0.0912**	0.0341**
2020	0.5009***	0.0957***	0.0365***
2021	0.3346***	0.0931***	0.0571***

Note: The parentheses indicate standard errors；*P<0.10,**P<0.05,***P<0.01

According to Table 8, Moran's I for pollutant emission intensity is greater than 0.2, indicating strong spatial autocorrelation; Although the initial value of Moran's I of carbon emission intensity is not high, it shows a continuous upward trend in 2011-2021,signifying that the spatial clustering effect of carbon emission intensity across provinces is gradually growing in significance; The Moran's I index for the development level of the digital economy exceeds 0, indicating a positive spatial correlation tendency but the value is relatively low. When using the economic spatial weight matrix proposed by Du Jingai [23], Moran's I is significantly greater than the geographically adjacent or distance weight matrix, which denotes that the digital economy's agglomeration is more inclined to depend on economic level similarity rather than geographical proximity. This is related to the characteristics of the digital economy, which uses information networks as carriers and is less constrained by geography, and regions with similar economic levels are more likely to form division of labor, cooperation, and scale effects in terms of resources and industrial models.

3.2 Local Moran's Index Test

After the global Moran index test in the previous section, it was found that pollutant emission intensity, carbon emission intensity, and the digital economy's development level demonstrates the attribute of spatial autocorrelation. Next, a local Moran index test will be conducted using ArcGIS 10.8 software to identify specific regions with clustering.



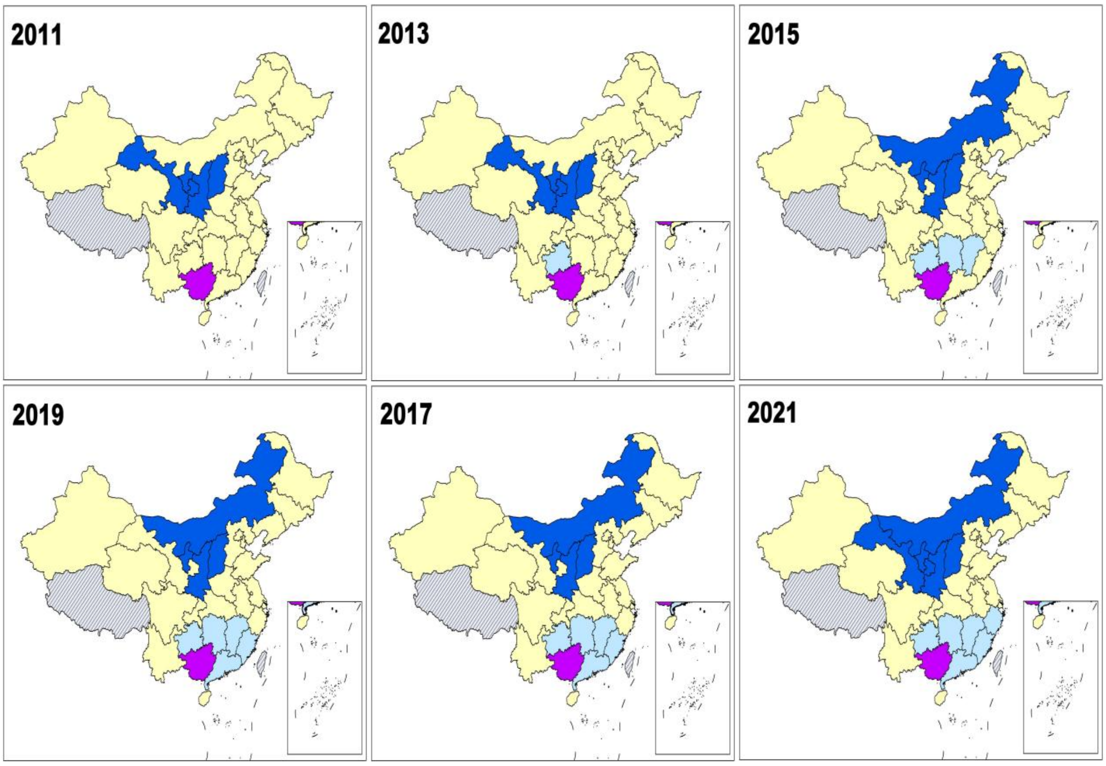
Note: Based on the standard map production of Gaode Map Review No. GS (2019) 756, the base map has not been modified.

