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The Triple Dimensions of Digital Economy Promoting High-Quality Development of Rural Economy

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Abstract: Against the backdrop of the national comprehensive advancement of the rural revitalization strategy, the digital economy is gradually becoming a key driving force for the high-quality development of rural economy. Guided by the research approach of value analysis, problem diagnosis, and path exploration, this paper affirms the positive role of the digital economy in advancing agricultural industrial upgrading, facilitating the linkage of urban-rural factors, and enhancing the resilience of rural economy. Meanwhile, it reveals practical challenges encountered in its development, such as weak infrastructure, prominent digital divide, unbalanced regional development, and lagging institutional guarantees. To address these issues, the study proposes measures including improving rural information and logistics infrastructure to smooth service "last-mile" connections, implementing hierarchical digital skills training to enhance farmers' application capabilities, promoting in-depth integration of digital technology with industries such as agriculture and rural tourism, improving the legal system and supervision framework, and strengthening regional coordination and risk prevention. These efforts aim to unleash the structural, institutional, and innovative value of the digital economy. The research not only provides an academic reference for understanding the role and path of digital technology in the transformation of rural economy but also offers policy guidance for practical implementation.

Keywords: Digital Economy; Rural Economy; High-Quality Development; Significance; Problems; Strategies
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Introduction

General Secretary Xi Jinping pointed out: "In today's era, digital technology and the digital economy are at the forefront of the global scientific and technological revolution and industrial transformation, and they are key areas in the new round of international competition. We must seize this opportunity and occupy the commanding heights of future development."[1]
Currently, a new round of scientific and technological revolution and industrial transformation characterized by digitalization, networking, and intelligentization is advancing in depth worldwide. As a crucial driving force, the digital economy is profoundly reshaping the allocation of factor resources, economic structure, and competitive landscape. Against this backdrop, China is steadily advancing the construction of a "Digital China" and the "Rural Revitalization Strategy," striving to empower the modernization of agriculture and rural areas with digitalization, resolve the urban-rural dual structure, and promote higher-quality, more equitable, and more sustainable development.

Rural areas, as the weak link yet with great potential in national modernization, urgently need the empowerment of the digital economy to achieve transformation and upgrading. With its extensive penetrability, significant synergy, and continuous innovation, the digital economy has injected a new paradigm of precision production and intelligent management into traditional agriculture. It also provides unprecedented opportunities for the integration of rural industries, optimization of public services, and modernization of governance capabilities. From production to circulation, and from consumption to governance, digital technology is reshaping the operational logic and development path of rural economic and social systems. Empowering rural digital and intelligent governance with new-quality productive forces in agriculture can significantly improve rural governance efficiency and promote the building of a harmonious and stable beautiful rural society.[2]

In practice, the development of rural digitalization is still constrained by multiple factors: unbalanced coverage of digital infrastructure, generally low digital literacy of farmers, slow digital transformation of rural industries;[3] in addition, there are obvious regional differences in the development of digital industries, and relevant systems and governance frameworks are not yet mature. To a large extent, these problems have restricted the inclusive and shared effects that the digital economy should bring. Especially in remote areas, poverty-alleviated regions, and among smallholder farmers, the "digital divide" has not narrowed; instead, it has shown new forms due to the accelerated pace of technological iteration. If these issues cannot be systematically addressed, they will pose severe constraints on the implementation effect of the rural revitalization strategy and the high-quality development of rural economy.

Against this background, in-depth analysis of the functional logic of the digital economy empowering rural economy, identification of bottlenecks and risks in its development process, and proposal of practical optimization strategies are of great theoretical significance and practical urgency. Based on this, this study focuses on the three analytical dimensions of value interpretation, dilemma analysis, and path exploration, attempting to construct a systematic cognitive framework. It aims to provide an academic reference and practical guidance for understanding the role and path of digital technology in the transformation of rural economy.

1.The Logic of Digital Economy Empowering High-Quality Development of Rural Economy

1.1 Promoting Industrial Upgrading and Efficiency Improvement

Through emerging technologies such as big data, artificial intelligence, and the Internet of Things, the digital economy has injected new management paradigms and decision-making logic into agricultural production. The promotion of precision agriculture enables farmers to make scientific decisions based on real-time data, realizing refined operations from sowing, fertilization to pest and disease control, thereby reducing costs and improving output and quality. Rural e-commerce platforms have broken down the layers of barriers in traditional circulation channels, enabling agricultural products to directly enter urban markets. While shortening the supply-demand chain, they also reduce additional costs caused by intermediate links, significantly improving transaction efficiency.[4] Through dynamic monitoring and data-based management of agricultural production conditions, farmers can obtain more targeted guidance and support, thereby significantly enhancing the overall production efficiency and quality of crops. This not only transforms the traditional model of agricultural production but also provides a practical path for the adjustment and upgrading of rural industrial structure.

1.2 Advancing Urban-Rural Coordination and Common Prosperity

The digital economy breaks the constraints of time and space, enabling rural areas to be deeply integrated into the national and even global markets. Through e-commerce platforms, agricultural products have gradually shifted from "being sold" to "being sold well," and branding and differentiation have become important drivers for increasing the value of agricultural products. The digital economy also promotes the downward allocation of public service resources such as education and medical care, further narrowing the urban-rural gap. The construction of digital education platforms has promoted remote collaboration between urban and rural schools, which not only improves the quality of rural education but also enhances educational equity. The development of digital inclusive finance provides farmers with low-threshold credit and payment services, solving the problems of insufficient coverage and high financing difficulty of the traditional financial system, and injecting vitality into rural entrepreneurship and small and medium-sized business entities. The two-way flow of resources between urban and rural areas has laid a more solid practical foundation for the goal of common prosperity.[5]

1.3 Enhancing Rural Economic Resilience and Sustainable Development Capacity

The digital economy not only improves efficiency but also demonstrates unique advantages in enhancing rural economic resilience and sustainability. In the agricultural production link, digital platforms help farmers diversify risks. Through agricultural insurance technology, risk prediction and rapid response are realized, effectively alleviating the impact of natural disasters on agricultural production. In terms of rural governance, digital means improve the level of emergency management and public services, promote more flexible and efficient resource allocation, and ensure the continuity and security of rural economic operations. Overall, the digital economy not only enhances the stability of the rural economic system but also promotes the transformation of agriculture towards sustainability through the concept of green development and intelligent management methods, providing institutional and technological support for the long-term healthy development of rural economy.

2.Practical Dilemmas in the Process of Promoted by Digital Economy

2.1 Coexistence of Insufficient Basic Conditions and Urban-Rural Gaps

Although the penetration rate of the Internet in China has been continuously accelerating, its popularity in vast rural areas still does not exceed 50%.[6] In recent years, although the state has continuously made efforts in “new infrastructure,” the level of rural network coverage and information infrastructure has been continuously improved, there are still significant shortcomings. The quality of broadband and mobile signals in some remote mountainous areas and border areas is still poor, with slow network speed and insufficient stability, which seriously restricts the popularization of digital applications. For example, even if some farmers own smartphones, they cannot smoothly conduct e-commerce transactions or online learning due to network delays or high data costs. The imperfect logistics system has also become a bottleneck for agricultural products to “go from villages to cities.” Rural areas generally face problems such as insufficient cold chain facilities, limited warehousing capacity, and poor connection between trunk transportation and “last-mile” distribution. These issues lead to high loss rates and quality degradation of agricultural products during transportation, weakening their market competitiveness. These problems not only reduce farmers’ enthusiasm for participating in the digital economy but also widen the gap in basic conditions between urban and rural areas to a certain extent. In other words, there is a significant mismatch between the development speed of the digital economy and the improvement of rural basic conditions, which has become a key factor restricting the high-quality development of rural areas.

2.2 Parallel Existence of Insufficient Digital Literacy and Unbalanced Development

The “digital divide” between urban and rural areas is still obvious, showing the characteristics of “double insufficiency” in technology access and capacity development. A large number of farmers lack necessary digital skills and have limited mastery of application tools such as smart terminals, e-commerce platforms, and online payments, making it impossible for them to fully utilize the opportunities brought by the digital economy. In some places, even if the government or enterprises promote the establishment of rural e-commerce platforms, the utilization rate of the platforms is low and they eventually become formalities because farmers cannot operate them and lack training support. At the same time, unbalanced regional development further amplifies this problem. Relying on advantages in capital, talents, and markets, the digital industry system and service ecology in the eastern coastal areas have begun to take shape. However, the development of digital industries in the central and western regions and underdeveloped areas is lagging behind, and there is a lack of a mature supporting environment. More prominently, agricultural products generally lack standardization, large-scale production, and branding, which restricts the sustainable development of e-commerce platforms. For example, although many local characteristic agricultural products have high quality, they are difficult to stand out in the highly competitive market due to the lack of unified standards and effective brand communication. The superimposed effect of insufficient literacy and unbalanced development makes the participation and income level of rural areas in the digital economy significantly lower than that of urban areas.

2.3 Intertwining of Institutional Lag and Risk Challenges

The rapid expansion of the digital economy in rural areas has exposed the lag of the legal system and governance capabilities. The relevant legal and regulatory system is not yet perfect, and there are many gaps in data security, privacy protection, the validity of electronic contracts, and cross-border e-commerce, resulting in insufficient protection of farmers’ rights and interests in the transaction process. More importantly, the digital governance capacity of grass-roots governments is limited, and there is a phenomenon of relying on superior instructions and lacking localized innovation. This leads to inflexibility and lack of long-term effectiveness in the implementation of policies and the promotion of digital projects. At the same time, social risk issues cannot be ignored. Due to the generally limited digital literacy of farmers, online fraud is prevalent in rural areas, which not only damages the economic interests of farmers but also undermines their trust in the digital economy. In addition, some large platforms have strong monopolistic power in the rural e-commerce market, controlling traffic and the right to formulate rules. This places farmers in a weak position of asymmetric bargaining power and uneven interest distribution. In the long run, it is easy to cause farmers' over-reliance on platforms, weaken their independent development capabilities, and may even trigger new social contradictions. The intertwining of institutional lag and risk challenges means that the development of the rural digital economy has both opportunities and hidden concerns.

3.Path Choices for Digital Economy to Promote High-Quality Development of Rural Economy

3.1 Consolidating Infrastructure and Institutional Guarantees

The implementation of the digital economy in rural areas first requires solid "hardware" and "institutional" support. In recent years, the state has vigorously promoted the extension of "Broadband China" and 5G networks to rural areas, and initial results have been achieved in some regions. However, there is still a gap in the overall coverage and stability. To truly realize the digital transformation of rural areas, it is necessary to further accelerate the construction of information infrastructure, especially the full coverage of network base stations, fiber-optic broadband, and 5G networks. The improvement of the smart logistics system is also crucial. Due to the perishable nature of agricultural products, without the support of cold chain transportation, they are prone to loss during circulation, leading to the dilemma of "good harvest but no increase in income." Therefore, the government should not only increase financial investment but also attract social capital through the PPP (Public-Private Partnership) model[7] to form a diversified investment mechanism, promoting the coordinated development of information and communication, warehousing, cold chain, transportation, and other fields.

At the same time, institutional guarantees cannot be ignored. The development speed of the digital economy is much faster than the update of relevant laws and regulations. There is a widespread legal vacuum in rural areas regarding data security, privacy protection, and electronic contracts, which directly affects the protection of farmers' rights and interests. It is necessary to speed up the improvement of the legislative framework for digital villages, clarify the rights and responsibilities of platforms and users, and establish a multi-level supervision system. In particular, legal measures are needed to regulate the access and monopoly of large e-commerce platforms to ensure that farmers can participate in competition in a fair market environment. Local governments should also improve their digital governance capabilities, avoid the situation of "high enthusiasm at the top but low response at the grassroots," and enhance farmers' trust in and participation in the digital economy through the establishment of standardized and transparent governance mechanisms.

3.2 Cultivating Digital Talents and Enhancing Farmers' Literacy

The core of the digital economy lies not only in technology but also in people. Stalin once said, "Without talents who master technology, technology is a dead thing. With talents who master technology, technology can and will surely create miracles."[8] Technologies relied on by the digital economy, such as big data, artificial intelligence, and blockchain, can truly play a role in promoting economic development only when workers have corresponding knowledge and skills and are supported by social systems and organizational structures. In other words, the development of the digital economy is not only a process of accumulating technical conditions but also a manifestation of the all-round development of people. Even if network facilities are complete, if farmers lack necessary digital skills, they will find it difficult to truly participate and benefit. Therefore, enhancing farmers' digital literacy and cultivating professional talents have become the key to promoting the digital transformation of rural areas. Specifically, three parallel paths can be adopted: First, led by the government, special training programs should be established, and concentrated training should be organized during the slack farming season to help farmers master practical skills such as e-commerce operation, smart device use, and data management. Second, educational institutions should participate by setting up majors or courses related to the rural digital economy in colleges and vocational schools to cultivate compound talents. At the same time, university-local cooperation should be promoted to allow students to directly conduct practical work in rural areas. Third, social forces should provide supplementary support. Internet enterprises and e-commerce platforms should be encouraged to assume social responsibilities, establish training centers or demonstration bases in rural areas, which not only improve farmers' practical operation capabilities but also expand the brand influence of enterprises.

In addition, attention should be paid to the introduction and return of talents. Preferential policies can be used to attract groups such as college graduates, returned youth, and veterans to participate in the construction of the rural digital economy, alleviating the "talent shortage" in rural areas. It is also necessary to encourage "local experts" and "rural talents" to integrate with the digital economy, leveraging their familiarity with the rural environment and industries to drive farmers around them to achieve digital transformation.[9] Through the method of "introducing external talents and cultivating internal talents," a team of compound talents who understand agriculture, love rural areas, and are proficient in digital tools should be gradually built.

3.3 Promoting Industrial Integration and Regional Coordination

The value of the digital economy lies not only in improving the efficiency of a single industry but also in promoting in-depth integration of multiple industries and spawning new business formats and models. The integration of agriculture and e-commerce has broken the traditional circulation barriers, enabling agricultural products to shift from "being sold" to "being sold well"; the "agriculture + cultural tourism" model promotes rural tourism through digital platforms, which not only increases farmers' income but also enriches the leisure options of urban and rural residents. In addition, the integration of financial technology and agriculture is also forming a new driving force. Blockchain technology can be used for agricultural product traceability to ensure food safety while increasing the added value of agricultural products; digital inclusive finance provides farmers with low-threshold credit and payment services, alleviating the problem of financing difficulties.

While promoting industrial integration, attention should also be paid to the coordinated development of regions. At present, the development of the digital economy in the eastern coastal areas is relatively mature, but there is still an obvious gap in the central and western regions and remote mountainous areas. If this imbalance persists for a long time, it will widen the gap between urban and rural development and regional development. Therefore, the state should increase financial and policy support for the central and western regions, promote cooperation between the eastern and western regions, and form a complementary pattern of "eastern experience + western resources." At the same time, cross-regional digital agricultural industrial parks and agricultural product distribution centers can be established to realize the flow and sharing of factors and improve the overall coordinated development capacity. Only by achieving the diversified integration of industries and the balanced development of regions can the potential of the digital economy empowering rural areas be maximized.

4.Conclusion

Based on the logical framework of value interpretation, dilemma analysis, and path exploration, this paper systematically analyzes the mechanism and practical path of the digital economy promoting the high-quality development of rural economy. The research results show that the digital economy not only injects new momentum into rural transformation by promoting industrial upgrading, advancing urban-rural coordination, and enhancing economic resilience but also is constrained by multiple factors such as insufficient infrastructure, widened digital divide, unbalanced regional development, and lagging institutional guarantees. To realize the in-depth integration of the digital economy and rural economy, it is necessary to synergistically promote the intelligent transformation of infrastructure, the overall improvement of farmers' digital literacy, the integrated innovation of multiple industries, and the improvement of the digital governance system in the future. In this process, the overall planning of regional resources and policy coordination are indispensable; technological empowerment and institutional adaptation must advance in parallel. At the same time, potential technological and market risks should be prevented, and the interests of smallholder farmers should be effectively protected.

The high-quality development of the digital economy in rural areas is not only a process of technology application but also a systematic transformation project covering economy, society, and governance. Future development should continue to promote technology popularization and industrial innovation while strengthening humanistic care and mechanism innovation, and build a digital economy pattern that balances efficiency and equity. With the further breakthrough of emerging technologies such as artificial intelligence and blockchain, the digital economy will show greater potential in promoting the green development of agriculture, facilitating the free flow of urban-rural factors, and improving rural governance capabilities. Only by forming a synergy in institutional design, talent training, and social participation can the in-depth value of the digital economy in serving rural revitalization and realizing common prosperity be fully unleashed.

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Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Research Hotspots and Cutting-Edge Discussions on Data Element Configuration: Analysis Based on Bibliometric Method and Knowledge Graph

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Abstract: In the era of digital economy, the strategic value of data as a key production factor has become increasingly prominent, and its efficient allocation has become a core issue driving economic growth and social governance innovation. This paper employs bibliometric analysis and knowledge mapping techniques to analyze literature from the Web of Science and CNKI databases, constructing a topic co-occurrence network, keyword evolution path, and author collaboration map. It systematically reviews the research trajectory and frontier trends in the field of data element allocation both domestically and internationally. The research findings are as follows: (1) data governance, data ownership confirmation, production factors, frontal crash reconstruction, and federal interagency are the current core focuses of research. (2) Data assetization, scenario-based configuration models, and digital economy governance systems are emerging as cutting-edge exploration directions. (3) the field is showing a trend of interdisciplinary integration, with a multitude of innovative achievements emerging in the intersection of economics, law, and computer science. This study provides theoretical references for policymakers to improve the market-oriented allocation system of data elements.

Keywords: Data Elements; Data Element Configuration; Bibliometrics; Knowledge Graph; Hotspots and Trends
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1.Introduction

As a core resource in the era of digital economy, the efficient allocation of data elements through orderly circulation and in-depth development has given rise to new economic forms of digitization, networking and intelligent integration, and has played a key role in reconfiguring the value chain of traditional industries and accelerating the fusion of digital technology and the real economy. This efficiency improvement has become the core driving force for unleashing productivity potential and shaping new competitive advantages [1,2]. Under the digital era, the global digital transformation process is accelerating and technology is constantly evolving, and the importance of data, as a new form of supporting network systems in digital transformation, is becoming increasingly prominent [3]. The new elements have given rise to new needs, promoting closer inter-regional connections and synergies under the data and information linkage [4]. However, the current global level of data factor allocation is still relatively weak, facing challenges such as imperfect trading mechanisms, difficulties in asset valuation and pricing, data barriers and the phenomenon of silos, data security and privacy protection issues, as well as the unbalanced construction of digital information infrastructure, and insufficient capacity for independent control of core technologies

[5]. Therefore, how to play an efficient role in the allocation of data elements has become an important hot issue for the government and academia.

Since 2016, there has been an increasing abundance of research on the topic and perspective of data elements, with an increasing trend of academic research output. In general, many insights have been provided on the utilization of data factor allocation in the digital era. In order to systematize the development and trend of the field of "data factor allocation", this article is based on the research results from China Knowledge Network (CNN) and weibo.com. The article takes the research papers on the topic of "data factor allocation" published in China Knowledge Network and web of science in the past 10 years as the object, and utilizes the bibliometric and knowledge mapping methods to sort out the trend of publication and explore the evolution path of the research hotspots, so as to provide a reference for the future research.

2.Research data and methodology

2.1 Data sources

The article selects China Knowledge Network (CNKI) and Web of science (WOS) domestic and international core anthology databases as the source of literature, and the search time is up to February 2025. In the CNKI database, 604 articles were retrieved by direct search with "data elements" as the title or keywords highly relevant to the topic of "data element configuration", and 556 articles were retrieved after manual screening, spanning the period from 2016 to 2025. In Web of Science, 604 articles were retrieved with "Data elements" as the title or keywords highly relevant to the topic of "data element configuration". 2025. In Web of Science, we searched the literature with "Data element" as the title or "Data element configuration" as the keyword, and eliminated the literature that was not related to the research topic. The total number of literature obtained was 228, excluding those that were not related to the research topic.

2.2 Research methodology

The article combines bibliometrics and knowledge graph technology to mine and analyze multiple knowledge nodes and their logical relationships through network structuring and graph visualization at . Through the integration of knowledge mapping technology and bibliometrics, the powerful computing power and intuitive graph form can statistically and reveal the evolution dynamics, research hotspots and potential trends of a certain subject area [6]. Based on this, the article explores the research lineage and development frontiers of data element configuration with the help of CiteSpace software. At the same time, in order to reduce the possible bias of the analysis results of CiteSpace software, the article combines the traditional literature combing method, combines the quantitative analysis results of CiteSpace with the subjective analysis of the traditional literature, in order to comprehensively, systematically, and objectively present the development dynamics and characteristics of the field [7]. The specific principles are detailed in Ref.

3.Statistical analysis of communications

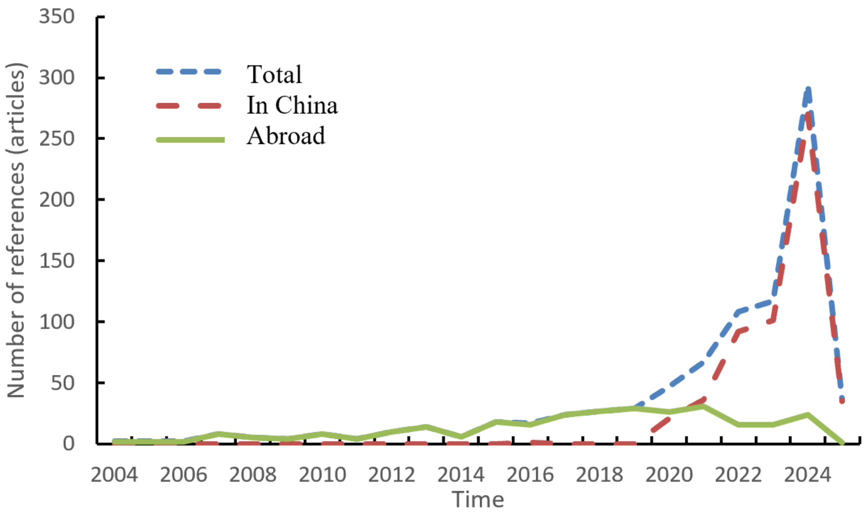
3.1 Distribution of publications

As a key indicator for assessing the activity level of a research field, the time series distribution of the number of articles can intuitively map out the development trajectory and stage characteristics of the field, which provides an important reference basis for in-depth investigation of research hotspots and scientific prediction of the future development direction. According to the analysis of the core collection of articles collected by CNKI and WOS, it is found that since 2004, the field of data element configuration has shown an obvious upward trend. Specifically, as shown in Figure 1.

From Figure 1, it can be found that foreign research in this field is more important than domestic, although in 2004 foreign scholars began to pay attention to this field, but the growth rate of the number of publications after that is relatively flat. However, for the domestic, although the domestic start is late, in 2016 only began to publish the core journals in this field, but after 2019, the number of domestic literature is growing rapidly, and the distance with the level of foreign research in the same period has widened.

For the country, 2019 and 2023 are two important time turning points. In October 2019, the Fourth Plenary Session of the 19th CPC Central Committee proposed for the first time to incorporate data into the socialist market economic system as a new factor of production, which promoted in-depth research on data factors in academia, and the number of related researches increased rapidly. In 2023, the “Opinions of the Central Committee of the Communist Party of China and the State Council on Constructing a More Perfect Factor Market-based Allocation In 2023, the Opinions of the CPC Central Committee and State Council on Constructing a More Perfect Institutional Mechanism for the Marketized Allocation of Factors was released, which further stimulated the enthusiasm of the academic community, causing the growth rate of the number of articles issued from 2023 to 2024 to reach a peak.

Figure 1 Statistical distribution of the number of publications



3.2 Analysis of national and international literature sources, institutions and authors

With the help of Cite Space 6.3 software to extract the publication information, the top 10 journals in terms of the number of literature in the field of data element configuration were analyzed in the WOS and CNKI databases during the period of 2004-2025, and the results are shown in Table 1.

In the WOS database, Sustainability Journal contains the most literature in the field of data element configuration, totaling 25 articles. 12 articles each from JAMIA and Traffic Injury Prevention, and a total of 8 articles from BMJ Open. In the CNKI database, on the other hand, the literature in the field of data element configuration was mainly from EGovernment, Statistics and Decision Making, Books and Intelligence, Journal of Information Resources Management, and Science and Technology Progress and Countermeasures, which were relatively less dispersed.

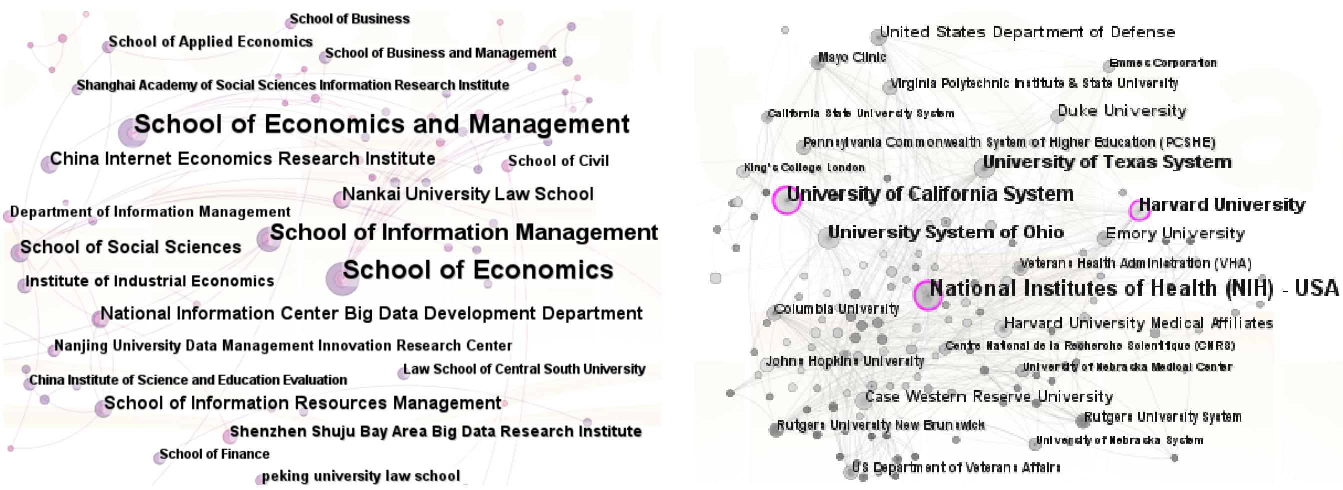
Table 1 Top 10 journals in WOS and CNKI databases that contain literature in the field of data element configuration

Literature sources	Article Count	Literature sources	Article Count
Sustainability	25	E-Government	23
JAMIA	12	Statistics and Decision Making	17
Traffic Injury Prevention	12	Library and Information	15
BMJ Open	8	Journal of Information Resource Management	14
J NURS SCHOLARSHIP	6	Technological Progress and Countermeasures	11
IEEE Template	4	Information Intelligence Theory and Practice	11
ARCH PHYS MED REHAB	4	Management Review	9
CIN	4	Business Research	9
J NEUROTRAUM	4	Shanghai Economic Research	9
JAIS	3	Jiangxi Social Sciences	8

The analysis of the number of papers issued by research institutions shows that Chinese research institutions are more active in publishing research articles on data element allocation in Chinese journals, up to 13. The main institutions include the School of Economics and Management of Northwest University, the School of Management of Wuhan Information University, the School of Information Resources Management of Renmin University of China, and the Big Data Development Department of the National Information Center. From the perspective of cooperation relationships among domestic research institutions (Figure 2 (a)), the figure contains 169 nodes and 107 connections, indicating that the cooperation circle is closely connected. Internationally, WOS data shows that research institutions are more active in publishing in this field, with institutions with higher publication volumes including the National Institutes of Health (18 articles), University of California (14 articles), Harvard University (12 articles), Ohio University (11 articles), and University of Texas (10 articles). From the analysis of cooperation relationships among global scientific research institutions (Figure 2 (b)), the graph contains 294 nodes and 687 connections, indicating a higher density of institutional cooperation networks and closer connections within the cooperation circle compared to China.

Figure 2 Research institution publication volume chart

(a) Obtained from CNKI *(b) Obtained from WOS*



An analysis of the CNKI database shows that in the field of data factor allocation research, Chinese scholars Ouyang, Rihui (9 articles), Chen, Bing (8 articles), Wang, Jiandong (6 articles), Lin, Zhenyan (5 articles), Yu, Liuyi (5 articles), Xia, Yikun (5 articles), and Huang, Qianqian (5 articles) are more prominent in the number of articles published. From the analysis of WOS database, Abdallah, Chadi G (4 articles), Austin, Joan K (3 articles), Bailey, Donald E (3 articles), Bakken, Suzanne (2 articles), Barton, Debra (2 articles), and Corazzini, Kirsten (2 articles) have published more papers in this field with a high number of publications.

3.3 Cooperation between countries and regions

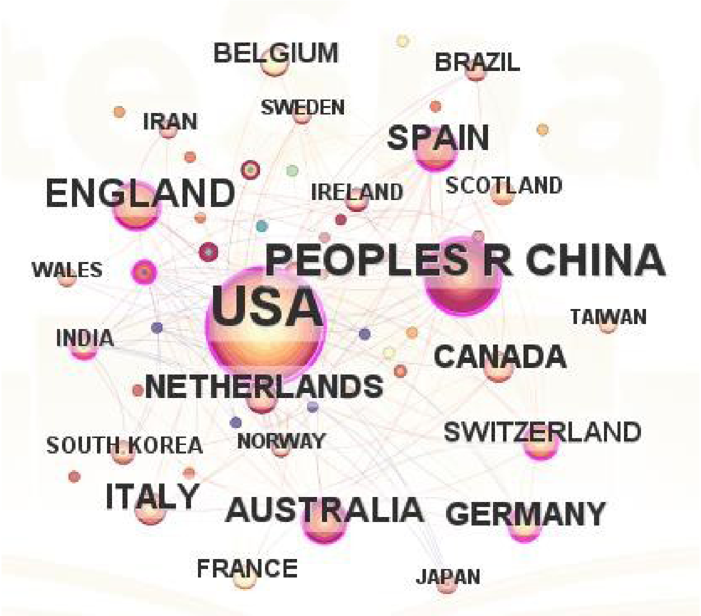
Interregional exchanges and cooperation have helped to deepen the breadth and depth of research. As of February 2025, 54 countries have participated in research in the field of data factor allocation. There are significant differences in the number of publications across countries (Table 2), with the United States leading with 91, followed by China (41), England (22), Australia (17), the Netherlands (17), and Italy (13). The country cooperation mapping (Fig. 3) showed a total of 54 nodes and 167 connecting lines, with a network density of 0.1667, indicating that cooperation exists between most countries, but their connections are not strong.

Table 2 Top 10 countries in terms of number of publications in the area of data factor allocation

Nations	Article Count	Proportion
USA	91	31.06%
China	41	13.99%
England	22	7.51%

Nations	Article Count	Proportion
Australia	17	5.80%
The Netherlands	17	5.80%
Italy	13	4.44%
Canada	12	4.10%
Germany	10	3.41%
Switzerland	10	3.41%
Brazil	8	2.73%
Other countries	52	17.75%
Total	293	100.00%

Figure 3 Mapping of country cooperation in the area of data factorization



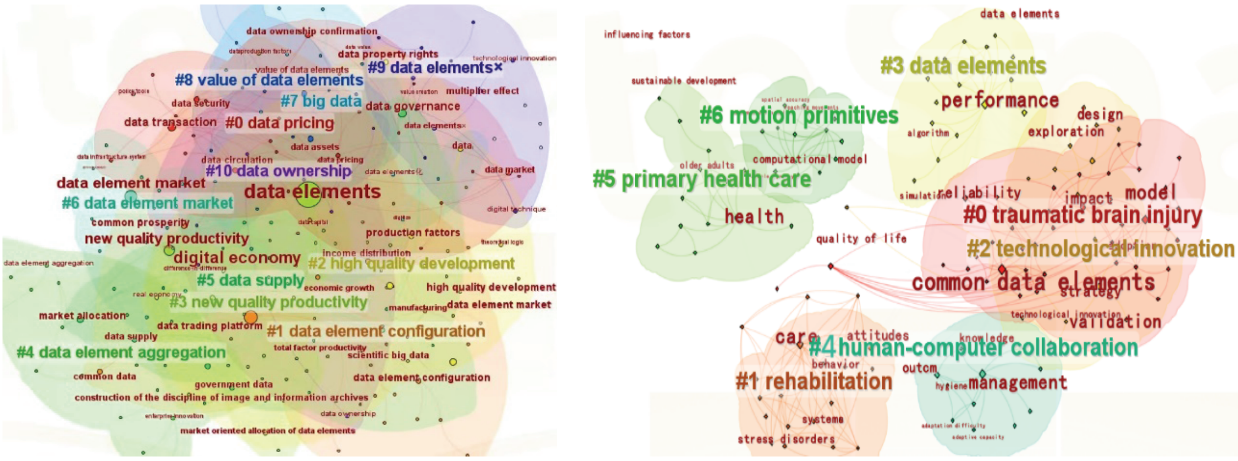
3.4 Differences in research hotspots in China and abroad

Through CiteSpace analysis, a keyword clustering map of data element configuration was generated (Figure 4). For domestic literature (Figure 4a), the map contains 240 nodes and 500 connections, with a density of 0.0174, a Q value of 0.5226, and an S value of 0.9324. The clustering results are reasonable and of research value. The clustering results show that keywords such as “digital economy”, “data governance”, “data confirmation”, “production factors”, and “income distribution” are located at the center of the cluster, forming seven main clusters, including data pricing (#0), data element configuration (#1), high-quality development (#2), net quality of productivity (#3), data element aggregation (#4), data supply (#5), data element market (#6), big data (#7), value of data elements (#8), data elements x (#9), and data ownership (#10).

