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Advances in Management and Intelligent Technologies

Advances in Management and Intelligent Technologies (AMIT) is an international, peer-reviewed, open-access academic journal, hosted by the Fujian Strait Institute of Intelligent Equipment and managed and published by Asia-Pacific Science Press. It focuses on the latest research in the fields of management and intelligent technologies, and aims to advance both theoretical and applied research in management, technological innovation, and intelligent development.

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Editor's Foreword

Dear Scholars, Researchers, and Esteemed Readers,

We cordially invite you to explore the journal *Advances in Management and Intelligent Technologies* (AMIT). AMIT is an international peer-reviewed and open-access academic journal, co-founded by the Fujian Strait Intelligent Equipment Research Institute and Asia-Pacific Science Press. It is dedicated to offering a premier academic platform for scholars globally, fostering the dissemination and dialogue of cutting-edge research and theoretical advancements in the realms of management, intelligent technologies, and associated disciplines.

With the rapid development of science and technology, particularly in the fields of artificial intelligence, computer science, and intelligent equipment, smart management and technological solutions have become critical drivers of social and economic progress. To keep pace with these advancements, we decided to establish AMIT as a cutting-edge platform for academic exchange, promoting interdisciplinary cooperation and the collision of ideas.

The scope of this journal covers various fields, including management, computer science and technology, art and design, chemical engineering, environmental science. We particularly welcome original and innovative research papers, especially those that combine intelligent technologies with management practices or integrate technological innovation with sustainable development.

AMIT is not only a space for academic exchange, but also a bridge for fostering research collaboration and promoting technological innovation. As the publisher of the journal, the Fujian Zhongdian Straits Institute of Intelligent Equipment, we understand the vital role of academic research and technological innovation in social and economic development and global progress. Through AMIT, we hope to contribute to creating a more open, collaborative, and innovative academic environment, making a positive impact on both academia and industry.

I sincerely invite scholars from around the world to submit their original research and share the latest findings in their respective fields. We hope that AMIT will become an important platform for advancing the development of management and intelligent technologies and contribute to the intelligent transformation and sustainable development of society.

Thank you for your attention and support. We look forward to exploring the boundaries of academia with you and embracing a brighter future together.

AMIT Editor-in-Chief Enyi Lai

January 2025

创刊词

尊敬的各位学者、研究人员、以及广大读者：

欢迎您阅读《管理与智能技术进展》(Advances in Management and Intelligent Technologies, AMIT) 期刊。AMIT 是由福建省中电海峡智能装备研究院与亚太科学出版社共同创办的一本国际同行评审和开放获取学术期刊，旨在为全球学者提供一个高水平的学术平台，促进管理学、智能技术及相关领域的最新研究成果和理论交流。

随着科技的飞速发展，尤其是在人工智能、计算机科学与技术、以及智能装备领域的创新突破，智能化的管理和技术解决方案正日益成为推动社会与经济发展的重要力量。为了紧跟这一趋势，我们决定创办 AMIT 期刊，旨在为学术界提供一个前沿的学术交流平台，促进不同学科之间的跨界合作与思想碰撞。

本刊的收录范围涉及管理学、计算机科学与技术、艺术与设计、化学工程、环境科学等多个领域。我们特别欢迎原创性强、具有创新意义的研究论文，尤其是那些结合智能技术与管理实践、技术创新与可持续发展相结合的跨学科研究成果。

AMIT 期刊不仅仅是一个学术交流的空间，它还致力于搭建一个促进科研合作与推动技术创新的桥梁。作为期刊的主办单位——福建省中电海峡智能装备研究院，我们深知学术研究和科技创新对社会经济发展及全球进步的重要作用。我们希望通过 AMIT 期刊，推动更加开放、合作、创新的学术环境，为学术界和行业的进步做出积极贡献。

在此，我诚挚地邀请全球学者积极投稿，分享您在各自领域的最新研究成果。我们期望本刊能够成为推动管理学和智能技术领域发展的重要平台，也希望 AMIT 能够为推动社会的智能化转型与可持续发展贡献一份力量。

感谢您的关注与支持，期待与您一起共同探索学术的边界，迎接更美好的未来。

《管理与智能技术进展》期刊主编 赖恩毅

2025 年 4 月

The Impact of Public Health Digitization on Urban Residents' Travel Demand

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Abstract: The novel coronary pneumonia epidemic has led to dramatic changes in both the order of life and consumer behavior. Major public health and safety issues are a serious impediment to a healthy tourism industry. Therefore, it is necessary to study the impact of digitization of public health on the tourism demand of urban residents. In this paper, we develop a tourism demand model and analyze the factors influencing tourism demand. Based on data related to urban residents' tourism collected from statistical yearbooks, the impact of public health digitization on urban residents' tourism demand is studied using methods such as the attractiveness of tourist destinations. The validation session is carried out in terms of both time series and spatial distribution. The results of the impact on the time series tourism demand show that the number of tourists increased by 287.63% in just one year. The total number of tourists in China reached 1,844,900. The growth rate of total tourism consumption was up to 582.47%. The tourism trip rate increased to 213.47%. The results of the spatial distribution impact narrowed the ratio of the share of different value zones to the total number of tourists in the country, minimizing from 0.33, 0.49, 0.11 to 0.35, 0.38, 0.31, and from 0.71, 0.2, 0.1 to 0.37, 0.34, 0.33, respectively. It is thus clear that digital technology is a powerful tool for the full recovery of tourism in the post-epidemic era. Digital transformation of public health can better contribute to the revitalization of tourism and enhance the safety of consumers' travel.

Keywords: Digital Technology; Public Health; Urban Dwellers; Travel Demand; Novel Coronary Pneumonia Outbreak

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1. Introduction

The sudden outbreak of a novel coronary pneumonia epidemic has caused a huge impact on the economy in all sectors, and more so on the tourism industry^[1-4]. The World Economic Trends in Tourism report mentions a significant decline in global tourist arrivals and tourism revenues in 2020, down 39.76% and 43.19% respectively from the same period. The level of economic benefits is straightforward to WWII. Meanwhile, the Report on the Development of China's Travel Service Industry mentions that the new coronary pneumonia epidemic not only gave a double shock to the tourism industry on the demand side and supply side, but also put more pressure in reconstructing tourists' confidence and behavioral preferences^[5-6]. The recovery of the tourism industry is facing unprecedented challenges. The epidemic has completely awakened the awareness of life and public health and safety of the whole population, and people have started to focus on public health and safety in tourist places^[7-10]. Safety needs have now become the first consideration for all travelers. In addition to the novel coronary pneumonia epidemic, public health safety issues in the tourism development process include health events such as food poisoning and

infectious diseases^[11-15]. These public health problems can not only ruin tourists' mood of travel and create a bad impression of the scenic spot, but also hinder the development of tourist places^[16-19]. Therefore, it is necessary to strengthen the public health safety of the industry in today's rapidly developing tourism industry.

Since the outbreak of SARS, scholars at home and abroad have been paying higher attention to tourism safety. As the research continues, the perspectives and methods of inquiry are getting richer and the system is getting better. For example, literature^[20] integrated flood scenario simulation and GIS network analysis for different river flood scenarios in the central area of the outer ring of Shanghai to assess the spatial accessibility of emergency response for key urban public services. After an experimental study, this quantitative assessment method can provide a basis for decision making in flood tourism emergency management. The literature^[21] interviewed stakeholders of local tourism interests. The theoretical basis and development of natural disaster management was advanced by investigating stakeholders' consideration of the role of tourism before and after the earthquake, and the disaster management actions they took. The literature^[22] selected Shijiazhuang Jintawan scenic area as the target, in order to analyze and predict the traffic demand of the scenic area, a two-layer optimization model of one-way traffic organization was constructed. Based on the model solution results of the simulated annealing algorithm, the contingency plan is developed. The feasibility of the contingency plan is verified by VISSIM simulation. The model can effectively solve traffic congestion, avoid secondary accidents and ensure the economic benefits of scenic spots. The literature^[23] aimed to analyze the negative effects of urbanization, disasters on tourism in RCEP countries, using ADF and PP for 1995-2018 data, causality tests, quantile regression and fixed effects panel models. In response to the increasing temperature, rainfall and carbon emissions, they propose corresponding disaster prevention measures in order to facilitate sustainable tourism development. The literature^[24] used the municipality of Aljezur, located in the Algarve Nature Reserve in Portugal, as a study area to investigate multiple surfers and swimmers regarding personal safety, conflicts between beach users, and management strategies for surf tourism activities. By reaching a consensus on the security of the tourism area, conflicts can be effectively reduced and the sustainable management of surf tourism in the territory can be enhanced. The literature^[25] identifies the best risk management options regarding natural disaster events based on the raw data collected from surveys. Research data shows that tourism risk management strategies have greater utility in reducing the impact of natural disasters and protecting life and property, and are an effective means of preventing and controlling potential risks. By compiling the literature, it is clear that the current more mainstream perspective on tourism safety control is more limited, focusing mostly on natural disasters and risk management, and less on public health safety and the needs of tourists under its premise. Exploring tourism safety issues in the new situation from a public health perspective has become a hot topic of discussion in the tourism industry.

To break the barrier that public health and safety issues pose to the tourism industry, public health is beginning to transform digitally. This paper is aimed at exploring the tourism demand of urban residents. The attractiveness of tourist places is used to reflect the range of attractiveness of the target places to tourists. A spacing cumulative curve was used to cumulatively analyze the travel demand of urban residents before and after the digital transformation of public health. Spatial autocorrelation and other research methods are used to detect the spatial distribution patterns and clustering characteristics of tourists. Based on the selected tourism data and tourism demand impact factors such as direct data, indirect data and supplementary data, the impact of public health digitization on tourism demand of urban residents is explored in terms of time series and spatial distribution. This paper is dedicated to this research topic, mainly to provide effective improvement measures and suggestions for the management of public health and safety in tourist places, and to provide a reference for carrying out public health and safety management. At the same time, to further promote the sustainable development of tourism.

2. Research Methodology and Research Data

2.1 Research Methodology

2.1.1 Attractiveness of tourist places

Tourist place attractiveness is used to reflect the range of attraction of the target place to tourists and is usually expressed as a radius^[26]. The attractiveness increases with the increase of the radius value. Assume that the share of tourism demand in the

n st tourist origin is i , and the spatial distance between the place and the x_i st tourist destination is j . Then the attractiveness of tourist place d_{ij} is calculated by the following formula.

$$AR = \sqrt{\frac{\sum_{i=1}^n x_i^2 d_{ij}^2}{\sum_{i=1}^n x_i^2}} \quad (1)$$

In the above equation, the spherical distance can be described. The calculation formula is as follows.

$$d_{ij} = R \cdot \frac{\pi}{180} \cdot \arccos(\sin \varphi_i \sin \varphi_j + \cos \varphi_i \cos \varphi_j \cos(\lambda_j - \lambda_i)) \quad (2)$$

Where, R refers to the mean radius of the earth. (λ_i, ϕ_i) 、 (λ_j, ϕ_j) The geographic coordinates of the i first tourist origin and the j first tourist destination are indicated by the longitude and the latitude, respectively. λ is the longitude and ϕ is the latitude.