Figure 1 LISA Aggregation Chart of Pollutant Emission Intensity

As shown in Figure 1, the LISA concentration map of China's pollutant emission intensity in 2011-2021 shows significant distribution characteristics and dynamic changes:

High high concentration areas: In 2011, they were concentrated in traditional industrial provinces in the central, northern, and southern regions (with high pollution industries such as steel and chemical), distributed in a north-south pattern; After 2017, with the promotion of the Western Development, resource-based regions such as Xinjiang were included and evolved into an east-west distribution, which is related to the layout of the heavy chemical industry. High low outlier area (such as North China in 2013): There are large high polluting enterprises in the region, and the surrounding areas have formed a "low valley" of emissions due to industrial cleanliness or strong environmental protection efforts. Low high outlier area (East China after 2015): The local area has taken the lead in promoting industrial upgrading and environmental governance, with emission intensity lower than the surrounding areas.

Trend of change: High high concentration areas are expanding from traditional industrial core areas in central and southern China to resource-based areas in northeast and northwest China. The main reason is that the upgrading of industries in the east drives the westward migration of highly polluting industries, coupled with the introduction of resource dependent industries in regional development strategies such as the revitalization of Northeast China, leading to the reconstruction of the spatial pattern of emission intensity.



Note: Based on the standard map production of Gaode Map Review No. GS (2019) 756, the base map has not been modified

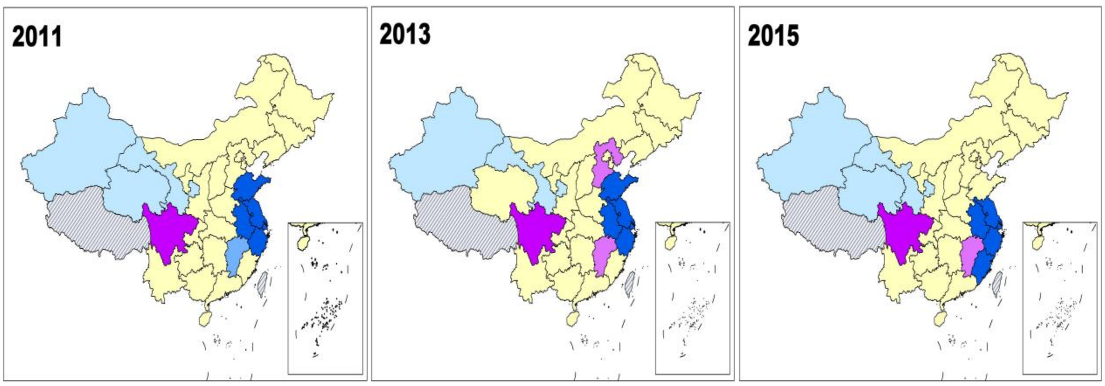
Figure 2 LISA Aggregation Plot of Carbon Emission Intensity

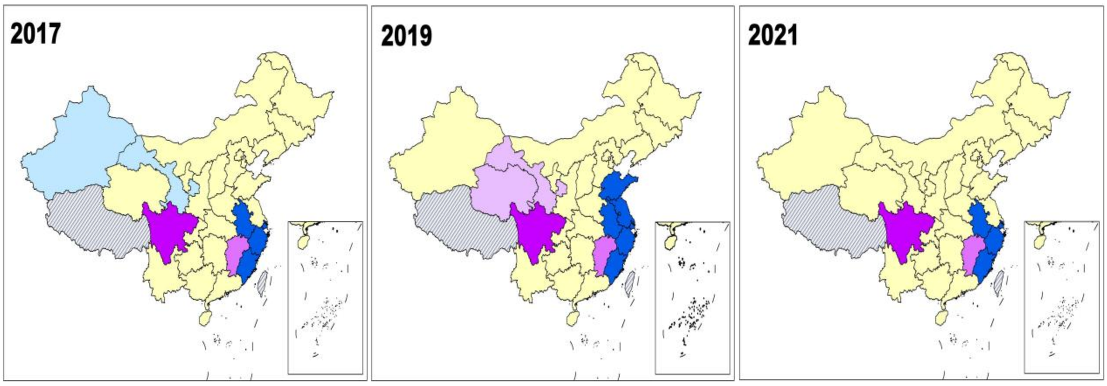
As shown in Figure 2, the LISA aggregation map of China's carbon emission intensity in 2011-2021 shows significant temporal and spatial differences:

Distribution characteristics: In 2011, high high concentration areas were concentrated in North China (Shanxi coal industry and related high energy consuming industries), Northwest (traditional energy development areas), and Northeast old industrial bases (heavy industries such as steel and machinery manufacturing with lagging energy efficiency), displaying an initial distribution pattern characterized by "higher levels in the north and lower levels in the south".