The keyword map of foreign literature (Figure 4b) comprises 280 nodes and 549 connections, with a density of 0.0141, a Q value of 0.8641, and an S value of 0.9649. The clustering effect is good, and the results are reasonable. In the keyword clustering map of foreign literature, keywords such as “frontal crash reconstruction”, “federal interagency”, “toe framework-a”, and “visual workspace” are at the center of the clusters. A total of six clustering results are obtained, including traumatic brain injury (#0), rehabilitation (#1), technological innovation (#2), data element (#3), human-computer collaboration (#4), primary health care (#5), and motion primitives (#6).

Figure 4 Keyword co-occurrence mapping

(a) Obtained from CNKI *（b）Obtained from WOS*



4.Discussion

4.1 Literature review of data factor allocation

By analyzing and comparing the results of the data factor allocation literature obtained from two different literature databases, it is possible to classify the research on data factor allocation into four phases, namely, the early exploration phase, the theory and market research phase, the empirical analysis and application phase, and the future outlook phase.

4.1.1 Early Exploratory Phase

In the early exploration stage (2015-2017), scholars preliminarily explored the importance and definition of data as a new production factor, focusing on understanding the basic principles and potential socio-economic impacts of data element allocation. For example, Zhong et al. [11] proposed that from the perspective of data-driven factors, the key to high-quality digital transformation of enterprises lies in optimizing resource allocation through the use of data elements. Soete et al [12] pointed out that market-oriented allocation of data elements is a dual combination of "production factor oriented" and "allocation market-oriented". The key lies in endowing data with the attribute of "commodity" and promoting the transformation of stakeholders from internal closed circulation to cross subject open circulation. These studies have laid an important theoretical foundation for understanding the configuration of data elements.

4.1.2 Theoretical framework and market mechanism research stage

In the research phase of theoretical framework and market mechanism (2018-2020), more scholars have constructed a specific theoretical framework for data factor allocation and analyzed the market mechanism in depth, which provides an important foundation for subsequent research [15]. For example, Kishi [16] established the "data demand - data supply - data transaction" as the core of the value movement path of "value discovery - value realization - value distribution". Lai [17] built a theoretical framework of market allocation of data production factors with "data demand - data supply - data transaction" as the core, revealing the basic structure of the market, the internal mechanism, and the relationship between data demand, production, and transaction in the digital economy. Haaland et al. [18] also pointed out that the use of the Internet plays a positive role in the market allocation of factors of production in agriculture through the mechanism of information access. positive effect.

4.1.3 Empirical analysis and application promotion phase

The phase of empirical analysis and application promotion (2021-2023) has seen the emergence of a large number of empirical studies, which have verified theoretical assumptions and explored practical application scenarios, enriched theoretical understanding and provided scientific basis for policy formulation, for example, Yang's [19] study shows that public data openness can significantly enhance the enterprise's total factor productivity, and that the local government should improve the environment of openness of data elements to improve the the level of public data openness. The empirical study of Guo [20] shows that market-based allocation of data factors significantly enhances urban economic resilience, mainly through improving the efficiency of capital and labor allocation. Both studies emphasize the importance of data trading platforms and their positive impact on regional economic development.

4.1.4 Integrated assessment and future outlook phase

Research in the comprehensive assessment and future outlook phase (2024 to present) focuses more on comprehensively assessing the data element configuration system, predicting future development trends, and emphasizing interdisciplinary cooperation, multidimensional analysis, and long-term planning in order to better respond to the challenges and seize the development opportunities [21]. Scholars have attempted to synthesize the research related to data factor allocation , which is mainly categorized into the synthesis on the influencing factors of data factor allocation, the synthesis on data factor allocation itself and the synthesis on the impact of data factor allocation [22]. Among them, regarding the synthesis of factors affecting data factor allocation, Yin et al. [23] summarize how these points affect data factor allocation from the aspects of market supply and demand mechanism, price mechanism and competition mechanism. In the review on data factor allocation itself, Gereffi [24] points out that data factor allocation needs to take into account its characteristics such as non-competitiveness, complementarity, externality and exponential proliferation. The fact that data can be used by multiple users simultaneously without compromising its utility promotes its shareability. The fusion of data from different sources enhances its value, requiring configuration to focus on data diversity and fusion [25]. However, data externality may lead to negative effects such as privacy leakage, so privacy protection and regulation need to be strengthened. Meanwhile, the exponential proliferation of data implies that it can generate more new data during its use, requiring configuration systems that can support the continuous growth and iteration of data.

5.Conclusions of the study

5.1 Conclusions of the study

Based on CNKI and WOS databases, using bibliometrics and knowledge mapping methods, the following conclusions are drawn from the literature on the topic of "data factor allocation" in the past 20 years at home and abroad:

First, between 2004 and 2025, the overall upward trend in the number of articles issued. Foreign scholars have taken the lead in focusing on the problem of data factor allocation, and the research has focused on the initial application in the fields of health care, transportation, environment, etc., but the overall growth rate has been flat, and a large-scale research system has not yet been formed. Domestic research lags behind the international, core journal papers were first published in 2016, focusing on policy interpretation and theoretical framework construction, but the number of articles is relatively small, in the exploration period.

Secondly, in terms of keywords, relevant studies cover a wide range of topics, including "data governance", "digital economy", "rights-based", "production", "production factors" and "revenue distribution", "frontal crash reconstruction", "federal crash reconstruction", and "data governance". factors" and "distribution of benefits", "frontal crash reconstruction", "federal interagency", and "data governance". interagency", "toe framework-a" and "visual workspace". Among them, data governance and the digital economy are important elements in the area of data factorization.

Thirdly, papers come from a wide range of sources, with a relatively decentralized distribution of authors, but there is close cooperation between highly productive and research-intensive institutions. International research maintains multidisciplinary penetration, and domestic research deepens the integration of theory and practice, but the density of international cooperation networks is low, and there is a need to strengthen cross-regional knowledge flow.

Fourthly, from the content point of view, the research on data factor allocation presents a significant "governance-technology" dual-track differentiation pattern: domestic research takes policy interpretation and mechanism design as the core driving force, and focuses highly on the institutional issues in the market allocation of data factors (e.g., the system of confirming the right, the mode of revenue distribution, and the shape of the digital economy), forming a "policy-driven" research paradigm. The research paradigm is "policy-driven", with disciplinary crossover focusing on the fields of public management, economics and law, and the methodology focusing on the analysis of policy texts and the design of governance frameworks. International research pays more attention to the technical application scenarios, and carries out empirical explorations around the technological pain points such as medical data sharing, traffic trauma analysis, and human-machine collaboration, which presents a "problem-oriented" research paradigm. The international research focuses more on technology application scenarios and empirical explorations around medical data sharing, transportation trauma analysis, human-computer collaboration and other technological pain points, presenting a "problem-oriented" feature, with disciplines integrating computer science, medical science, engineering, etc., and a tendency towards quantitative model construction and technological ethical reflections in methodology.

The conclusions are more relevant.

The analysis shows that research attention to the topic of "data factor allocation" is characterized by the following features:

First, strong policy-driven. Domestic research is directly influenced by policy, and the post-2019 literature surge is highly synchronized with policy nodes. International research is more pulled by technological needs (e.g., medical data applications).

Second, there are differences in the distribution of disciplines. Domestic focus on governance and economy (e.g., digital economy, rights allocation), journals are concentrated in public management and information management. International focus on technology and social issues (e.g., medical rehabilitation, technological innovation), with a higher proportion of interdisciplinary journals.

Third, the heterogeneity of cooperation networks. The cooperation network of domestic scientific research institutions has begun to take shape but has a low density (169 nodes, 107 connections), while the international cooperation network is more compact (294 nodes, 687 connections), and needs to be strengthened for domestic synergies.

Fourth, research hotspots are stratified. Domestic hot spots revolve around marketoriented allocation mechanisms (such as revenue distribution and multiplier effects), while foreign countries focus on technological application scenarios (such as trauma reconstruction and human-computer collaboration), reflecting the dual-track approach of "governance" and "technology".

5.2 Shortcomings and Prospects of Current Research

Scholars have different means of defining data factor allocation and measuring the level of allocation, which has triggered many debates on data factor allocation . How to define and measure the configuration level and measurement index of data elements has not yet formed a unified standard. In view of this status quo, future research on data elements needs to carry out in-depth studies in the following aspects: first, firstly, the conceptual connotation of data element configuration must be further improved and unified, and the difference between the stock and increment of data must be fully considered in order to more accurately describe and assess its configuration status. Secondly, a set of scientific, comprehensive and operable indicator system should be constructed for accurately measuring the configuration level of data elements, which should cover multiple dimensions such as configuration efficiency, utilization rate, security, etc., so as to provide empirical support for optimal configuration. Finally, to address the real problems of data silos and data barriers, it is necessary to synthesize the needs and interests of the government, society, enterprises, scholars and other parties to explore and propose effective mitigation countermeasures, and jointly promote the efficient allocation and full use of data elements.

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no

Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Research Hotspots and Cutting-Edge Discussions on Digital Innovation Ecosystems

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Abstract: In the context of the digital transformation of the global economy, the digital innovation ecosystem has become the core engine driving economic growth and social progress. Based on CiteSpace knowledge mapping and bibliometrics, this paper systematically compiles the research hotspots and cutting-edge trends in this field, and reveals its theoretical evolution and practical development. It is found that the research themes of digital innovation ecosystem focus on technological innovation and value creation, ecosystem evolution mechanism, path selection and sustainable development. Platform enterprises, as the core architects, promote complementary innovation and optimal allocation of resources through the formulation of technical standards and governance rules, and promote the sustainable development of the ecosystem. However, system evolution faces challenges such as technology path dependence, increasing digital divide, and environmental resource pressure. Future research should deepen the enabling mechanisms of digital technologies, strengthen the study of dynamic evolution mechanisms, expand cross-cultural and cross-regional comparative studies, and focus on its synergistic evolution with sustainable development.

Keywords: Digital Transformation; Innovation Ecosystem; CiteSpace; Bibliometrics
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Introduction

With the worldwide transformation of economic patterns towards digitization, innovative digital ecosystems have gradually become a key driving force for the economic uplift and social development of all countries. As the world's second-largest economy, China has attached great importance to digitalization in recent years, incorporating it into its strategic planning at the national level. Especially in 2021, the relevant departments issued a series of guiding documents such as the "14th Five-Year Plan for the Development of the Digital Economy", which provides policy protection and directional guidance for the orderly development of the digital economy. These policies are committed to promoting the deep integration of digital technology and the real economy by optimizing the digital innovation environment, strengthening the construction of digital infrastructure, and promoting the market allocation of data elements[1]. The rapid development of digital technology is reshaping the allocation of innovation resources and injecting new vitality into the science and technology innovation ecology[2]. This innovation model breaks through the limitations of traditional theories, and through the deep integration of information technology, products and services, it not only changes the product form and service mode, but also the wave of digital transformation is reshaping the economy and society in many dimensions. On the demand side, consumers' purchasing behaviors and preferences have significantly changed; on the supply side, enterprises have adjusted their operation modes to adapt to the new environment; and on the market level, the competitive situation of the industry has also shown different characteristics from the past[3]. At the same time, the evolution path and organization of technological innovation are undergoing profound changes, mainly due to the continuous penetration and integration of the new generation of digital technologies. Collaboration among enterprises and between enterprises and other organizations has become increasingly close, and partners, funds, resources, suppliers, R&D transformation and customers and other elements have formed a wider and deeper network[4]. This technology-driven innovation model not only expands the theoretical boundaries of the traditional innovation ecosystem, but also gives it a new connotation [5]. Therefore, in-depth investigation of the operation mechanism of digital innovation ecosystem and its symbiotic evolution path is of great significance for both theoretical research and practical development.

In recent years, with the in-depth promotion of digital transformation, digital innovation ecosystem research has gradually become a hot topic of academic attention. This emerging research field has evolved along with the rapid development of new-generation information technologies such as artificial intelligence and big data, and its theoretical boundaries and research scope have continued to expand. International academics have carried out multi-dimensional exploration around this topic, focusing on core issues such as system composition, operation logic, development trajectory and its socio-economic effects. Meanwhile, domestic researchers have also actively engaged in this field, promoting the construction and improvement of the relevant theoretical system through diversified research perspectives and methods. For example, Lv Kun et al. [6] constructed the analytical framework of "center-periphery" from the perspective of system elements. In terms of system hierarchy, Xu[7] proposed a four-level model, which subdivided the system structure into kernel, core, expansion and derivation layers, which provides a new way of thinking to understand the hierarchy of innovation ecosystems. In addition, Ma[8] used the scientometrics method to systematically trace the theoretical origin of innovation ecosystems through bibliometric analysis, and made an in-depth combing of its knowledge evolution vein, which laid an important foundation for the subsequent research; while foreign scholars paid attention to the research of digital innovation ecosystems earlier, Lopez[9] put forward the framework of the innovation strategy under the perspective of ecosystems, which emphasized the value co-creation and ecosystem competition; Quero[10] focused on platform ecosystems and explored the interaction mechanism of platform leaders and complementaries; Rentschler[11] systematically sorted out the conceptual connotation, characteristics and evolution mechanism of digital innovation ecosystems; and Draschbacher[12] constructed a theoretical model of digital innovation ecosystems' value creation from the perspective of value co-creation. model. Although academics have made some progress in the construction of the knowledge system and development of the innovation ecosystem and its digitalization process, the theoretical foundation of the digital innovation ecosystem is still weak. Specifically, the definition of core concepts is still controversial, the research paradigm has not yet been unified, and the boundaries of disciplines are ambiguous. To a certain extent, these theoretical deficiencies have constrained the in-depth development of the field, and also provided room for exploration for subsequent research. Existing studies are mostly confined to specific fields and lack a systematic exploration of the knowledge structure and research trends of digital innovation ecosystems from a holistic perspective. This status quo highlights the urgent need to explore the research hotspots and frontiers in this field from a macro level. From a methodological point of view, the application of knowledge mapping analysis technology in China's academic research is still in a preliminary stage of exploration, and the depth and breadth of its practice in different disciplines need to be further expanded. As an advanced scientometric tool, CiteSpace, with its powerful data processing and visualization functions, can effectively reveal the development of a specific research theme, clearly show the key nodes and cutting-edge trends in the evolution of disciplines, provide powerful technical support for researchers to grasp the development trend of the field, and provide strong methodological support for the study of digital innovation ecosystem[13]. This knowledge graph-based analysis method not only helps to clarify the research lineage, but also provides scientific guidance for the future research direction.

Based on the comprehensive examination of existing theoretical research and practical progress, this study adopts a mixed research method, combining bibliometric analysis with knowledge mapping technology. The research data comes from the internationally renowned Web of Science database and the domestic authoritative China Knowledge Network platform.

By systematically collecting and organizing the relevant English literature, and using CiteSpace visualization and analysis tools, the study analyzes the whole research landscape in the field of digital innovation ecosystems in a multi-dimensional way, aiming at revealing the trajectory of the development and the hotspots of research in this field. The study focuses on the development overview, research hotspots and evolutionary trajectory of the field, refines the core research content through systematic analysis, and prospectively explores the future research direction. This study not only helps to deepen the theoretical construction of digital innovation ecosystem, but also provides a reliable theoretical basis and practical guidance framework for subsequent research.

1.Data sources and research methodology

1.1 Data sources

The literature data source of this paper consists of two parts, domestic and foreign, and the starting date of searching is set as January 2015, and the deadline is set as January 2024. The foreign literature data comes from Web of Science database, with "Digital Innovation Ecosystem" and "Digital transformation" as the keywords. After eliminating the search results of duplicated literature and non-relevant disciplinary content, 301 foreign literatures were finally obtained; the domestic literature data came from the China Knowledge Network (CNKI) database, with the keywords "Digital Innovation Ecosystem", "Innovation Ecosystem", "digital transformation" as keywords, after eliminating the search results of duplicated literature and non-relevant disciplinary content, 224 effective documents were finally obtained, and the specific search method is shown in Table 1.

Table 1 Literature search methods related to digital innovation ecosystems

form	comprehensive database	Search method	Type of literature	time span	retrieval time	Search results
English Literature Search	WoS database	TS = "Digital Innovation Ecosystem", etc.	Article	2015-2024	February 2025	Part 301
Chinese Literature Search	China Knowledge Network Database	keyword = "digital innovation ecosystem", etc.	periodicals	2015-2024	February 2025	224 articles

1.2 Research methodology

This study adopts a quantitative research method to systematically analyze the research data through bibliometric means. Firstly, Excel and other data processing tools are used to carry out basic statistical analysis of the literature in the field, and then the CiteSpace visualization and analysis platform developed by Chen's team is introduced to carry out in-depth mining of the literature data in the field of digital innovation ecosystems and the construction of the knowledge graph, so as to realize the visual presentation and interpretation of the research topic. The software is able to form a knowledge map with dynamic, diversified and time-sharing characteristics in time by clustering and burst analysis of keywords, authors, institutions and even citations on the basis of knowledge unit analysis, and at the same time embedding a series of artificial intelligence algorithms, such as text processing, data mining and detection, etc., to draw the interconnection between the required information.

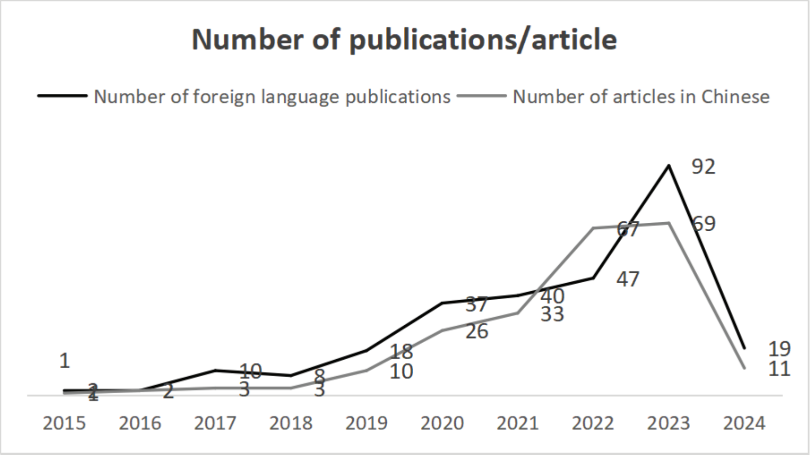
Utilizing the above tools, this paper analyzes the existing studies on digital innovation ecosystems by bibliometrics and text mining, in order to reveal the structure, characteristics and regularity of the studies on digital innovation ecosystems. Through the statistical analysis of the original research data, this study conducts a quantitative study in terms of the growth trend of the number of documents, the cross-disciplinary characteristics and the distribution pattern of journals. This analytical process helps to grasp the overall development profile and disciplinary distribution characteristics of this research topic. Finally, we analyze the co-occurrence of keywords and draw a more ideal keyword clustering time view and keyword clustering information table by appropriately adjusting the parameter settings, so as to systematically summarize the main research hotspots emerging from the digital innovation ecosystem as well as the evolution trend of the research hotspots, in order to more comprehensively grasp the current research frontiers.

2.Visual analysis of digital innovation ecosystems

2.1 Analysis of the volume of publications

Since 2015, the literature on digital innovation ecosystem research at home and abroad has continued to grow every year (see Figure 1). Taking 2021 as the time point, the amount of English literature issued has seen a sustained and substantial growth, much higher than that of Chinese literature, and with the development and progress of the research direction, the amount of Chinese literature issued has begun to fall back and stabilize. From the point of view of foreign research: the number of articles issued during the period of 2016-2019 is developing steadily, and the number of articles issued from 2021 to the present is developing rapidly. From the viewpoint of domestic research: from the perspective of the time dimension, the output of research results in this field presents obvious stage characteristics. The research data show that the number of literature maintains a stable growth trend between 2018 and 2020, while significant fluctuations occur after 2022. It is worth noting that after reaching the historical peak in 2024, the annual literature output gradually leveled off, indicating that the research field may have entered a relatively mature stage of development. The point at which the number of domestic publications reaches the peak of the phase shows that domestic research is closely related to the policies introduced at the national level.

Figure 1 Annual Distribution of Digital Innovation Ecosystem Literature at Home and Abroad, 2015-2024



2.2 Analysis of disciplines and journals

According to the statistics, the domestic literature on digital innovation ecosystem is scattered and published in 132 journals, and overall, the distribution of journals is relatively wide. The top 10 journals have published 77 papers related to digital innovation ecosystems (see Table 2), 34.37% of the academic papers related to digital innovation ecosystems are published in 1.3% of the journals, indicating that the main journals carrying articles about digital innovation ecosystems in China are relatively concentrated.

Table 2 Names of domestic source publications

rankings	Name of source publication	record (in sports etc)
1	Scientific and technological progress and responses	15
2	scientific research	14
3	Science and Technology Management Research	9
4	research management	8
5	China Science and Technology Forum	6
6	Industrial Technology and Economics	6
7	techno-economic	5
8	Technical Economics and Management Studies	5
9	Science and Science and Technology Management	5
10	soft sciences	4

In terms of discipline distribution, the main journals carrying articles in the field of digital innovation ecosystem in China are mostly concentrated in the disciplines of enterprise economy, industrial economy, macroeconomic management and sustainable development, economic system reform, scientific research management and so on. In foreign countries (see Table 3), the distribution of journals of digital innovation ecosystem research literature presents similar to that in China, with the top 10 journals in terms of publication volume publishing a total of 206 articles, accounting for 68.43% of the total number of articles published in foreign language literature, which is a more concentrated distribution.

Table 3 Names of foreign source publications

rankings	Name of source publication	record (in sports etc)
1	TECHNOVATION	34
2	SUSTAINABILITY	33
3	MIS QUARTERLY	28
4	IEEE ACCESS	24
5	JOURNAL OF ENGINEERING AND TECHNOLOGY MANAGEMENT	17
6	COMPUTERS & INDUSTRIAL ENGINEERING	17
7	JOURNAL OF STRATEGIC INFORMATION SYSTEMS	14
8	IEEE TRANSACTIONS ON ENGINEERING MANAGEMENT	13
9	HELIYON	13
10	EUROPEAN JOURNAL OF INFORMATION SYSTEMS	13

3.Research Hot Spots and Research Trends

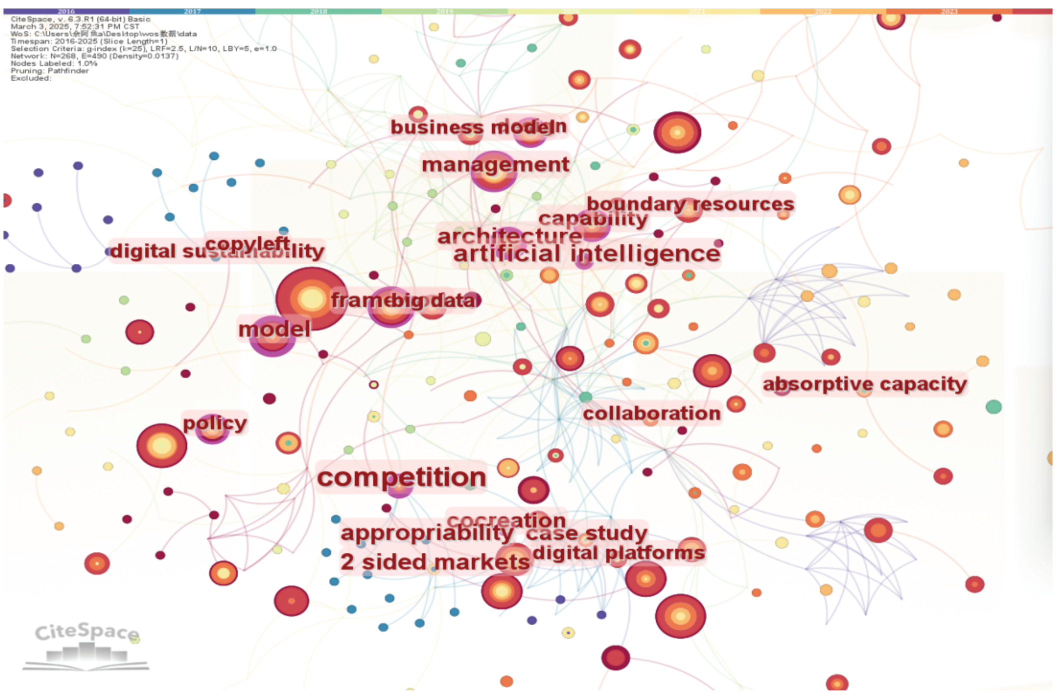
3.1 Keyword co-linear analysis

In view of the current theoretical research foundation and the development trend of the discipline, this study adopts CiteSpace, a knowledge visualization tool, and bibliometrics to systematically research the relevant English-language literature included in CNKI and WoS databases. By integrating and analyzing the academic resources of the two databases, the study focuses on the overall development of the field of digital innovation ecosystems, the distribution of core issues and the evolution path of the discipline, and then summarizes the key research themes in the field and analyzes the predictive trend of the future development of the field. The establishment of this research path is not only conducive to the improvement of the theoretical system of digital innovation ecosystems, but also provides a systematic academic reference and practical guidance for the subsequent exploration of this field.

Fig. 2 Knowledge map of keyword co-occurrence in domestic digital innovation ecosystems

This study adopts the knowledge graph analysis method to carry out a metrological study of related literature worldwide with the help of CiteSpace visualization tool. Through in-depth mining of massive literature data, keyword co-occurrence network analysis was conducted systematically, and a knowledge map reflecting the research hotspots of digital innovation ecosystem was drawn. The results of this visualization analysis clearly show the distribution of research topics and their intrinsic connection, which provides an important reference for grasping the development dynamics of the discipline. The research data show that the graph generated by the WoS database contains 198 keyword nodes, forming 873 associated lines, with a network density of 0.0448 (shown in Figure 3). The size of the nodes in the graph is positively correlated with the frequency of keyword occurrence, and the node color gradually changes from the center to the periphery, reflecting the temporal distribution characteristics of the research topic - the darker the color of the periphery, the more relevant research is concentrated in the recent past. This visualization result contrasts with the analysis results of CNKI domestic database, which intuitively demonstrates the hotspot distribution and evolution trend of international research.

Fig. 3 Knowledge map of keyword co-occurrence in foreign digital innovation ecosystems



Through the above comparative analysis, it is found that domestic scholars pay more attention to the keywords of ecosystem, digitization, value deduction, digital technology, etc., while the keywords of competition, model, artificial intelligence, information technology, etc., are widely paid attention to and discussed by foreign scholars. The study shows that although there are significant differences in the research focus of domestic and foreign academics in the field of digital innovation ecosystem, the core issues are centered on the two basic dimensions of “digital innovation” and “ecosystem”. Specifically, domestic research focuses more on the practical application of the theory, while international academics tend to explore the key technological elements that support digital innovation ecosystems. This difference in research orientation reflects the diversity of research perspectives in different academic contexts, as well as the richness and multidimensionality of research content in this field.

3.2 Keyword clustering analysis

Keyword clustering analysis is an effective method to reveal the knowledge structure and developmental lineage of the research field. In this study, the LLR algorithm in CiteSpace software is used to cluster the literature data, and the distribution characteristics of the research topics are presented through visual mapping. The clustering effect is mainly evaluated based on two quantitative indexes: module value (Q value) and profile value (S value). When the Q-value exceeds 0.3, it indicates that the clustering structure is statistically significant; the S-value is greater than 0.5 means that the clustering results are reasonable, and if it exceeds 0.7, it indicates that the clustering credibility is high. This method can help researchers accurately grasp the dynamics of the development of the discipline and identify the current research hotspots and frontier directions.

The keyword clustering time series mapping of the literature on supply chain digital transformation from China Knowledge and WOS databases are shown in Figures 4 and 5.

Fig. 4 Timeline mapping of keyword clustering in domestic digital innovation ecosystems

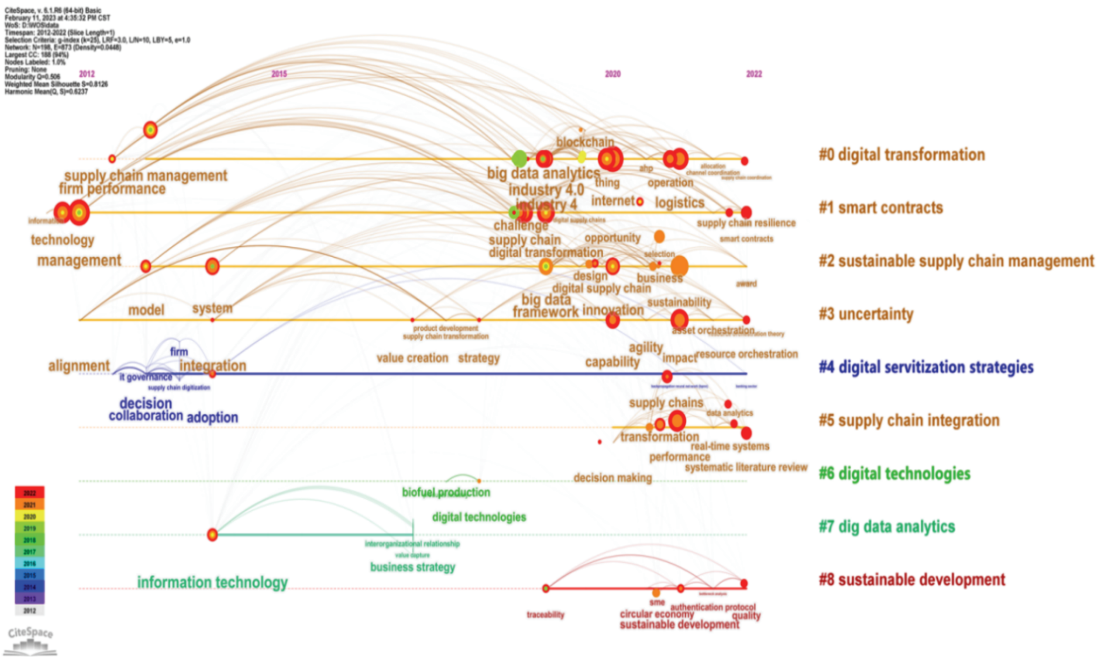
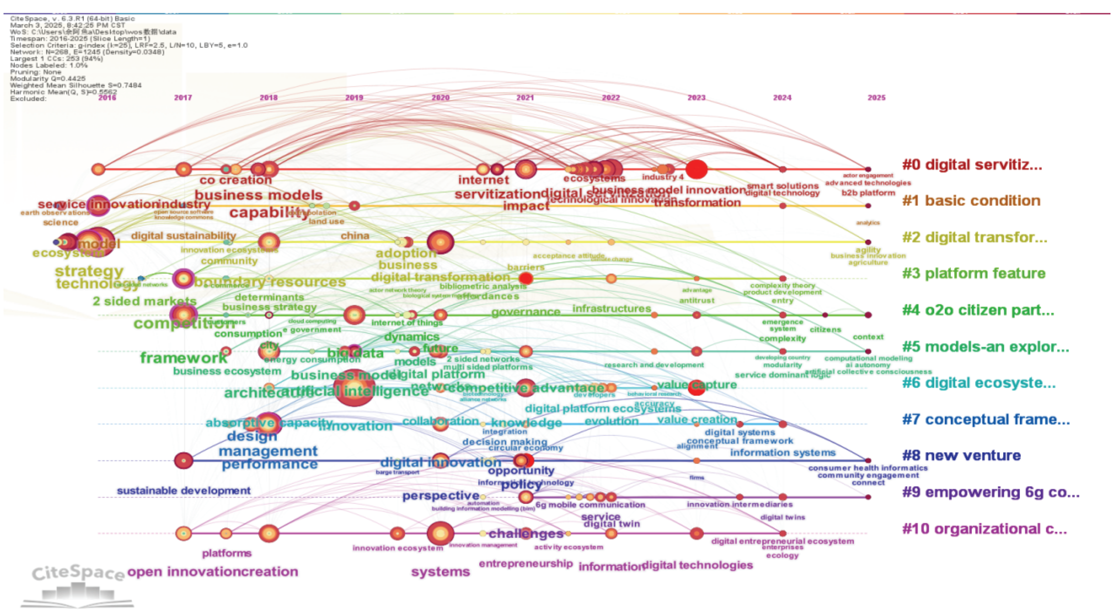


Fig. 5 Timeline mapping of keyword clustering in foreign digital innovation ecosystems



The results of the cluster analysis of the two major databases show (as shown in Figs. 4 and 5) that the knowledge structure of the research field of digital innovation ecosystems presents a high degree of credibility. Specifically, the modular value (Q-value) of the China Knowledge Network (CNN) literature sample is 0.5738, and the profile value (S-value) reaches 0.9626; in contrast, the Q-value and S-value of the Web of Science database are 0.506 and 0.8126, respectively.These quantitative indexes are all over the threshold standards set by the CiteSpace tool, which indicates that the results of the clustering analysis have a high degree of reliability and validity.