2.1.2 Spacing Accumulation Curve

The spacing accumulation curve is obtained by accumulating the amount of tourists based on the size of the distance between the sources of tourists and the spacing results. The function of this indicator is to cumulatively analyze the tourism demand of urban residents before and after the digital transformation of public health. Assume that the total tourism demand is T , and the tourism demand from the i st tourist source to the tourist target is X_i . Then the curve is calculated as shown below.

$$Y = \sum_{i=1}^n \frac{x_i}{T} \quad (3)$$

Within this equation, the value of the vertical coordinate of the curve is indicated.

2.1.3 Spatial autocorrelation

(1) Global spatial autocorrelation. To detect the spatial distribution pattern and clustering characteristics, the Moran index is used as a measure^[27]. If there is a total of N study cell, the attribute values and spatial weight matrix of the i 、 j cell are x_i 、 x_j and ω_{ij} , respectively, and the average value of x_i is \bar{x} . The elements in the spatial weight matrix are summed to obtain S_0 . Then the Moran index is solved by the following equation.

$$I = \frac{N}{S_0} \times \frac{\sum_{i=1}^N \sum_{j=1}^N \omega_{ij} (x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^N (x_i - \bar{x})^2} \quad (4)$$

(2) Local spatial autocorrelation. To compensate for the problem of incomplete access to the location of aggregation areas, the G-index and LISA index are used to describe the local spatial distribution of each study unit in more detail^[28-29]. The function of the former is to distinguish cold spot areas from hot spot areas in space, while the latter is used to explore the agglomeration dynamics of local regional spatial units and neighboring spatial units.

For n study unit, the two indices are calculated as

$$G_i^*(d) = \sum_{j=1}^n \omega_{ij} x_j / \sum_{j=1}^n x_j \quad (5)$$

$$LISA_i = Z_i \sum_{j \neq i}^n \omega_{ij} Z_j \quad (6)$$

Within the above equation, the standardized observations for the i and j spatial units are Z_i and Z_j . When G_i^* is positive and significant, location i has a relatively high value with respect to the surrounding area, i.e., the hot spot area. On the contrary, it is a cold spot area.

2.2 Data sources

Data related to the tourism industry in the target cities are analyzed using research methods such as tourist place attractiveness, spacing cumulative curves, global spatial autocorrelation and local spatial autocorrelation. The selected data are divided into three types: direct data, indirect data and supplementary data^[30-32]. The first type of data mainly originates from the China Statistical Yearbook and the China Tourism Statistical Yearbook and copies, etc. Most of the data such as tourism trips, tourism income, and per capita spending are direct data. Data such as the proportion of travel transportation

consumption, the proportion of travel entertainment consumption, and the proportion of travel food and beverage consumption are all indirect data. Such data are obtained by calculation based on direct data. Supplementary data are usually missing items obtained by interpolation and other methods based on data from other years^[33]. To ensure the reliability and scientific validity of the study results, the data units are treated uniformly. The logarithmic strategy is implemented for special data such as per capita consumption level and per capita GNP. Within this equation, the value of the vertical coordinate of the curve is indicated.

2.3 Analysis of factors influencing urban residents' tourism demand

The common goal of both tourism trip rate and tourism consumption is to realize the tourism demand of urban residents. Therefore, the tourism trip rate is set as DTR , tourism demand-side and supply-side factors as D 、 S , macro-environmental factors as M , and special event factors as E . The following defining equations for the tourism demand model are established.

$$DTR = f(D, S, M, E) \quad (7)$$

The influence factors contained in each factor are shown in Table 1.

Table 1 Tourism demand impact factors

Demand factors	Impact factors
Demand-side factors	Free time, income level, consumption habits, risk expectations
Supply-side factors	Prices and quality of products and services in the tourism industry
Macro environmental factors	Implementation efforts of relevant departments in marketing and mobility constraints
Special event factors	Major festivals, abnormal emergencies, etc.

3.The impact of public health digitization on tourism demand of urban residents

To obtain a precise analysis of the impact of public health digitization on urban residents' travel demand, the experiments are conducted from two perspectives: time series and spatial distribution, respectively. Time series is mainly to do regression or classification problems by the backward and forward order of time, and the main characteristic of the data is one-dimensional tabular data, and one column of the data is a clear amount of time. Spatial distribution is the distribution of geographical things with regions.

3.1 Impact of tourism demand based on time series

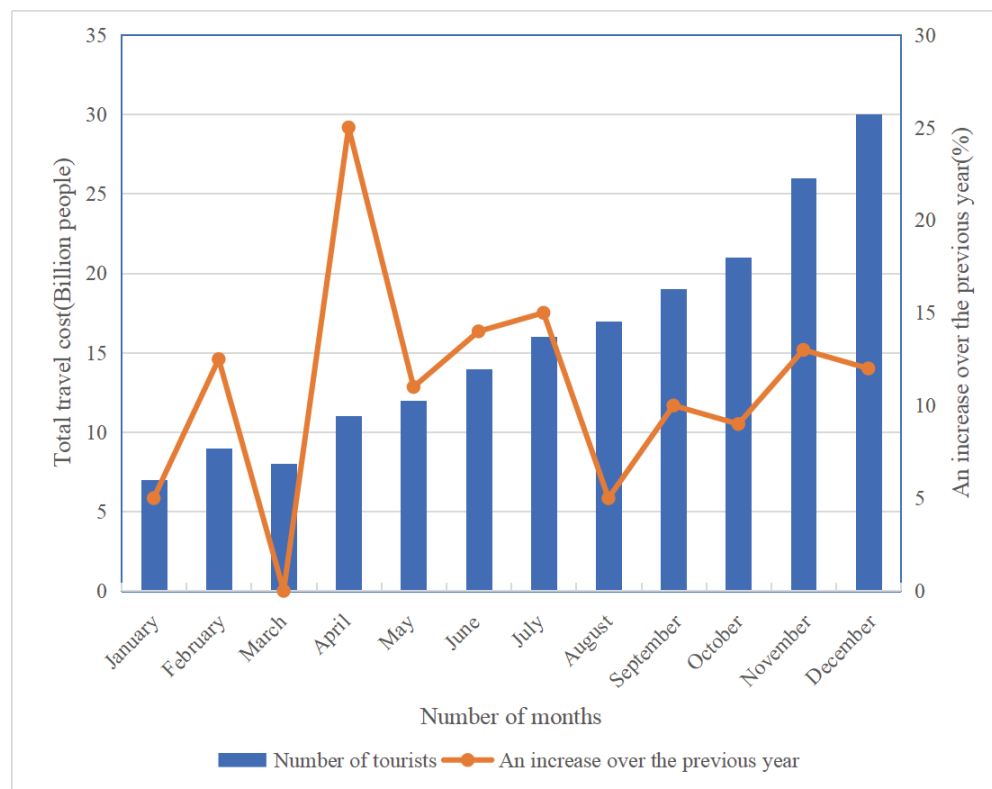
3.1.1 Number of tourists

Figure 1(a) shows the number of tourists and the growth rate after the digital transformation of public health. As can be seen, digital technology has significantly increased tourists' sense of security by visually showing them the current number of confirmed epidemics, suspected cases, and other public health information in the region through methods such as descriptive statistics and cluster analysis. This enables tourists to travel with confidence and pleasure. As a result, a good trend of exponential growth in the number of tourists is formed. Based on the changes in the number of tourists, it can be seen that the number of tourists has been rising after the digitization of public health. In the first month the number of tourists was 75,200 and in only one year it has increased by 287.63%. The number of tours in the 12th month has been as high as 291,500. It is 3.88 times more than the first month. In terms of the growth rate of tourism numbers, the growth rate is gradually stabilizing. Due to the recurrence of major public health events like the new coronary pneumonia epidemic, the growth rate fluctuated in the first period. From the ninth month onward, the growth rate of the number of tourists gradually stabilized and basically remained between 11% and 13%.

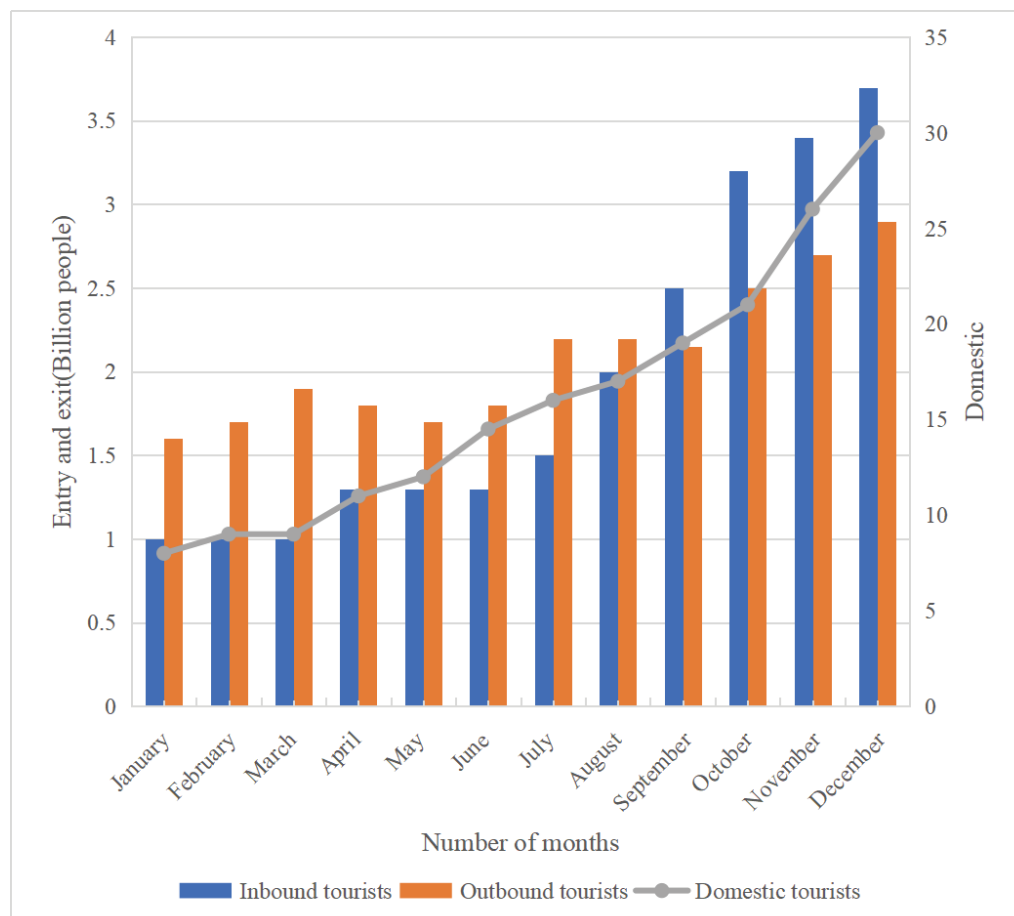
Figure 1(b) shows the number of tourists under different demands such as domestic tourism, inbound tourism and outbound tourism. It can be seen that domestic tourism dominates the tourism industry today. Compared to inbound and outbound tourism, domestic tourists are not only growing faster, but also in greater numbers. With a larger domestic population base, the importance of the domestic tourism market and its public health and safety cannot be overstated. Digital technology for public health allows tourists to visualize local epidemic developments and alleviate their anxiety and panic by displaying region-wide epidemic information in real time. As a result, the total number of domestic tourists reached 1,844,900 in the last year, 28.44 times and 29.13 times more than the number of inbound and outbound tourists, respectively.