Dynamic changes: After 2015, the range of high high concentration areas in some parts of Northeast China has expanded, reflecting the carbon emission pressure brought about by industrial development in the process of industrialization; After 2017, low low concentration areas appeared in East China (Zhejiang, Jiangsu, etc.), thanks to the elimination of outdated production capacity, high-tech industry development and the escalation of environmental protection investment, leading to a substantial decrease in regional emission intensity.

Driving factors: High emission clusters are constrained by traditional energy dependence (coal mining, heavy chemical industry) and heavy industrial structure, resulting in low energy utilization efficiency; Low emission areas achieve breakthroughs in emission reduction through industrial upgrading and the application of clean energy.





Note: Based on the standard map production of Gaode Map Review No. GS (2019) 756, the base map has not been modified

Figure 3 LISA Agglomeration Chart of Digital Economy Development Level

As shown in Figure 3, the LISA aggregation map of the digital economy in 2011-2021 shows significant regional differences:

Distribution characteristics: since 2011, the eastern coastal areas (such as the Yangtze River Delta) have formed high high concentration areas. Relying on strong economic foundation, scientific and technological talents and improving Internet facilities, leading enterprises lead the development of digital economic clusters; Jiangxi and other regions have long been characterized by low to high concentration, reflecting the industrial radiation effect of surrounding developed areas.As a result of the rapid growth of its endogenous digital economy, a province in central China has formed a high low outlier zone, while its surrounding areas are limited by lagging development in technology, funding, and other areas.

Dynamic changes: From 2013 to 2017, some areas in Northwest China formed low low clustering areas due to a single economic structure and a late start in informatization; After 2019, some cities gradually moved away from low-level clustering by deploying data centers through the "East Data West Calculation" project. The high high concentration areas continue to consolidate in the east, while spreading to central cities, reflecting the trend of regional gradient transfer and coordinated development.

Driving factors: High concentration areas rely on economic foundations, policy support, and leading enterprises to drive; Low concentration areas are limited by insufficient input of factors, and breakthroughs in infrastructure construction will be achieved through national strategies such as "counting from the east to the west" in the later stage.

3.3 Estimation Results and Analysis of Spatial Durbin Model

Table 9 Estimation Results of Spatial Durbin Model

VARIABLES	(1)lnP	(2)lnC
lnDIG	-0.024*** （-5.92）	-0.033*** （-5.08）
lnPD	0.039** （2.19）	0.135***
lnIS	-0.059*** （-1.59）	-0.744*** （-12.51）
lnECI	-0.014* (-0.37)	1.054*** (17.28)
lnFDI	-0.017*** (-1.40)	-0.115*** (-5.68)
lnTD	-0.081*** (-3.49)	0.171*** (4.68)
lnED	-0.384*** (-8.86)	-0.021* (-0.31)
rho	0.121* (1.89)	0.287*** (3.51)

Note: The parentheses indicate standard errors；*P<0.10,**P<0.05,***P<0.01

In order to ensure that the model reflects the actual diffusion process of pollutants and effectively explains spatial spillover effects, 0-1 spatial adjacency matrix and economic geographic distance weight matrix are used in the SDM model. The results are shown in Table 9.

The digital economy has a significant negative impact on pollutant and carbon emission intensity, and promotes emission reduction through factor allocation, green technology diffusion, and energy structure adjustment, which is consistent with the "dual carbon" and "Digital China" policies; Population density has a stronger impact on carbon emission intensity, reflecting the pressure of carbon governance in high-density urban areas and responding to the requirements of urbanization during the 14th Five Year Plan period; The level of economic development is negatively correlated with two types of emission intensity. Developed regions have significant advantages in pollution control, while carbon emission control needs to deepen institutional incentives due to lagging energy structure adjustments; The significant suppression of carbon emission intensity by industrial structure highlights the key role of high energy consuming industries in transformation, which is in line with the Industrial Green Development Plan; The positive and significant impact of energy consumption intensity on carbon emission intensity confirms that energy structure is the core factor; Foreign direct investment demonstrates a significant negative influence on both types of emission volumes, verifying the 'pollution halo hypothesis'; Technological progress effectively reduces pollutants,but demonstrates a positive effect on the volume of carbon emissions.