From Figure 4, Chinese literature research mainly emerged in 2018, and before 2018, research on digital innovation ecosystem aspects in China is still in a blank stage. Domestic literature mainly focuses on the content of five themes, including digital economy (#0), ecosystem (#1), value co-creation (#2), digital innovation (#3), digital technology (#4), and complementors (#5). Among them, Digital Economy (#0) has been the hotspot of domestic scholars' research from 2018-2025, the application of Digital Innovation (#3) in supply chain has been deeply concerned by scholars since 2019, and Ecosystem (#1) and Value Co-creation (#2) have been gradually incorporated into scholars' research in 2019 2020, respectively.

From Figure 5 , English literature research has been covered since 2016. Its keywords have been classified into 10 categories: digital servitization (#0), basic condition (#1), digital transformation (#2), platform feature (#3), o2o citizen partment (#4), and so on. Among them, basic condition（#1）、platform feature（#3）have been concerned by foreign scholars from 2012-2022, digital servitization（#0）、digital transformation（#2）、o2o citizen partment（#4）have entered the research scope of scholars from 2017, and have been focused on by foreign scholars. digital servitization (#0), basic condition (#1), digital transformation (#2), and new venture (#8) have received more attention from foreign scholars in the recent years have received more attention from foreign scholars and become the research hotspot in recent years.

The keyword clustering information of digital innovation ecosystems in China Knowledge Network and WoS database literature is shown in Table 4 and Table 5, respectively.

Table 4 Keyword clustering information of literature in digital innovation ecosystems China Knowledge Network database

serial number	Size	S-value	particular year	LLR clustering keywords (partial)
#0	32	0.996	2020	Digital economy, digitization, application scenarios, cloud services, paperless, digital middleware
#1	13	0.869	2021	Ecosystems, continuous improvement, sustainable procurement, Green New Deal, strategic transformation
#2	11	0.932	2021	Value co-creation, manufacturing, whole industry chain, value chain, innovation chain, double cycle
#3	9	0.972	2020	Digital Innovation, Blockchain, Cloud Computing, Artificial Intelligence, Internet of Things, Big Data
#4	7	0.993	2021	Digital technology, cloud manufacturing, real-time monitoring, online monitoring, smart factory, intelligence
#5	6	0.968	2020	Complementarities, industrial economy, diffusion of innovations, level of modernization, synergistic operations

Table 5 Keyword clustering information for the digital innovation ecosystem WoS database literature

serial number	Size	S-value	particular year	LLR clustering categories
#0	31	0.753	2019	digital servitization
#1	29	0.760	2018	basic condition
#2	27	0.643	2018	digital transformation
#3	22	0.768	2021	platform feature
#4	20	0.989	2021	o2o citizen partment
#5	18	0.808	2021	Models-an explorer
#6	12	0.986	2018	digital ecosystem
#7	10	0.950	2016	Conceptual framework
#8	10	0.875	2017	New venture
#9	7	0.915	2021	Empowering 6g condition
#10	6	0.672	2017	Organization

Data analysis shows (see Tables 4 and 5) that the average contour value S of all subclusters exceeds 0.5, indicating that the results of cluster analysis are reliable and representative. By comparing the clustering characteristics of the Chinese and English literature, it can be found that despite the differences in the research perspectives of domestic and international scholars on digital innovation ecosystems, they all focus on the core topic of digital transformation and technological innovation in the context of the digital economy. The research data further reveal that the international research in this field started earlier, while the domestic related research is mainly concentrated after 2018, and the research hotspots show an obvious chronological evolution characteristic.

4.Analysis of research frameworks for digital innovation ecosystems

4.1 Connotation of digital innovation ecosystem and related theoretical foundations

Digital innovation ecosystem refers to a dynamic evolutionary system driven by digital technology and jointly constructed by multiple subjects (enterprises, universities, research institutions, governments, users, etc.) through open collaboration, resource sharing, value co-creation, etc., aiming at realizing digital technological innovation, application, and diffusion, and ultimately promoting high-quality economic and social development [14]. In the theoretical exploration of digital innovation ecosystem, scholars have put forward insightful views from different perspectives. Some researchers have focused on exploring the technology-driven factors, such as Ren Rongrong, who pointed out that the emerging information technology represented by cloud computing and big data constitutes the core driving force of the system development, which promotes the in-depth fusion and innovative application of technologies [15]. At the same time, Regel and other scholars draw on the theory of ecology to regard digital innovation as a complex system with the participation of multiple subjects, focusing on analyzing the synergistic mechanism and evolutionary law among the participating elements [16]. From the perspective of research scope, the field has formed a relatively complete research framework, and foreign scholars represented by Camila mainly focus on the core issues such as the basic theory of the system, structural characteristics, development laws and governance strategies [17]. Domestic scholars, Shi Jiaining, focus more on the construction path, policy support, and case studies of digital innovation ecosystems in the Chinese context [18]. To summarize, scholars' research on digital innovation ecosystem covers many aspects such as system concept, development and evolution law, and role mechanism, which lays a solid foundation for subsequent research.

4.2 Analysis of research themes in digital innovation ecosystems

Systematically exploring the core issues of digital innovation ecosystem not only helps to grasp the current research dynamics, but also provides a basis for predicting the future development direction. Based on the results of keyword co-occurrence analysis, combined with the literature review, it is found that the research in this field mainly focuses on the following dimensions: the reasons and evolution mechanism of digital innovation ecosystems, the evolution strategy and path selection of digital innovation ecosystems, and the evolution results of digital innovation ecosystems.

4.2.1 Evolutionary mechanisms of digital innovation ecosystems

The dynamic development of the digital innovation ecosystem is mainly due to the continuous promotion of technological innovation. The disruptive technology clusters represented by cloud computing, artificial intelligence, etc. have continuously broken through the existing technological boundaries, and injected a strong impetus for the evolution of the system through technological integration and collaborative innovation. The iterative upgrading of these emerging technologies not only solves the many limitations under the traditional technological framework, but also opens up new development space and application scenarios for digital innovation [19]. At the same time, the constant changes and upgrading of user needs also drive the continuous evolution of the digital innovation ecosystem. For example, Huy[20] pointed out in his study of the development of China's e-commerce platform that it has driven the transformation of e-commerce platforms from pure commodity trading platforms to comprehensive service platforms, which in turn has led to the evolution of the entire e-commerce ecosystem. Jointly promoting digital technology innovation, application and proliferation [21].Pham[22] stated that when studying the autonomous driving ecosystem, he found that close cooperation between automobile manufacturers, technology companies, universities and research institutes, government departments and other subjects is a key factor in promoting the rapid development and commercial application of autonomous driving technology. Shen[23]believes that the interaction between the subjects within the system will spontaneously form a certain order and structure, and emerge new functions and characteristics. Wang[24] believes that in studying the open source software ecosystem, it is found that the self-organizing mechanism of the open source community and the active participation of community members promote the rapid development and innovation of open source software. In summary, the evolution of the digital innovation ecosystem is a complex and dynamic process that is the result of a variety of factors such as technology, demand, subject, environment, and system. Future research can further focus on the power mechanism, path selection, governance model and other issues of digital innovation ecosystem evolution to provide theoretical support and practical guidance for building a healthy and sustainable digital innovation ecosystem.

4.2.2 Evolution Strategy and Path Selection of Digital Innovation Ecosystems

The evolution of the digital innovation ecosystem requires multiple subjects to collaboratively develop and implement effective strategies to cope with the complex and changing environment and challenges. Scholars at home and abroad have proposed a variety of evolution strategies from different perspectives. First, strengthening the breakthrough of core technology and consolidating the foundation of digital innovation, core technology is the root of the development of digital innovation ecosystem [25]. For example, Li[26] pointed out in her research on the development of the chip industry that strengthening the independent research and development of core technology is the key to breaking the monopoly of foreign technology and building a safe and controllable chip industry ecosystem. The government should encourage the construction of an open, shared, and collaborative digital innovation platform to promote the efficient flow and allocation of innovative resources such as data, technology, and talent. For example, Sun[27] pointed out in his research on the development of industrial Internet platform that building an open and collaborative industrial Internet platform can promote the digital transformation and intelligent upgrading of manufacturing enterprises. The government should encourage enterprises to actively participate in international standardization and technical cooperation, integrate into the global digital innovation network, and enhance the international competitiveness of China's digital innovation ecosystem. For example, Lago[28] pointed out in his study of open source software ecosystems that active participation in the international open source community can enhance the international influence of China's open source software ecosystem.

The path selection of digital innovation ecosystem is a complex and dynamic process, which needs to be considered comprehensively according to its own resource endowment, development stage, external environment and other factors. Oriented by the breakthrough of core technology, it can build a digital technology innovation highland with international competitiveness by increasing R&D investment, introducing high-end talents, and strengthening the cooperation between industries, universities and research institutes. For example, Zhou[29] pointed out in his study of the development experience of Silicon Valley in the United States that the success of Silicon Valley is due to its strong scientific and technological innovation capability and active entrepreneurial atmosphere, which provides useful reference for the construction of China's digital innovation ecosystem. Guided by market demand, we cultivate and grow the digital industry through the development of digital products and services that satisfy users' needs, forming a virtuous cycle of market ecology. For example, when studying the development of China's e-commerce platform, Rong[30] pointed out that the success of e-commerce platforms such as Alibaba is due to its keen market insight and strong user base, which provides important insights for the construction of China's digital innovation ecosystem. With the goal of ecological construction, a symbiotic and co-prosperous digital innovation ecosystem is formed by creating a favorable innovation ecosystem, attracting and cultivating diversified innovation subjects. For example, Huang Shan pointed out in his study of open source software ecosystems that the self-organizing mechanism of open source communities and the active participation of community members are the key to the success of open source software ecosystems [31].

The benign development of the digital innovation ecosystem relies on the collaborative participation and continuous investment of multiple actors. Stakeholders such as governments, enterprises and academic institutions need to form a synergy to promote the innovative breakthroughs and practical applications of digital technologies through the formulation of scientific development strategies, so as to promote the transformation and upgrading of the economy and society. It should be emphasized that due to the differences in the development foundation and resource endowment of each region, the construction path of digital innovation ecosystems should be adapted to local conditions, and a development model suitable for its own characteristics should be explored in practice. Future research can further focus on the evaluation index system, influencing factors, optimization strategy and other issues of digital innovation ecosystem path selection, so as to provide theoretical support and practical guidance for the construction of digital innovation ecosystem.

4.3 Exploring the research frontiers of digital innovation ecosystems

4.3.1 Technological innovation and value creation in digital innovation ecosystems

Technological innovation and value creation in digital innovation ecosystems is a core issue of academic concern, which involves multi-subject synergy, dynamic evolution, and complex network effects.Pohlmann et al[32] first systematically described how digital technologies reshape the innovation process, suggesting that digital technologies not only change the way of value creation, but also redefine the boundaries and structure of innovation ecosystems. This view has been widely supported by subsequent studies, and Shen[33] further pointed out that digital technology can break through the traditional resource limitations and realize more efficient value co-creation by providing a new "empowerment mechanism". It is worth noting that platform enterprises play a key role in the process of technological innovation and value creation. By constructing technological architectures and governance rules, platform enterprises not only promote complementary innovation, but also create new value networks. However, the relationship between technological innovation and value creation is not linear, and Liu[34] proposed the concept of "innovation alignment", emphasizing that technological innovation must be matched with other elements in the ecosystem in order to realize value creation. This viewpoint was further expanded in the study of Hu et al[35], who found that technological innovation often triggers the reconfiguration of ecosystem structure, which in turn affects the pattern of value distribution. In recent years, Ozor[36] pointed out that these technologies not only change the process of value creation, but also redefine the value capture mechanism.

4.3.2 Digital innovation ecosystems and sustainable development

The synergistic evolution of digital innovation ecosystems and sustainable development is the current frontier of innovation research, which centers on how to utilize digital technologies to promote multidimensional sustainable development of economy, society and environment. In recent years, scholars have explored this topic from multiple perspectives, with the most representative research directions including the enabling mechanism of digital technology for sustainable development, the green transformation path of innovation ecosystems, and ecosystem governance under the orientation of the SDGs. Özdemir et al.[37] first systematically elaborated the key role of digital innovation ecosystems in achieving the SDGs, emphasizing that digital technology contribute to sustainable development by improving resource efficiency, promoting circular economy and supporting green innovation. This view is widely supported by subsequent studies, with Sun et al.[38] further stating that digital innovation ecosystems provide new paths to achieve sustainable development by reducing information asymmetry, promoting knowledge sharing and optimizing resource allocation. Notably, platform companies play an important role in promoting sustainable development, Du[39] emphasized that platform companies can significantly enhance the sustainability of ecosystems by setting green standards, promoting sustainable innovation and guiding user behavior. However, the synergy between digital innovation ecosystems and sustainable development also faces a number of challenges, with Chen et al.[40] pointing out that the widespread use of digital technologies may bring about new environmental problems, such as increased e-waste and rising energy consumption. This view was further expanded in the study of Li et al.[41] who found that the rapid expansion of digital innovation ecosystems may exacerbate the digital divide and affect social equity. In recent years, with the deepening of the Sustainable Development Goals (SDGs), scholars have begun to pay attention to the governance of digital innovation ecosystems, and Tonelli et al.[42] suggest that a new governance framework needs to be constructed to balance innovation efficiency with the SDGs.

5.Conclusion

Using bibliometrics and knowledge mapping analysis methods and CiteSpace visualization tools, this study conducted a systematic examination of the research field of digital innovation ecosystem. By comparing and analyzing domestic and international literature, it reveals the theoretical development and research dynamics of the field. The study shows that academics mainly focus on the following core issues: the mechanism of technological innovation and value realization, the law of system evolution, the choice of development mode, and the key issues of sustainability. As the core architect of the ecosystem, platform enterprises promote complementary innovation and optimal allocation of resources through the formulation of technological standards and governance rules, thereby promoting the sustainable development of the ecosystem. However, the evolution of digital innovation ecosystems also faces many challenges, such as technological path dependence, the aggravation of the digital divide, and the pressure on environmental resources, which are in urgent need of further research. In the future, we should focus our research on these points:

I. Deepen the understanding of the enabling mechanism of digital technology and explore the synergistic effect of technological innovation and institutional innovation.

The rapid iteration of digital technology is profoundly changing the organisational form and operation logic of traditional industries, and the study of its enabling mechanism needs to break through the perspective of pure technical efficiency and build an analytical framework driven by both 'technology and system'. On the one hand, technological innovation reduces information asymmetry through the flow and reconfiguration of data elements, giving rise to new industries such as platform economy and shared manufacturing, but the full release of technological potential is often limited by lagging institutional design. For example, the application of blockchain technology in supply chain finance needs to be promoted in tandem with institutional innovations such as the determination of the legal effect of smart contracts and the regulation of cross-border data flows. On the other hand, institutional innovation can provide a stable environment for technology diffusion through mechanisms such as property rights definition, standard setting and incentive compatibility. The practice of China's 'Digital Economy Promotion Regulations' and the EU's 'Digital Market Act' shows that a moderately forward-looking institutional design can guide the development of technology in an inclusive direction. Future research should focus on the match between technological characteristics and institutional flexibility, especially on how AI ethical standards can be synergised with industrial policies, and how to balance the incentives for innovation and risk prevention in the legal system. By constructing a multi-level case base and a simulation model for institutional experiments, the differential impact of different synergy models on total factor productivity can be quantitatively assessed.

II. Strengthen research on the dynamic evolution mechanism of digital innovation ecosystem, especially the interaction of multiple factors such as technology, demand, subject and environment

The non-linear evolutionary characteristics of digital innovation ecosystems require researchers to adopt complex adaptive systems theory to deconstruct the dynamic coupling relationships among the technology supply side, market demand side, multiple subject networks and institutional environment. From the technological dimension, breakthroughs in basic digital technologies (such as 5G and AI big models) will trigger chain innovations in 'technology clusters', but there is a dynamic game between the speed of technological track and the absorption capacity of the industry. Demand-side changes are manifested in the explosive growth of demand for personalised customisation and the rigidity of demand for public digital services, which force enterprises to build flexible innovation networks. At the subject interaction level, heterogeneous subjects such as platform enterprises, 'small giants' with specialised expertise and open source communities form a value network of competition and symbiosis, whose power asymmetry may lead to the risk of ecological niche locking. Environmental disturbances, such as carbon tariffs or geopolitical conflicts, can indirectly change the flow path of innovation resources through supply chain restructuring. It is recommended that a simulation model with positive and negative feedback loops be constructed using a system dynamics approach, focusing on capturing the threshold effects of key elements, such as the emergence of eco-level innovations that may be triggered when the coverage of digital infrastructure exceeds 70 per cent.

III.Expanding cross-cultural and cross-regional comparative research to analyse the development paths and governance models of digital innovation ecosystems under different institutional environments

Global digital innovation practice presents significant institutional diversity characteristics, which requires the establishment of a multidimensional analysis matrix based on a comparative political economy perspective. In free-market dominant economies, digital innovation is mainly led by tech giants and driven by venture capital and patent systems, but is prone to data monopoly and regional innovation polarisation. In the developmental country model, the government is directly involved in digital infrastructure construction through the 'Smart Nation' strategic plan, but it may inhibit the vitality of grassroots innovation. The EU's 'digital sovereignty' strategy shows an attempt to balance normative forces (GDPR) with technological sovereignty (Gaia-X cloud programme). On the cultural dimension, high uncertainty avoidance cultures may slow down the adoption of disruptive technologies, while high individualism cultures are more likely to generate breakthrough innovations. The study suggests using qualitative comparative analysis (QCA) to identify the causal paths between institutional combinations (industrial policy intensity, data governance model, financial support system) and innovation performance, with a special focus on the BRICS countries' experience of "leapfrogging" against the backdrop of the digital divide.

IV.Focus on the synergistic evolution of digital innovation ecosystem and sustainable development, and explore the path of green transformation and governance framework.

The in-depth integration of digital technology and the 'dual-carbon' goal is giving rise to a new paradigm of 'digital green symbiosis'. At the technical level, the Industrial Internet can achieve precise optimisation of the carbon footprint of processes through device-level energy consumption monitoring, but the energy consumption of computing infrastructure constitutes a paradox of 'digital carbon emissions'. In terms of institutional innovation, it is necessary to build a three-dimensional governance toolkit that includes digital carbon accounts, green computing power certification and ESG digital disclosure standards. The case of the 'digital twin wind farm' in the Netherlands shows that digital twin technology can improve the operation and maintenance efficiency of wind turbines by 30 per cent and reduce carbon emissions by 15 per cent at the same time, but this kind of synergy requires supporting reforms of the grid scheduling system and the carbon trading market. In terms of subjective behaviours, digital platform companies need to embed carbon constraints in their algorithms for allocating arithmetic resources, while consumers rely on behavioural economics to facilitate their digital low-carbon choices. It is proposed to establish a Digital-Green Collaboration Index (DGCI) to quantitatively assess the progress of each country in the three dimensions of greening digital infrastructure, digital transformation of industries and digitally-enabled environmental governance, so as to provide a basis for the formulation of differentiated transformation policies. In the future, it will be necessary to focus on breaking through key technological bottlenecks, such as carbon tracking of the entire life cycle of digital products and distributed energy management of edge computing nodes.

The research in this paper not only provides new perspectives for the theoretical study of digital innovation ecosystems, but also provides useful references for policy making and ecosystem governance in practice. With the continuous development of the digital economy, the digital innovation ecosystem will play an increasingly important role globally, and future research should continue to focus on its dynamic evolution and sustainable development to cope with the complex and changing economic and social environment.

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Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Empowering Sustainable and Quality Education via 3D Printing: A Case Study of Kindergarten Environment Creation

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Abstract: This study explores the application of 3D printing technology in preschool curricula with a focus on the Dragon Boat Festival, examining its potential in cultural transmission, cost-effectiveness, and Education for Sustainable Development (ESD). Twenty preschool teachers participated as research subjects. Data were collected through written responses and semi-structured interviews, and based on their feedback, three age-appropriate 3D-printed teaching aids were designed: Zongzi Stamps/Dragon Boat Drawing for younger children, Assembly Dragon Boat for inner groups, and Handmade Small Boat for older groups. Cost analysis revealed that the printing time for each item ranged from 1.5 to 1.7 hours, with material costs below 1 RMB, demonstrating both affordability and feasibility for classroom implementation. Further analysis suggested that the use of recyclable or biodegradable materials could reduce environmental impact while fostering children's awareness of ecological responsibility, thus aligning with the core principles of ESD. Moreover, the study revealed that teachers did not need advanced 3D modeling skills; instead, they could rely on pre-set template selection mechanisms based on teaching themes and difficulty levels. This lowered the technological barrier, enabling teachers to pay greater attention on integrating the printed products into interactive learning activities. Overall, the findings indicate that 3D printing, when combined with artistic education and sustainability principles, not only enhances preschoolers' engagement and promotes their hands-on skills, environmental awareness, and cooperative learning abilities but also provides a practical model for innovation in early childhood education.

Keywords: 3D Printing; Sustainable Development; Environmental Creation in Kindergartens
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1.Introduction

In the current process of global educational development, the United Nations' Sustainable Development Goals (SDGs) have become a crucial reference point for national education policies. Among them, Goal 4: Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all is particularly central, underscoring the pivotal role of quality education in sustainable development. With the sweeping wave of technological innovation worldwide, the integration of 3D printing into the agenda of sustainable quality education has entered the mainstream, gradually permeating primary and secondary school curricula as well as early childhood education environments. More than a technological advancement, 3D printing can be regarded as a vital catalyst for realizing the United Nations' SDG 4 on quality education. In 2019, I conducted a study on environmental design in a kindergarten in Putian City, where I found that creating and arranging educational environments was both highly costly and time-consuming. The emergence of 3D printing technology now offers a promising solution to this challenge. Moreover, the impact of 3D printing on education can be observed on multiple levels, among which its influence on traditional teaching methods and environmental design is the most direct and evident. It disrupts the conventional teacher-centered, textbook-based, one-way knowledge transmission model and instead fosters a new ecosystem characterized by interaction, inquiry, and creativity. Early childhood education, as the starting point of lifelong learning, exerts a profound influence on children's cognitive, emotional, and social development as well as their future learning attitudes (Sylva, Melhuish, Sammons, Siraj-Blatchford & Taggart, 2010). However, how to effectively integrate the concept of sustainable development into the creation of kindergarten environments, and to employ the environment as a form of “hidden curriculum” to cultivate children's sustainability literacy, has become a pressing issue for both academic research and educational practice (Elliott & Davis, 2009). From the perspectives of educational sociology and philosophy of education, the kindergarten environment is not merely a physical space but also a site of cultural reproduction and value transmission (Brooker, 2002). Through consciously designed environments, teachers can guide young children to understand core concepts of sustainable development—such as resource recycling, energy conservation and carbon reduction, and ecological protection—in the course of everyday activities (Davis, 2015).

2.Problem Statement and Research Objectives and Motivations

2.1 Problem Statement

In contemporary kindergarten pedagogy, the construction of learning environments—particularly through the provision of toys and instructional materials—frequently stands in tension with the principles of sustainable development. The manufacturing of such toys typically entails substantial energy consumption, while their design often privileges novelty and marketability over durability and pedagogical value, resulting in markedly shortened life cycles. Moreover, the prevalence of standardized and highly homogeneous teaching aids not only neglects the cultural diversity and developmental heterogeneity of children but also reinforces a paradigm of disposability within early childhood education. This “use-and-discard” logic contributes to the proliferation of non-biodegradable plastic waste, thereby exacerbating environmental pressures. More critically, it conveys to young learners an implicit but problematic value orientation toward consumption, which undermines the early cultivation of ecological consciousness and responsibility that is essential for sustainable education.

2.2 Research Objectives and Motivations

In response to the aforementioned challenges, emerging digital manufacturing technologies provide new opportunities for transformation in educational practice. Three-dimensional (3D) printing, also referred to as additive manufacturing, is characterized by its ability to generate artifacts “from nothing”, with high customization and rapid prototyping capabilities. These features highlight its considerable potential within the educational domain (Trust & Maloy, 2017). The present study is motivated by the need to explore how 3D printing technologies can operationalize the principles of the Sustainable Development Goals (SDGs) within early childhood education settings. We argue that 3D printing should not be regarded merely as a fabrication tool, but rather as an educational medium that integrates design thinking, local culture, and circular economy perspectives. Through concrete case analyses, this paper demonstrates how 3D printing empowers both teachers and young children to collaboratively design and produce toys and educational materials that are environmentally sustainable, pedagogically meaningful, and locally contextualized. In doing so, kindergartens can be transformed into micro-societies for the practice of sustainable development.

3.Literature Review

Since its emergence, 3D printing technology has progressively shifted from industrial applications to educational contexts, attracting increasing scholarly attention. Existing research has predominantly focused on its integration into STEM education, where 3D-printed artifacts—such as molecular structures, geographic terrains, and engineering components—serve to concretize abstract concepts. Scholars generally highlight two distinctive advantages of this technology: rapid prototyping and high levels of customization. Through iterative cycles of design manufacture test revise, students are able to engage in hands-on engineering practices, which in turn enhance conceptual understanding, creativity, and problem-solving abilities.

3.1 The Current Application Situation of 3D Printing Technology in Kindergarten Environment Creation

At present, the overall implementation of 3D printing in the educational system remains at an early stage (Ford & Minshall, 2019). Its applications are diverse but relatively fragmented, lacking systematic curriculum integration and interdisciplinary collaboration (OECD, 2017). The use of 3D printing in teaching has been categorized into six major types (Ford & Minshall, 2019), among which the most relevant to the creation of kindergarten environments include: producing tangible teaching aids that concretize abstract concepts, developing assistive technologies to support special educational needs, and providing technical training for both teachers and students (Ford & Minshall, 2019).

The primary focus of these studies lies in the customization and personalization of teaching aids. The technological potential of 3D printing is reflected in its ability to rapidly and cost-effectively produce customized and complex educational tools (Gershenfeld, 2012). For instance, it can be applied to create tactile teaching materials specifically designed for children with special needs, or to transform abstract curricular concepts—such as anatomical structures or geographical models—into tangible objects, thereby deepening learning experiences (Ford & Minshall, 2019). Secondly, another line of emphasis is the empowerment of maker education. The growing accessibility and affordability of 3D printing contribute to the "democratization of technology" (Gershenfeld, 2012), enabling even kindergartens to establish miniature "Fab Labs". Such environments can foster exploratory learning and embody the spirit of hands-on maker culture.

3.2 How Does 3D Printing Technology Support the Sustainable Development Goals of Kindergarten Education

Relevant literature indicates that, if properly applied, 3D printing technology can support the sustainable development of kindergarten education across three dimensions: resources, supply chains, and product life cycles. From the perspective of global sustainability, studies suggest that the widespread adoption of 3D printing holds the potential, in the medium to long term in 2025, to significantly reduce energy consumption and CO_2emissions in the manufacturing sector (Gebler, Schoot Uiterkampl and Vusser, 2014).

It highlights three major areas. First is the enhancement of resource efficiency: due to its additive manufacturing nature, 3D printing can significantly reduce material waste (Gebler, Schoot Uiterkampl and Vusser, 2014; Khosravani & Reinicke, 2020). In the kindergarten context, this means that teaching aids can be produced with fewer materials or with recyclable and bio-based printing resources, thereby reducing environmental burdens (Shuaib, Haleem and Kumar, 2021). Second, supply chain optimization and carbon footprint reduction: by enabling localized production—such as printing the required items directly within the kindergarten or community—3D printing shortens traditional supply chains and substantially decreases transportation-related carbon emissions. Finally, the extension of product life cycles: the technology facilitates customized designs, rapid prototyping, and on-demand repair, such as directly printing replacement parts for broken teaching aids. This not only prolongs their usability but also minimizes disposal and waste (Gebler, Schoot Uiterkampl and Vusser, 2014).

3.3 What challenges are encountered when applying 3D printing technology in the creation of kindergarten environments?

Although applications of 3D printing in education are increasing, overall implementation remains immature, with many practices still confined to isolated projects rather than being embedded into long-term curriculum design (Ford & Minshall, 2019). The main challenges can be summarized as follows:

1.Cost and efficiency barriers: High-quality and environmentally friendly printing materials remain expensive, while the relatively slow deposition rates limit scalability, making it difficult to meet large-volume and rapid production needs. These constitute major obstacles to broader adoption (Baumers et al., 2016).

2.Insufficient teacher capacity and training: The diffusion of 3D printing requires educators to acquire new skill sets. However, systematic teacher training programs are still largely absent, highlighting the urgent need for professional development initiatives (Ford & Minshall, 2019; OECD, 2017).

3.Potential environmental and safety risks: The sustainability of 3D printing is not inherent; its ecological benefits depend heavily on technological choices and policy interventions (OECD, 2017). Certain processes may consume more energy and emit more carbon than traditional manufacturing (Khosravani & Reinicke, 2020). Moreover, issues such as material toxicity and waste recycling raise important ethical and safety concerns (Shuaib, Haleem and Kumar, 2021).

Nevertheless, current studies reveal an imbalance in research orientations. While the majority of literature emphasizes applications in science and engineering education, relatively few investigations have explored the pedagogical potential of 3D printing in early childhood contexts. This gap is particularly salient given that 3D printing can reduce the cost of producing small-scale, customized educational resources, thereby offering possibilities for creating developmentally appropriate, tailored materials for young children. From this perspective, extending the discussion of 3D printing beyond STEM to early childhood education not only responds to emerging pedagogical demands but also expands the scope of research on educational technologies.

Although substantial progress has been achieved in both domains respectively, integrative investigations that explicitly link 3D printing technology, early childhood education, and sustainable development remain scarce. Most existing studies focus on STEM education in primary and secondary schools, while this study fills the gap by exploring 3D printing's application in cultural-themed early childhood education and its role in ESD practice Existing studies on the educational application of 3D printing have predominantly focused on STEM subjects at the primary and secondary school levels, while its pedagogical potential in kindergarten settings has received limited scholarly attention. Similarly, current research on early childhood education for ESD largely emphasizes curriculum design and nature-based experiences, yet pays insufficient attention to how emerging technologies may fundamentally reshape the material environment to mitigate resource waste. Against this backdrop, the present study addresses this research gap by examining how 3D printing, as both a technological tool and an educational approach, can contribute to sustainable kindergarten environment design, serving as a strategic lever for advancing SDG 4 (Quality Education) and SDG 12 (Responsible Consumption and Production).

4.Research Methods and Design

4.1 Research Methods

In the pilot study, an online questionnaire survey using Questionnaire Star was conducted to understand the cognition and current situation of novice kindergarten teachers' perceptions and current practices of 3D printing in kindergarten environment creation. Based on the feedback data collected from 100 teachers between June and July 2025 (see Table 1 below):

Table1: Understanding of 3D Printers by Kindergarten Teachers

Item	Category	Number	Percentage
Gender	Male	12	12%
	Female	88	88%
Age	20–29 years	100	100%
Years of Teaching Experience	1–3 years	33	33%
	More than 3 years	67	67%
Kindergarten Ownership of 3D Printer	Yes	10	10%
	No	80	80%
	Unclear	10	10%

As for teachers' knowledge and understanding of 3D printers, the specific results are as follows: 8 teachers (8%) have heard of and are very familiar with them; 30 teachers (30%) have heard of and have some understanding; 42 teachers (42%) have heard of but do not understand; and 20 teachers (20%) have never heard of them (see Figure 1). In terms of hands-on experience with 3D printers: 2 teachers (2%) use them frequently; 5 teachers (5%) use them occasionally; 10 teachers (10%) have only tried them once or twice; and 83 teachers (83%) have never used them (see Figure 2).