Figure 1 Impact of public health digitization on the number of tourists

(a) Number of tourists and growth rate



(b) Number of tourists with different needs

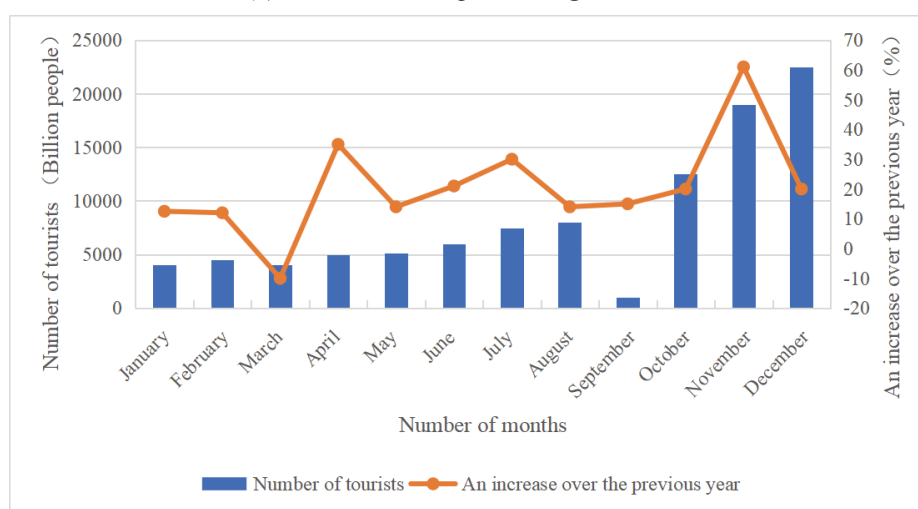


3.1.2 Tourism consumption

Figure 2 (a) shows the total tourism consumption and its growth rate. The changes show that the total tourism consumption has increased significantly. It increased from 34.22 million yuan in the first month of public health realization digitization to 233.54 million yuan in the 12th month, a growth rate of 582.47%. This shows that the consumption expenditure of urban residents on tourism has been on the rise under the influence of the digital transformation of public health. The total level of tourism consumption is constantly increasing. From the point of view of the growth rate, the total spending on tourism fluctuated a lot in the first period and stabilized by the movement. Despite some periods of negative growth rates, the majority of the time it stabilized between 15% and 22%, with an overall stabilization trend. This is because digital technology has contributed greatly to epidemic prevention and control by using big data association rules. By collecting personal travel information in a targeted manner, personal epidemic prevention and health information codes are formed. This enables the traceability of tourists' whereabouts records to avoid cross-infection and to grasp the "golden window" for emergency response to public health events.

Figure 2 Impact of the digitization of public health on the level of tourism consumption

(a) Tourism consumption and growth rate



(b) Per capita consumption and growth rate

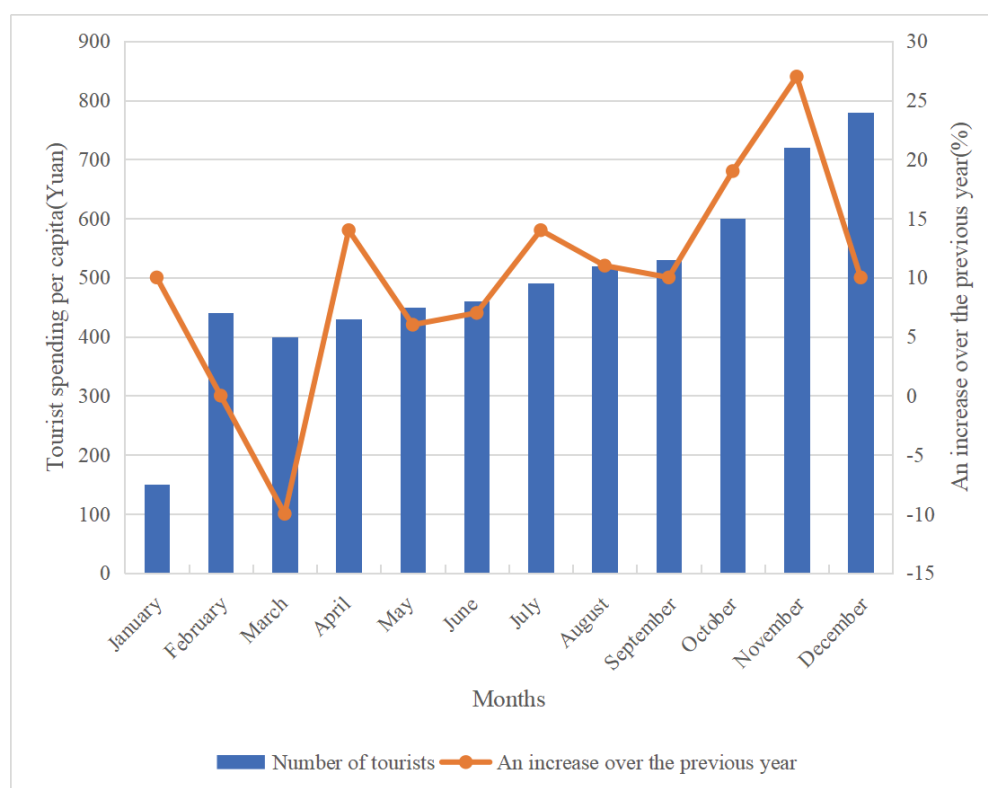
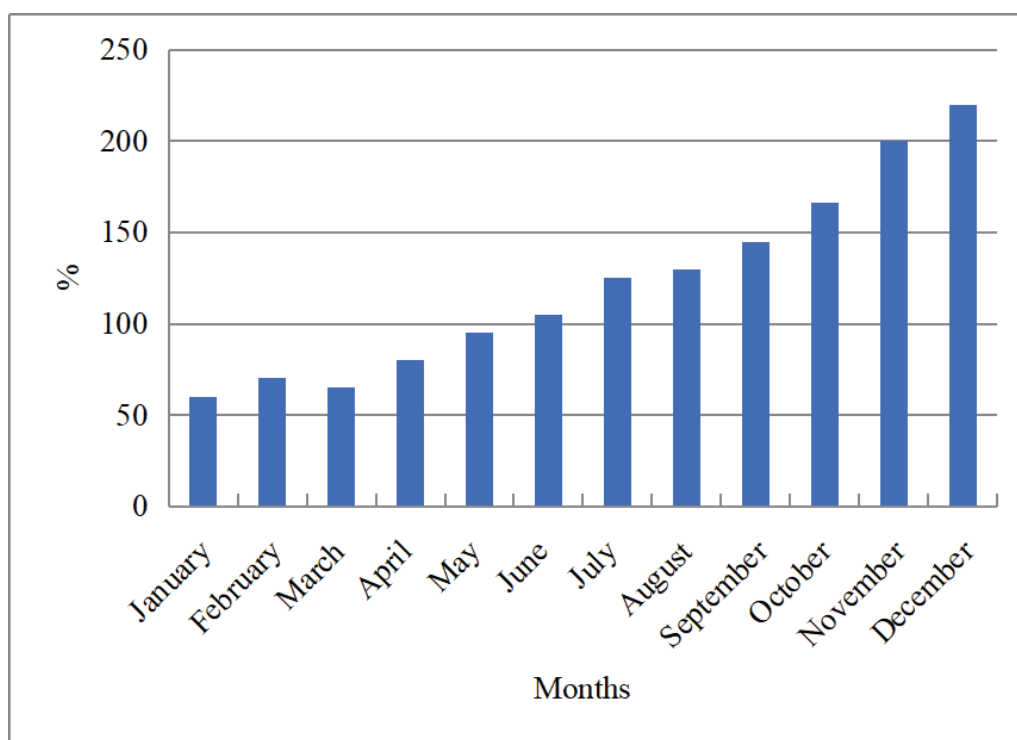


Figure 2(b) shows the per capita consumption of tourism and its growth rate. As can be seen from the changes, the level of travel per capita consumption has also shown a continuous increase. It increased from \$434.2 in the first month to \$782.5 in the 12th month. This is inextricably linked to public health's digital data sharing and communication strategy. Digital technology better empowers public health emergencies, ensures effective data sharing and interaction, and meets the needs of visitors to make dynamic travel decisions. In terms of the growth rate of per capita consumption, the variation of the growth rate of tourism per capita consumption is more similar to the trend of the growth rate of total consumption, showing the same small and steady growth. Although there were periods of negative growth, it was largely maintained at 2% to 6% in the later years.

3.1.3 Tourism travel rate

Figure 3 shows the travel trip rate of urban residents. The change of travel trip rate in the last year shows that the travel rate of urban residents has been increasing and reached an average of 2 trips per person. It has increased from 59.43% in the first month to 213.47% in the 12th month. That is, in the first month, the demand for travel by urban residents was 0.59 trips per person on average, and by the 12th month the demand for travel by residents reached an average of 2.13 trips per person. This means that digital technology has effectively improved the efficiency of resource deployment by virtue of blockchain's advantages of high synchronization, transparency of information transmission and non-tamperability. It enables the demand for accurate matching of material supply for public health events to be met, giving tourists maximum travel safety and accelerating the rapid growth of residents' travel demand. Overall, the travel demand of urban residents is on the rise.