The spatial lag term (rho) is significantly positive, supporting regional collaborative governance strategies such as the Beijing Tianjin Hebei and Yangtze River Delta regions, and providing empirical evidence for cross regional environmental policy coordination.

In summary, the model reveals how factors such as the digital economy and industrial structure contribute to reducing pollution and carbon emissions, along with the mechanisms of their spatial spillover. This is in line with China's policy focus on regionally coordinated green development and serves as a reference for policy improvement.

This study used the SDM model to estimate pollutant intensity (lnP) and carbon emission intensity (lnC), and decomposed the total effect into direct and indirect effects, so as to further explore the mechanisms of various influencing factors in regional environmental pollution and carbon emissions.

Table 10 Decomposition of Spatial Durbin Model Effects

VARIA-BLES	direct effect		indirect effect		total effect	
	lnP	lnC	lnP	lnC	lnP	lnC
lnDIG	-0.123*** (1.46)	-0.133*** (5.89)	-0.060*** (0.42)	-0.069*** (-1.54)	-0.183*** (1.42)	-0.065*** (1.47)
lnPD	-1.755*** (-4.99)	-0.398*** (-4.14)	1.616** (2.00)	-1.495*** (-5.63)	-0.139 (-0.18)	-1.893*** (-6.85)
lnIS	-0.234*** (-3.06)	-0.023 (-1.06)	-0.093 (-0.58)	-0.017 (-0.33)	-0.327* (-1.94)	-0.040 (-0.69)
lnECI	-0.070 (-0.64)	0.264*** (8.76)	-0.320 (-1.25)	0.029 (0.36)	-0.390 (-1.55)	0.294*** (3.43)
lnFDI	-0.058*** (-3.87)	-0.013*** (-2.99)	-0.043 (-1.10)	-0.024* (-1.78)	-0.101** (-2.32)	-0.036** (-2.41)
lnTD	-0.150*** (-4.08)	-0.029*** (-2.80)	-0.044 (-0.54)	-0.025 (-0.89)	-0.195** (-2.12)	-0.054* (-1.69)
lnED	-1.031*** (-6.17)	-0.749*** (-16.44)	-0.079 (-0.28)	0.241*** (2.65)	-1.110*** (-3.93)	-0.509*** (-5.29)

Note: The standard error is in parentheses; *P<0.10,**P<0.05,***P<0.01

According to Table 10, the digital economy (lnDIG) significantly suppresses pollution and carbon emissions, with both local pollution reduction and regional technology spillover effects. Therefore, it is necessary to strengthen its strategic support; The total effect of population density (lnPD) is significantly negative, reflecting the intensive infrastructure and regional technology coordinated emission reduction, echoing the policies of green infrastructure and joint prevention and control. The industrial structure (lnIS) only significantly reduces the intensity of pollutants and has no significant impact on carbon emissions, and green upgrading needs to be promoted; The significant increase in energy consumption intensity (lnECI) has led to higher carbon emissions, confirming that energy structure is the core factor and the need to accelerate low-carbon transformation. The total negative effect of foreign direct investment (lnFDI) on two types of emission intensity is significant, which verifies the "pollution halo hypothesis" and should guide foreign investment towards the green sector; Technological progress (lnTD) mainly focuses on direct emission reduction and requires a focus on green technology innovation; Emissions are significantly negatively impacted by the level of economic development (lnED), a finding that is consistent with the Environmental Kuznets Curve and the orientation of high-quality development. The model reveals the local and spatial spillover effects of variables, supports regional green linkage governance, and provides empirical evidence for optimizing the "dual carbon" policy.