Figure 1: Familiarity with 3D Printing Technology

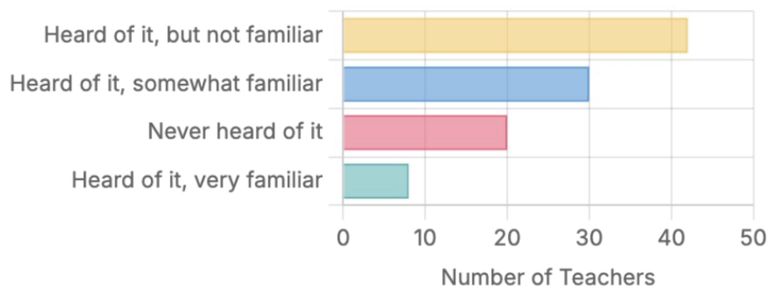
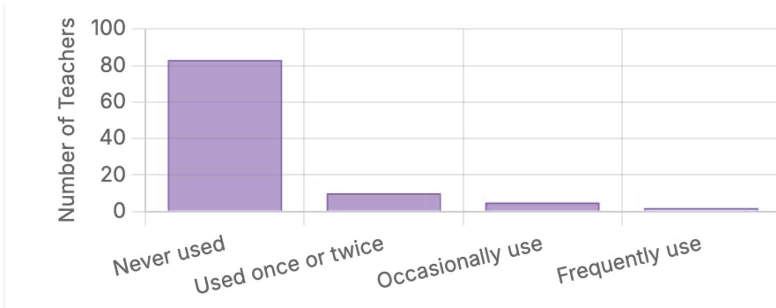


Figure 2: Experience with Operating 3D Printers



According to the survey results in Figures 1 and 2, it is evident that for young teachers aged 20–39, most have limited basic knowledge of 3D printing technology, with even fewer having practical hands-on experience. This study does not focus on training teachers to master complete 3D modeling skills, but rather aims to guide them in flexibly utilizing existing templates and models to enrich the teaching and environmental construction in kindergartens, thereby enhancing innovation and diversity within educational settings.

4.2 Research Design

Given that most teachers still lack the necessary skills and operational limitations in the application of 3D printing technology, this research does not aim to provide a comprehensive teaching of professional skills. Instead, it focuses on guiding teachers to effectively apply 3D printing within the limited technical framework. The research design is based on the traditional Chinese festival - the Dragon Boat Festival, and through contextualized teaching activities and environmental creation, it explores the practical possibilities and educational value of 3D printing in early childhood education.

The question design consists of 11 questions. Apart from the basic information in the first part, the second part, "Cultural Understanding of the Dragon Boat Festival and 3D Printing Application", has four questions, mainly focusing on the subjects' understanding of the symbolic elements of the Dragon Boat Festival and the appropriate application of 3D printing technology. The third part, "Personal Preferences and Future Outlook", contains three questions, aiming to explore the teachers' willingness to participate in DIY activities and their assessment of the challenges that 3D printing may face in the continuation of traditional culture(As detailed in Table 2).

Table 2 :Summary of Questionnaire Content

Part Two	1. Distribution of teachers' familiarity with 3D printing 2. The most frequently selected representative elements of the Dragon Boat Festival 3. What advantages does 3D printing have in creating the environment for the Dragon Boat Festival 4. The most favored 3D printing application projects
Part Three	5. Analysis of the willingness to participate in DIY activities 6. The main challenges perceived by teachers (such as technical barriers, cost, cultural preservation) 7. What possibilities does 3D printing technology have in the inheritance and promotion of Chinese traditional culture in the future

This study involved 20 preschool teachers as the research subjects. The 20 subjects were selected to cover different teaching experience levels (1-3 years vs. >3 years) and familiarity with 3D printing (familiar vs. unfamiliar), ensuring representativeness of the sample. The researchers, in response to the aforementioned research questions, invited the participating teachers to provide their responses. By collecting their responses, the aim was to understand the teachers' comprehension and viewpoints on the topic, and to further analyze the commonalities and differences among them, in order to serve as a reference for subsequent research and educational practice.

5.Research Results

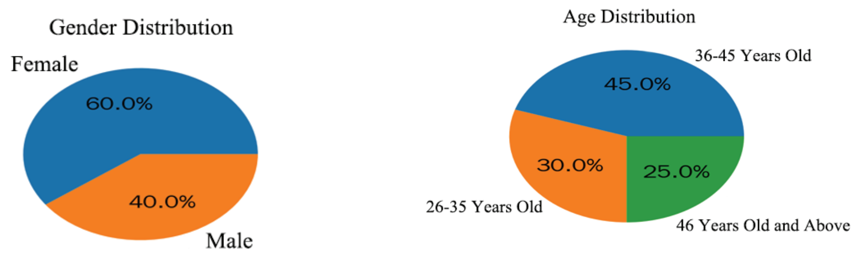
5.1 Gender and Age Distribution

From the data on gender distribution, the number of females is greater than that of males(18:2). This might indicate that within the scope of this survey, women have a higher participation rate in related topics (such as 3D printing and traditional culture-related content), or that the sample selection of this survey has a certain bias in terms of gender ratio. If this is a representative sample, then in the subsequent promotion, product design, or service provision related to these topics, more consideration can be given to the needs and preferences of women.

5.2 Age distribution

In terms of age distribution, the 36 - 45 age group has the largest number, followed by the 26 - 35 age group, and the 46 and above age group has relatively fewer people. This might indicate that the 36 - 45 age group is more concerned about the content related to this survey, possibly because they are in a relatively stable career and life situation, and have more energy and resources to engage with and participate in such topics. The 26 - 35 age group might have a slightly lower participation rate due to reasons such as their career being in an upward phase. The 46 and above age group has the lowest participation rate, which is speculated to be due to factors such as a relatively lower acceptance of new technologies (such as 3D printing) (as shown in Figure 3).

Figure 3: Proportion of Teachers by Gender and Age



5.3 Distribution of Interest in DIY Activities

From this statistical result, it can be inferred that 19 teachers have a positive attitude towards DIY activities, while only 1 teacher shows no interest. This might indicate that DIY activities have a high appeal in this group, possibly because they can satisfy people's creativity, sense of achievement, or social needs, etc. For the organizations or businesses that organize DIY activities, they can fully utilize this high level of interest to promote related activities or products. Additionally, through the questionnaire data, it was learned that they consider the dragon boat and zongzi as the most representative items of the Dragon Boat Festival. The advantage of 3D printing lies in its convenience and low cost. If 3D printing can be applied to other areas in the future, most teachers are also willing to try it.

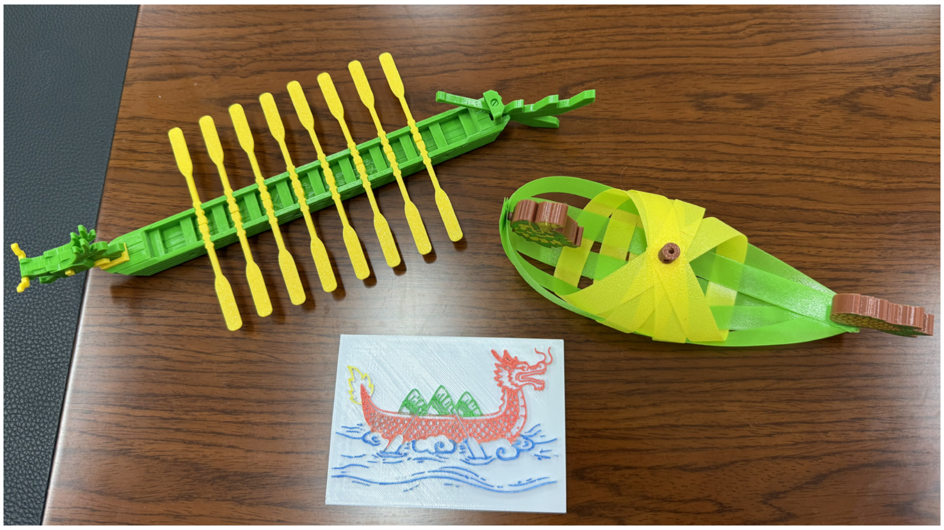
5.4 3D Printing and Sustainable Development

Since most teachers consider the dragon boat and the zongzi as the representative symbols of the Dragon Boat Festival, the researchers designed and developed 3D-printed toys related to these. Considering the operational abilities and cognitive development of children at different age stages, this study planned three different levels of 3D-printed designs(as shown in Figure 4):

1. Low difficulty: Presenting the elements of zongzi or dragon boat in simplified geometric shapes, suitable for younger children to trace or operate.

2. Medium difficulty: Incorporating movable or assembleable parts, encouraging middle-class children to develop spatial concepts and hand-eye coordination during the operation.
3. High difficulty: Designing a more intricate dragon boat model that can be assembled in multiple steps, suitable for older children to challenge and emphasizing the learning process of cooperative construction.

Figure 4: Products related to the Dragon Boat Festival



To further explore the feasibility and sustainability of 3D printed teaching materials in the theme teaching of the Dragon Boat Festival, this study estimated the costs and time required for the 3D printed toys designed for different age groups. Considering the printing time and material costs, the researchers summarized the data as shown in Table 3 below, providing a reference for the teaching site when planning the teaching materials.

Table 3: Printing Costs

	Younger Class	**Middle Class**	**Senior Class**
Toy Name	Zongzi Stamp / Dragon Boat Drawing	Assembly Dragon Boat	Handmade Assembly Small Boat
Printing Time(hr)	1.5 / 1.7	1.5	1.7
Material Cost	0.4	0.42	0.48

Note: Material cost is calculated based on biodegradable PLA filament (unit price: 50 yuan/kg), with each toy consuming ~8-10g of filament; printing time is tested with a FDM 3D printer (print speed: 60mm/s)

As can be seen from Table 3, 3D printed toys maintain a low to medium level in terms of material cost and printing time, indicating that such teaching materials have practical operability in the classroom. Taking the "Zongzi Stamp/ Dragon Boat Painting" in small classes as an example, the printing time is approximately 1.5 - 1.7 hours, and the material cost is only 0.92 - 0.40 yuan. Moreover, the zongzi stamps can be produced in groups of four, further reducing the unit cost and demonstrating high cost-effectiveness.

In the middle and senior class teaching materials section, the printing time for "Assembling the Dragon Boat" and "Handmade Assembly of a Small Boat" is 1.5 hours and 1.7 hours respectively, with costs of 0.42 yuan and 0.48 yuan respectively. Although the printing time is slightly longer, since they are assembly-type toys, they can simultaneously promote children's fine motor skills and cooperative learning. Therefore, in terms of educational value, they have a higher return on investment.

Furthermore, if the consumables used in 3D printing can be selected from recyclable or biodegradable materials, it will better align with the core spirit of sustainable development. In other words, the design of this study not only provides cultural-themed teaching aids at a low cost, but also incorporates environmental education into daily teaching through the selection of sustainable materials, achieving the dual goals of "cultural inheritance" and "environmental sustainability".

5.5 Discussion

As the manufacturing industry continues to face pressure to minimize its environmental impact, the energy consumption associated with the 3D printing process is receiving close attention. Although traditional manufacturing typically involves a large amount of material waste and high energy input, 3D printing or additive manufacturing offers a unique opportunity to solve these problems (Shuaib, Haleem and Kumar, 2021). However, can this innovative technology become more environmentally friendly and how can it be promoted to kindergartens? For kindergartens, optimizing print parameters (e.g., reducing infill density to 20% for non-load-bearing toys) or using solar-powered 3D printers could further reduce energy consumption, which deserves further exploration in future research.

This article takes the Dragon Boat Festival as the theme for environmental creation, designs toys suitable for different age groups using 3D printing technology, and analyzes them from the perspectives of cost and sustainable development. In terms of the meaning of sustainable development, the use of recyclable or biodegradable materials for consumables not only reduces environmental burden but also integrates environmental education into children's cultural learning. This makes teaching aids not only fulfill the function of "cultural inheritance" but also embody the value of ESD.

Although the application of 3D printing technology in early childhood education scenarios has significant potential, for kindergarten teachers, the complexity of technical operation, design threshold, and compatibility for teaching integration pose difficulties in practical implementation. This study uses existing resources, where teachers do not need to possess professional 3D modeling knowledge, but only need to select appropriate templates through a preset screening mechanism (such as grading by teaching theme and operational difficulty) to quickly start the printing process. This model not only reduces the time investment of teachers in technical learning and design but also allows them to focus more on how to integrate the printed products into environmental creation. In other words, the application of 3D printing in the Dragon Boat Festival courses in kindergartens does not transform the role of teachers into "technical operators", but strengthens their core functions of "teaching designer" and "learning guide". In summary, this study shows that the combination of 3D printing technology and the Dragon Boat Festival cultural theme can not only support early childhood cultural education with low cost and high flexibility, but also achieve the triple value of cultural inheritance, environmental education, and teaching practice through sustainable materials and low-tech operation modes.

6.Conclusions and Recommendations

This research focuses on the Dragon Boat Festival and designs teaching aids suitable for different age groups using 3D printing technology. It also discusses the design from perspectives of cost-effectiveness, sustainable development, and teaching application. The research results show that this design is not only low-cost and highly feasible, but also can achieve a balance between cultural inheritance and environmental education. At the same time, it reduces the operational threshold for teachers and enhances the possibility of teaching innovation. In the future, further research samples and cultural contexts can be expanded, and the actual teaching effectiveness can be evaluated to verify the applicability and long-term impact of 3D printing textbooks in various courses, thereby promoting the integrated development of early childhood education in culture, technology, and sustainability.

In terms of suggestions, for kindergartens willing to adopt 3D printing: 1) Start with low-cost FDM 3D printers and biodegradable PLA materials to control initial investment; 2) Establish a "3D printing template library" for traditional festivals (e.g., Mid-Autumn Festival, Spring Festival) to reduce teachers' design burden; 3) Integrate 3D printing activities into weekly cultural courses (e.g., 1-2 hours per week) to ensure continuity of teaching practice.

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Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Study on the Influence of "New Retail" Mode on Financial Performance of Yonghui Supermarket

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Abstract: In the new wave of retail industry reform, the dual challenges of constrained growth in offline physical stores and the gradual fading of online dividend have forced retail enterprises to accelerate their transformation. Both online retailers and physical supermarkets have realized that in order to maintain the company's long-term sustainable development, it is necessary to achieve a seamless connection between the company's online and physical businesses, and use the latest technologies such as big data to provide customers with targeted products and services, improve the customer shopping experience, achieve better operational results, and continuously improve performance. The inevitability of transformation is obvious, but how to integrate it into the overall work is a problem faced by most retail enterprises. As a leader in China's retail industry, Yonghui Supermarket has played a pioneering role in the new retail transformation.

This paper takes Yonghui Supermarket as a research sample and comprehensively uses literature research and case analysis methods to construct a multi-dimensional framework to evaluate the effect of new retail transformation. Firstly, the connotation of new retail theory is traced, and the core theory of enterprise performance evaluation is sorted out. Secondly, through the cross-analysis of financial indicators, non-financial indicators and economic added value (EVA) model, the transformation effect is quantitatively evaluated. Finally, the research concludes that Yonghui Supermarket's profitability fluctuated during the transformation of new retail, the expansion of brand awareness in non-financial performance fell short of expectations, and the comprehensive evaluation based on the EVA model showed that the EVA value of Yonghui Supermarket from 2018 to 2022 showed a trend of fluctuating first and then deteriorating significantly.

Through a series of analyses of the case, this paper intends to put forward several application suggestions for other companies facing transformation: first, optimize capital allocation and structure; second, deepen supply chain integration and cost control; third, differentiate online business positioning and implement precise marketing; fourth, optimize store layout and business format innovation.

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1.Indroducation

With the upgrading of consumption and technological innovation, the retail industry is undergoing profound changes. traditional physical retail is limited by high rents, high labor costs and e-commerce impacts, and the growth is weak; Online retail is also facing growth bottlenecks due to the fading of traffic dividends and intensified homogeneous competition. In this context, the “new retail” model has become the core direction of the transformation of the retail industry by integrating online and offline channels, using big data and artificial intelligence technology to reconstruct the relationship between “people, goods and fields”. China’s State Council further accelerated this trend with its Opinions on Promoting Innovation and Transformation in Brick-and-mortar Retail in 2016.

Under the new economic norms and highly Internet-based forms of human society, traditional retail enterprises should take advantage of current new technologies and combine them with logistics to create new businesses. Retail enterprises should take the initiative to update their business models and combine the advantages of online and offline in order to have the possibility of sustainable development. As a leading enterprise in the field of fresh retail in China, Yonghui Supermarket has taken the lead in exploring new retail transformation since 2015, and its development path is typical. On the one hand, Yonghui has carried out business innovation through “super species” and “warehousing stores”, and cooperated with JD.com and Tencent to carry out omni-channel integration and supply chain optimization, realizing business model upgrades; On the other hand, the financial risks exposed during its transformation also reflect the general challenges of the new retail model.

Therefore, this paper takes Yonghui Supermarket as the research object to evaluate the financial performance of its transformation to a new retail model, analyze the factors affecting financial performance and put forward suggestions to improve financial performance, which has certain reference value for the future development of Yonghui Supermarket and even the retail industry and enhances its competitiveness, and can also provide practical reference for similar enterprises.

2.Current situation research

2.1 New retail-related research

Some scholars have conducted research on relevant aspects of new retail, elaborating on the background, connotation, and development trends of the new retail model, and have published related literature.

At the level of new retail business models, Zhang Jianjun pointed out through trend analysis that in the context of the digital era, it is difficult for a single retail channel to meet market demands, and the collaborative integration of online and offline resources is becoming the inevitable direction of industry development[1]. Wang Zhengpei proposed from the perspective of development logic that the evolution path of the new retail model presents significant problem-oriented characteristics - to solve the shortcomings of traditional retail experience as a breakthrough, relying on technological innovation to form a dual driving mechanism of service upgrading and value appreciation[2]. At the level of business model innovation, Wang Xuhui systematically explained the ecological characteristics of new retail, believing that it breaks through the boundaries of traditional retail and builds an integrated business ecology that integrates omni-channel services, smart logistics networks, financial technology support and scenario-based social networking[3]. The classical analysis framework proposed by Osterwalder and Pigneu is more operational, and its nine-element model covers key modules such as value proposition design, customer relationship management, and core resource integration, providing a systematic tool for business model innovation[4]. Qi Yan’s research conclusions further added that in the innovation practice of retail enterprises, technology iteration constitutes the basic support for transformation, and the reconstruction of value network needs to be realized through specific means such as channel optimization, business focus and deepening of customer relationships[5]. In terms of the development trend of new retail, Hao Shujun innovatively proposed from the perspective of brand marketing that digital technology empowerment makes product personalization strategies possible, which can effectively strengthen consumers’ sense of brand belonging and stimulate the transformation of consumer behavior by giving products anthropomorphic characteristics[6]. Wen Yuxuan warned of potential risks in the expansion of new retail, pointing out that although the asset-light operation model can quickly expand the market, the imbalance of capital structure caused by high leverage may exacerbate financing constraints, which in turn affects the stability and long-term competitiveness of the supply chain[7].

2.2 Research on financial performance

In the evolution of financial performance evaluation theory, Tallal and Jared emphasize that corporate performance evaluation needs to comprehensively consider financial and non-financial dimensions, and relying solely on monetization indicators will lead to one-sided decision-making basis[8]. Sun Haiying argued from the perspective of scientific evaluation that financial performance, as the core yardstick of enterprise value measurement, directly affects the effectiveness of corporate governance decisions[9]. In terms of evaluation method innovation, Stewart's economic value added (EVA) model is a milestone. This indicator breaks through the limitations of traditional accounting profit and ignoring the cost of equity capital through the full-caliber accounting of net operating profit and cost of capital, and realizes the accurate measurement of shareholders' value creation ability. Fan Jinjuan and Guo Hui's latest research suggests that a composite evaluation framework should be constructed including traditional financial indicators, EVA value analysis and DuPont decomposition model, and the robustness of conclusions should be improved through multi-dimensional cross-verification[10]. In the study of the influencing factors of financial performance, Xue Qiao pointed out that the executive equity incentive mechanism can optimize the efficiency of R&D resource allocation and ultimately drive the growth of enterprise value by alleviating agency conflicts in R&D investment[11]. In view of the heterogeneity characteristics of enterprises, Tang Wenxiu's comparative research found that compared with enterprises dominated by state-owned capital, private enterprises have more advantages in R&D input-output efficiency, and the intensity of product market competition will positively adjust the promotion effect of R&D investment on financial performance[12]. Wang Xinhong warned of capital structure risks, and his research shows that a high proportion of equity pledges by major shareholders will exacerbate agency problems and significantly weaken company performance, and a sound internal control mechanism can form effective checks and balances on this[13].

2.3 Literature review

From the perspective of research methodology, the academic research on the transformation effect of new retail mostly uses cross-enterprise panel data to carry out large-sample quantitative analysis, and its conclusions generally verify the positive effect of this model on enterprise performance, indicating that the business indicators after transformation show a significant optimization trend compared with the baseline level. Based on the complexity and multifaceted nature of the new retail model in China's localization practice, although the digital transformation of the retail industry has continued to deepen in recent years, the longitudinal tracking research on the evolution of performance before and after the transformation of specific enterprises is still insufficient. The purpose of this study is to quantitatively evaluate the impact of the implementation of the new retail strategy on the value creation of Yonghui enterprises, find out the problems of financial performance under the new retail model and give specific improvement measures, enrich the research on the financial performance of Yonghui Supermarket's new retail transformation, and put forward transformation and optimization measures to adapt to China's retail ecology, so as to provide methodological and empirical reference for subsequent research.

3.Introduction to Yonghui Superstores' New Retail Model Transformation

3.1 Overview of Yonghui Supermarket

3.1.1 Company profile and main business

Founded in 1995, Yonghui Supermarket Co., Ltd. (hereinafter referred to as "Yonghui Supermarket") is a benchmarking comprehensive enterprise in China's retail industry. Its business network covers a variety of commodity categories such as fresh food, household daily necessities and consumer electronics, relying on the supply chain advantages and brand accumulation formed by deep cultivation in the past 30 years, and firmly ranks in the leading camp of domestic chain supermarkets. Adhering to the concept of "customer value first", the company continues to consolidate its market competitiveness through business innovation such as warehousing member stores and community fresh food stores and intelligent shopping scene service upgrades. The implementation of the differentiation strategy has enabled it to break through in the Red Sea competition, and in 2022, it will continue to rank among the top 100 Chinese chains with a revenue scale of more than 100 billion yuan, and the consumer satisfaction index will reach the industry-leading level.

In terms of Yonghui Supermarket's main business by industry, the retail industry accounts for the vast majority, specifically about 93.38%; In terms of products, fresh food and processing accounted for about 47.43%, nearly half, which fully reflects the distinctive characteristics of Yonghui Supermarket based on fresh commodity management. Combined with the gross profit margin indicators, it can be seen that although the gross profit margin of fresh food retail is relatively low, due to its rigid demand, it will attract a large number of regular customers to consume here, and drive the sales of other products with this volume, see Table 3-1 below.

Table 3-1 Yonghui Supermarket's main business by industry in 2022 (unit: 100 million yuan)

Industry						
Retail	841.28	720.66	11.34	-0.98	-2.07	0.96
services	59.63	2.95	95.05	-2.32	-32.67	2.22
Fresh and processed	399.00	349.31	12.45	-2.27	-3.47	1.09
Food supplies	442.28	371.34	16.04	0.22	-0.72	0.79

Source: Yonghui Superstores' 2022 Annual Report

3.1.2 Industry Position and Development Journey

Yonghui Supermarket was founded in 2001. Starting with its first store in Fujian, it gradually expanded and grew into the remarkable scale of thousands of stores today. Its development journey can be divided into the following stages:

（1）Initial stage（1995-2001）：The supermarket transformation model of traditional farm markets laid the foundation.

In the 1990s, China's consumption structure underwent accelerated upgrading, with a continuous decline in the Engel coefficient driving innovation in retail formats. At that time, traditional farm markets faced a crisis of trust due to issues such as management disorder and lack of quality control over goods. In 1995, Zhang XuanSong keenly identified policy trends and opened the first "Gule Weili Supermarket" in Fuzhou, initiating the practice of transforming traditional farm markets into supermarkets. In 1998, the brand was upgraded to "Yonghui Superstores," establishing a foundation for differentiated competition through standardized operations and a direct fresh produce procurement model.

（2）Expansion Phase（2001-2016）：Fresh Product Strategy Driving National Layout

Facing competitive pressure from foreign giants like Walmart, Yonghui focused on the high-frequency, essential nature of the fresh product category to build a supply chain moat. In 2001, Fuzhou Yonghui Supermarket Co., Ltd. was established, implementing a strategy of "regional consolidation followed by inter-provincial replication."This phase unfolded in several key steps:Regional Penetration: Starting with its initial entry into the Chongqing market in 2004, Yonghui added over 20 new stores within five years.Capital Boost: Its 2010 IPO on the A-share market, which raised 4.18 billion RMB, accelerated expansion into first-tier cities (Beijing, Shanghai, Guangzhou, Shenzhen) and central/western regions.Model Replication: Through mergers, acquisitions, and integration, Yonghui achieved standardized, cross-regional replication of its fresh product supply chain. By 2016, the number of stores surpassed 500.During this phase, Yonghui established its industry position as the "Fresh Food Champion," leveraging its core capability of maintaining a fresh product loss rate 50% lower than the industry average.

（3）Transition period（2016-2024）：New Retail Ecosystem Restructuring

In response to consumption upgrades and e-commerce competition, Yonghui launched its "Four-Cloud Strategy" (Yunchuang, Yunshang, Yunchao, Yunjin). Through business model innovations such as the "Super Species" and membership-based warehouse stores, online sales accounted for 14.3% of total revenue by 2022. Partnerships with JD.com and Tencent enabled smart supply chain enhancements and technological empowerment, reducing inventory turnover days to 28. By the end of 2022, Yonghui operated 1,033 stores nationwide, generating over 91 billion RMB in revenue and ranking fourth among China's Top 100 Chain Retailers, achieving significant economies of scale.

3.2 Transformation Outcomes of Yonghui Supermarket's New Retail Model

3.2.1 A store closure wave surges at Yonghui Superstores, as explorations of new business models falter

Yonghui Supermarkets' new retail transformation has yielded mixed results amid fierce industry competition. While the company successfully expanded its online sales contribution to 14.3% by 2022 and reduced inventory turnover days to 28 through technological partnerships, its store network underwent significant contraction. After peaking at 1,440 stores in 2019, the company closed 407 locations over the next three years, leaving 1,033 stores by 2022. Several much-hyped new formats failed to gain traction: the premium "Super Species" concept shrank from 88 stores to just 6 locations; the community-focused Yonghui Mini stores reported losses of 130 million yuan in 2021; and the non-membership warehouse format, limited by its conversion from existing hypermarkets, saw only 55 renovations with no further expansion, criticized for lacking inherent "warehouse DNA." This contrast between digital progress and physical retrenchment highlights the challenges traditional retailers face in balancing innovation with sustainable growth.

3.2.2 Yonghui Yunchuang, the new retail division established in 2015, consistently reported losses, with its equity divestment further impeding development.

Yonghui Yunchuang, the new retail division established in 2015, consistently reported losses, with its equity divestment further impeding development. Its "Yonghui Life" format integrated convenience store features, fresh produce, and online operations but struggled with external competition and internal inefficiencies, accumulating 1.32 billion yuan in losses from 2016 to 2018 and becoming a financial burden. Due to strategic differences, the founding Zhang brothers split the business in 2018, with Yonghui Superstores transferring 20% of Yunchuang's equity to Zhang Xuanning. Although the parent company repurchased the stake two years later, Yunchuang's performance remained dismal—generating merely 475 million yuan in revenue against 379 million yuan in losses in 2021. Repeated equity transfers failed to resolve the issue, ultimately leaving the listed entity to bear the losses and dragging down overall performance.

3.2.3 Yonghui Yunshang's core business spiraled out of control, with its subsidiary Caishixian becoming insolvent.

The core central kitchen operations of Caishixian under the Yunshang division faced similar challenges. Yonghui's subsidiary, Shangshu Yonghui, underwent bankruptcy liquidation in 2020, while Caishixian was insolvent during the same period. Although it received a capital injection of 1 billion yuan from Tencent and other investors to alleviate financial pressure, the low gross margin of the fresh food business necessitated reliance on external funding. In 2019, Yonghui lost control over Caishixian, leading to its exclusion from the consolidated financial statements. That year, Caishixian reported revenue of 3.194 billion yuan with a loss of 370 million yuan. By 2022, Yonghui recognized an investment loss of 1.08 billion yuan from Caishixian under the equity method.

3.2.4 Yonghui Yunjin faced business contraction amid frequent compliance issues

In 2019, Yonghui Cloud Finance, despite holding a financial license, faced obstacles in business development: its enterprise financial product "Hui Shangchao" was criticized for non-standard user information collection and opaque loan terms; its consumer finance product "Xiao Hui Dai" encountered the chaos of third-party collection even after repayment, which led to user complaints. Such compliance issues led to a decline in the trust of Cloud Finance's business. Coupled with intensified industry competition, the overall business showed a contracting trend and failed to effectively support the construction of Yonghui's ecological closed loop.

4.Financial Performance Evaluation of New Retail Transformation

4.1 Financial Performance Analysis Based on Financial Indicators

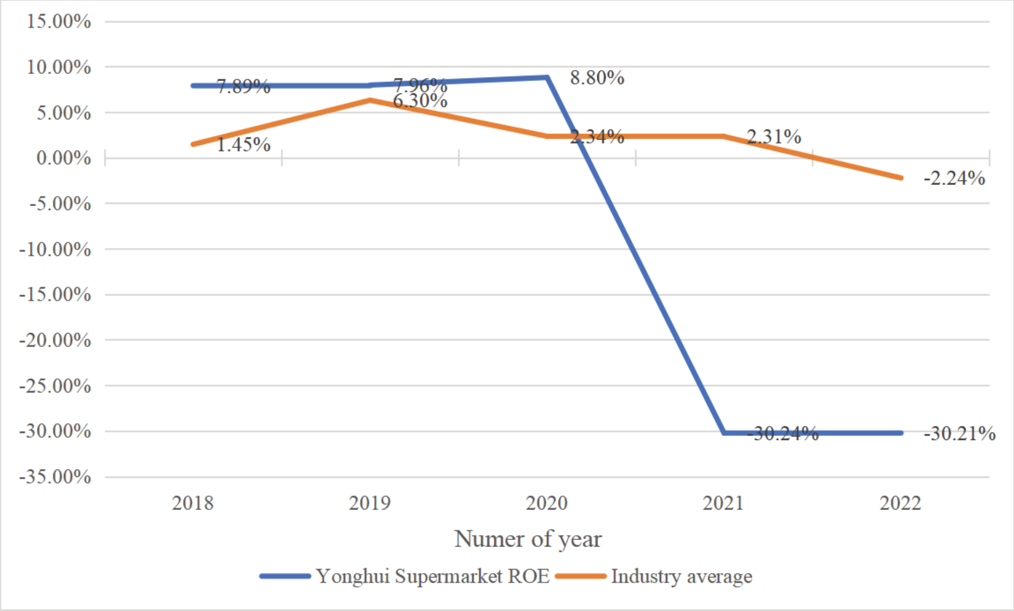
This article includes return on equity and total asset turnover under the financial performance category, using Yonghui Superstores' financial data from 2018 to 2022 as a basis to conduct financial performance evaluation and analysis from the perspectives of profitability, operational capability, debt-paying ability, and development capability.

4.1.1 Profitability Analysis

For traditional retail enterprises, under the dual pressures of overall industry slowdown and rising labor costs, achieving high profitability has become the core goal of their new retail transformation. A critical evaluation metric in this transformation process is ROE (Return on Equity), which comprehensively reflects the company's profitability.

Data source: Guotai An Database

Figure 4-1: Chart of Return on Equity for Yonghui Superstores and Industry Average from 2018 to 2022



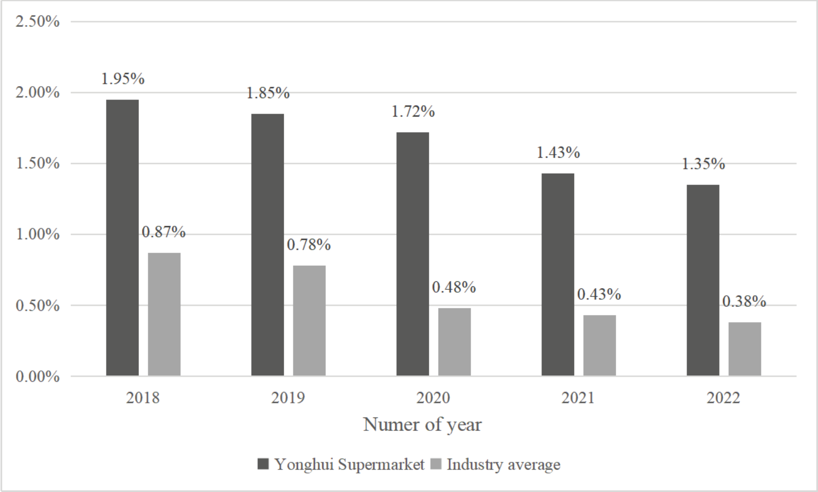
As shown in Figure 4-1, from 2018 to 2020, Yonghui Supermarket's ROE showed a steady upward trend, particularly achieving slight growth during the pandemic period from 2019 to 2020, contrary to the overall downward trend in the retail industry. This was mainly due to the vigorous expansion of community-based businesses represented by Yonghui Mini Stores. However, from 2020 to 2022, Yonghui's ROE exhibited a sharp decline and remained consistently below the industry average, falling to -30.21% in 2022. Overall, considering the industry as a whole, Yonghui's ROE showed a continuous downward trend, indicating that its new retail transformation failed to provide sustained support for improving ROE and instead became a drag on the company's development. It is worth noting that after 2021, Yonghui Supermarket vigorously promoted its self-developed YHDOS system. By 2022, the infrastructure for large-scale investment, including the data middle platform, was basically established. Relying on the YHDOS system, Yonghui Supermarket was able to curb continued losses to some extent, but the overall situation remains far from optimistic.