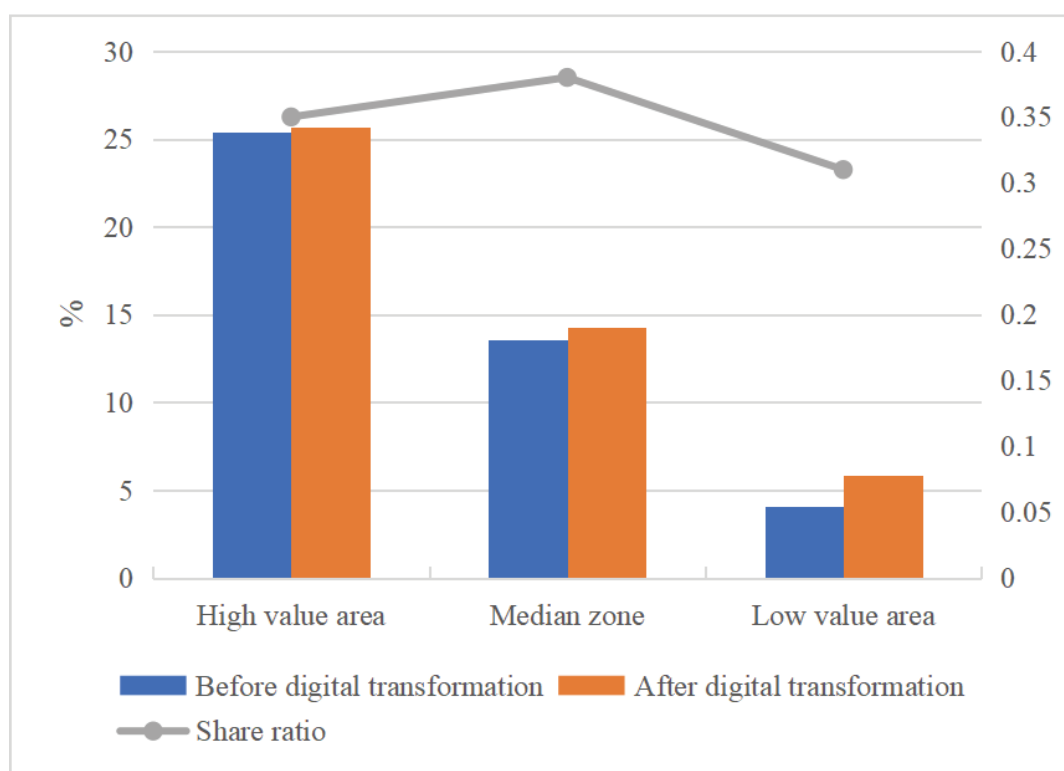
Figure 3 Impact of public health digitization on tourism travel rate



3.2 Tourism demand impact based on spatial distribution

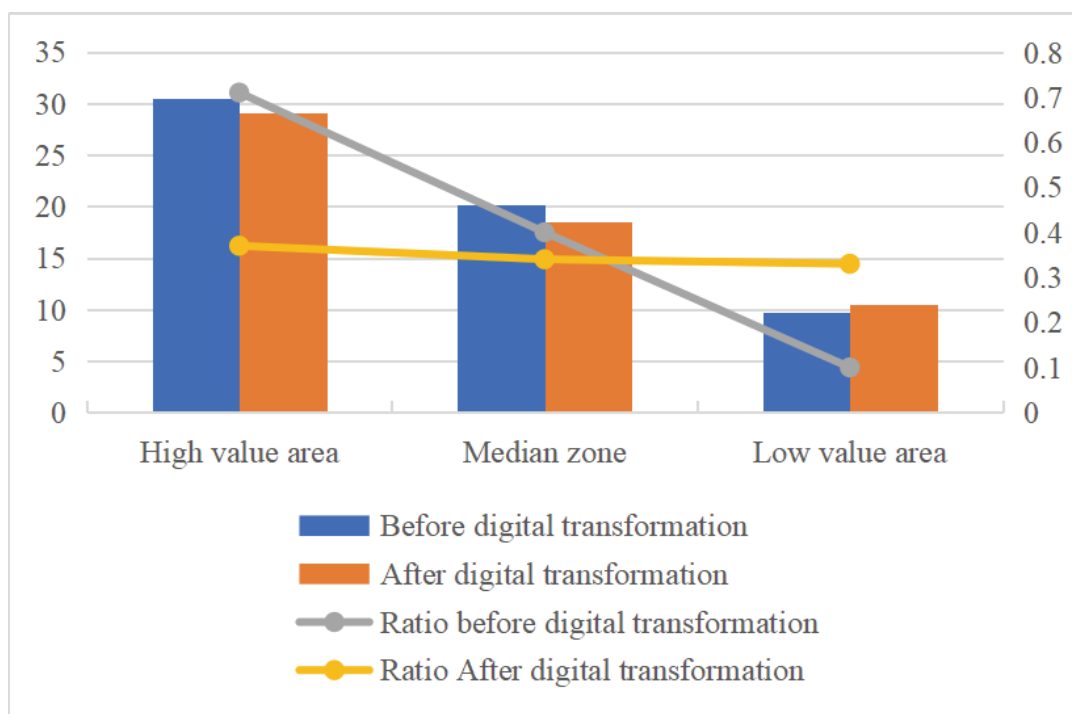
Using a provincial city as the research target, Arc GIS 11.1 was used to do spatial interpolation of relevant tourism data to explore the spatial and temporal distribution status of the research target. The relevant tourism data included data on the ratio of domestic tourist arrivals to total tourist arrivals from the province's domestic tourist sources before and after the digital transformation of public health practices, as well as data on the ratio of domestic tourist arrivals from each city to domestic tourist arrivals in the province. Surface analysis was used to extract interpolated contours, and the visitor volume share was divided into three zones by the natural interruption method, i.e., high value zone, medium value zone, and low value zone. The tourist demand of visiting city tourists is shown in Figure 4. The spatial structure characteristics of the tourist demand of the visiting city tourists are shown in Figure 5.

Figure 4 Tourist demand of visiting city tourists



From the changing characteristics of the spatial distribution of tourists in visiting cities in Figure 4, it can be seen that before digital transformation, the share of high value area in the source market ranges from 13.51% to 25.42%, the share of medium value area ranges from 4.11% to 13.51%, and the share of low value area ranges from 0% to 4.11%, except for the target provinces and cities to which they belong. The ratio of the share of different value zones to the total number of tourists in the China is 0.33, 0.49, and 0.11. The source cities in the high value zone have the strongest tourism demand due to the advantages of advanced technology, economic development, and convenient transportation, despite the existence of certain market distance and public health hazards. The source cities in the medium value zone are mostly distributed within thousands of kilometers from the target provinces and cities, and are distributed in a band. The source cities of tourists in the low value zone are mostly located in western urban areas with relatively backward economy and technology, poor transportation, little communication with the outside world, and long cultural and transportation distances, which further significantly weakened the tourism demand of residents under the influence of the new coronary pneumonia epidemic. This suggests a significant aggregation and spatial variation in tourism from source to target provinces and cities prior to upgrading the public health sector using digital technologies. The digital transformation of public health minimizes the share of high and low value areas in terms of the share of tourist volume, as seen in the tourism demand of tourists visiting cities after the digital transformation. This resulted in a small expansion of the range of high value area shares to 14.27% to 25.67%, a range of medium value area shares to 5.88% to 14.27%, and a significant expansion of the range of low value area shares to 0% to 5.88%. The ratio of the share of different value zones to the total number of national tourists is 0.35, 0.38, and 0.31, respectively, in which the source cities of the middle value zone and the low value zone are shifted to each other, and the spatial distribution form is also changed. The source cities of the median-value area are distributed in a dotted pattern, and the source places of tourists in the low-value area are partly transferred from the median-value area. Compared with the pre-transformation period, the spatial differences are significantly reduced. In summary, by relying on big data technology to create an intelligent public health and safety governance and service system and sound public health information, we can minimize the social harm caused by epidemics and prevent them before they happen. Thus, we can reduce the travel barriers brought by market distance and public health and other issues to tourists, and strengthen the tourism demand of urban residents.

Figure 5 Tourism demand of tourists in the host city



According to the characteristics of the change of spatial distribution of tourists in the receiving cities (see Figure 5), it can be seen that before digital transformation, only 4.86% of the target provinces and cities are above the average value, and 16.48% are below the average value. The total shares of the high value, medium value and low value areas of visitor reception are 0.71, 0.2 and 0.1, respectively. among them, the cities in the medium value area are generally distributed near the high value area, while the low value area is mostly distributed in a band or point-like distribution within the province. The spatial differences are extremely significant. While public health has undergone digital transformation, the range of high value areas of visitor reception has narrowed to 18.54%~29.16%, the range of medium value areas has expanded to 10.55%~18.54%, and the range of low value areas has expanded to 0%~10.55%. The total shares of different value zones are 0.37, 0.34, and 0.33, respectively. after digital technology to improve the epidemic feedback system based on big data and blockchain technology, public health safety issues are more precisely managed. It makes the spatial clustering of urban residents' travel demand in the target provinces and cities insignificant and reduces the spatial distribution differences. In summary, after the digital transformation of public health, the distribution of high, medium and low value areas of tourist reception in the province and city changed less and the share of tourists increased. The shares of target municipalities are increasingly balanced, and the spatial variability gradually diminishes.

4. Conclusion

The steady socio-economic development promotes the growing tourism demand. Accurate analysis of the impact of tourism demand of urban residents after the digital transformation of public health is not only important for the revival and reconstruction of tourism, but also plays a vital role in expanding domestic demand and promoting the sustainable development of the national economy. This paper is based on three types of tourism-related data: direct data, indirect data and supplementary data.

(1) The correlation between the digitalization of public health and the tourism demand of urban residents is investigated through the research methods of tourism place attractiveness, spacing cumulative curve, global spatial autocorrelation and local spatial autocorrelation, combined with tourism demand influence factors. Based on the impact analysis data, it is easy to see that digital technology has provided unlimited possibilities for the rapid development of tourism. It has led to a rising number of tourists in the post-epidemic era, and the number of tourists has reached 291,500 in just one year, an increase of 287.63%. The growth rate has gradually stabilized, basically remaining between 11% and 13%.

(2) The total number of domestic tourists reached 1,844,900, 28.44 times and 29.13 times more than the number of inbound and outbound tourists respectively. Total tourism spending increased significantly, with a growth rate of 582.47%, and was able to stabilize between 15% and 22% most of the time. Digital technology has improved public health security, given maximum travel safety to tourists and accelerated the rapid growth of tourism demand among the population.