4 CONCLUSION

Based on the panel data of 30 provinces in China from 2011-2021, this study systematically explored the impact of digital economy development on pollution reduction and carbon reduction, its mechanism and spatio-temporal heterogeneity by using entropy weight method, benchmark regression model, mediation effect model, spatial Durbin model (SDM), spatio-temporal geographical weighted regression (GTWR), and map attention network (GAT). The main conclusions are as follows:

Firstly,A direct facilitative effect of the digital economy is exerted on the reduction of pollution and carbon emissions. The improvement of the digital economy's development level enables a remarkable reduction in both pollutant and carbon emission intensity, and indirectly facilitates the reduction of pollutant levels and carbon emission intensity through multiple mechanisms including industrial structure upgrading, technological progress, and green finance. The test results show that for every unit of growth in the digital economy, the average decrease in pollutant and carbon emission intensity is 0.2575 and 0.2773 units, respectively, which is the core driving force for achieving pollution reduction and carbon reduction.

Secondly, the pollution reduction and carbon reduction effects exhibit significant spatial dependence and regional heterogeneity. There is a clear spatial autocorrelation between pollutant and carbon emission intensity, with high emission clusters concentrated in traditional industrial provinces and resource-based areas, while low emission clusters are mostly distributed in the eastern coastal industrial upgrading areas. The emission reduction effect of the digital economy shows a gradient difference of "strong in the east and weak in the west", and over time, the emission reduction effect gradually emerges in the central and western regions due to the promotion of digital infrastructure.
Thirdly, multiple mechanisms drive pollution reduction and carbon reduction, and energy structure remains a key constraint factor. The digital economy plays a dual role through technological empowerment and structural optimization. Meanwhile, population density, the degree of economic development, and foreign direct investment all exert a notable influence on the process of emissions reduction, but energy consumption intensity remains the main positive driving factor for carbon emissions, reflecting the urgency of energy structure adjustment.
Fourthly, the digital economy’s role in promoting emission reduction demonstrates both spatiotemporal dynamism and differentiated characteristics in regional responses. The GTWR model shows that the impact coefficient of the digital economy on pollution reduction and carbon reduction varies dynamically over time and space. After 2017, the marginal effect in the eastern region stabilized, while the effect gradually increased in the central and western regions due to industrial absorption and digital transformation. GAT clustering identifies four types of regional response patterns, reflecting regional adaptation differences between digital economy and environmental performance.

5 FUTURE DIRECTION

While this study systematically examines the impact mechanisms and spatiotemporal heterogeneity of the digital economy on pollution and carbon reduction, several avenues for future research remain:
(1).Micro-level Mechanisms and Firm Behavior
Future research could incorporate firm-level data to explore specific pathways through which the digital economy influences corporate emission reduction decisions, such as digital technology adoption, incentives for green innovation, and intelligent energy management, to reveal the role of micro-level actors in digital-driven emission reduction.
(2).Synergistic Effects Between Digital Economy and Energy Structure
This study highlights that energy structure remains a key constraint on carbon emissions. Future work could investigate how the digital economy promotes the integration of renewable energy, smart grid development, and energy internet systems to facilitate low-carbon energy transition.
(3).Regional Coordination and Policy Linkage Mechanisms
Building on the spatial spillover effects identified in this study, future research could develop cross-regional collaborative policy frameworks for digital emission reduction, exploring mechanisms for joint digital infrastructure development, data sharing, and green technology cooperation in regions such as the Beijing-Tianjin-Hebei Region, the Yangtze River Delta Region, and the Guangdong-Hong Kong-Macao Greater Bay Area.
(4).Research on the “Rebound Effect” of Digital Technology Applications
While the digital economy enhances efficiency, it may also lead to a “rebound effect” due to increased energy consumption or expanded production scale. Future studies should assess the net emission reduction effects of digital technologies from a lifecycle perspective and propose strategies to mitigate rebound effects.
(5).International Comparisons and Global Governance Perspectives
Extending the analysis to cross-country panel data allows for comparisons of the digital economy’s emission reduction effects in various national contexts, providing insights for China’s participation in global digital-green governance and the greening of the “Digital Silk Road.”
(6) Dynamic Forecasting and Policy Simulation
Integrating machine learning, system dynamics, or adopting other computational methods to build dynamic forecasting models for the digital economy and carbon emissions allows for the simulation of emission reduction outcomes under multiple policy scenarios, supporting the optimization of medium- to long-term “dual carbon” pathways.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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