4.1.2 Operating Capacity Analysis

Total asset turnover is a key indicator for assessing a company's asset management efficiency and operational capability. The turnover of current assets directly reflects the speed of asset circulation and the activity level of sales. An increase in turnover speed often implies enhanced profitability and the ability to convert investment returns.

Data source: Guotai An Database

Table 4-2 Changes in Total Asset Turnover of Yonghui Superstores and Industry Average from 2018- 2022

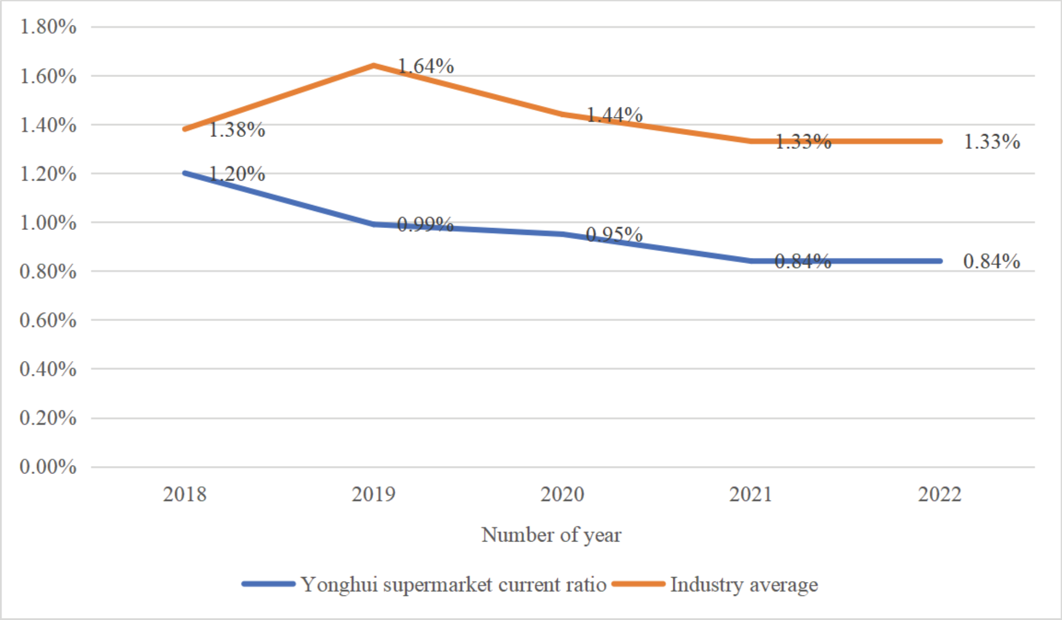


According to Figure 4-2, from 2018 to 2022, Yonghui Superstores' total asset turnover continuously declined, highlighting challenges in its asset management efficiency. This phenomenon mainly stems from the company's structural adjustments and the advancement of innovation strategies, such as large-scale physical store expansion and the development of new business segments. Although these investments aim to expand the market, they have partially resulted in diluted customer density, thereby lowering asset turnover. How to optimize asset utilization efficiency and balance expansion scale with returns has become an urgent operational challenge for Yonghui Superstores.

4.2.3 Solvency Analysis

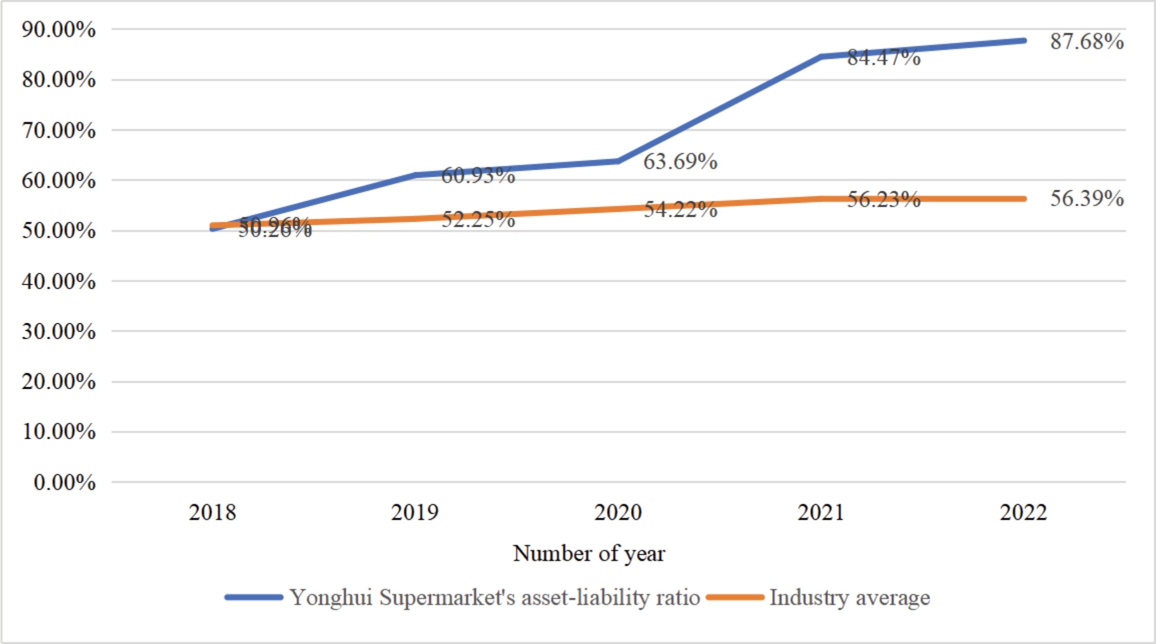
Data source: Guotai An Database

Figure 4-3 Changes in Yonghui Supermarket's Short-term Solvency and Average Values from 2018 to 2022



Data source: Guotai An Database

Figure 4-4 Changes in Solvency of Yonghui Superstores and the Industry Average from 2018 - 2022



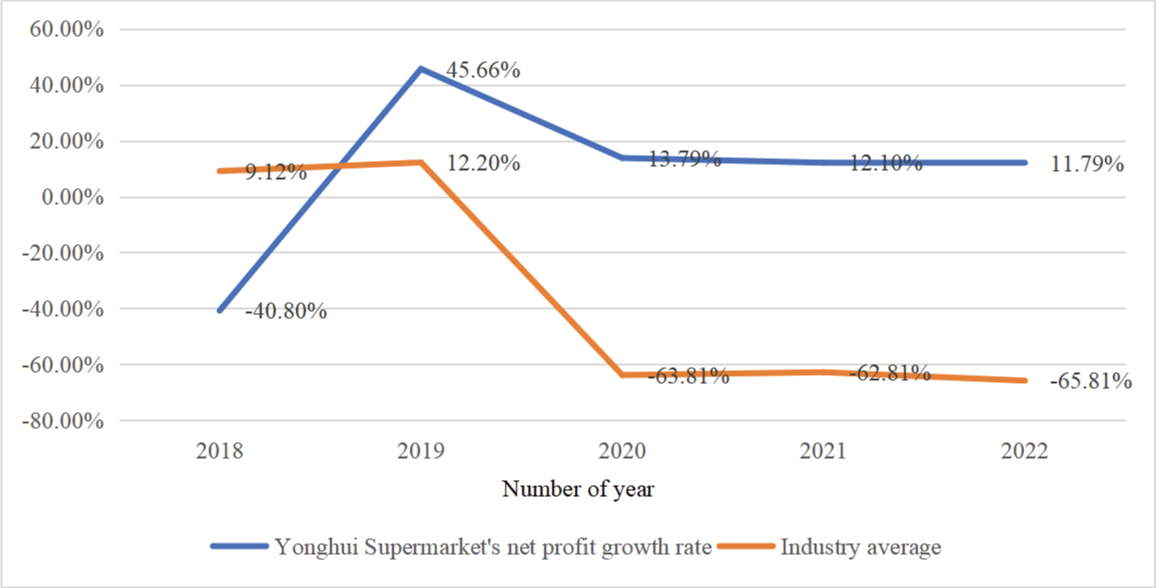
Figures 4-3 and 4-4 present Yonghui Supermarket's post-transformation debt repayment indicators, including the current ratio and debt-to-asset ratio. The current ratio measures short-term debt-paying ability, while the debt-to-asset ratio reflects long-term debt repayment stability. The data show that Yonghui's debt-to-asset ratio is higher than the industry average, whereas its current ratio remains below the industry standard. This situation may be related to the advancement of the new retail strategy: inventory management delays lead to a reduction in current assets, while scale expansion accompanied by increased purchase frequency may slow down the payment cycle to suppliers. Although overall debt has risen, the growth of current liabilities directly lowers the current ratio, weakening short-term debt flexibility. Therefore, optimizing liquidity management under the new retail model has become key for Yonghui to improve its short-term debt-paying ability.

4.2.4 Development Capability Analysis

In terms of measuring the development capability of Yonghui Superstores, this paper starts from two indicators: total asset growth rate and net profit growth rate, and conducts comparative analysis in conjunction with the industry averages of each indicator. Among them, the total asset growth rate represents the changes in the growth of a company's total assets and can be used to measure the company's expected development potential and overall stability.

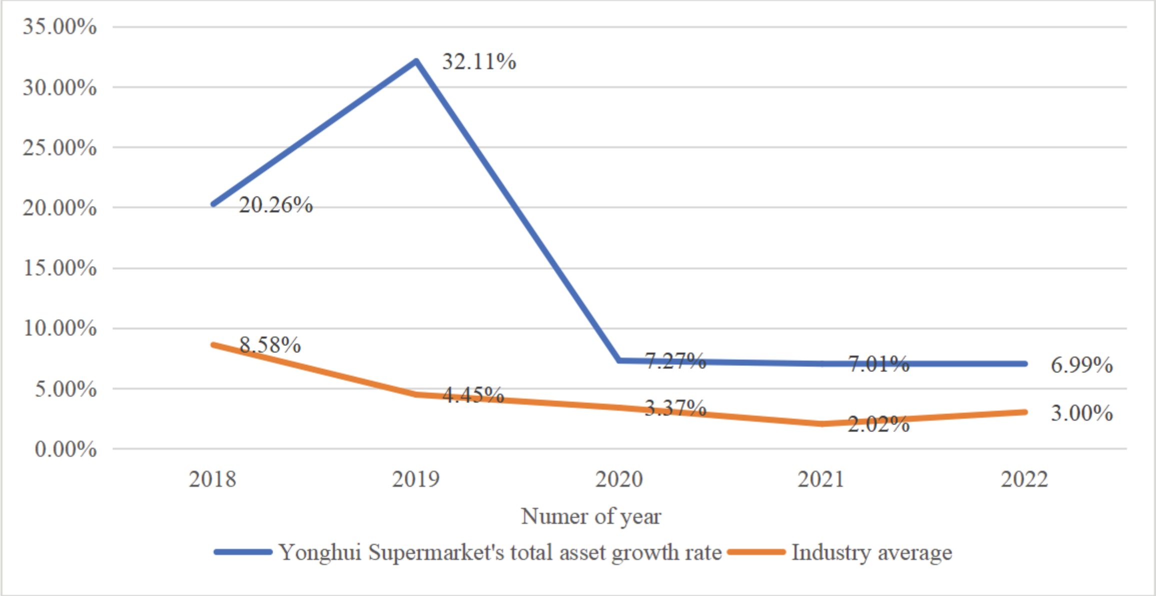
Data source: Guotai An Database

Figure 4-5 Changes in Net Profit Growth Rate of Yonghui Superstores and Industry Average, 2018-2022



Data source: Guotai An Database

Figure 4-6 Changes in Total Asset Growth Rate of Yonghui Superstores and Industry Average, 2018-2022



As can be seen from Figures 4-5 and 4-6, Yonghui Superstores' total asset growth rate in 2018 was significantly higher than the industry average, but the gap with the industry gradually narrowed in the following years, reflecting a gradual weakening of its total asset growth momentum. Net profit growth rate, as an important indicator of a company's value expansion and development capacity, was affected by the overall shift of the industry from positive to negative and frequent store closures after the 2020 pandemic. Although Yonghui was impacted, it still maintained positive net profit growth from 2020 to 2022, maintaining an expansion trend. Overall, although Yonghui's development speed has slowed, it still shows a certain positive growth trend compared to the industry average.

4.2 Analysis of Non-Financial Performance Based on Non-Financial Indicators

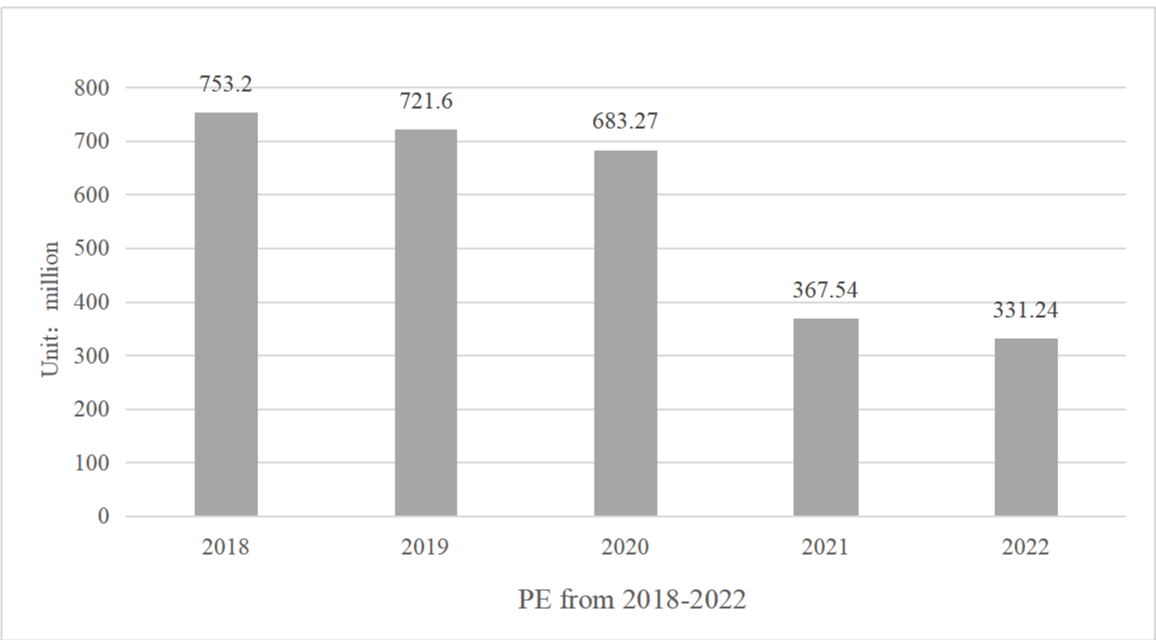
Based on Yonghui Supermarket's new retail model, this paper incorporates brand awareness, category sales proportion, and gross profit ratio into the non-financial performance dimension for enterprise performance analysis.

4.2.1 Brand awareness

Brand awareness reflects the extent to which consumers are aware of a brand and, to some extent, indicates a company's industry status and competitiveness. Since customer awareness is difficult to quantify directly, here we use Yonghui Superstores' market value (PE) as a reference indicator.

Data source: Guotai An Database

Figure 4-7 Yonghui Superstores 2018-2022 Market Value (PE) Change Chart

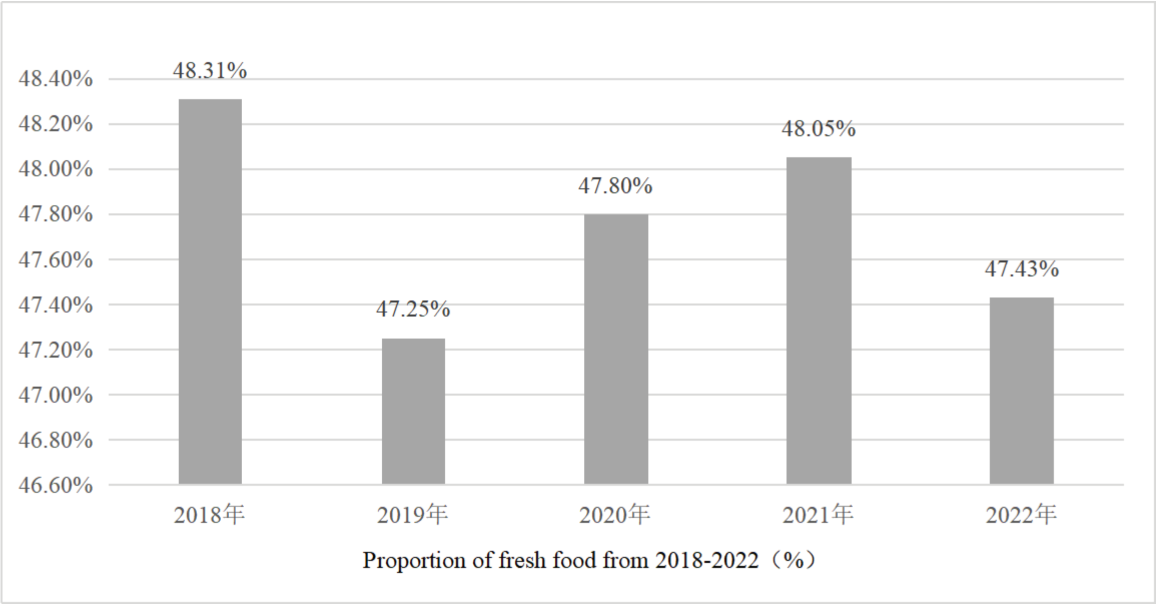


From the trend of the data in Figure 4-7, Yonghui Superstores experienced a significant decline in market value between 2018 and 2022, with its market value dropping sharply from 75.32 billion yuan in 2018 to 33.124 billion yuan in 2022, nearly halving. There are two main core factors behind this phenomenon. First, the store expansion strategy did not achieve the expected goals. In 2022, the operational data of Yonghui Superstores' Bravo stores showed that 36 new stores were opened throughout the year, while 60 stores were closed, and only 10 new store agreements were signed. The frequent store closures and lagging store expansion not only triggered negative market expectations regarding its stock price but also severely constrained the continuous expansion of the brand's market influence and were unfavorable to improving consumer brand awareness. Second, growth in customer traffic encountered bottlenecks. Yonghui Superstores initially relied on fresh food categories as the core means to attract customers, driving sales growth in other categories. However, with the rise of e-commerce platforms, community group buying, and other emerging retail models, its target customers were largely diverted. Weak growth in customer traffic directly led to fewer brand exposure opportunities, which in turn caused a decline in consumer brand awareness of Yonghui Superstores, ultimately negatively affecting its market value performance.

4.2.2 Store Operations Status

Category sales proportion is an important indicator for assessing the inventory structure and rationality of purchasing in a store. Enterprises can use this data to optimize their product mix and accurately position their key products, thereby enhancing overall sales efficiency. Taking Yonghui Superstores, which focuses on fresh produce as its core business, as an example, the fresh produce category holds a strategic central position in its business structure. The following analysis is based on the proportion of fresh produce in its retail business over the past five years.

Figure 4-8 Change in the Proportion of Fresh Produce at Yonghui Supermarket from 2018 to 2022



Yonghui Supermarkets' main business is comprised of two major segments: food products and fresh produce. According to the data shown in Figure 4-8, in 2022, revenues from food products and fresh produce reached 39.9 billion yuan and 44.2 billion yuan respectively, with fresh produce consistently accounting for 47%-49% of the total. The operation of fresh produce has distinct characteristics: it involves a wide and dispersed variety of products, low standardization, high spoilage rates, strict requirements for turnover efficiency, and comparatively lower profit margins than other supermarket categories. For offline supermarkets, customer traffic is fundamental to sales conversion, which is why locations are often concentrated in densely populated areas. Fresh produce, with its high-frequency consumption nature, serves as a core traffic driver. In China, daily demand for fresh produce is robust, and frequent purchasing habits make it a traffic engine for both physical stores and e-commerce platforms. Moreover, fresh produce can guide consumer movement within stores, stimulating 'impulse buying' behaviors, thereby indirectly increasing the average transaction value.

Table 4-1 Gross Profit Margin by Product Category of Yonghui Supermarket, 2018-2022

Project Proportion（%）	**2018**	**2019**	**2020**	**2021**	**2022**
Fresh produce	14.86	13.22	13.84	11.36	12.5
Food products	19.23	18.72	18.60	15.25	16.4

Data source: Guotai An Database

In terms of the gross profit margin performance of fresh products, although the pandemic had a certain impact, causing a slight decline in gross profit margins, fresh products, as essential daily necessities during the pandemic, allowed Yonghui Superstores' supply advantages in fresh products to be fully highlighted. From 2021 to 2022, although the sales of Yonghui Superstores' fresh products fell by 2.2%, their gross profit margin grew by 1.14% contrary to the trend. At the same time, sales of food products increased by 1.15%. This data indicates that the fresh product business and food business are showing coordinated growth, further confirming that Yonghui Superstores' business model, characterized by fresh products, effectively drives traffic and promotes overall business development, demonstrating that its business structure is reasonable.

4.3 Comprehensive Evaluation of Financial Performance Based on the EVA Model

EVA is a metric used to measure a company's performance. It can reflect the achievement of the company's current operational goals and also allow managers to make scientific and rational forecasts about the company's future development. Economic Value Added (EVA) is an indicator for evaluating business performance. If EVA is positive, it indicates that the company has created new value; if it is negative, the opposite is true.The EVA calculation formula is as follows：

Economic Value Added = Net Operating Profit After Taxes - Total Invested Capital × Weighted Average Cost of Capital

Among them,

Among them, Net operating profit after tax = Sales - Operating expenses - Related taxes; Total invested capital = Interest-bearing debt + Cost of equity

Weighted average cost of capital = Cost of debt × (Debt / Total capital) × (1 - Tax rate) + Cost of equity × (Equity / Total capital)

4.3.1 EVA Calculation Adjustment Item

Based on adjustments made by domestic and international companies when applying the EVA theory and considering the uniqueness of the industry in which Yonghui Supermarket operates, the accounting adjustments for calculating EVA under the new retail business model, following the principles of materiality priority, controllability, data availability, and industry applicability, are specifically as follows:

（1）Asset Impairment Adjustment: Under the new retail model, Yonghui Supermarket's inventory and receivables increase with sales growth. Asset impairment losses need to be included in the EVA adjustments to proactively manage potential asset loss risks.

（2）Non-operating Income and Expenditure Adjustment: Non-operating income such as government subsidies should be excluded, as such short-term policy support does not reflect core operating capabilities and should be deducted from EVA calculations.

（3）Construction in Progress Adjustment: Traditional accounting treats construction in progress as an asset, but under the new retail model, newly added stores under construction have not yet generated actual benefits, and thus should be excluded from assets in the adjustments.

（4）Deferred Income Tax Adjustment: When calculating EVA, it should be based on current income tax, with deferred tax liabilities added back and deferred tax assets deducted, focusing on the impact on current cash flow.

4.3.2 Calculation of Net Operating Profit After Taxes and Capital Cost

After-tax Net Operating Profit (NOPAT) = Operating Profit - Income Tax Expense + (Interest Expense + Asset Impairment Loss + Development Expenditure) × (1 - Corporate Income Tax Rate) + Increase in Deferred Tax Liabilities - Increase in Deferred Tax Assets.

Table 4-2 Net Operating Profit After Taxes from 2018 to 2022 (Unit: 100 million yuan)

Year	2018	2019	2020	2021	2022
Operating Profit	12.64	16.40	22.85	-48.28	-32.98
Income tax expense	4.52	3.24	5.21	-2.27	-2.19
Including:Interest expenses	1.48	3.51	2.23	15.52	15.38
Asset impairment losses	0.69				
Development expenditures					0.11
Increase in deferred tax Liabilities	0.82	1.55	3.35	-4.44	-0.47
Increase in Deferred Tax Assets	0.37	2.18	0.52	5.63	2.20
Income Tax Rate (%)	25	25	25	25	25
Net operating profit after tax	10.19	15.16	22.14	-44.43	-21.84

Data source: Calculated and compiled from the CSMAR database

As shown in Table 4-2, the after-tax operating profit from 2018 to 2022 was positive, with the highest being 2.214 billion yuan in 2020. Factor analysis revealed that the after-tax operating profit in 2021 was negative mainly due to an increase in operating costs. The company's R&D investment in 2021 increased by 428 million yuan compared to 2020. In terms of technology investment and platform development, the company continued to increase investment in 2022.

According to Yonghui's annual report and the EVA adjustment principles, the formula used in this paper to calculate total capital is: Total Capital = Total Shareholders' Equity + Asset Impairment Provisions − Impairment Provisions for Construction in Progress − Net Construction in Progress + Deferred Tax Liabilities − Deferred Tax Assets + Short-term Borrowings + Trading Financial Liabilities + Non-current Liabilities Due Within One Year + Long-term Borrowings + Bonds Payable + Long-term Payables.

Table 4-3 Total Assets Calculation Table from 2018 to 2022 (Unit: 100 million yuan)

Year	2018	2019	2020	2021	2022
Total Equity	204.08	194.32	204.54	203.93	110.77
Net amount of construction in progress	4.23	2.92	1.74	1.94	4.1
Deferred tax liabilities	0.45	1.27	2.82	6.17	1.73
Deferred tax assets	1.65	2.03	4.21	4.73	10.36
Short-term loan		36.9	108.13	138.9	109.48
Non-current liabilities due within one year					20.7
Long-term loan					10.21
Total assets	198.65	227.54	309.54	342.33	238.42
Debt-to-capital ratio	0.00%	16.22%	34.93%	40.57%	58.88%
Equity capital ratio	100.00%	83.78%	65.07%	59.43%	41.12%

Data source: Guotai An Database

4.3.3 Calculate the weighted average cost of capital

Weighted Average Cost of Capital = Cost of Debt × (Debt / Total Capital) × (1 - Tax Rate) + Cost of Equity × (Equity / Total Capital)

Debt capital = short-term loans + long-term loans + non-current liabilities due within one year + long-term loans + bonds payable + long-term payables；

Equity capital = Total capital - Debt capital

The first step is to calculate the cost of debt capital. For simplicity, this article takes the cost of debt capital for Yonghui Superstores by choosing the benchmark one-year bank loan interest rate.

The second step requires calculating the cost of equity capital for Yonghui Superstores. This article uses the Capital Asset Pricing Model (CAPM) to calculate it: $Re = Rf + \beta \times (Rm - Rf)$, where: Re is the cost of equity capital; Rm is the expected return of the asset portfolio; Rf is the risk-free market rate; Rm − Rf is the risk premium of the asset portfolio; and β is the market risk coefficient of the investment. The risk-free interest rate is chosen as the benchmark one-year bank deposit rate; the risk premium is based on China's GDP growth rate; and the risk factor is taken as the beta value weighted by the market capitalization over 250 trading days. The calculation results are shown below.

Table 4-4 Cost of Equity Capital Calculation Table

Year	2018	2019	2020	2021	2022
Risk-free interest rate	1.50%	1.50%	1.50%	1.50%	1.50%
Risk factor	1.32	0.99	0.77	0.62	0.62
Market risk premium	6.90%	6.60%	6.10%	2.30%	8.10%
Cost of Equity Capital	10.61%	8.03%	6.20%	2.93%	6.52%
Cost of debt capital	4.35%	4.35%	4.35%	4.35%	4.35%

Data source: Guotai An Database

Table 4-5 Table of Weighted Average Cost of Capital

Year	2018	2019	2020	2021	2022
Debt-to-capital ratio	0.00%	16.22%	34.93%	40.57%	58.88%
Equity capital ratio	100.00%	83.78%	65.07%	59.43%	41.12%
Cost of debt capital	4.35%	4.35%	4.35%	4.35%	4.35%
Cost of Equity Capital	10.61%	8.03%	6.20%	2.93%	6.52%
Weighted Average Cost of Capital (WACC)	10.61%	7.44%	5.55%	3.50%	5.24%

Data source: Guotai An Database

4.3.4 Calculate the EVA value of Yonghui Superstores

By calculating the after-tax net profit, total investment cost, and weighted average cost of capital as mentioned earlier, we now apply the EVA calculation formula to obtain the EVA values of Yonghui Superstores for the years 2018-2022. The results are shown in the table below:

Table 4-6 EVA Values from 2018 to 2022 (Unit: 100 Million Yuan)

Year	2018	2019	2020	2021	2022
Net operating profit after tax	15.60	10.19	15.16	22.14	-44.43
Total Investment at the End of the Period	198.65	227.54	309.54	342.33	238.43
Weighted Average Cost of Capital	10.61%	7.44%	5.55%	3.50%	5.24%
EVA value	-5.47	-6.73	-2.02	10.15	-56.93

Data source: Obtained through compilation and calculation from the Guotai An database

From Table 4-6, it can be observed that the EVA values of Yonghui Superstores from 2018 to 2022 show an overall trend of initially fluctuating and then significantly deteriorating. In 2018-2019, EVA remained negative and the negative value expanded, mainly due to the impact of e-commerce on traditional supermarkets, low gross margins in fresh food, and cost increases from store expansion, coupled with relatively high weighted average cost of capital. In 2020, due to the essential demand for fresh food during the pandemic, growth in online business, and cost control measures, the losses narrowed. In 2021, with the maturity of the online-offline integration model, the emergence of economies of scale, and a reduction in capital costs, EVA turned positive for the first time. In 2022, affected by the recurrence of the pandemic, a surge in cost pressures, and a sharp increase in asset impairment losses, EVA plummeted to -56.93, indicating significant value destruction. This change is closely related to the particular characteristics of the industry in which Yonghui operates: the fresh food sector is characterized by low margins, high wastage, and continuous investment demands due to the transformation to new retail, which, combined with the challenges of a capital-intensive business model, leads to considerable fluctuations in value creation capability. Overall, however, since implementing new retail strategies, Yonghui has shown overall positive progress, and its innovation and layout in business formats are sustainable. In the future, by optimizing capital allocation, integrating the supply chain, differentiating online business positioning, and optimizing capital structure, the company can seek a balance between efficiency improvement and risk control to achieve sustainable value creation.

5.Research Conclusions and Recommendations

5.1 Research conclusion

Yonghui Superstores' transformation to a new retail model has, to some extent, propelled the company's development but also exposed many issues affecting its performance. Specifically:

In terms of financial performance, the company's profitability showed a fluctuating trend of rising first and then falling. From 2018 to 2020, Yonghui Superstores steadily increased its return on equity (ROE) through measures such as community business expansion, even achieving growth against the trend during the pandemic. However, after 2020, due to various factors, ROE sharply declined and remained below the industry average, falling to -30.21% in 2022, indicating that the new retail transformation failed to provide sustained support for ROE.

In terms of non-financial performance, brand awareness was affected by slower-than-expected store expansion and bottlenecks in customer traffic growth. Market value dropped sharply from 75.32 billion yuan in 2018 to 33.124 billion yuan in 2022, nearly halving, and consumer brand recognition showed a declining trend. Regarding product category sales share, fresh produce consistently accounted for 47%-49% of total sales. While it drove overall business growth through its traffic-attracting effect and maintained a reasonable business structure, the high spoilage and low-margin characteristics of the fresh produce category remained, with its gross margin fluctuating slightly due to the pandemic and other factors.

Based on a comprehensive evaluation using the EVA model, Yonghui Superstores' EVA from 2018 to 2022 generally fluctuated initially and then deteriorated sharply. From 2018 to 2019, under competitive pressure from traditional supermarkets, the characteristics of the fresh produce business, and high capital costs, EVA remained negative and the negative values expanded. In 2020, due to the essential demand for fresh produce during the pandemic, enhanced online business, and cost control, losses narrowed. In 2021, the maturity of the online-offline integration model, scale effects, and lower capital costs resulted in EVA turning positive for the first time. In 2022, repeated pandemics, surging cost pressures, and a sudden increase in asset impairment losses caused EVA to plummet to -56.93, leading to substantial value destruction. This change is closely related to the low-margin and high-spoilage nature of the fresh produce sector, the continuous investment pressure from the new retail transformation, and capital structure issues under the company's heavy-asset model.

5.2 Suggestion

5.2.1 Optimizing Capital Allocation and Structure

Focus on core businesses and high-margin categories, reduce investments in inefficient stores and loss-making new business formats, and concentrate resources on fresh produce core business and high-margin proprietary brand products to improve capital efficiency. By optimizing the product mix, increase the sales proportion of high-margin categories to enhance profitability. Optimize the capital structure by reasonably adjusting the debt-to-equity ratio to reduce financial risks caused by high leverage. Financing channels can be broadened through equity financing and asset securitization to lower debt costs, extend debt maturities to match the return cycle of new retail investments, and improve corporate credit ratings to secure more favorable financing conditions.