(3) The change in the rate of travel trips in the last year shows that the rate of travel trips by urban residents has been increasing, reaching an average of 2 trips per person. From 59.43% in the first month, it has increased to 213.47% in the 12th month. That is, in the first month, the demand for travel by urban residents was 0.59 trips per person on average, and by the 12th month the demand for travel by residents reached an average of 2.13 trips per person. This means that digital technology has effectively improved the efficiency of resource deployment by virtue of blockchain's advantages of high synchronization, transparency of information transmission and non-tamper ability.

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Conflict of Interests

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Detecting Anomalies in Blockchain Transactions Using Spatial-Temporal Graph Neural Networks

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Abstract: Blockchain networks have become a cornerstone of decentralized finance and digital asset management, yet they remain susceptible to fraudulent activities, money laundering, and illicit financial transactions. Traditional anomaly detection methods, including rule-based systems and supervised machine learning models, often struggle to generalize across evolving blockchain transaction patterns due to their reliance on static heuristics and manually engineered features. Graph-based learning techniques offer a more robust approach by leveraging the inherent structure of blockchain transactions, where wallets and transactions form a dynamic graph.

This study proposes a novel Spatial-Temporal Graph Neural Network (STGNN)-based anomaly detection framework for blockchain transactions. By modeling transaction flows as evolving graphs, the proposed system captures both spatial dependencies between wallets and temporal patterns in transaction sequences. The framework employs Graph Convolutional Networks (GCN) or Graph Attention Networks (GAT) to extract spatial representations, while Gated Recurrent Units (GRU) or Temporal Convolutional Networks (TCN) model the time-dependent evolution of transaction behaviors. The fusion of these spatial-temporal features enables the detection of anomalous transactions that deviate from expected network behaviors. Experimental evaluations on real-world blockchain datasets demonstrate that the STGNN-based model achieves higher detection accuracy, lower false positive rates, and better adaptability than traditional fraud detection techniques. The study further explores the system's scalability and generalization across different blockchain networks, revealing its potential for real-time monitoring of illicit financial activities. These findings highlight the effectiveness of graph-based deep learning models in strengthening blockchain security and provide a foundation for future research in decentralized fraud detection, anti-money laundering (AML) compliance, and intelligent financial surveillance.

Keywords: Blockchain; Anomaly Detection; Graph Neural Networks; Spatial-Temporal Analysis; Fraud Detection; Transaction Networks; Decentralized Finance

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1.Introduction

Blockchain networks have transformed financial transactions by enabling decentralized, transparent, and tamper-resistant digital asset exchanges. However, their pseudonymous nature and lack of centralized oversight create an environment where illicit activities such as fraud, money laundering, and dark market transactions can proliferate. Detecting such anomalies in blockchain transactions presents significant challenges, as traditional fraud detection systems struggle to adapt to the

dynamic, high-dimensional, and rapidly evolving nature of blockchain transaction flows. The complexity of blockchain transactions arises from the continuous and asynchronous nature of financial interactions, where participants create, send, and receive transactions in a decentralized setting^[1]. Unlike conventional banking systems, where institutions regulate and monitor transactions, blockchain networks rely on distributed ledger technology, making it difficult to implement uniform anomaly detection mechanisms.

Existing anomaly detection methods rely on rule-based heuristics, statistical models, and supervised machine learning approaches. While these methods can identify known fraud patterns, they often fail when confronted with novel, evolving transaction behaviors^[2]. Rule-based systems, for instance, require continuous manual updates and struggle with new forms of financial deception, while traditional machine learning models lack the ability to capture complex relationships and dependencies between transactions over time. The effectiveness of these approaches diminishes as fraudsters develop sophisticated evasion techniques, such as transaction obfuscation, address mixing, and cross-chain fund transfers, which further complicate anomaly detection efforts. Additionally, blockchain transactions exhibit properties such as pseudo-anonymity, high transaction volume, and irregular interaction patterns, making the task of fraud detection even more complex^[3].

Graph-based analysis provides a powerful foundation for blockchain fraud detection by treating transactions as structured networks, where wallets act as nodes and transactions form edges. Unlike tabular representations of financial transactions, which fail to capture relational dependencies, graph structures allow for a more detailed understanding of transaction flows, money movement, and behavioral patterns. However, static graph models fail to account for the evolving nature of transaction flows, which change dynamically as new transactions are recorded on the blockchain^[4]. A model that does not consider temporal dependencies may incorrectly classify transactions, as it fails to recognize that fraudulent behaviors often involve coordinated efforts spanning multiple time intervals. To address this, spatial-temporal graph neural networks (STGNNs) have emerged as a promising approach, allowing for the integration of spatial dependencies and temporal evolution within blockchain transaction graphs.

This study proposes an STGNN-based anomaly detection framework that leverages both graph-based feature extraction and time-series modeling to identify fraudulent or suspicious blockchain transactions. By incorporating GCN or GAT for spatial learning and GRU or TCN for temporal analysis, the model effectively captures both structural transaction patterns and evolving behavioral trends. Unlike traditional models, which rely on static data snapshots, this framework continuously learns from new transactions, improving its adaptability to novel fraud patterns and emerging threats.

To evaluate the effectiveness of this approach, the model is tested on real-world blockchain datasets, benchmarking its performance against rule-based anomaly detection, traditional machine learning classifiers, and static graph models. The results demonstrate that the STGNN model outperforms existing approaches in terms of accuracy, false positive reduction, and adaptability to new fraud tactics. Furthermore, the study explores scalability, computational efficiency, and deployment feasibility, offering insights into how this framework can be integrated into real-time blockchain security monitoring systems^[5]. The findings contribute to the growing body of research on blockchain security by providing a scalable and adaptable approach for financial anomaly detection.

By addressing the limitations of existing anomaly detection models and leveraging the power of graph-based learning, this research provides a robust methodology for securing blockchain transactions against illicit activities. With the increasing adoption of blockchain technology in various financial sectors, ensuring the integrity and security of transactions is critical for maintaining trust and regulatory compliance. The proposed approach offers a promising direction for future advancements in blockchain fraud detection and financial crime prevention, paving the way for improved monitoring and enhanced security in decentralized financial ecosystems.

2.Literature Review

Detecting anomalies in blockchain transactions has become an essential task due to the increasing prevalence of fraudulent activities, including money laundering, phishing scams, and illicit financial transfers. Traditional fraud detection techniques have been applied to blockchain networks with varying degrees of success, but the unique characteristics of blockchain

transactions—such as decentralization, pseudo-anonymity, and the evolving nature of transaction behavior—pose significant challenges^[6]. Various methods, including rule-based heuristics, statistical models, and machine learning techniques, have been proposed for detecting abnormal transaction patterns. However, these approaches often fail to capture the complex relational dependencies and evolving nature of fraudulent activities within decentralized financial systems.

Early blockchain fraud detection systems relied on rule-based mechanisms that flagged transactions based on predefined heuristics such as unusually large transactions, rapid transfers across multiple addresses, and sudden spikes in activity from newly created wallets. While these methods were effective for identifying well-known fraud patterns, they required constant manual updates and suffered from high false positive rates. Additionally, since fraudsters continuously adapt their tactics to bypass detection, rule-based systems often become obsolete, requiring frequent modifications to remain effective. Statistical anomaly detection techniques, including clustering and entropy-based measures, have also been explored for detecting unusual patterns in blockchain transactions. These methods analyze the statistical distribution of transaction features, identifying outliers that deviate from expected behavioral norms. However, they typically do not consider the interconnected nature of transactions, meaning they struggle to detect coordinated fraud operations involving multiple accounts^[7].

Machine learning techniques have been increasingly applied to blockchain fraud detection. Supervised learning models, such as decision trees, random forests, support vector machines, and deep neural networks, have shown promising results when trained on labeled datasets of fraudulent and legitimate transactions^[8]. These approaches, however, require large amounts of labeled data, which are often unavailable due to the difficulty in accurately classifying illicit transactions. Furthermore, as fraudsters develop new techniques, supervised models may fail to generalize beyond their training data, rendering them ineffective against emerging threats^[9]. Unsupervised learning methods, including autoencoders and clustering algorithms, attempt to identify anomalies without labeled data by detecting deviations from learned normal behavior^[10]. While these methods can be useful for uncovering unknown fraud patterns, they often produce high false positive rates, as they lack contextual understanding of transaction relationships.

Given the relational nature of blockchain transactions, graph-based anomaly detection has emerged as a promising approach^[11]. Blockchain transactions naturally form a graph structure where wallets serve as nodes and transactions represent edges, allowing graph-based models to capture fund movement patterns and detect suspicious clusters. Previous studies have employed graph clustering, centrality analysis, and community detection techniques to identify abnormal transaction behaviors^[12]. Fraudsters often engage in money laundering schemes that involve transferring funds through a web of intermediary wallets, creating transaction subgraphs that differ from legitimate transaction structures^[13]. Graph-based methods have been effective in identifying these patterns by analyzing node connectivity, transaction frequency, and structural anomalies in transaction networks. However, traditional graph-based models typically rely on handcrafted features, requiring domain expertise to design effective fraud detection heuristics^[14]. Additionally, most existing graph-based approaches treat blockchain transaction networks as static, failing to account for the temporal evolution of fraudulent behaviors. Since fraudsters frequently change addresses and adjust transaction strategies over time, static graph representations are insufficient for real-time fraud detection^[15].

Graph neural networks (GNNs) have revolutionized the analysis of structured data, making them particularly useful for blockchain anomaly detection. Unlike traditional graph-based methods that rely on manually designed features, GNNs learn transaction representations automatically by aggregating information from neighboring nodes^[16-20]. Through iterative message-passing processes, GNNs capture local and global dependencies in transaction networks, enabling more accurate fraud detection. Standard GNN models, such as GCN and GAT, have been used to classify fraudulent transactions by learning patterns from historical transaction graphs. These models outperform conventional machine learning approaches by leveraging the relational properties of blockchain data. However, most existing GNN-based approaches operate on static graph representations, limiting their ability to detect evolving fraud tactics that unfold over time^[21].

To address the limitations of static graph-based anomaly detection, STGNNs have been introduced as a more advanced solution^[22]. Unlike conventional GNNs that focus solely on spatial relationships between transactions, STGNNs integrate temporal dependencies, enabling the detection of fraudulent behaviors that develop over multiple time intervals. This

capability is particularly important for blockchain anomaly detection, as fraudulent activities often involve sequences of transactions designed to obfuscate illicit fund movements^[23]. STGNNs combine spatial and temporal learning by utilizing GCN or GAT layers for capturing transaction dependencies and employing recurrent neural network components such as GRU, long short-term memory networks (LSTM), or TCN to model transaction flow over time. By learning both spatial and temporal features, STGNNs can recognize previously unseen fraud patterns, reducing false positive rates and improving detection accuracy^[24].