5.2.2 Deepen supply chain integration and cost control

Strengthen vertical integration of the supply chain, further expand the scope of "direct sourcing from origin," establish long-term strategic alliances with more high-quality suppliers, and build or collaborate in constructing more fresh produce production bases to ensure the quality and stability of fresh products while reducing procurement costs. Optimize the cold chain logistics network, improve warehousing and distribution efficiency, reduce fresh produce loss rates, and consolidate a market position of both competitive pricing and quality. Promote digital supply chain management by utilizing technologies such as big data analysis and the Internet of Things to optimize the entire supply chain, accurately forecast market demand, reasonably control inventory levels, shorten inventory turnover days, and improve asset turnover rate. Achieve efficient data management and enhance operational efficiency through the supply chain management platform.

5.2.3 Differentiated positioning and precise marketing for online business

Clearly define an online business differentiation strategy, avoiding low-price competition with community group buying, and focus on 'premium fresh produce, instant delivery, and scenario-based services.' Provide customized and personalized products and services for mid-to-high-end customers, such as high-end imported fresh produce and specialty meal combinations, to enhance the online business's premium capability and user stickiness. Strengthen user operations and precision marketing by leveraging the technology and traffic advantages of partners like Tencent, deeply analyzing user data, accurately profiling consumers, and formulating personalized marketing strategies. Enhance the membership system through points, coupons, exclusive events, and other methods to increase member repurchase rates and loyalty, while also using social platforms for brand promotion to raise brand awareness and online traffic conversion rates.

5.2.4 Optimize store layout and business format innovation

Plan store layouts rationally, optimizing the number and types of stores based on regional consumer demand and market competition. Close inefficient stores and focus on developing community fresh food stores, warehouse membership stores, and other formats that meet consumers' high-frequency essential needs. Use models such as 'one large store supporting three small stores' to increase store density and service coverage, thereby boosting foot traffic and market share. Proceed with caution in business format innovation; conduct thorough market research and feasibility analysis before launching new business models to avoid blind expansion. Focus on upgrading and optimizing existing formats, such as enhancing the shopping experience in warehouse membership stores, diversifying product offerings, and optimizing SKU structures to strengthen competitiveness and sustainability.

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Research on the Market-Oriented Construction of China's Blue Carbon Value Realisation: Mechanisms, Obstacles, and Pathway Innovations

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Abstract: In recent years, blue carbon has opened up a new frontier for global efforts to address climate change, protect biodiversity, and achieve sustainable development. It is regarded as a strategic resource supporting the implementation of the Paris Agreement and provides an important option for 'Nature-based Solutions'. China possesses abundant blue carbon resources, and the national 'Dual Carbon' strategy has provided significant policy drivers for blue carbon development. However, the development of China's blue carbon market remains in its early stages, characterised by project-based and pilot initiatives, and the market-based realisation of blue carbon value still faces institutional barriers. This study argues that the realisation of blue carbon value is no longer a conceptual idea. Blue carbon possesses comprehensive service value, and its value can be most effectively realised through marketisation. Contemporary technological advancements have created the conditions for blue carbon transactions. The marketisation of blue carbon value requires systematic institutional design, particularly focusing on mechanisms for defining blue carbon property rights, standard certification, transaction operations, and market supervision. Addressing the primary obstacles to the marketisation of blue carbon value in China, this study proposes four pathways: first, strengthening systematic legislation to establish a solid institutional foundation; second, developing a multi-tiered blue carbon market to stimulate market dynamics; third, promoting diversified blue carbon financial innovations to activate blue carbon assets; and fourth, strengthening international technical cooperation to advance the integration of blue carbon production and research. It is hoped that this research will contribute to realising the value of China's blue carbon, while providing more diverse references and recommendations for global climate change mitigation and the achievement of sustainable development goals.
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1.Introduction

The realisation of blue carbon value and innovation in market-based pathways represent critical issues in the current efforts to address climate change, achieve biodiversity conservation, and promote sustainable development. Blue carbon, or ocean carbon sinks, refers to the processes, activities, and mechanisms whereby marine activities and marine organisms absorb carbon dioxide from the atmosphere and sequester it within marine ecosystems (Nellemann et al., 2009; IPCC, 2019)[3][14].

The formal signing of the Paris Agreement in December 2015 marked a milestone in controlling global greenhouse gas emissions. Notably, the Paris Agreement's introduction of Nationally Determined Contributions (NDCs) to replace the Kyoto Protocol's mandatory emissions reduction mechanism has pioneered new compliance pathways for voluntary emissions reductions. Against this backdrop, the value of blue carbon has become increasingly prominent.

According to the 2009 joint report Blue Carbon: The Role of Healthy Oceans in Binding Carbon–A Rapid Response Assessment by UNEP and FAO, marine ecosystems sequester 55% of the world's biological carbon annually. The ocean carbon reservoir holds 20 times more carbon than terrestrial reservoirs and 50 times more than the atmospheric reservoir. Additionally, marine biological carbon capture efficiency is high, with seagrass carbon capture efficiency being approximately 35 times that of tropical rainforests. Blue carbon storage has a long lifespan, potentially lasting thousands of years. Compared to terrestrial green carbon, blue carbon offers greater development advantages and potential. The process of realising blue carbon value provides 'Nature-based Solutions' (NbS) for addressing climate change, achieving biodiversity conservation, and promoting sustainable development. (UNEP, 2021)[15]. Marketisation is the primary pathway for realising the value of blue carbon. Transforming the intrinsic ecological value of blue carbon into measurable and tradable economic value, and allocating it through market-based mechanisms, not only aligns with global carbon emission reductions but also provides additional funding sources for the protection and restoration of global marine ecosystems, while encouraging a broader range of stakeholders to engage in global sustainable development initiatives.

As a signatory to the Paris Agreement, China pledged to the world in 2020 that it would reach peak carbon emissions by 2030 and strive to achieve carbon neutrality by 2060. As the world's largest emitter of carbon dioxide, China faces immense pressure and challenges in meeting these dual carbon reduction targets within the shortest possible timeframe. Implementing stringent emission reduction measures and continuously expanding carbon sink increments are strategic choices that cannot be delayed. China has nearly 300 square kilometres of marine territory and approximately 18,000 kilometres of continental coastline. It is one of the few countries in the world that simultaneously possesses the three major blue carbon ecosystems of mangroves, salt marshes, and seagrass meadows. Its scale of marine aquaculture ranks among the world's leading nations, endowing it with abundant blue carbon resources. Realising the value of blue carbon is a key means for China to secure a proactive position in its future development. Since 2021, the national government has introduced a series of macro policies aimed at achieving carbon peaking and carbon neutrality, and has formulated the 'Implementation Plan for Consolidating and Enhancing Ecosystem Carbon Sink Capacity', placing the enhancement of ecosystem carbon sink capacity within the context of the 'Dual Carbon' strategic needs.

Although China's blue carbon value potential is enormous, the blue carbon market is underdeveloped, the policy and legal framework is incomplete, calculation standards are not unified, and the inability to integrate compliance markets with voluntary markets creates institutional barriers, resulting in blue carbon value being underutilised or even undervalued. Additionally, the marketisation of blue carbon value involves multiple stakeholders and is constrained by various uncertainties and risks related to society, governance, finance, and technology, all of which similarly impact the development of China's blue carbon market. This study summarises the theoretical foundations for realising blue carbon value, establishes a core mechanism framework for blue carbon marketisation, and develops an analytical perspective for marketising blue carbon value. Based on this, it examines the current state of China's blue carbon marketisation and institutional barriers, and proposes targeted optimisation pathways for marketising China's blue carbon value.

2.Theoretical Basis and Market Mechanisms for Blue Carbon Value Realisation

2.1 Theoretical Basis for Blue Carbon Value Realisation

Blue carbon value realisation is not merely a conceptual idea but is grounded in a solid theoretical foundation and scientific support.

2.1.1 Theory of Ecosystem Services Value Based on Ecological Economics

Blue carbon ecosystems inherently provide integrated services such as carbon sequestration, shoreline protection, biodiversity conservation, and the provision of high-quality food sources for humans. This forms the foundation for their value conversion and realisation. The theory of ecosystem services value emphasises that humans directly or indirectly obtain indispensable material and non-material benefits from ecosystems, which can be converted into quantifiable value through scientific assessment. In 1997, a multidisciplinary team led by Robert Costanza made the first systematic attempt to estimate the economic value of 17 ecosystem services provided by 16 biomes worldwide, with the total value far exceeding the global gross national product (GNP) at the time (Costanza et al., 1997)[1]. This study strongly demonstrated the significant contributions of ecosystems to human well-being, emphasising the necessity and urgency of incorporating the value of ecosystem services into global pricing systems and decision-making processes. The MEA defined ecosystem services as the various benefits humans derive from ecosystems, including provisioning services, regulating services, cultural services, and supporting services (MEA, 2005)[11].

2.1.2 Marketisation and Trading Theory Based on Environmental Economics

From the perspectives of public goods theory and property rights economics, blue carbon exhibits typical characteristics of a 'quasi-public good'. On the one hand, the climate regulation benefits generated by mangroves and seagrass meadows absorb carbon dioxide radiate to the surrounding and even global regions. No enterprise or individual can be excluded from the scope of benefits derived from 'mitigating global warming', fulfilling the criterion of 'non-excludability'. On the other hand, when blue carbon sequestration capacity reaches ecological carrying capacity limits, additional carbon removal services acquired by new emitters displace existing beneficiaries' shares. Human activities—particularly corporate pollution—thus generate negative externalities. This quasi-public good nature leads to insufficient spontaneous market supply. Relying solely on voluntary corporate or individual protection of blue carbon ecosystems invites free-riding, representing a classic manifestation of market failure under public goods attributes. Property rights economics theory offers a 'pathway to rights clarification' for resolving blue carbon market failure. Environmental economics posits that the externalities of ecological resources fundamentally stem from ambiguous property rights demarcation. When blue carbon's 'carbon sink property rights' lack clear attribution, protectors cannot secure commensurate benefits, while polluters bear only partial costs of carbon emissions. This results in excessive negative externalities (pollution) and insufficient positive externalities (blue carbon sequestration). The Coase Theorem posits that under ideal conditions where property rights (such as carbon emission rights) are clearly defined and transaction costs are absent, markets can self-regulate and achieve optimal resource allocation at equilibrium. This implies that establishing clear property rights for blue carbon would enable marketisation through trading mechanisms. Such a system could internalise the positive external environmental benefits generated by blue carbon ecosystems, allowing producers and protectors to receive economic compensation or returns. This, in turn, would incentivise greater conservation and restoration efforts. Consequently, from the perspective of value realisation and efficient trading, environmental economics provides theoretical support for the market-based operation of blue carbon and the reduction of transaction costs.

2.1.3 Blue Carbon Value Assessment Model Based on Environmental Science and Ecology

The development of blue carbon methodologies and value assessment models provides a comprehensive, standardised, and scientific framework for carbon sink measurement and pricing. Blue carbon methodologies are comprehensive technical specifications, standards, and processes for defining, quantifying, monitoring, reporting, and verifying the carbon removal or reduction quantities generated by blue carbon projects. They aim to ensure the authenticity of blue carbon projects and provide a scientific basis for carbon credits and market transactions. The established consensus on blue carbon methodologies includes the applicability conditions for blue carbon (geospatial scope, ecosystem types, project activity methods such as conservation or restoration), project boundaries (geographical boundaries and accounting boundaries of carbon pools and greenhouse gas sources), baseline scenarios (natural trends in carbon storage under no-intervention conditions), additionality (scenarios where project implementation exceeds usual conditions), quantification of removals (carbon increments relative to the baseline scenario), monitoring plans (standards for monitoring carbon sink changes), leakage (the possibility of increased greenhouse gas emissions due to the project), and permanence (measures to ensure the long-term stable storage of carbon sinks). Blue carbon value assessment models extend the methodological outcomes, with the core function of pricing and evaluating the economic and social value of projects. The internationally recognised assessment model is primarily InVEST (Integrated Valuation of Environmental Services and Tradeoffs). The InVEST blue carbon module establishes a basic carbon pool by summing the carbon stocks of above-ground biomass carbon pools, below-ground biomass carbon pools, soil organic carbon pools, and dead organic matter carbon pools to derive the total carbon stock and calculates its net present value (NPV). However, assessing the value of blue carbon is an extremely complex issue, as marine biodiversity is diverse, and carbon capture capacity and carbon sequestration efficiency vary. As a result, institutions in different countries have developed diverse blue carbon accounting methods tailored to specific regional ecosystems, further complicating efforts to establish uniform standards.

2.2 Market-Oriented Mechanism Framework for Blue Carbon Value Realisation

According to the definition of the blue carbon concept, the core of realising blue carbon value lies in converting the inherent ecological value of blue carbon ecosystems into economic returns through market transactions or ecological compensation mechanisms, thereby establishing an incentive structure where protectors benefit, users pay, and destroyers compensate. Realising blue carbon value through market-based pathways offers significant advantages. The carbon market itself has an incentive effect in terms of value discovery. Through market transactions, it maximises the economic benefits of carbon sinks, incentivises social capital to focus on and invest in blue carbon projects, and drives the allocation of social resources toward directions more conducive to ecological protection and greenhouse gas emission control, thereby maximising both social and ecological benefits. Based on existing research (Zhu Hui & Zhao Jiaqi, 2025)[18] and carbon trading practices, this study proposes that the institutional framework for realising blue carbon value through market-based mechanisms primarily encompasses four aspects.

2.2.1 Clear Property Rights Definition Mechanism

Clear property rights are a prerequisite for market transactions. Blue carbon is legally recognised as a tradable ‘commodity’ and a special type of usufructuary right. The realisation of blue carbon value is also an important form of realising the rights of natural resource asset owners. (Xu Yingbiao & Liu Mingxin, 2024)[17] In real-world transactions, blue carbon resources possess public goods attributes, and their service values are multidimensional, making property rights definition more challenging. This necessitates legal clarification of carbon property rights ownership and the separation and definition of blue carbon ownership, usage rights, income rights, and transfer rights (Li Shu-juan et al., 2023)[8]. For example, coastal vegetated systems such as mangroves occupy intertidal and subtidal zones, which are often contested spaces from a legal perspective. Who owns blue carbon assets and who has the right to trade carbon credits for specific blue carbon projects are also contentious issues. (Macreadie et al., 2022)[10]

2.2.2 Unified Standard Certification Mechanism

A unified standard certification mechanism is a crucial means for facilitating market-based blue carbon transactions and minimising transaction costs. In accordance with the MRV (Measurable, Reportable, Verifiable) principles established by the United Nations Framework Convention on Climate Change (UNFCCC, 2007)[16], only carbon sink projects certified through standardised procedures can generate blue carbon credits recognised by the market. This principle provides the foundational framework for harmonising global blue carbon standards. Current blue carbon standard certification faces significant fragmentation issues, constraining market circulation efficiency. At the international level, methodologies vary markedly between institutions and regions. China’s Accounting Methods for Ocean Carbon Sink incorporates shellfish and macroalgae into carbon sink calculations, whereas Verra’s Verified Carbon Standard (VCS) – a leading global certification body – currently does not recognise the carbon sink value of such ecosystems, citing scientific controversy over their net carbon sequestration capacity. This divergence necessitates complex standard conversions for cross-border transactions. Furthermore, existing standards predominantly focus on three traditional blue carbon systems: mangroves, salt marshes, and seagrasses. Certification frameworks for emerging blue carbon ecosystems, such as deep-sea coral reefs and halophytes, remain largely undeveloped.

2.2.3 Efficient Transaction Operation Mechanism

The blue carbon trading market is developing diversely, and the design of blue carbon trading operational mechanisms must consider the trading demands during the cultivation, growth, and maturity phases of blue carbon. Carbon prices exhibit variations under different transaction operating mechanisms. Currently, from the perspective of trading objects, the global blue carbon trading market is primarily divided into two categories: carbon-based direct trading and non-carbon-based indirect trading. From the perspective of trading entities, carbon-based direct trading is further divided into voluntary markets, compliance markets, and inclusive markets. Voluntary markets (e.g., CCER) are based on voluntary carbon neutrality commitments from buyers (including enterprises, institutions, and individuals) and are suitable for corporate ESG strategies, product carbon neutrality labels, and carbon offsets for public welfare activities. Transaction prices in voluntary markets are typically higher than those in quota markets. Compliance markets (e.g., EU-ETS) involve mandatory emissions-reducing enterprises that must purchase carbon credits to offset excess carbon emissions. However, countries impose limits on offset quotas to promote corporate carbon reduction and emissions cuts, and such demand-side restrictions inevitably influence the formation of blue carbon prices. In the inclusive market, buyers are primarily small and medium-sized enterprises, communities, households, and individuals. Policies or commercial incentives are used to promote public participation in decentralised carbon reduction activities, fostering a stronger societal carbon neutrality atmosphere. Non-carbon-based indirect transactions utilise financial instruments such as funds, bonds, loans, and mortgages, as well as market-based measures like blue carbon industry development, to support blue carbon project financing, maximise the value of blue carbon assets, and optimise social and ecological benefits.

2.2.4 Robust Market Supervision Mechanism

Establishing a market supervision mechanism to maintain a fair and orderly market order is a crucial safeguard for the mature development of the blue carbon trading market. Creating a blue carbon trading center or platform, where transactions are conducted within a regulated exchange or system, helps enhance transparency, standardize processes, and ensure fund security. Blue carbon trading started late and is currently conducted primarily in voluntary markets. Compared with compliance markets, which already have strict quota supervision systems in place, the blue carbon market needs to strengthen the management of potential risks and compliance oversight.

3.Current Progress and Core Challenges in China's Blue Carbon Market

3.1 Development Status and Key Achievements

3.1.1 Preliminary Establishment of a National Blue Carbon Policy Framework

China ranks among the earliest nations to incorporate blue carbon into its marine management and greenhouse gas management policy agenda. As early as 2012, the State Council issued The 12th Five-Year Plan for the development of China's Marine Economy, explicitly advocating the utilisation of 'blue carbon sinks'. In 2015, The Opinions on Accelerating the Advancement of Ecological Civilisation were proposed, integrating marine carbon sinks into the overarching design of ecological civilisation development and mandating their application as a means to control greenhouse gas emissions. In 2019, The Implementation Plan for the National Pilot Zone for Ecological Civilisation (Hainan) proposed piloting marine ecosystem carbon sink initiatives and researching blue carbon standards and trading mechanisms. In 2020, the National Development and Reform Commission (NDRC) and the Ministry of Natural Resources (MNR) jointly issued the General Plan for Major Projects on the Protection and Restoration of Key Ecosystems in China (2021–2035), which included the deployment of a 'Major Project for Coastal Zone Ecological Protection and Restoration'. In 2021, the Central Financial and Economic Affairs Commission emphasised that The 14th Five-Year Plan period represents a critical phase for achieving carbon peaking, stressing the need to leverage the carbon sequestration capacity of oceans and enhance the incremental carbon sink potential of ecosystems. In January 2022, the MNR, NDRC, and National Forestry and Grassland Administration (NFGA) jointly issued the Planning for Major Engineering Projects on Coastal Ecological Protection and Restoration (2021–2035), strengthening theoretical research, technological breakthroughs, and standardisation in coastal zone ecological conservation and restoration.

Beyond establishing policy frameworks, Chinese scientists have fostered productive collaboration with national policymakers and enterprises, forming innovation consortia that provide theoretical and technical underpinnings for national policy innovation. In 2013, Chinese scientists established the China Ocean Carbon Alliance (COCA) with government departments and corporate experts. The Future Ocean Alliance (FOA) was founded in 2014, launching China's Blue Carbon Initiative. By 2019, Chinese scientists co-initiated the Global Ocean Negative Carbon Emissions (Global-ONCE), which has since expanded to include 79 scientific teams from 35 countries. On 18 July 2025, China hosted the International Blue Carbon

Forum in Hainan, bringing together experts, scholars and industry representatives from China, Norway, Brazil, Indonesia, Belgium, Germany, France, Canada and other nations. The event systematically showcased technological achievements in mangrove restoration, shellfish carbon sinks and related fields.

3.1.2 Accelerated and Active Exploration of Local Blue Carbon Marketisation

Since 2021, China's blue carbon marketisation process has begun to accelerate. In June 2021, the mangrove afforestation project in Zhanjiang, Guangdong Province, completed China's first transfer of 5,880 tCO_2e of carbon emissions reductions. In January 2022, Lianjiang County, Fujian Province, completed China's first fisheries carbon credits transaction. In September 2023, Shenzhen, Guangdong Province, completed the first auction of mangrove carbon credits. The transition from carbon sink agreement subscriptions to successful auctions marks China's entry into the market-based trading phase for blue carbon value realisation. In July 2024, the 10-year mangrove carbon sink development rights in Huidong County, Guangdong Province, were successfully transferred, pioneering the first mangrove carbon sink development rights transaction. In November 2024, Shenzhen collaborated with Enping City in Jiangmen to complete the auction of carbon credits from the mangrove forest conservation project in Zhenhai Bay, Enping. This transaction drew upon Shenzhen's mangrove carbon credit methodology and auction mechanism, achieving cross-regional standard recognition and advancing the development of the blue carbon trading market within the Guangdong-Hong Kong-Macao Greater Bay Area.

3.1.3 Blue Carbon Trading Service System Gradually Taking Shape

Local pilot projects have taken the lead in methodological exploration. In 2020, Dapeng New Area in Shenzhen issued the first local marine carbon sink accounting guidelines, identifying seven tradable carbon sink types, including mangroves, salt marshes, shellfish, and algae. In 2021, the Luoyang River Mangrove Ecological Restoration Project in Quanzhou, Fujian Province, completed a transaction based on the 'Mangrove Afforestation Carbon Sequestration Project Methodology' developed by Xiamen University. In 2023, the MNR issued the Accounting Methods for Carbon Sink, China's first comprehensive national standard for blue carbon accounting. This methodology expands the scope of blue carbon accounting to six major categories: mangroves, salt marshes, seagrass meadows, phytoplankton, large algae, and shellfish. The development of blue carbon trading markets or platforms has also begun. In 2021, the Xiamen Property Rights Exchange Centre (XPREC) established China's first marine carbon sink trading platform, which has gradually grown into the largest local blue carbon market in terms of trading volume. By April 2025, the XPREC had completed 220,000 tCO_2e of blue carbon transactions, accounting for approximately 80% of the national blue carbon market (Jin Xuan, 2025)[6]. In 2022, Hainan province established the first carbon emissions trading centre targeting the international market, with the Hainan International Carbon Emissions Centre aiming to promote Hainan's blue carbon methodologies as internationally recognised standards through the market-based trading of blue carbon products. Cross-regional cooperation between domestic local markets has also seen breakthroughs. In March 2024, the XPREC and the Ningbo Property Rights Exchange Centre jointly established the nation's first cross-provincial blue carbon ecological account for Xiangshan County, Zhejiang Province.

3.1.4 Blue Carbon Financial Tools are Becoming Increasingly Diverse

Since 2017, Shenzhen, Weihai, and Xiamen have successively established "Blue Carbon Funds" to purchase marine carbon sinks for investing in blue carbon projects in impoverished areas, supporting marine ranching, mangrove conservation, and carbon inclusive initiatives. Industrial Bank's Qingdao branch issued the nation's first wetland carbon sink loan, with Qingdao Jiaozhou Bay SCO Demonstration Zone Development Company obtaining an 18-million-yuan loan using Jiaozhou Bay wetland carbon sinks as collateral, specifically earmarked for marine wetland protection. In 2022, Lianjiang County, Fujian Province, completed the country's first digital CNY marine fishery carbon sink transaction involving 1,000 tCO_2e. China Life P&C-Weihai launched the first marine carbon sink index insurance to compensate for seagrass bed losses post-disasters. In 2023, ICBC Yangjiang Branch facilitated the first marine carbon sink expected revenue rights-backed loan. In 2024, Xiamen Property Rights Exchange Center and PICC P&C Xiamen introduced the nation's first property safety insurance for blue carbon trading. The development of blue carbon finance has provided crucial market-based support for realizing the value of blue carbon. The participants in the blue carbon market have also evolved from early government and research institution dominance to a diverse landscape now involving numerous enterprises, financial institutions, social organizations, and individuals.

Table 1 Representative Blue Carbon Transaction Projects in China

Trading Hours	Subject of the Transaction	Transaction Price (Yuan /tCO_2e)	Method of Transaction	Buyer Entity	Scenario Innovation
2021.6	Mangrove Carbon Sinks	66	Agreement Subscription	NGOs	Zhanjiang Mangrove Forest Establishment Project, Guangdong Province.
2021.9	Mangrove Carbon Sinks	Not Disclosed	Platform Trading	Bank	Quanzhou Luoyang River Mangrove Ecological Restoration Project, Fujian Province.
2021.11	Mangrove Carbon Sinks	250	Purchase Carbon-neutral Flights Directly	Individual	Xiamen Airlines Has Partnered with Industrial Bank's Xiamen Branch to Offer 50,000 'Carbon-Neutral' Flight Tickets Priced at 10 Yuan Each, Offsetting 2,000 tCO_2e of Carbon Emissions from Air Travel (through the Carbon Sink Project at the Luoyang River Mangrove Ecological Restoration Project in Quanzhou, Fujian Province).
2022.1	Marine Fisheries Carbon Sinks	8	Platform Trading	Bank	Lianjiang Marine Aquaculture Project (Algae and Shellfish), Fujian Province.
2022.5	Mangrove Carbon Sinks	100	Platform Trading	Enterprise	Haikou Mangrove Restoration Project, Hainan Province.
2022.10	Marine Fisheries Carbon Sinks	20	Digital CNY Payments	Enterprise	Lianjiang Marine Aquaculture Carbon Sink (Bivalve Molluscs), Fujian Province.
2023.2	Marine Fisheries Carbon Sinks	106	Auction	Enterprise	Xiangshan Marine Aquaculture Carbon Sink (Algae), Zhejiang Province.
2023.4	Marine Fisheries Carbon Sinks	Not Disclosed	Carbon Account	Individual	"Blue Carbon + Justice" Carbon Sink Judicial Compensation in Xiangshan, Zhejiang Province.
2023.6	Mangrove Carbon Sinks	Not Disclosed	Options Agreement	Enterprise	The 10-year Carbon Sink from the Mangrove Afforestation Project in Yanpuwan, Cangnan, Zhejiang Province, is Pending Inclusion in the China Carbon Emission Reduction (CCER) Scheme Before Completion of Trading.
2023.9	Mangrove Carbon Sinks	485	Auction	Enterprise	Shenzhen Mangrove Conservation Project, Guangdong Province.
2023.9	Salt Marsh Carbon Sinks	Not Disclosed	Platform Trading	Enterprise	Yancheng National Rare Bird Nature Reserve Salt Marsh Ecological Restoration Project, Jiangsu Province.
2024.7	Mangrove Carbon Sinks	400	Platform Trading	Enterprise	Huidong Mangrove Creation Project Phase 10 Carbon Sink Development Right, Guangdong Province.
2024.7	Salt Marsh Carbon Sinks	Not Disclosed	Platform Trading	Institution	Alternative Ecological Restoration of Salt Marshes in the Yancheng National Nature Reserve for Rare Birds, Jiangsu Province
2024.7	Salt Marsh Carbon Sinks, Seagrass Meadows Carbon Sinks	44.4	Platform Trading	Enterprise	Ecological Restoration Project for the Yellow River Estuary Salt Marsh and Seagrass Meadows in Dongying, Shandong Province. Carbon-for-Compensation.
2024.11	Mangrove Carbon Sinks	1000	Platform Trading	Individual	Zhangzhou Jiulong River Estuary Mangrove Restoration Project, Ecological Public Interest Litigation, Fujian Province.

Trading Hours	Subject of the Transaction	Transaction Price (Yuan /tCO_2e)	Method of Transaction	Buyer Entity	Scenario Innovation
2024.11	Mangrove Carbon Sinks	336	Auction	Enterprise	Jiangmen Mangrove Ecological Restoration Project, Guangdong Province.
2025.4	Marine Fisheries Carbon Sinks	100	Platform Trading	Individual	Fuzhou Lvjuren Ecological Technology Co., Ltd. Has Developed an 'Sedimentary and Refractory Carbon' Carbon Credits Product for Alternative Ecological Restoration in Illegal Fishing Cases, Fujian Province.
2025.6	Marine Fisheries Carbon Sinks	100	Agreement Subscription	Institution	Zhoushan's 'Carbon Offsetting' (Shellfish Carbon Sinks) and Alternative Ecological Restoration in Illegal Fishing Cases, Zhejiang Province.
2025.6	Mangrove Carbon Sinks	557.7	Platform Trading	Individual	Shenzhen Mangrove Conservation Project. Alternative Ecological Restoration for the Illegal Seabed Sand Extraction Case, Guangdong Province.
2025.6	Marine Fisheries Carbon Sinks	164	Auction	Enterprise	Oyster Farming Project in Houmen Town, Shenzhen-Shantou Special Cooperation Zone, Guangdong Province.

Source: Compiled from publicly available information

3.2 Core Challenges in Blue Carbon Marketisation

Presently, whether driven by fulfilling international climate governance obligations under the Paris Agreement, advancing the implementation of China's dual carbon strategy, or addressing the practical need for high-quality ecological conservation to empower high-quality development, the market-based pathway for realising blue carbon value has become markedly significant and urgent. However, a series of institutional shortcomings pose tangible challenges to the orderly advancement of blue carbon marketisation. These shortcomings encompass gaps in the legal framework, fragmented standards and certification systems, and immature market mechanisms. These factors directly constrain the effective conversion of blue carbon's ecological value into economic value, hindering the full realisation of marine carbon sinks' supportive role in achieving the dual carbon goals.

3.2.1 Incomplete Legal Framework for Transactions

Blue carbon trading lacks nationwide legal or administrative regulations specifically designed for blue carbon. Its legal status within national climate change mitigation actions remains undefined, and blue carbon is currently excluded from China's national greenhouse gas inventory system. There are gaps in defining the rights attributes of blue carbon and establishing guiding principles for its conservation, development, and utilisation. Core issues such as property rights demarcation, benefit distribution, and regulatory responsibilities lack uniform national standards, significantly increasing market uncertainty. China's existing carbon markets primarily comprise the mandatory national carbon emissions trading market (China Carbon Emission Allowances, CEA) launched in 2021 and the voluntary emissions reduction trading market (China Certified Emission Reduction, CCER) initiated in 2024. The multi-tiered policy framework for the national carbon market—comprising administrative regulations, ministerial measures, normative documents, and technical standards—has been largely established (MEE, 2024)[12]. This comprehensive legal system provides crucial safeguards for its development. Currently, this market covers approximately 5.1 billion tCO_2e of carbon dioxide emissions annually, accounting for over 40% of China's total carbon dioxide emissions, making it the world's largest carbon market in terms of greenhouse gas emissions coverage. In contrast, the CCER remains in the foundational stage of institutional development, primarily operating under departmental regulations such as the 'Administrative Measures for Voluntary Greenhouse Gas Emission Reduction Trading' issued by the Ministry of Ecology and Environment (MEE) and the State Administration for Market Regulation (SAMR). Its legal standing is relatively low, and blue carbon has yet to become a core trading category. Transactions for blue carbon projects completed under local pilot schemes largely rely on regional regulations, such as the 'Zhoushan Municipal Measures for the

Management of Ocean Carbon Sink (Blue Carbon) Development and Trading', lacking the legal authority at the national level. This makes it difficult to support the formation of a unified national market.

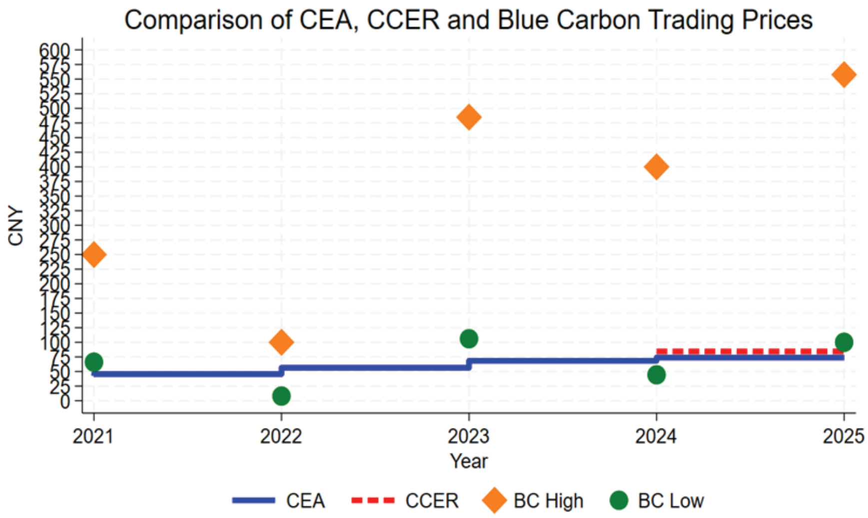
3.2.2 Inadequate Standards and Certification Framework

Despite diverse methodological explorations in local blue carbon projects, a unified national blue carbon accounting standard system remains unestablished. Furthermore, no coordinated standardisation mechanism has been formed across relevant departments. The MEE previously solicited greenhouse gas voluntary emission reduction project methodologies from the public, receiving 361 submissions. Ultimately, only four methodologies were approved in the first batch, with mangrove afforestation being the sole blue carbon project included (MEE, 2024)[12]. Among the three internationally recognised core blue carbon ecosystems (mangroves, salt marshes, and seagrass beds), national methodologies for salt marshes and seagrass beds remain absent. Similarly, methodologies for fisheries carbon sinks explored at the local level in China—such as shellfish aquaculture and algae cultivation—have not been incorporated into the national CCER system. Furthermore, China's CCER methodologies exhibit significant discrepancies with internationally recognised standards such as the Verified Carbon Standard (VCS). Taking mangroves as an example, the CCER methodology, designed for operational simplicity, diverges markedly in aspects including carbon pool selection, additionality assessment, crediting period definition, leakage quantification, and project boundary delineation. Certain requirements are comparatively lenient, resulting in limited international recognition. This lack of standard alignment directly constrains the international conversion of China's blue carbon resource value. Currently, only the Zhanjiang mangrove project in Guangdong Province has obtained certification under both the Verified Carbon Standard (VCS) and the Climate, Community and Biodiversity Standards (CCB), thereby qualifying for international trading.