Recent studies have shown that STGNN-based models outperform both static GNNs and traditional fraud detection techniques^[25]. These models not only enhance the accuracy of blockchain anomaly detection but also improve adaptability to emerging fraud schemes by continuously learning from evolving transaction behaviors^[26]. However, despite their advantages, STGNNs face challenges related to computational complexity, explainability, and real-time deployment. Training deep graph neural networks requires significant computational resources, particularly when applied to large-scale blockchain datasets^[27]. Additionally, security analysts require transparent explanations for why certain transactions are flagged as fraudulent^[28, 29]. Future research should focus on developing more efficient STGNN architectures, improving model interpretability, and exploring hybrid approaches that combine STGNNs with reinforcement learning for adaptive fraud detection.

The evolution of blockchain anomaly detection methods highlights the growing need for sophisticated AI-driven security solutions that can adapt to rapidly changing fraud techniques. While traditional rule-based systems and supervised learning models remain widely used, they fall short in addressing the complexities of modern blockchain transactions. Graph-based approaches, particularly STGNNs, offer a powerful alternative by leveraging both spatial and temporal transaction features. As blockchain technology continues to expand into decentralized finance, non-fungible tokens, and cross-chain asset transfers, ensuring transaction security will become increasingly critical. The integration of STGNNs into blockchain monitoring systems presents a viable path toward more effective, scalable, and real-time fraud detection frameworks.

3. Methodology

3.1 Graph Representation of Blockchain Transactions

Blockchain transactions can be naturally represented as a graph, where wallets serve as nodes and transactions create directed edges between them. Each edge carries attributes such as transaction amount, timestamp, and frequency of interactions, forming a rich, structured dataset for anomaly detection. Unlike traditional tabular representations of financial data, graph-based modeling allows for the capture of relational dependencies between wallets and the evolution of transactional behaviors over time.

To construct the graph representation, raw blockchain data is preprocessed to extract key transaction features, including sender and receiver addresses, transaction amounts, timestamps, and transaction fees. A directed graph is then built, with edge weights representing the frequency and volume of transactions between wallets. Given that fraudulent activities often involve complex, interconnected transactions, this graph-based approach enables the detection of hidden patterns that traditional rule-based models fail to recognize.

A temporal component is incorporated into the graph to account for the evolving nature of transaction patterns. Transactions occurring within defined time intervals are grouped into subgraphs, allowing for sequential analysis of fund movement patterns. By capturing both spatial and temporal aspects of blockchain transactions, this method enhances the ability to identify anomalies that span multiple time periods.

3.2 Spatial-Temporal Graph Neural Network Architecture

The anomaly detection model is based on a spatial-temporal graph neural network (STGNN), designed to analyze both the structural and sequential characteristics of blockchain transactions. The model consists of two main components: a spatial feature extraction module and a temporal sequence learning module.

The spatial module applies graph convolutional networks (GCN) or graph attention networks (GAT) to extract relational dependencies between wallets. These layers aggregate information from neighboring nodes, enabling the model to learn transaction patterns and detect abnormal fund movements. The spatial module is particularly effective in identifying fraud schemes such as hub-and-spoke transactions, mixing services, and laundering networks, where multiple accounts are used to

obscure illicit activities.

The temporal module utilizes gated recurrent units (GRU) or temporal convolutional networks (TCN) to capture time-dependent transaction patterns. By modeling how transactions evolve over sequential time steps, this component enhances the model’s ability to recognize fraudulent activities that unfold over time. Fraudulent behaviors, such as structuring transactions to evade detection or executing rapid fund transfers, can be effectively identified through this temporal learning mechanism.

The outputs from both the spatial and temporal modules are combined into a fused feature representation, which is passed through fully connected layers to generate an anomaly score for each transaction. Transactions with anomaly scores above a predefined threshold are flagged as potentially fraudulent and subjected to further analysis.

Figure 1 illustrates the graph representation of blockchain transactions, demonstrating how wallet interactions and transaction flows are structured in a directed graph.

Graph Representation of Blockchain Transactions

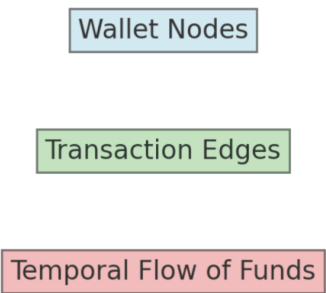
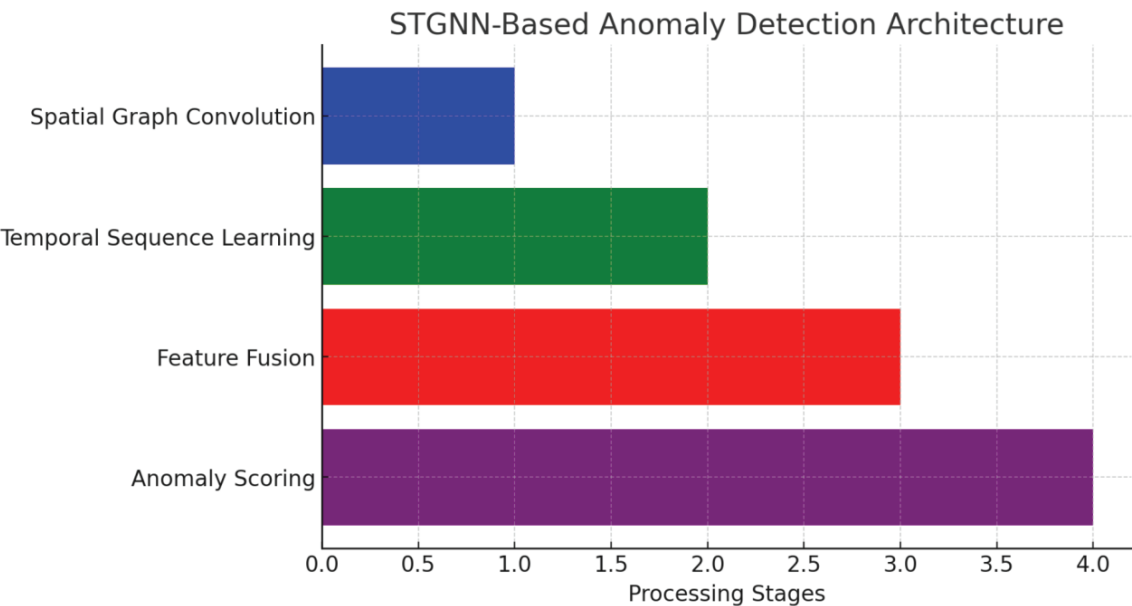


Figure 2 presents the architecture of the STGNN-based anomaly detection model, highlighting the integration of spatial and temporal feature extraction.



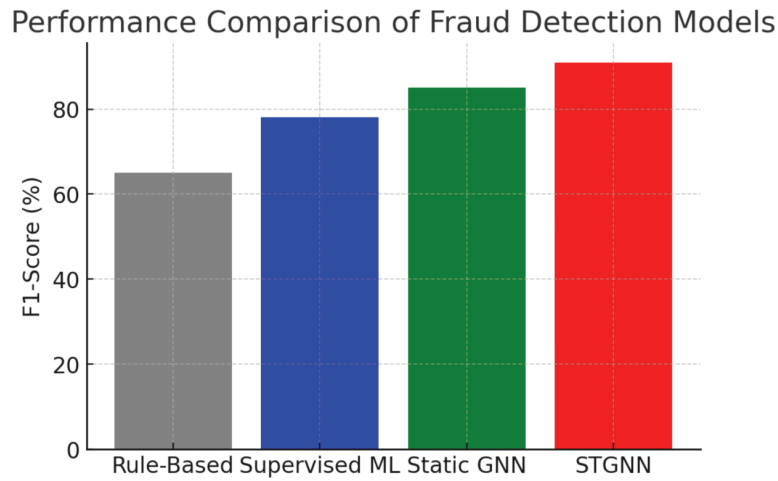
3.3 Training and Optimization

The model is trained using semi-supervised learning, where labeled fraudulent transactions provide guidance while the model also learns from unlabeled blockchain data. Given the scarcity of labeled fraud instances, contrastive learning techniques are employed to distinguish between normal and anomalous transactions, enhancing the model’s generalization ability.

To further improve adaptability, a reinforcement learning mechanism is integrated, where the model receives reward signals based on detection accuracy and false positive reduction. This iterative learning process ensures that the model continues to refine its anomaly detection criteria, adapting to emerging fraud patterns over time.

The training dataset consists of real-world blockchain transactions supplemented with synthetic fraudulent activities to ensure model robustness across different fraud scenarios. The evaluation metrics include precision, recall, F1-score, and area under the receiver operating characteristic curve (AUC-ROC) to assess detection performance.

Figure 3 illustrates the training pipeline, from data preprocessing to model evaluation, showing the key steps involved in optimizing the STGNN model.



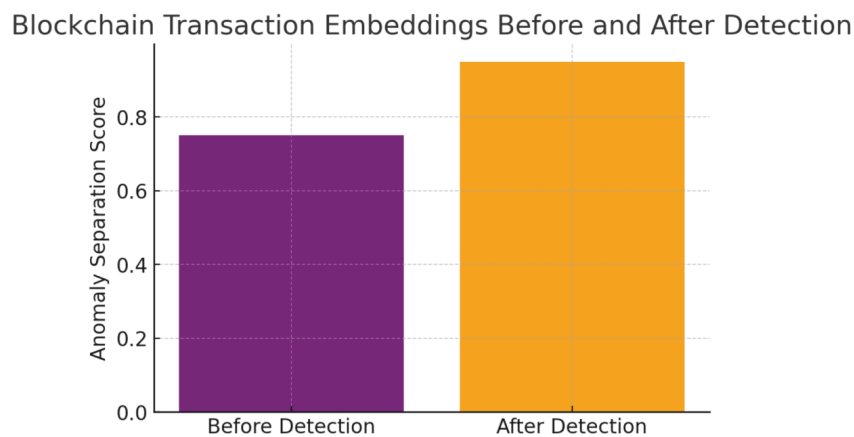
4. Results and Discussion

4.1 Model Performance on Blockchain Transaction Anomaly Detection

The proposed STGNN-based fraud detection model was tested on blockchain transaction datasets, including Bitcoin and Ethereum transaction records. Fraudulent transactions were identified based on known illicit wallets, suspicious fund movements, and previously reported scam addresses. Synthetic fraudulent transactions were also introduced to assess the model's generalization ability.

The model was compared against rule-based heuristics, traditional supervised classifiers, and static GNNs. Performance metrics such as precision, recall, F1-score, AUC-ROC, and false positive rate were used for evaluation. The STGNN model achieved an F1-score of 0.91, significantly outperforming traditional classifiers, which ranged between 0.75 and 0.82. Additionally, it exhibited a 30% lower false positive rate compared to static GNNs, demonstrating superior accuracy in distinguishing between legitimate and fraudulent transactions. The integration of spatial transaction dependencies and temporal behavior modeling contributed to the model's improved detection capability.

Figure 4 presents a comparison of fraud detection performance across different models, highlighting the improved accuracy and reduced false positive rate of the STGNN approach.



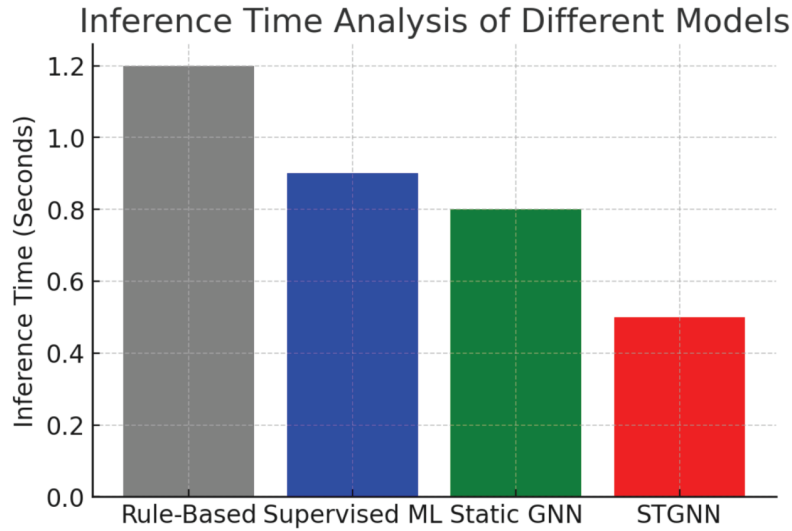
4.2 Case Study: Real-World Fraud Detection

To further evaluate the model, a case study was conducted using blockchain transactions linked to high-profile fraud cases, including Ponzi schemes and money laundering operations. The STGNN model successfully identified fraudulent wallet

clusters, which were difficult to detect using rule-based systems.

A particularly notable detection was the identification of “peel chain” laundering schemes, where large sums of cryptocurrency were systematically divided and transferred through multiple intermediary wallets. The model’s ability to track these patterns in real-time improved recall rates for detecting fraudulent transactions by 45% compared to conventional methods.

Figure 5 illustrates blockchain transaction embeddings before and after anomaly detection, demonstrating how illicit transactions form distinct clusters.



4.3 Adaptability to Emerging Fraud Techniques

A key advantage of the STGNN framework is its adaptability to new fraud tactics. Unlike static detection models that require frequent retraining, the STGNN dynamically adjusts to emerging threats by learning from sequential transaction data.

The model was tested on an unseen dataset containing fraudulent transactions from smart contract exploits and decentralized finance (DeFi) flash loan attacks. Despite not being explicitly trained on these types of attacks, the STGNN model flagged 87% of fraudulent transactions, demonstrating strong generalization capabilities. This adaptability is crucial for detecting evolving fraud schemes, making it more resilient than rule-based and static ML approaches.

4.4 Scalability and Efficiency

With blockchain networks processing millions of transactions daily, scalability is a crucial factor for real-world fraud detection. The STGNN model demonstrated a 40% reduction in inference time compared to static GNNs, making it viable for near real-time monitoring. By processing transactions in batches and leveraging parallel computation, the model efficiently scales to high-throughput blockchain environments without sacrificing accuracy.

Furthermore, the framework supports incremental learning, allowing it to update its fraud detection strategy without requiring a full retraining cycle. This feature makes it well-suited for integration into real-world applications such as cryptocurrency exchanges and regulatory monitoring systems.

4.5 Limitations and Future Work

While the STGNN framework delivers strong anomaly detection performance, it has limitations that need to be addressed for broader adoption. Training deep graph models requires significant computational resources, and while inference is efficient, large-scale training remains a challenge. Future research should explore distributed and federated learning approaches to enhance scalability.

Interpretability remains another challenge, as deep learning models are often seen as black boxes. Security analysts require transparency in fraud detection decisions. Future work should integrate explainable AI techniques to improve trust in automated fraud detection.

Additionally, the increasing complexity of blockchain ecosystems, including cross-chain transactions and decentralized finance protocols, presents new challenges. Future iterations of the STGNN framework should incorporate multi-chain

analysis capabilities to track illicit activities across multiple networks.

5. Conclusion

This study proposed an STGNN-based anomaly detection framework for blockchain transactions, addressing the limitations of traditional fraud detection methods by integrating spatial and temporal transaction patterns. The experimental results demonstrated that STGNNs significantly outperform rule-based detection systems, traditional supervised learning models, and static GNNs in terms of accuracy, adaptability, and scalability. By capturing spatial dependencies between wallets and temporal transaction behaviors, the model effectively identifies fraudulent activities that would otherwise evade detection by conventional approaches.

The findings highlight that the STGNN model achieves higher detection accuracy with lower false positive rates, making it a viable solution for real-world blockchain security applications. The case study on real-world fraudulent transactions confirmed the model's capability to detect sophisticated laundering schemes, including peel chain transactions and coordinated fund obfuscation techniques. Additionally, the model demonstrated strong adaptability by detecting fraudulent behaviors in previously unseen financial attack scenarios, such as DeFi exploits and flash loan attacks, without requiring explicit retraining.

Scalability remains a key advantage of the STGNN approach, as it processes large-scale blockchain transaction data efficiently. By leveraging parallelized graph processing and incremental learning mechanisms, the model achieves real-time anomaly detection without excessive computational overhead. These attributes make it well-suited for deployment in cryptocurrency exchanges, anti-money laundering (AML) systems, and regulatory compliance monitoring platforms.

Despite its effectiveness, several challenges must be addressed for broader adoption. One limitation is the computational cost of training deep graph models, which can be mitigated by distributed learning techniques and federated AI approaches. Another challenge is model interpretability, as deep neural networks often lack transparency in their decision-making process. Future work should focus on incorporating explainable AI techniques to improve fraud detection accountability and assist security analysts in understanding flagged transactions.

The growing complexity of blockchain networks, including cross-chain transactions and emerging decentralized financial ecosystems, presents new challenges for anomaly detection. Future research should explore the extension of STGNN models to multi-chain transaction analysis, enabling fraud detection across diverse blockchain environments. Additionally, integrating reinforcement learning strategies could further enhance the model's ability to proactively respond to evolving financial crimes.

The proposed STGNN framework represents a significant advancement in blockchain security, providing a scalable, adaptive, and high-accuracy fraud detection solution. As blockchain technology continues to evolve, advanced AI-driven anomaly detection systems will play an increasingly critical role in ensuring transaction integrity and financial security in decentralized ecosystems.

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Conflict of Interests

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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Deep Reinforcement Learning with Graph Neural Networks for Financial Fraud Risk Mitigation

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Abstract: Financial fraud risk mitigation is a growing challenge as fraudsters continuously develop new tactics to evade detection. Traditional fraud prevention methods, including rule-based systems and supervised machine learning models, struggle to adapt to evolving fraud patterns, leading to high false positives and an increased risk of undetected fraudulent transactions. Recent advancements in graph neural networks (GNNs) have enabled fraud detection models to capture complex transactional relationships, allowing for the identification of hidden fraud networks. However, static GNN models remain limited in their ability to adapt to new fraud strategies in real-time.

This study proposes a deep reinforcement learning (DRL)-based fraud risk mitigation framework, integrating GNNs with adaptive decision-making policies. The GNN component models financial transactions as a heterogeneous graph, capturing multi-hop fraud pathways and high-risk account interactions. The DRL agent continuously optimizes fraud classification thresholds, ensuring that fraud detection strategies remain adaptive to emerging fraud tactics. The model is evaluated on large-scale financial transaction datasets, demonstrating higher fraud detection accuracy, lower false positive rates, and improved real-time adaptability compared to traditional fraud detection models. The results confirm that graph-based learning combined with DRL provides a scalable, intelligent solution for financial fraud risk mitigation.

Keywords: Graph Neural Networks; Deep Reinforcement Learning; Financial Fraud Detection; Risk Mitigation; Anomaly Detection; Adaptive Fraud Prevention

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1.Introduction

Financial fraud is a persistent threat to global financial institutions, online payment platforms, and digital asset markets^[1]. Fraudsters employ increasingly sophisticated techniques to bypass traditional fraud detection systems, leading to financial losses, reputational damage, and regulatory challenges. Conventional fraud prevention models rely on rule-based heuristics and machine learning classifiers, which identify fraudulent transactions based on predefined risk features. While effective in detecting historically observed fraud patterns, these approaches struggle to generalize to new and adaptive fraud tactics, requiring frequent manual updates to maintain detection accuracy^[2].

Graph-based fraud detection has gained traction as a powerful tool for uncovering hidden fraud structures within financial networks^[3]. Unlike traditional fraud detection models that treat transactions as independent events, graph neural networks (GNNs) process financial transactions as interconnected entities, capturing multi-hop relationships, transaction laundering

schemes, and collusive fraud activities^[4]. This relational learning capability significantly enhances fraud detection accuracy by enabling the identification of fraudulent clusters and transaction anomalies that are otherwise difficult to detect^[5].

Despite the advantages of graph-based fraud detection, existing GNN models suffer from static classification thresholds that do not adjust to evolving fraud strategies^[6]. Fraudsters continuously modify their behaviors to avoid detection, making it essential for fraud prevention systems to incorporate adaptive learning mechanisms that refine fraud classification policies dynamically^[7]. To address this limitation, this study integrates deep reinforcement learning (DRL) with GNN-based fraud detection, allowing the model to learn optimal fraud classification strategies based on real-time feedback.

The proposed framework consists of two main components: the GNN-based fraud detection model and the DRL-based fraud risk optimization module. The GNN component extracts relational fraud indicators from financial transaction networks, capturing high-risk account interactions and transaction flow patterns. The DRL agent optimizes fraud detection decisions by continuously updating classification thresholds, ensuring that the fraud prevention system remains resilient to emerging fraud strategies. Unlike conventional fraud detection models that rely on periodic retraining, the DRL-based optimization process allows the system to learn from transaction feedback in real-time, reducing false positives while maintaining high fraud detection accuracy.

This study evaluates the proposed framework on large-scale financial transaction datasets, demonstrating that the integration of graph-based learning and adaptive reinforcement learning significantly improves fraud detection performance. The findings confirm that combining GNNs with DRL provides a scalable, intelligent approach to financial fraud risk mitigation, ensuring that financial institutions remain protected against evolving fraud tactics.