3.2.3 Immature Market Trading Mechanisms

Presently, China's voluntary carbon market (CCER) serves only as a supplementary function to the national carbon emissions trading market (CEA), with markedly insufficient market activity. According to data from the National Carbon Market Information Network, since its reactivation until 21 August 2025, the CCER market has recorded a cumulative trading volume of merely 2,492,611 tCO_2e. This falls short of the weekly trading volume (3,153,852 tCO_2e) achieved by the CEA during the same period (15-21 August 2025). Due to institutional design prioritising 'emission reduction' objectives over 'carbon sink enhancement', the trading mechanisms of the two markets have failed to achieve full integration. Furthermore, stringent regulatory thresholds exist: carbon offsets purchased by enterprises from the voluntary market may not exceed 5% of their own emission reduction quotas during allocation settlement. This restriction has significantly dampened corporate purchasing interest. Supply-side constraints remain pronounced: only two mangrove restoration projects are currently registered and participating in CCER trading. The Xiapu Yantian Township and Changchun Town mangrove restoration project in Ningde, Fujian, achieves average annual emissions reductions of 1,085 tCO_2e, while the Jiulong River Estuary (Longhai) mangrove project in Zhangzhou contributes 1,720 tCO_2e annually. Neither project scale suffices to support the CCER market's demand for large-scale transactions. Since 2021, local blue carbon trading has exhibited characteristics of 'small scale and scattered distribution'. Most transactions consist of sporadic one-off contractual transfers or small-scale auctions, lacking sustained, stable, and large-scale trading activities. This has resulted in the market losing its core price discovery function. Regarding transaction prices, blue carbon projects exhibit significant volatility: mangrove projects range from a low of ￥66/tCO_2e of carbon dioxide equivalent to a high of ￥1,000/tCO_2e; fisheries carbon sinks range from a low of just ￥8/tCO_2e to a high of ￥164/tCO_2e. This excessive price disparity fails to accurately reflect the comprehensive ecological and economic value of blue carbon projects and makes it difficult to provide investors with stable return expectations. More notably, despite blue carbon's high carbon sequestration efficiency and significant ecological value, its transaction prices remain substantially lower than green carbon. In 2024, the transaction price for the Yellow River Delta salt marsh project in Dongying, Shandong, was approximately ¥44.4/tCO_2e, compared to approximately ¥70/tCO_2e for forest carbon sinks during the same period. This price also falls below the average transaction price in the CCER market from its 2024 restart to August 2025 (approximately ¥85/tCO_2e). Beyond being influenced by the core factor of cyclical market supply and demand, the current agreement transfer prices for pilot projects in many regions are largely administratively guided rather than fully market-determined. This reflects the breakthrough signal of local blue carbon markets moving from ‘zero-to-one’, rather than the value expression of a mature market.

Figure 1 Comparison of CEA, CCER and Blue Carbon Trading Prices



Source: Calculated based on publicly available data from the National Carbon Market Information Network (https://www.cets.org.cn.)[13] and other sources.

Notes:

1. The CEA market commenced in July 2021, with annual average transaction prices of ￥42.9/tCO_2e in 2021, ￥45.6/tCO_2e in 2022, ￥56.4/tCO_2e in 2023, and ￥68.3/tCO_2e in 2024;

2. The CCER market commenced in January 2024, with an average transaction price of ￥84.4/tCO_2e since inception;

3. Blue carbon transactions lack continuity and are fragmented, precluding the calculation of an average price. Comparisons are thus based on annual peak and trough prices. Notably, 2024 witnessed a record high of ￥ 1,000/tCO_2e, reflecting judicial penalty pricing that lacks comparability and is therefore excluded from analysis.

3.2.4 Blue Carbon Projects Exhibit Shortcomings in Risk Management Capabilities

Blue carbon ecosystems may be damaged by human activities such as urban expansion, agricultural development, aquaculture, shoreline destruction, and wastewater discharge, or may degrade and lose their carbon sequestration functions due to natural changes, posing high risks of value loss. In early 2008, low temperatures in Guangxi caused widespread freezing of mangrove forests. Additionally, blue carbon conservation and restoration projects require significant upfront investments, particularly for carbon sequestration projects that require long-term monitoring. Development and MRV costs are high, and the return on investment cycle is lengthy, making it difficult to attract social and commercial capital. Project funding sources are overly reliant on government budgets and charitable donations, creating significant pressure on sustained funding, which may lead to fluctuations in carbon credits. According to statistics, from 2019 to 2023, there were a total of 28 mangrove ecosystem protection and restoration projects nationwide, covering an area of 3,346.21 hectares. During this period, approximately 10.687 billion yuan in financial support was provided by central and local governments, with an average investment of 3.19 million yuan per hectare (Li Jianping, 2024)[7]. The more project funding relies on government support, the lower the activity of the blue carbon market becomes, and the longer the path to achieving market-based blue carbon value. It is important to note that a national blue carbon trading information platform has not been established, and there are no mandatory regulations for disclosing key information such as blue carbon project resources, certification, and transactions. This leads to information asymmetry in the market, making it difficult to promptly identify ‘bluewashing’ behaviour, which could potentially trigger carbon financial risks through fake carbon credits.

4.Building New Pathways for China’s Blue Carbon Value Realisation

Globally, blue carbon development is gaining momentum, and the realisation of blue carbon value is increasingly being integrated into national ecological competitiveness. Leveraging the strong driving force of China’s national ‘dual carbon’ strategy and its growing body of pilot experience, combined with innovative market-based pathways for value realisation, China is fully capable of transforming its vast blue carbon resource advantage into a competitive edge in addressing climate change and achieving sustainable development.

4.1 Strengthen Systematic Legislation to Lay a Solid Institutional Foundation

Refine the legal framework governing blue carbon. Accelerate the compilation of the National Ecological and Environmental Code, establishing a dedicated section on green and low-carbon development (including a chapter on climate change response). Systematically incorporate the dual carbon goals and green transition requirements into the legal framework, providing principled and forward-looking legal norms for emerging ecological fields such as blue carbon. Simultaneously establish an 'Ecological Protection Chapter' explicitly designating blue carbon ecosystems (mangroves, salt marshes, seagrass meadows, etc.) as priority conservation targets. Authorise the State Council and relevant departments to formulate supporting regulations for realising the value of ecological products, providing overarching planning and institutional foundations for resolving core issues such as blue carbon property rights demarcation and market mechanism gaps.

Revise the national 'Administrative Measures for Voluntary Greenhouse Gas Emission Reduction Trading' to formally recognise blue carbon projects' legal status within the China Certified Emission Reduction (CCER) mechanism. Integrate blue carbon into China's national greenhouse gas inventory system and establish substantive and procedural rules for its full incorporation into the unified national carbon market. Given blue carbon's high dependence on marine natural resources, the 'Blue Carbon Resource Management Regulations' should be enacted to clearly define property rights attribution, establish comprehensive transaction protocols, and delineate interdepartmental regulatory responsibilities. Building upon the existing unified natural resource rights registration system, detailed rules and operational procedures for blue carbon property rights registration should be refined to achieve standardised and traceable registration.

Strengthen the blue carbon methodology framework by concentrating research efforts on developing carbon sink measurement methodologies for seagrass beds, salt marshes, and key marine aquaculture species (such as oysters and kelp). Expedite their inclusion in the national CCER methodology catalogue to ensure all blue carbon project types have a legal basis for development. Simultaneously, accelerate the narrowing of technical gaps between China's CCER methodologies and internationally recognised standards (such as VCS and Gold Standard). Promote international alignment on key indicators (including carbon pool accounting scope and additionality verification criteria) to remove standardisation barriers for China's blue carbon projects accessing global markets.

4.2 Build a Multi-tiered Blue Carbon Market to Stimulate Market Dynamics

Establish a multi-tiered, differentiated blue carbon market system to facilitate the comprehensive integration of blue carbon into the national carbon market framework. This will create a unified blue carbon trading market characterised by high standards and transparent, regulated transactions, gradually increasing market scale and activity. Optimise compliance market trading rules to permit non-compliant entities (such as public welfare organisations and ESG-oriented enterprises) to participate in trading. Gradually expand the proportion of blue carbon CCERs eligible for offsetting within the national carbon emissions trading market (e.g., from the current 5% to 10%-15%), while broadening the scope of offset applications. This will foster effective market demand incentives, thereby enhancing the intrinsic value of blue carbon assets.

Consolidate the foundation of the voluntary carbon market by reducing administrative intervention and establishing a mature, market-driven price formation mechanism to prevent price distortions caused by excessive local government guidance. Encourage enterprises to purchase blue carbon as a key means of achieving ESG objectives and fulfilling social responsibilities. Establish an official blue carbon purchase certification system and information disclosure platform to enhance transaction transparency and credibility. Accelerate the development of inclusive markets by encouraging the establishment of personal carbon accounts nationwide and optimising carbon revenue distribution systems (e.g., through personal carbon sink credits, charitable carbon sink subscriptions, and carbon-neutral flight/ferry tickets). This will channel blue carbon dividends directly to local communities, ecological conservation participants, and vulnerable groups, substantially boosting public engagement in blue carbon initiatives. The 2022 designation of Xiamen's Guomao Tiancheng Residential Community as China's first 'zero-carbon community' achieving community carbon neutrality through blue carbon offsets exemplifies such public engagement scenarios (Lian Wei, 2023)[9].

Strengthen coordination among existing local blue carbon trading centres to explore establishing regional blue carbon trading hubs (e.g., in the Guangdong-Hong Kong-Macao Greater Bay Area and Yangtze River Delta). Develop integrated 'blue carbon plus' products to promote deep integration of carbon sinks with coastal tourism, green exhibitions, ecological fisheries, and marine culture industries. This approach achieves diversified value accumulation across regions, sectors, and multiple stakeholders.

4.3 Promote Diversified Blue Carbon Financial Innovation and Activate Blue Carbon Assets

Promote and deepen the 'blue carbon plus finance' model, extending products such as 'marine carbon sink loans' and blue carbon pledge financing from pilot regions nationwide. Rushan, Shandong province, has secured a ¥50 million pledge loan against anticipated oyster carbon sink revenue rights, while Zhoushan has launched a mussel carbon sink pledge financing product. Such successful experiences can be replicated across coastal provinces through specialised guidance from the China Banking and Insurance Regulatory Commission (CBIRC). Simultaneously, drawing on local initiatives such as Zhangzhou securing the inaugural blue carbon loss insurance policy for mangrove projects in 2024, financial institutions should be encouraged to develop innovative products based on blue carbon assets. These include blue bonds, blue carbon insurance, and blue carbon trust funds, explicitly covering carbon sink losses caused by marine disasters like typhoons and red tides. Integrating blue carbon into Ecology-Oriented Development (EOD) projects will drive innovation in blue carbon financial applications.

Establish a national or regional blue carbon development fund, adopting a government-guided, market-oriented operation model to attract long-term capital and patient capital, and mobilise social capital to provide long-term, low-cost financial support for blue carbon projects. Explore blue carbon futures and other derivative transactions. When conditions are ripe, launch blue carbon futures, options, swaps, and other financial derivatives to provide risk hedging tools and help investors manage price risks. Strengthen international cooperation, connect global blue carbon markets, issue offshore blue yuan bonds, and attract international capital to invest in China's blue carbon projects.

4.4 Strengthening International Technical Cooperation to Advance Blue Carbon Industry-Research Integration

Whilst the nation's international commitments to climate change have catalysed the blue carbon market, policy-driven measures alone cannot sustain its long-term prosperity. The expanding developmental needs of the blue carbon industry itself constitute the core prerequisite for the market's enduring vitality. The value of blue carbon stems from significant scientific discoveries, and technological advancement constitutes the core foundation for its industrial development. This represents a distinct characteristic distinguishing blue carbon value realisation from other ecological products. The industrial support role of cutting-edge blue carbon technologies manifests primarily in three aspects:

Firstly, through in-depth research into the regulatory mechanisms governing blue carbon formation processes, new models, business formats, and application scenarios for the blue carbon industry are continually cultivated, integrating carbon science, carbon ecology, and carbon economics. In recent years, Chinese scientists have emerged as one of the leading groups in international blue carbon research. Original theories such as the 'Marine Microbial Carbon Pump' (MCP) have gained widespread recognition within the global scientific community and have been incorporated into reports by the UNEP. Research by scholars including Jiao Nianzhi and Dai Minhan indicates that relying solely on natural marine carbon sinks is insufficient to achieve carbon neutrality goals. Systematic investigation into marine negative emissions theory and methodologies is required, alongside the development of implementable technical pathways and action plans (Jiao Nianzhi & Dai Minhan, 2022)[4]. Accordingly, technical solutions have been proposed to transform traditional carbon sources into sinks, including integrated land-sea emission reduction and carbon sequestration, restoration of degraded marine areas to enhance sequestration, comprehensive sequestration in marine aquaculture zones, and alkalisation of wastewater from sewage treatment plants for carbon sequestration upon discharge into the sea.

Secondly, by establishing scientific standards for marine carbon sinks, support is provided for the development of blue carbon trading systems. The technical pathways proposed by ONCE build upon MRV (Measurable, Reportable, Verifiable) requirements by introducing the higher-order NOCE-3R standard—Reasonable, Reliable, Reproducible. This framework has secured approval from the International Organisation for Standardisation (ISO) to establish the 'Ocean Negative Emissions and Carbon Neutrality' International Standard Working Group (ISO-TC8WG15) (Jiao Nianzhi, 2025)[5].

Thirdly, strengthening international collaborative innovation in blue carbon technologies represents a critical pathway to overcoming industrial bottlenecks and enhancing global influence. China may leverage the ONCE programme to establish transnational technical cooperation platforms, jointly founding 'Blue Carbon Technology Joint Laboratories' with international institutions such as the Institute of Marine Research (Norway) and the Indonesian Mangrove Research Centre. These laboratories should prioritise tackling common technological challenges including carbon sequestration regulation in tropical and subtropical mangroves and deep-sea carbon sequestration monitoring. Concurrently, deepen alignment with the EU's Horizon 2020 blue carbon projects, establishing regular exchange mechanisms in areas such as mutual recognition of carbon measurement methodologies and sharing of ecosystem restoration technologies. For instance, drawing on Germany's experience with 'blue carbon remote sensing satellite constellations' could enhance China's three-dimensional monitoring network (satellite + UAV + underwater sensors), promoting deeper compatibility between blue carbon technical standards and international systems. Furthermore, initiate the 'Global Blue Carbon Young Scientists Training Programme' to jointly cultivate multidisciplinary talent with institutions, thereby building intellectual reserves for international blue carbon technology cooperation.

These endeavours present a pivotal opportunity for China to develop internationally recognised blue carbon project methodologies and certification standards. This will help resolve the longstanding challenges of inconsistent standards and difficulties in mutual recognition that have hindered China's blue carbon industry development, providing robust scientific and technological support for blue carbon marketisation.

5.Conclusions and Outlook

Realising the value of blue carbon represents not only a crucial measure for global collaborative action against climate change and China's fulfilment of international emission reduction commitments, but also a proactive choice in advancing Chinese-style modernisation characterised by harmonious coexistence between humanity and nature. China's practical experience has fully demonstrated the feasibility and developmental potential of commercialising blue carbon value. Local pilot schemes—such as the mangrove carbon sink trading in Zhanjiang; the fishery carbon sink pilot in Lianjiang; and the judicial trading of mussel carbon sinks in Zhoushan—have explored market-based pathways for blue carbon through multiple dimensions, including trading models, product innovation, and scenario integration. The powerful policy impetus of the national 'dual carbon' strategy has formed an organic synergy with pragmatic innovation at the local level. Managers, scientists and enterprises have formed cross-sector innovation consortia; financial institutions piloted 'ocean carbon sink loans'; the private sector participated in blue carbon project investments; and public welfare organisations promoted blue carbon science communication. Attention and participation from all parties continue to intensify. Combined with the public's strong endorsement of the concept of 'harmonious coexistence between humanity and nature, symbiosis between humans and the sea', these factors have collectively created unprecedented favourable conditions for establishing China's blue carbon marketisation system.

Nevertheless, the overall effectiveness of realising blue carbon value in China remains insufficient: market development commenced relatively late, and transaction volumes remain fragmented (blue carbon CCER trading in 2025 accounted for merely 0.3% of the national carbon market total), falling far short of unlocking the latent value of China's vast blue carbon resources, including mangroves, seagrass beds, and fisheries carbon sinks. While foundational consensus on blue carbon marketisation exists, the disconnect between theoretical understanding and practical implementation requires bridging through systematic institutional design. The core challenge lies in transforming the implicit ecological value of blue carbon ecosystems into carbon credits or carbon sink products characterised by clear property rights, scientific measurement, standardised verification, and seamless trading. The core challenges in blue carbon marketisation centre on ambiguous property rights, inconsistent measurement and certification standards, dysfunctional market price discovery mechanisms, and limited application scenarios. Consequently, China's blue carbon marketisation requires a four-dimensional support system encompassing ‘institutional frameworks, trading mechanisms, capital mobilisation, and technological innovation’: Strengthen systematic legislation to solidify the institutional foundation; Developing multi-tiered blue carbon markets to stimulate market momentum; Promoting diversified blue carbon financial innovation to unlock blue carbon assets; Advancing blue carbon technological innovation and industrial integration aligned with global scientific frontiers.

Currently, global blue carbon trading occurs almost exclusively within voluntary markets, with very limited practice in integrating it into mainstream compliance markets at scale. Even within the EU-ETS—the world’s most mature and active carbon market—blue carbon transactions account for less than 1% of total volume. Consequently, there is strong advocacy for incorporating blue carbon as high-quality carbon offset credits into emissions trading schemes. The United Nations COP29 conference, which concluded in November 2024, approved Article 6.4 of the 2015 Paris Agreement. This provision establishes a global carbon market mechanism overseen by the United Nations, designed to support climate action by increasing demand for carbon credits. It is not difficult to foresee that as the carbon peak target period draws nearer, the global blue carbon market will witness tremendous growth. More importantly, in the long term, as we approach net-zero emissions, carbon pricing could be set according to the cost of direct greenhouse gas capture, with revenues used to fund carbon removal from the atmosphere. This would fundamentally alter our perception of commodities. (Bill Gates, 2021)[2] Blue carbon, with its high carbon sequestration value, is poised to become the most sought-after commodity in the market, positioning the blue carbon market as an emerging sector underpinned by cutting-edge technology. Institutionally, existing national blue carbon markets exhibit relatively narrow gaps in awareness and development levels. Although China’s blue carbon market development commenced later, its close integration with frontier technologies will constitute a significant competitive advantage for future market growth. In this sense, China’s blue carbon value realisation has not been ‘start at a disadvantage’. Moreover, China’s practical experiences and case studies in blue carbon value realisation will provide valuable insights for the global blue carbon market’s development.

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Research on the Construction and Application of Personalized Learning Mode in Colleges and Universities under the Smart Classroom Environment

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Abstract: The digital transformation of education is the development direction for deepening the reform of China's education system and also the contemporary demand for promoting higher education to keep pace with the times. As a major form to apply digital information technology in education, smart classrooms can help students make use of fragmented time for autonomous learning, enhance thinking and exploration abilities as well as their sense of autonomy, and provide technical support for students' personalized learning. This research is based on the personalized learning needs of students in China's higher education institutions. It conducts construction and application research on the personalized learning model of college students in smart classrooms from aspects such as the drawing of digital graphs of personal learning characteristics, the identification of learning goals, the design of personalized learning, and individualization learning support. It is hoped that this research can provide more references and perspectives for optimizing the personalized learning of college students. It also contributes its humble efforts to promoting the development of Chinese higher education towards a more personalized and intelligent direction.

Keywords: Smart Classroom Environment; College and University; Personalized Learning Mode
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1.Preface

The report of the 20th National Congress of the Communist Party of China clearly put forward the educational development goal of "Promoting the digitalization of education and building a lifelong learning society and nation for all", which provides an important basis for promoting the reform and development of China's education system and also serves as a guide for schools to continuously advance the digitalization of education. At present, with the development of information technologies like artificial intelligence, the Internet of Things, precision algorithms and blockchain, the digital transformation process of education in China is accelerating. Especially during the COVID-19 pandemic, the exploration and application of online education technology by educational institutions in China have further promoted the upgrading and development of digital education technology. The construction and application of smart classrooms can fully leverage the significant role of digital technology in the interaction between teachers and students, among students, and between humans and computers. Relying on the advantages of digital teaching virtual scenarios and massive information resources, it provides conditions for students to rationally utilize their spare time, enrich their learning methods, and formulate personalized learning plans. Therefore, in general, the application of smart classrooms is conducive to return education in China to its original purpose of cultivating people with both ability and integrity.

Colleges and universities are the main ground for cultivating outstanding young talents in China. Personalized learning is a key factor in fostering innovative talents and also an urgent need for students to possess the lifelong learning ability to adapt to a learning society. The National Medium and Long-Term Education Reform and Development Plan (2010-2020) clearly states that “We should adhere to the people-oriented concept, respect students’ individual choices, encourage individual development, innovate talents cultivation models, and cultivate talents in a flexible way.” Meanwhile, the “Ten-Year Development Plan for Education Informatization (2011-2020)” also proposes to attach great importance to personalized learning, emphasizes to stress the provision of personalized and lifelong learning and offer environmental support for all learners. It can be seen from this that the education department of China highly affirms the positive role of personalized learning in cultivating innovative talents. The research on the construction and application of personalized learning models in colleges and universities under the smart classroom environment will help to explore a more efficient, convenient and personalized learning path for college students, and also contribute to promoting the development of higher education in China towards a more intelligent and humanized direction.

2.Analysis of the Connotations and Coupling Mechanism of Smart Classroom Environment and Students’ Personalized Learning

2.1 The Connotation of Smart Classroom and Personalized Learning for Students

2.1.1 The Connotation of the Smart Classroom

To promote the development of smart classrooms, the Ministry of Education in China has successively issued policy documents such as the Ten-Year Development Plan for Education Informatization (2010-2020), the 13th Five-Year Plan for Education Informatization, and the Action Plan for Education Informatization 2.0. Among them, the Action Plan for Education Informatization 2.0 has clearly put forward the concept of Smart Learning Environment. And in the 2022 work priorities, it was pointed out that “We should promote the construction of smart classrooms and accelerate the transformation of classroom teaching models”. With the support of a series of policy documents, smart classrooms in China have begun to enter a stage of regular exploration and application.

Regarding the definition of smart classrooms, scholars like Cheng Wei (2024) defined it as an important model that integrates modern digital technology and teaching methods into traditional teaching, and promotes the digital development of education. Comparing with traditional teaching environments, smart classrooms are more informationalized and intelligent, and provide stronger interactivity environment between teachers and students. Scholars like Xu Hongkai(2023) believe that smart classrooms can achieve two-way interaction between teachers and students through a human-machine combined mode, deepen and optimize the process of students’ knowledge construction, emphasize the subjectivity of students’ learning, and thereby promote the development of students’ comprehensive qualities and overall abilities. The application of smart classrooms is of great significance for cultivating students’ independent exploration and autonomous learning abilities.

Based on the above viewpoints, the research concludes that a Smart Classroom refers to a new teaching method and means that relies on digital information technology for reform and innovation. That is, digital information technology, artificial intelligence and other information tools are added to the traditional classroom teaching model to facilitate teachers in using intelligent technology to analyze students’ efficiency and learning needs, promote individualized learning, and improve overall teaching efficiency. Compared with traditional classroom teaching where the teacher is the main body, the smart classroom is a process of interaction between teachers and students, rather than a simple process of knowledge transmission and acquisition. It places greater emphasis on the student as the main body and focuses on cultivating students’ innovative thinking, inquisitive spirit and individualized learning ability.

2.1.2 The Connotation of Personalized Learning

The personalized learning refers to in this research is a customized learning plan formulated by students in a smart classroom environment based on their own learning schedules, ability levels, learning progress, and learning goals. It is a value manifestation of the smart classroom empowering students' autonomous learning. Students can conduct online and offline autonomous learning, assessment, and watch teaching videos in the smart classroom environment according to their own learning situations, and build exclusive learning scenarios, thereby cultivating independent thinking and autonomous judgment abilities.

Compared with middle and primary school students, college students usually have more mature logical thinking and learning abilities. Moreover, universities offer a more open learning environment for them. Therefore, it is particularly important to cultivate personalized learning plans for college students. In the smart classroom environment, college students can flexibly adjust their learning plans based on their own learning characteristics and needs, and choose suitable learning resources and methods for themselves. This personalized learning model not only can stimulate students' interest and motivation in learning, but also encourage college students to explore actively and practice bravely. This is of great significance for cultivating innovative and practical talents in China.

2.2 Coupling Mechanism between Smart Classrooms and Personalized Learning Education Function in Higher Education Institutions

2.2.1 Smart Classrooms are Helpful in Cultivating College Students' Individualized Learning Ability

With the diversity of career choices, college students group also shows significant differences in learning needs during their study. The traditional One-size-fits-all teaching model has become unable to meet college students' different learning needs in preparing for civil servant recruitment, postgraduate entrance exams, or employment application. At the same time, in traditional classroom teaching, time and space limitations, such as the uneven distribution of teaching staff, different study time arrangement and learning effectiveness, have further exacerbated the contradiction between individualized learning needs and the One-size-fits-all teaching model. Smart classrooms rely on digital technology to track students' learning performance, homework completion, and online learning behaviors in real time across multiple dimensions. It can precisely draw a digital learning profile for each student and intelligently recommend course content and exercise resources that are adapted to different knowledge foundation and learning progress. Moreover, students can also use fragmented time to communicate and discuss with teachers and classmates through tablets, smart terminals, etc. in the virtual learning community, and raise personalized learning questions. Thus, the application of the smart classroom has broken the time and space limitations of traditional classrooms, providing technical support for students' individualized learning needs and comprehensively cultivating students' comprehensive learning abilities.

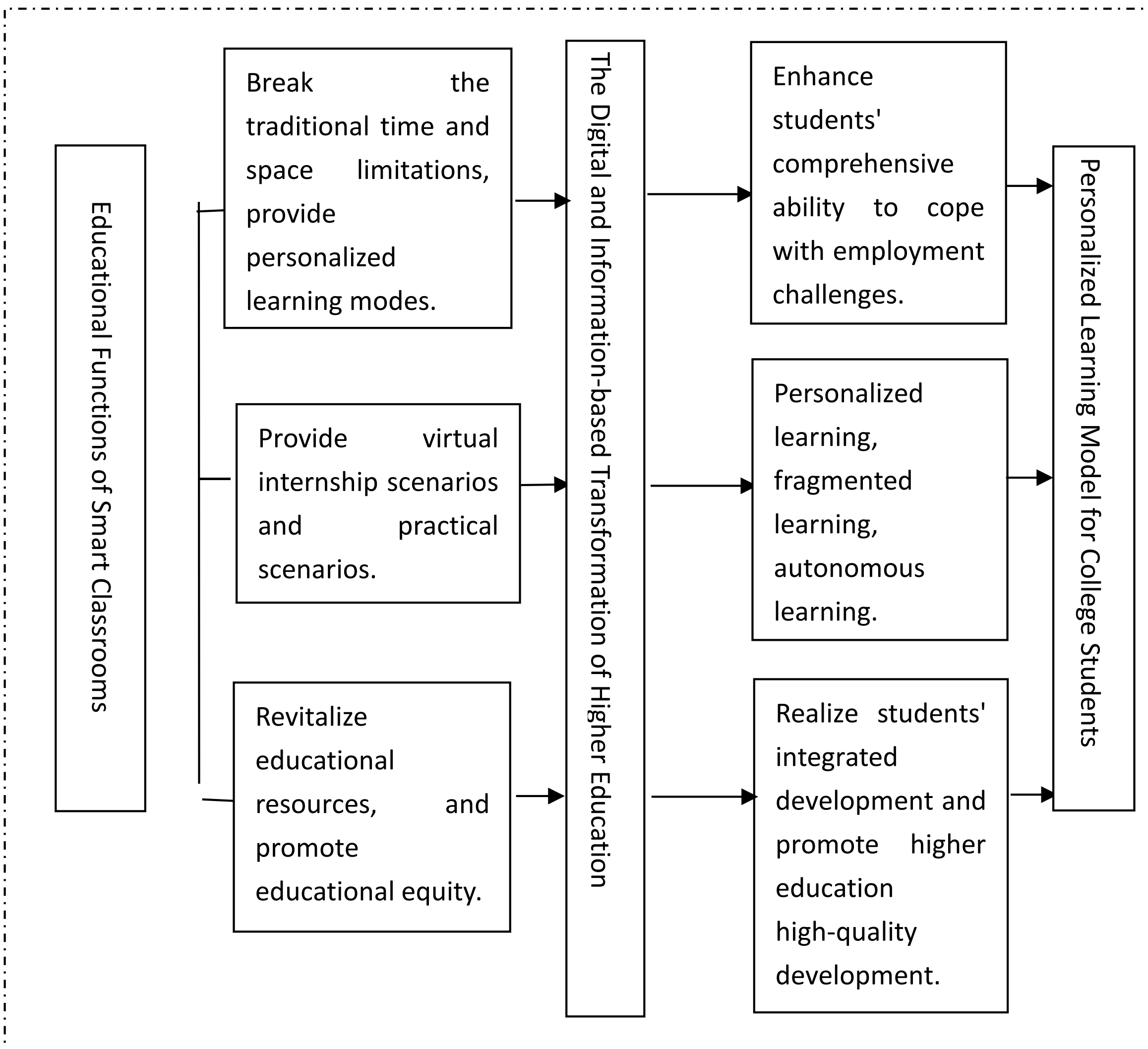
2.2.2 Smart Classrooms are Helpful to College Students in Better Adapting to the Development of the Intelligent Era

The development and application of smart classrooms are mutually reinforcing with artificial intelligence technology. In the context of the artificial intelligence era, the industrial structure of China's manufacturing sector has been rapidly optimized and upgraded. Traditional manual labor positions have been replaced by mechanical and intelligent technologies, and automated production has been fully implemented. College students, as the main body of quality-oriented higher education in China, have received social attention due to changes in the external employment environment. In the employment environment where artificial intelligence technology is widely applied, traditional low-skilled industries and jobs have suffered unprecedented impacts, which also places higher demands on the practical ability, independent exploration ability, and innovative ability of college students in their careers. Smart classrooms are different from traditional classroom education, they create more virtual employment scenarios and practical scenarios for students' learning through digital technology, providing more learning opportunities for college students to combine theoretical knowledge with practical ability, and creating a favorable learning environment for students to better cope with employment challenges.

2.2.3 Smart Classrooms Promote the Optimization of Educational Resources Allocation and Application in Universities and Colleges

In traditional classroom teaching, due to differences in educational staff, facilities, and policies, college students often have difficulty accessing fair educational resources. However, in the smart classroom environment, the allocation and utilization of educational resources have become more efficient and reasonable. Smart classrooms rely on massive network information and digital technology to break geographical barriers and achieve the sharing of educational resources. They can gather high-quality educational forces and advanced teaching methods to form online education courses, and distribute high-quality digital education courses equally. This optimization of resource allocation not only improves students' learning efficiency but also promotes the fair distribution of educational resources, enabling each student to obtain suitable learning opportunities and resources. In the long run, the application of smart classrooms will promote a continuous expansion of the higher education resources scope in China. Through personalized learning and utilization, students will drive the positive feedback and interaction between smart classrooms and higher education, ultimately promote the sustainable development of higher education in China.

Figure 1 : The Theoretical Framework For the Coupled Development of the Smart Classroom Environment and Students' Personalized Learning.



3.Research on the Construction of Personalized Learning Models for College Students in Smart Classrooms

3.1 Drawing of Digital Maps of Students' Learning Characteristics

The personalized characteristics while learning are the basis for identifying college students' individualized learning needs. To provide personalized learning models for college students in an intelligent classroom environment, it is necessary to first identify and construct the learner's profile. Through the precise algorithms of the smart classroom, learners' individualized characteristics can be mined, and then the students' learning time arrangement, learning level and ability, learning attitude, learning interactivity, and learning habit preferences can be comprehensively evaluated. By drawing personal digital maps, corresponding personalized learning materials can be precisely pushed.

Table 1:Personalized Digital Profiles of College Students as Learners

Information Dimension	Information Decomposition	Third-level Sub-information
Basic Information	Identity	gender\grade\major\hometown\nation\politics status, etc.
	Economic Situation	annual household income range\ loans and scholarship situation\ monthly living expense standard
	Enrollment style	Whether be enrolled by recommendation or special talents.
Learning Level and Ability	Basic ability	English proficiency level\computer skills\mandarin Chinese level
	Professional competence	GPA\professional competition award situation\ scientific research experience(paper publishing or research participating situation)
	Study potential	learning ability self-assessment\test results of thinking ability (including dimensions such as logical reasoning and innovation ability)
Learning Habit Preferences	Study Time Management	average daily study duration\ peak study times (morning/noon/afternoon)\ fragmented learning habits (such as study during commuting)
	Learning Resource Preferences	preferred learning platforms (MOOCs, Bilibili, Netease Cloud Classroom, etc.)\ preferred learning formats (video courses / textual materials / live lectures)\ frequently followed learning bloggers or public accounts
	Learning Style	self-study frequency\ participation in group cooperative learning\ whether willing to make public statement, etc.
	Types of Learning Motivation	self-motivated (seeking knowledge)\ goal-driven (for exams/certifications)\ pressure-driven (fear of failing)
Interests and Special Talents	Interested Subject	interested subjects apart from the major (such as psychology, economics)
	Interests	hobbies (music, painting, sports) and club activities participation (positions held situation)
	Skills	skills that be proficient in (such as sports, programming, innovative design, writing)

3.2 Identification of Students' Personalized Learning Goals

By applying digital models and artificial intelligence technologies to draw the personalized learning digital map of college students, personalized learning goals can be calculated based on their learning habits. In the smart classroom environment, students' personalized learning goals can be decomposed into short-term goals, medium long-term goals, and coordinated development goals. Thus, the personalized learning environment for students can be designed with a focus on their learning goals. Table 2 shows the decomposition of students' learning goals.

Table 2: Identification of College Students' Personalized Learning Goals

Learning Goals	Short-term Goals	expected semester GPA\ passing the final exams of specific subjects\ obtaining certain certificates (such as the junior accounting qualification certificate, teacher qualification certificate)
	Medium and Long-term Goals	postgraduate entrance examination goals (target university, major, preparation progress)\ civil servant recruitment goals (target application, position type, study plan)\ employment goals (expected career, position, enterprise type)\ study abroad goals (target country, university, language proficiency requirements)
	Coordinated Development Goals	improve communication and expression skills\ cultivate teamwork abilities\ enhance professional practical skills

3.3 Personalized Learning Design in Smart Classrooms

Firstly, targeted design and precise delivery of learning resources should be given. Compared with traditional offline classrooms, one advantage of smart classrooms is that they can provide students with a wealth of learning resources for their individualized learning, promoting the transformation of learning materials from single, static paper-based materials to various dynamic learning resources such as videos, audio, courseware, and electronic texts. Due to differences in learning styles, learning cognition, and preferences among students, they can freely choose from different resources. Moreover, in the smart environment, teachers' teaching methods are not limited to traditional lecturing-style teaching, but can also make greater use of the interactivity of digital technology to achieve interaction between teachers and students, and between humans and machines. By providing learning resources with different teaching characteristics such as explanatory, exploratory, and demonstration types, the needs of students' individualized learning can be met.

Secondly, personalized learning paths should be designed. Learning paths are important carriers that reflects the individualized learning process of students under the support of intelligent technology. The smart classroom, based on the preset curriculum model, can provide students with more options for initiating personalized learning. In the smart classroom environment, teachers can recommend learning courses and resources to students through the learning platform, and students can also choose self-study modes based on their learning goals. The former is that the learning system or platform, based on the students' electronic files, analyzes the data of their learning process and recommends an appropriate learning path for them, including a series of learning resources, learning content, test questions, etc. The latter is that students, based on their self-awareness of learning foundation, preferences and styles, independently choose the learning path. However, whether it is system recommendation or students' independent selection, the prerequisite is to conduct differential diagnosis of students' individual knowledge levels, interests, etc. Based on this, personalized learning paths need to provide learning content and evaluation methods with certain differences to meet different individualized learning needs.

Finally, personalized learning effectiveness evaluation should be implemented . Traditional offline classroom teaching evaluation often focuses solely on the students' academic performance, rarely considering the process-related evaluation elements such as students' attitudes, methods, and enthusiasm during the learning process. Smart classroom can precisely and objectively evaluate the overall learning effectiveness by tracking students' online platform learning performance in real time. Moreover, the smart classroom can break the single evaluation method in traditional classrooms that is dominated by the teacher, and evaluate students' personalized learning through human-computer interaction, student-student interaction, and teacher-student interaction, from different entities such as teachers, classmates, and group members. Thus, it realizes pre-evaluation, in-evaluation, and post-evaluation in the learning process; teacher evaluation, classmate evaluation, and member evaluation in terms of the main body; and questionnaire evaluation, scale evaluation, and student work evaluation in terms of methods. This enables various diversified evaluation methods such as questionnaire evaluation, scale evaluation, and student work evaluation, achieving closed-loop management of students' personalized learning.

3.4 Analysis of Support for Students' Personalized Learning in Smart Classrooms

To implement the personalized learning methods for college students in a smart classroom environment, it is essential to establish corresponding software and hardware teaching environments and corresponding teaching staff. From the above description of the essence of a smart classroom, it can be seen that the implementation of a smart classroom requires at least four elements: complete infrastructure, network environment, learning resources, and teaching staff.

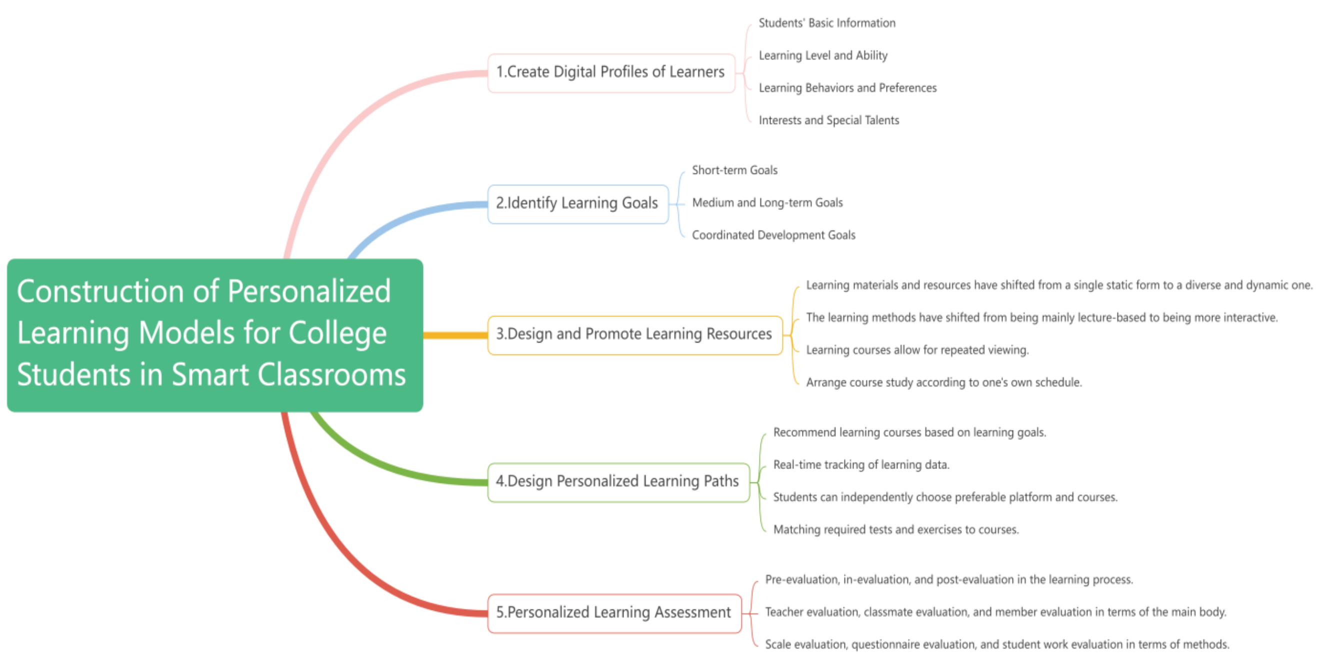
The Internet of Things infrastructure is the core of the entire physical facility layer. The network seamlessly connects the physical space and virtual space of the smart classroom. The Internet of Things infrastructure mainly includes switches, cameras, network communication systems, etc. The smart classroom focuses on the acquisition and preservation of generative resources. Learning resources are not static but are updated in line with the learning content. Generative learning resources are precisely pushed and designed based on students' digital profiles, embodying the concept of personalized learning. In addition, the courses provided by the smart classroom should also be able to support students to access rich learning resources at any time and anywhere for ubiquitous learning.

Finally, teachers remain the main body for conducting individualized teaching for students. Therefore, teachers need to be proficient in applying smart classrooms and online education platforms, be skilled in using digital teaching methods such as initiating discussions, organizing voting, assigning homework, and conducting online assessments, and also possess the ability to conduct in-depth analysis and interpretation of students' learning data. When implementing individualized learning for college students in a smart classroom environment, teachers also need to focus on cultivating students' autonomous learning abilities, encouraging them to explore actively and practice diligently, and helping students construct and internalize digital learning knowledge.

3.5 Individualized Learning Model in Smart Classrooms

Based on the above analysis, this study has constructed a five-dimensional personalized learning model based on four elements: infrastructure, network environment, learning resources, and teaching staff. The dimensions and contents of individualized learning for college students are specifically shown in Figure 2. Regarding the presentation of the entire model diagram, compared with the traditional learning model in offline classrooms, the personalized learning in the smart classroom environment places greater emphasis on students' autonomous learning and personalized choices, and weakens teachers' intervention role during the learning process. This model, based on the concept and method of scaffolding teaching, enables teachers to gradually withdraw these scaffolds while ensuring that students can ultimately complete the scaffolding learning tasks, which is conducive to better cultivating students' autonomous learning ability and logical inquiry ability.

Figure 2:The Overall Construction of Students' Personalized Learning Model in Smart Classroom Environment



4.Evaluation of the Application of Personalized Learning Model for College Students in the Smart Classroom Environment

After four-month observation on the personalized learning model designed in this study, the results show that the smart classroom environment can better support universities in implementing personalized learning models. The designed learning model has played a positive role in cultivating students' autonomous learning abilities, promoting the rational use of fragmented time, and helping students formulate personalized learning plans. However, at the same time, it was also found in the research that the implementation of the smart classroom still requires improvement.

4.1 The Advantages of the Personalized Learning Model for College Students in the Smart Classroom Environment

Through a four-month learning observation, college students in the smart classroom environment can reasonably plan their study time based on personal schedules and plans, the learning model provided more support for students to efficiently utilize fragmented time.

Secondly, online education courses allow students to repeatedly watch teaching videos, and teachers can provide in-depth explanations by combining dynamic learning resources. These technological supports help break through the time and space limitations of traditional offline classrooms in terms of teaching content. At the same time, the smart classroom environment supports functions such as student questioning and online discussions, which can enhance students' interest in learning and encourage them to actively participate in interactions. This not only promotes the development of students' logical thinking abilities but also boosts their learning enthusiasm.

Finally, the smart classroom environment provides more scenarios for college students to engage in personalized and in-depth learning. By simulating scenarios such as factory production, business negotiations, and court debates, students can exercise their practical abilities in a realistic environment, thereby better adapting to future career development. This in-depth learning experience enables a closer integration of theory and practice for students, enhancing their comprehensive qualities and employment competitiveness.

4.2 Deficiencies of the Personalized Learning Model for College Students in the Smart Classroom Environment

There are also some deficiencies exist in the designed personalized learning model, mainly manifested in the following two aspects.

Firstly, smart classrooms require high quality network environment. Unstable network conditions or slow speeds may occur when a large number of users crowd at a same peak time, causing lagging and affecting the normal operation of students. Therefore, when promoting the smart classroom, colleges must attach importance to the construction and optimization of the network environment to ensure that students can access the network stably and quickly, thereby fully utilizing the various functions and resources provided by the smart classrooms.

Secondly, some teachers are not yet proficient in the application of digital platforms when using the smart classroom. Teachers are still in lack of the ability to deeply analyze students' personalized learning needs and learning data. Some teachers are still accustomed to traditional lecturing-style teaching and have certain deficiencies in how to design personalized learning paths, push learning resources, and implement precise teaching using the digital technologies and interactive functions provided. Therefore, when promoting the smart classroom, colleges also need to enhance teachers' digital literacy and teaching ability, so that they can better adapt to the teaching needs of the smart classroom environment and better serve students' personalized learning.

5.Conclusion

The application of smart classrooms provides excellent external conditions for the individualized learning of college students and is an innovative teaching method that meets the talent cultivation needs of the 21st century in China. Under the environment of smart classrooms, college students can better adapt to the workplace demands of the intelligent era through self-directed learning arrangements. In the future, smart classrooms in universities will better integrate technologies such as bring artificial intelligence and big data into teaching process, achieve precise delivery of teaching content, make intelligent diagnosis of the learning process, and offer personalized evaluation of learning outcomes. Conducting research on the teaching practice of smart classrooms in universities will help promote the integration and innovation among disciplines and provide students with a more comprehensive and personalized learning experience.

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Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Research on the Digital Divide in Smart Healthcare for the Elderly under Portugal's "National Digital Strategy - Digital Simplification" Policy

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Abstract: The launch of Portugal's "National Digital Strategy - Digital Simplification" policy signifies the country's determination for digital development and application, comprehensively covering sectors such as education, healthcare, elderly care, and public administration. The elderly, as the largest group demanding healthcare services, face a significant digital divide problem in the context of smart healthcare development. This paper, based on the definition of core concepts and guided by the theory of digital governance, investigates the digital divide in smart healthcare for the elderly under the Portuguese policy from three dimensions: the access divide, the usage divide, and the outcome divide. The research findings indicate that the elderly in Portugal face issues such as inadequate access to network environments and smart healthcare devices, insufficient willingness to use smart healthcare, and diminished accessibility to smart healthcare services. Based on these findings, and grounded in Portugal's "National Digital Strategy - Digital Simplification" policy, the study proposes corresponding governance countermeasures from three aspects: improving the top-level design and supporting measures for elderly smart healthcare services; promoting multi-party collaboration to eliminate the elderly's resistance to smart healthcare; and enhancing the equity and effectiveness of smart healthcare usage among the elderly. This research aims to provide a reference for Portugal to better advance the multi-party collaborative governance of the "digital divide" in elderly healthcare under the "National Digital Strategy - Digital Simplification" context, and to effectively improve the accessibility, equity, and convenience of healthcare for the elderly in the digital age.
Keywords: Portugal; Elderly Population; Smart Healthcare; Digital Divide
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1.Introduction

On December 12, 2024, the Portuguese Minister of Education, Science and Innovation, together with the Minister of Youth and Modernization, unveiled Portugal's "National Digital Strategy - Digital Simplification". The strategy emphasizes that digital transformation is intended to simplify people's lives, enhance their quality of life, and promote the development of Portugal's productivity and competitiveness. This strategy will be applicable until 2030 and will impact areas such as healthcare, housing, government sectors, and corporate digitalization in Portugal.

With the advancement of public policies for digital healthcare in Portugal, the elderly, as the group with the greatest demand for medical services, have not had their medical rights and interests protected during the rapid transition from traditional to digital healthcare services. Instead, due to issues like the access divide, usage divide, and outcome divide of the digital gap, their original accessibility and equity in medical services have been compromised. Studying the digital divide in elderly healthcare under the national digital strategy policy is a critical topic for improving the governance capacity of an aging society and enhancing the equity and accessibility of smart healthcare for the elderly.

2.Core Concepts and Theoretical Foundation

2.1 Concept Definition

2.1.1 Smart Healthcare

Smart healthcare, as the name suggests, is the digital transformation of traditional medical service processes through the application of information technologies such as Artificial Intelligence, Blockchain, and the Internet of Things. Faris S Alghareb et al. (2025) define smart healthcare as the use of advanced internet information technology to manage residents' health records through a medical information system, thereby achieving interaction between medical institutions, personnel and equipment, and patients and medical staff, ultimately realizing an informatized and digitized smart healthcare system, regional health system, and home health system [1]. Ibrahim Ahmad et al. (2025) view the smart healthcare system as a comprehensive transformation of the entire process of traditional medical services, using residents' health records and electronic patient records as a database, medical cloud data as the technological core, and constructing an efficient medical system that integrates government supervision, information security, information standards, business applications, and health management through various information technologies [2].

Synthesizing the views of the above scholars, this paper defines smart healthcare as a process of medical digitalization and intelligent transformation based on AI technology, deeply applying online medical and intelligent medical technologies to overcome the spatial and temporal limitations of traditional offline medical care. Smart healthcare is a revolutionary wave of medical services based on AI technology. Portugal's "National Digital Strategy - Digital Simplification" also includes the digital transformation of healthcare. Under the guidance of this strategy, Portugal has planned and guided the development of telemedicine, electronic health records, and smart medical software and applications. The implementation of smart healthcare not only signifies an innovation in medical technology but also a profound social change. It requires the joint participation of medical institutions, technical personnel, policymakers, and the general public to build a more equitable, efficient, and humanized healthcare service system [3]. In this process, how to effectively narrow the digital divide for the elderly in the field of smart healthcare and ensure they can equally enjoy the convenience brought by digital medical care will be a crucial issue in the implementation of Portugal's "National Digital Strategy - Digital Simplification" policy.

2.1.2 Core Connotation of the Digital Divide

The concept of the digital divide first emerged in the late 1980s. In 1999, the U.S. National Telecommunications and Information Administration (NTIA) found that with the development of internet information technology, there was a gap in information access and the ability to use new technologies between those who could obtain them and those who could not, defining this disparity as the digital divide [4]. With the development of digital technology, the connotation of the digital divide has continuously expanded and enriched.

Figure 1: Core Content of the Digital Divide

Core Content of the Digital Divide	Description
Access Divide	Due to differences in environment and infrastructure, leading to unequal access to internet information ports and equipment.
Usage Divide	Due to differences in willingness to use, leading to disparities in the application of information technology.
Outcome Divide	Due to differences in knowledge levels, cognitive abilities, values, and acceptance capabilities, leading to disparities in the outcomes achieved from using the technology.

As shown in Figure 1, Anasuya K. Lingappa et al. (2025) categorize the digital divide into three levels: the first level is the access divide, mainly concerning the equipment and facilities for accessing the internet information port; the second level is the usage divide, referring to the individual's willingness to apply information technology; and the third level is the knowledge divide, referring to the differences in individuals' opportunities and abilities to apply information technology [5]. Apeksha Mewani et al. (2025) argue that the three levels of the digital divide symbolize new types of inequality caused by differences in technology access, technology use, and knowledge acquisition among different groups and individuals, and the digital divide will trigger other problems as society develops [6].

Compared to the younger generation, the elderly generally have lower educational levels and differ from the younger generation in their acceptance of information technology, frequency of information resource use, and mastery of information knowledge. Furthermore, physical decline, such as presbyopia and reduced finger dexterity, is common, making the elderly gradually become a vulnerable and marginalized group in the digital economy era.

At the access divide level, the elderly, due to economic and material constraints, use computers and smartphones at a significantly lower rate than the youth. This situation is more pronounced in rural areas, and the increase in the aging population will further exacerbate the digital divide problem for the elderly.

At the usage divide level, the elderly's demand for digital information services is significantly reduced. Coupled with the complexity of the interface design of various digital software, this further suppresses the elderly's motivation and willingness to use digital technology.

At the outcome divide level, due to significant differences from the younger generation in cognition, attitude, values, and behavioral patterns, the elderly also show significant disparities in the effectiveness of internet use. This situation is the main manifestation of the digital divide for the elderly in the digital economy era. The uneven distribution of the digital dividends created by the rapid promotion of digital service technology is making the elderly a digitally vulnerable group.

2.2 Theoretical Basis for Portugal's "National Digital Strategy - Digital Simplification"

In the 1990s, global digital technology and information developed explosively, and the digital economy environment compelled public administration to optimize and reform its processes. In this context, the British scholar Patrick Dunleavy proposed the theory of Digital Era Governance (DEG), arguing that the advent of the digital era would drive the re-engineering and simplification of government administrative processes. By applying digital technology to public service delivery, government administrative efficiency can be significantly improved, and public satisfaction with government work can be enhanced [7]. Therefore, the DEG theory advocates for a governance model that applies information technology to government public service processes, actively uses digital technology to enhance interaction between the government and businesses/the public, and promotes democratization by simplifying government procedures.

The DEG theory includes three main components: First, the re-integration and optimization of government processes and responsibilities through digital technology, reducing the waste and duplication of administrative resources. The concept of re-integration does not advocate for centralized management but aims to promote the enhancement of democratization in new public management. Second, needs-based holistic governance. The application of digital information technology will help change the situation where the government is the sole dominant governing body. By expanding the subjects of collaborative governance on digital information platforms, it can enhance the interaction between the government and the public, promote government information disclosure, and simultaneously boost the public's active participation in governance, improving the quality of supervision and management over government affairs [8]. Third, digital transformation. Digital transformation forces government departments to undergo digital change, leading to the digitalization of administrative work. Digital transformation meets the public's demand for high-efficiency government services and also breaks the single mode of communication between the traditional government and the public, thereby realizing a "data running instead of people" digital government and e-governance.

The DEG theory aligns with the trend of digital development. Currently, digital technology is one of the comprehensive indicators for measuring a country's development quality. Portugal is comprehensively advancing digital construction, with the technological revolution represented by information technology developing rapidly, and the healthcare industry has also undergone a technological revolution. The "National Digital Strategy - Digital Simplification" issued by Portugal includes the construction and application of smart healthcare systems. Specifically, it covers services such as online registration and card creation, online appointment scheduling, online diagnosis and treatment, online testing and examination booking, and mobile payment. It utilizes AI analysis technology, voice assistance technology, facial recognition technology, smart device association technology, and artificial customer service/family intervention technology in mobile application interfaces, online consultation processes, and intelligent assistance for online and offline consultations. The construction of smart healthcare is the specific practice of the DEG theory in the medical field. Under the guidance of Portugal's "National Digital Strategy - Digital Simplification," the practice of DEG theory in the medical field will continue to deepen, providing strong support for building a more equitable, efficient, and humanized healthcare service system.

3.Analysis of the Digital Divide in Smart Healthcare for the Elderly under Portugal's "National Digital Strategy - Digital Simplification" Policy

The application of smart healthcare brings great convenience to younger patients, but since residents' digital literacy varies, the rapid promotion of smart healthcare also poses significant challenges to the elderly, who have relative difficulty using smart information terminals. There is a significant digital divide between the elderly and modern smart healthcare.

3.1 Access Divide: Inadequate Access to Network Environment and Smart Healthcare Devices

A good network access environment is the fundamental element for realizing smart healthcare. Portugal is actively promoting the construction of network infrastructure, but problems such as unstable network access and insufficient network coverage still exist in remote and rural areas. In parts of Madeira and the Cape Verde Islands, due to relatively backward development, complex geographical environments, and scattered populations, the cost for network operators to lay high-speed networks is excessively high, resulting in very weak or even absent network signals in these areas. Smart healthcare services such as remote consultation and real-time health data upload require high network stability and speed [9]. If elderly patients cannot connect to the network stably, they will have difficulty communicating smoothly with doctors via video, and they will not be able to timely transmit data collected by home smart medical devices to the doctor's end, hindering the development of remote smart healthcare services.

Secondly, smart healthcare moves beyond the traditional interaction between medical institutions and patients, allowing the elderly to establish a remote care model with doctors through smart healthcare systems and devices. Smart healthcare is highly dependent on smart devices. Patients can wear health monitoring devices, and medical institutions can collect real-time health data such as blood pressure, heart rate, and blood oxygen from the elderly. However, the income sources of some elderly people in Portugal are very limited, mainly relying on pensions for living. According to data from the Portuguese National Statistics Institute, over 50% of the elderly have a monthly pension in the range of 600-800 Euros. After deducting basic living expenses such as rent, utilities, and food, the remaining funds are insufficient to cover smart medical devices that often cost hundreds of Euros. The constraint of economics and the high price of smart healthcare devices form a sharp contradiction, which leads to the significant problem of insufficient access to smart terminals for the elderly in the construction and promotion of smart healthcare in Portugal.

3.2 Usage Divide: Complex Operation of Smart Healthcare Devices Inhibits Willingness to Use

Due to age-related decline in learning and cognitive abilities, the elderly face greater difficulty in learning to operate complex smart healthcare device software [10]. Furthermore, common health management APPs often have complex interface designs and small fonts. Functions such as doctor selection, appointment booking, and settlement processes are numerous. Elderly patients, due to physical decline and poor finger dexterity, are prone to accidental touches, leading to operational errors or even incorrect payments. Despite the Portuguese government's call to promote digital transformation in healthcare, the government and communities have not provided corresponding training for the elderly on the use of smart healthcare devices. This leaves many elderly Portuguese people at a loss when trying to use these APPs and software.

According to surveys, over 70% of the elderly in Portugal cannot complete the registration and login process independently when using smart healthcare APPs for the first time. It is even more difficult for them to record, upload, view, or download medical examination reports during subsequent use. Such smart healthcare APPs, lacking age-friendly design, are clearly difficult to use smoothly on their own. Moreover, in the Portuguese healthcare system, public hospital resources are very strained, and patients need to book specialists in advance on online medical platforms, choosing the most suitable option from numerous departments and doctor schedules. These difficulties suppress the confidence and motivation of the elderly to use smart healthcare devices. Over time, the elderly develop a sense of caution and resistance towards smart healthcare, which is detrimental to their acceptance of it.

3.3 Outcome Divide: Diminished Equity in Accessing Smart Healthcare Services for the Elderly

The issuance of Portugal's "National Digital Strategy - Digital Simplification" aims to promote the digital application of social public services, simplify administrative procedures, and enhance the public's convenience in obtaining services. However, the elderly, as a vulnerable group in terms of digital literacy, not only fail to equally enjoy the benefits brought by digital technology during Portugal's digital promotion process but also have their equity and accessibility to smart healthcare services diminished due to the digital divide.

Currently, Portugal is actively developing smart healthcare, installing a large number of smart terminal devices in various medical institutions to improve the convenience and efficiency of patient visits. However, the corresponding offline registration and appointment channels and windows have been significantly reduced. Relevant departments and medical institutions are also allocating more resources to the construction of online healthcare, which is clearly unfavorable for the elderly, who have relatively low digital literacy. On the one hand, the elderly are the largest group demanding medical services, yet their digital literacy is relatively low, creating a contradiction in the structure of medical supply and demand. That is, the elderly have a high demand for medical services, but the accessibility of smart healthcare services is low. Although some elderly people actively try to use smart healthcare systems under the context of the national push for smart healthcare, the lack of unified training and their relatively low digital literacy means the effectiveness of their attempts is not significant. Over time, the problem of the outcome divide will dampen the enthusiasm of the elderly to use smart healthcare, thereby exacerbating the expansion of the digital divide.

4.Governance Countermeasures for the Digital Divide in Smart Healthcare for the Elderly under Portugal's "National Digital Strategy - Digital Simplification" Policy

From the above analysis, it is clear that the core content of the digital divide is mainly divided into the access divide for smart devices, the usage divide, and the outcome divide. Under Portugal's "National Digital Strategy - Digital Simplification" policy, the government is focused on promoting the digital transformation of processes in healthcare, education, elderly care, and public administration. The elderly, as the largest group demanding medical services, have become a digitally vulnerable group in the context of smart healthcare due to differences in digital literacy [11]. Based on this, to enhance the accessibility and equity of smart healthcare for all citizens and optimize the effectiveness of government digital governance, the governance countermeasures for the digital divide among the elderly under the "National Digital Strategy - Digital Simplification" framework can be approached from the following three aspects.

4.1 Improve the Top-Level Design and Supporting Measures for Elderly Smart Healthcare Services

In the process of advancing smart healthcare development, Portugal should improve the top-level design of smart healthcare services for the elderly to provide policy and legal guarantees for their smart medical visits. Firstly, in response to the situation where many elderly people do not know how to use smart healthcare, the government should issue corresponding regulations allowing relatives or community staff to assist with appointment booking services. In addition, the government should promote cooperation between urban medical institutions and rural/marginal institutions through methods such as tax reductions and increased subsidies, to facilitate the downward flow of high-quality medical resources. This will alleviate the situation where the elderly in remote rural areas cannot enjoy the benefits of smart healthcare, such as remote consultation and remote surgery [12]. At the same time, medical institutions should be mandated to provide dual-track services to ensure age-friendly medical provision. By creating elderly-friendly hospitals and inviting volunteers to guide the elderly in using smart healthcare, the resistance and fear of the elderly towards smart healthcare can be overcome. It is worth noting that a good and stable network environment is one of the fundamental conditions for effectively carrying out smart healthcare. The Portuguese government, in promoting digital transformation, should focus on the construction of high-quality network environments and simultaneously encourage the elderly to actively access smart terminal devices.

Furthermore, the Portuguese government should actively optimize the policy framework for smart healthcare services for the elderly, mandating that the government and communities regularly provide digital literacy training to the elderly to enhance their ability to use digital technology services. The relevant government should issue policy documents to regulate the orderly promotion of smart healthcare device usage in medical institutions at all levels, preventing the situation where medical institutions, in pursuit of short-term benefits, completely cut off offline medical services. Medical institutions should be required to retain a certain proportion of on-site registration slots, in-clinic appointment quotas [13], and promote the parallel development of online and offline services in the Portuguese healthcare system.

4.2 Social Collaboration to Eliminate the Elderly's Resistance to Smart Healthcare

Surveys show that a considerable proportion of the elderly in Portugal have a certain degree of fear and resistance towards using smart healthcare. They are uncertain about the consequences of using it and are also worried about being disliked due to their lack of proficiency, leading to low motivation and willingness to use smart healthcare over time, which further widens the usage divide for the elderly. In response to this situation, under the framework of the Portuguese policy, in addition to the government regulating and guiding medical institutions for digital transformation, a friendly atmosphere for the elderly to use digital technology services should also be created across society.

The government and communities can dispatch volunteers and relevant staff to explain smart healthcare technology to the elderly. For those in need, digital technology application skills training and assistance should be provided to eliminate their fear of using smart devices. For example, volunteers can explain and demonstrate how the elderly can download health APPs, how to book appointments, check reports, etc., and promote the convenience of smart healthcare to guide the elderly to recognize the benefits that digitalization brings to their lives and medical visits [14]. Furthermore, the government should encourage digital reverse-feeding from families and children to the elderly. The encouragement and guidance from children and family members regarding the use of smart healthcare can effectively eliminate the elderly's resistance and fear towards medical digitalization.

4.3 Enhance the Equity and Effectiveness of Smart Healthcare Usage for the Elderly

While smart healthcare is being vigorously promoted in Portugal, the government should focus on enhancing the equity of smart healthcare usage for the elderly. In addition to improving the digital literacy of the elderly and encouraging them to actively use smart healthcare, the government should also establish green medical channels outside of smart healthcare for specific digitally marginalized elderly groups. These channels should include various appointment methods such as telephone booking, online booking, in-clinic doctor booking, discharge follow-up booking, on-site booking, and dedicated "Help the Elderly and Disabled" manual windows. The elderly can choose according to their own situation. This approach, which fully considers the special circumstances of the elderly and provides diverse choices, effectively alleviates the digital dilemma in their medical visits [15].

In addition, to strengthen the age-friendly design of smart healthcare devices, the government should require medical institutions to categorize smart healthcare devices into age-friendly and standard versions. In the age-friendly smart healthcare devices, the interface and consultation process should be simplified, and the font size should be enlarged with added explanations, to comprehensively enhance the effectiveness of smart healthcare usage for the elderly [16].

5.Conclusion

In the process of promoting the popularization of smart healthcare under Portugal's "National Digital Strategy - Digital Simplification," the digital divide among the elderly is essentially a product of the collision between the policy's modernization goals and the reality of an aging society. The governance of the digital divide among the elderly in the context of smart healthcare exhibits distinct contemporary characteristics. Strengthening the governance of the digital divide among the elderly, creating an age-friendly smart healthcare service system, and enabling the elderly to truly enjoy the digital dividends released by smart healthcare services is a crucial component of achieving social equity and inclusive development. In the future, with the continuous development of digital technology and the acceleration of the aging trend, the governance of the digital divide among the elderly will become a long-term task jointly faced by governments and all sectors of society worldwide. Portugal will also promote the popularization and development of smart healthcare through continuous policy optimization, technological innovation, and social participation, ensuring that the elderly can equally and conveniently enjoy the medical service benefits of the digital age.

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