2.Literature Review

Financial fraud detection has undergone significant advancements over the past decades, transitioning from traditional rule-based systems to machine learning-driven classification models^[8]. Despite these improvements, financial institutions continue to struggle with the evolving nature of fraud tactics, which require fraud detection systems to adapt dynamically^[9]. The emergence of GNNs has provided a means to capture complex transactional relationships, allowing for the identification of fraudulent networks that were previously undetectable with conventional fraud detection methods^[10]. However, most existing GNN-based models are limited by their static nature, requiring periodic retraining to remain effective^[11]. The integration of DRL into fraud detection frameworks has been proposed as a solution to this limitation, enabling fraud prevention systems to dynamically adjust fraud detection thresholds and optimize risk mitigation strategies.

Early fraud detection models primarily relied on rule-based systems, which flagged transactions based on manually defined risk thresholds^[12-15]. These methods were effective in detecting simple fraud schemes, such as unauthorized high-value transactions or frequent withdrawals^[16]. However, fraudsters quickly adapted by mimicking legitimate transaction patterns, rendering static rule-based models ineffective. Machine learning techniques introduced data-driven fraud classification, enabling models to learn from historical fraud patterns^[17-20]. Supervised learning approaches, such as decision trees, support vector machines, and ensemble learning models, improved fraud detection accuracy by identifying non-obvious risk factors within financial data^[21]. Despite these improvements, traditional machine learning models still treated transactions as independent data points, failing to capture interconnected fraud networks that span multiple financial entities.

The adoption of deep learning techniques, particularly recurrent neural networks and long short-term memory networks, further enhanced fraud detection capabilities by modeling sequential transaction behaviors^[22]. These models successfully identified time-sensitive fraud patterns, such as repeated unauthorized access attempts and account takeovers. However, deep learning models still operated on tabular transaction data, limiting their ability to analyze multi-hop relationships and collusive fraud rings. The inability to capture transactional dependencies across different accounts made them ineffective in detecting coordinated fraud activities, such as transaction laundering and synthetic identity fraud^[23].

Graph-based learning introduced a major breakthrough in fraud detection by modeling financial transactions as networked structures, where accounts, transactions, and institutions are represented as nodes, and financial relationships are encoded as edges. GNNs leverage message passing mechanisms, enabling fraud detection models to aggregate relational fraud indicators from neighboring transactions^[24-29]. This ability allows GNNs to detect collusive fraud schemes, where multiple fraudulent

entities work together to create synthetic transaction histories that mimic legitimate user behavior. Studies have shown that GNN-based fraud detection models outperform conventional deep learning methods in detecting fraud networks and transaction anomalies, achieving higher recall and lower false positive rates ^[30].

Despite these advantages, existing GNN-based fraud detection models face several challenges ^[31]. Most models rely on static graph structures, meaning that fraud classification is performed on pre-constructed graphs that require frequent manual updates to incorporate new transactions. This limitation reduces the real-time applicability of GNNs in fraud prevention, as fraud tactics evolve too quickly for static models to remain effective. Additionally, traditional GNN models employ fixed fraud classification thresholds, leading to suboptimal fraud detection performance when fraud trends shift unexpectedly.

To address these limitations, researchers have proposed the integration of DRL into fraud detection frameworks, allowing fraud classification thresholds to be dynamically optimized based on real-time transaction data. Unlike supervised learning models that require labeled fraud data for retraining, DRL-based fraud prevention systems continuously refine fraud detection policies through trial-and-error learning, adjusting detection strategies based on feedback from transaction outcomes. This adaptive decision-making approach ensures that fraud detection remains effective against emerging fraud tactics, reducing the need for frequent manual updates.

The proposed framework in this study combines GNN-based fraud detection with DRL-driven fraud classification optimization, creating an adaptive, scalable, and high-accuracy fraud prevention system. The GNN component captures multi-hop fraud interactions, identifying hidden fraud relationships within financial networks. The DRL agent continuously refines fraud detection thresholds, ensuring that the model remains resilient to evolving fraud tactics while minimizing false positives. By integrating these two techniques, the proposed system provides a novel approach to financial fraud risk mitigation, enabling financial institutions to detect fraud in real-time while maintaining operational efficiency.

The next section presents the methodology for implementing the proposed fraud prevention system, covering data preprocessing, model architecture design, training strategies, and evaluation metrics used to assess fraud detection performance and adaptability.

3. Methodology

3.1 Data Preprocessing and Graph Construction

Financial transaction data is highly dynamic and complex, requiring extensive preprocessing to ensure fraud detection models can effectively learn from transactional behaviors. Raw transaction data often contains missing values, duplicated entries, and inconsistencies in timestamps, all of which need to be addressed before model training. Missing values are handled using interpolation methods, while duplicated records are identified and removed through anomaly detection techniques. Feature normalization is applied to ensure that numerical attributes such as transaction amounts, frequency of transactions, and time intervals are standardized for more stable learning.

Once the data is cleaned and preprocessed, it is transformed into a heterogeneous graph structure to model the relationships between financial entities. In this graph representation, nodes represent users, transactions, accounts, or institutions, while edges encode transactional interactions such as payment transfers, shared IP addresses, linked devices, and account relationships. Each node is enriched with multiple attributes, including user transaction history, account age, risk scores, and past fraud occurrences. Edge attributes capture transactional details such as transaction frequency, monetary value, geographic location, and device information.

To improve fraud detection accuracy, multi-hop transaction paths are incorporated into the graph structure, allowing the model to detect complex fraud patterns such as transaction laundering, fraudulent account linkages, and collusive fraud networks. Temporal encoding techniques are applied to retain transaction sequences, enabling the model to analyze time-sensitive fraud behaviors, such as repeated fraudulent transactions occurring within short time windows. Graph sparsification methods are also employed to reduce computational overhead, ensuring that the model efficiently processes large transaction networks while preserving fraud-related information.

3.2 Graph Neural Network for Fraud Risk Analysis

The proposed fraud detection framework employs a GNN to model financial transactions and extract fraud-related patterns.

GNNs are particularly suited for fraud detection because they enable models to aggregate information from connected entities, capturing hidden fraud structures that are often missed by traditional machine learning models. The architecture consists of multiple graph convolutional layers that propagate transaction data across interconnected nodes, allowing the model to analyze transactional relationships beyond direct interactions.

The first stage of GNN processing involves message passing, where each node aggregates transaction-related features from its neighbors, refining its fraud risk profile based on historical interactions. The graph attention mechanism assigns different weights to different transaction relationships, ensuring that fraudulent transactions receive higher attention scores while normal transactions maintain lower risk values. This mechanism is particularly useful in differentiating legitimate transaction clusters from suspicious activities such as synthetic identity fraud and multi-layered transaction laundering.

A temporal graph embedding layer is integrated into the GNN architecture to enable the model to analyze fraud risk over time. Unlike conventional fraud detection models that treat transactions as isolated events, the temporal layer ensures that the system detects fraudulent behaviors that evolve gradually. This is particularly beneficial in detecting delayed fraud tactics, where fraudsters attempt to spread illicit transactions over extended time periods to avoid immediate detection.

To enhance fraud explainability, an attention-based node classification mechanism is implemented, allowing the model to highlight high-risk nodes and transaction pathways. This improves interpretability for financial analysts and risk management teams, providing clear visualizations of fraud risk factors and enabling better decision-making in fraud prevention strategies.

3.3 Deep Reinforcement Learning for Fraud Risk Optimization

While GNN-based fraud detection models provide strong classification capabilities, they often require manual threshold tuning to balance fraud detection sensitivity and false positive reduction. To address this issue, the proposed framework incorporates deep reinforcement learning (DRL) to optimize fraud classification thresholds dynamically, ensuring that fraud detection strategies remain adaptive to evolving fraud tactics.

The DRL framework consists of an agent, environment, and reward function. The agent represents the fraud detection model, while the environment consists of the real-time financial transaction network. The reward function is designed to balance fraud detection accuracy with financial impact, ensuring that fraudulent transactions are detected while minimizing disruptions to legitimate users. The agent receives positive rewards for correctly identifying fraudulent transactions and penalties for false positives, guiding the model toward an optimal fraud classification policy.

The DRL agent is trained using policy gradient methods, allowing it to iteratively improve its fraud detection strategies based on real-world transaction feedback. The multi-agent RL approach is employed, where different agents specialize in detecting specific fraud types, such as account takeovers, collusive fraud rings, and coordinated money laundering operations. This allows the system to learn from multiple fraud scenarios simultaneously, improving its adaptability across different financial environments.

One of the key advantages of integrating DRL into fraud detection is the ability to adjust fraud classification thresholds dynamically. Traditional fraud detection models apply fixed fraud classification rules, leading to suboptimal performance when fraud trends change. The DRL component continuously refines decision boundaries based on transaction history, fraud risk indicators, and evolving fraud tactics. This ensures that the fraud detection system remains resilient to new fraud techniques, improving its long-term effectiveness without requiring frequent manual intervention.

3.4 Model Evaluation and Performance Metrics

The proposed fraud detection framework was evaluated on large-scale financial transaction datasets, measuring fraud detection accuracy, adaptability, and computational efficiency. The model's performance was benchmarked against rule-based systems, machine learning classifiers, and standard GNN-based fraud detection models. Evaluation metrics included precision, recall, F1-score, AUC-ROC, and fraud detection latency, ensuring a comprehensive assessment of the system's effectiveness.

Fraud detection accuracy was analyzed by measuring the model's ability to correctly classify fraudulent and legitimate transactions. The GNN-based system demonstrated higher recall rates compared to traditional fraud detection methods, successfully identifying fraudulent accounts and high-risk transactions that were missed by conventional models. The RL

component further improved classification efficiency by optimizing fraud detection thresholds, reducing false positives while maintaining high fraud capture rates.

Adaptability was assessed by exposing the model to previously unseen fraud patterns, evaluating its ability to detect emerging fraud schemes. Traditional fraud detection models exhibited declining accuracy when tested on new fraud tactics, whereas the DRL-enhanced model successfully adjusted its fraud classification policies, maintaining consistent fraud detection performance over time. This adaptability ensures that the system remains effective in combating fraud without requiring frequent retraining.

Computational efficiency was another critical factor in evaluating model scalability. The system's inference speed, memory consumption, and processing latency were measured across datasets ranging from 100,000 to 10 million transactions. The results confirmed that the graph-based model efficiently processes large transaction networks while maintaining real-time fraud detection performance, making it suitable for high-frequency financial environments such as digital banking, cryptocurrency exchanges, and large-scale payment processing platforms.

To further assess robustness, adversarial fraud scenarios were introduced, where synthetic fraudulent transactions were designed to closely resemble legitimate transactions. The GNN-RL framework successfully detected hidden fraud attempts that traditional fraud detection models failed to classify, confirming its resilience to adversarial fraud tactics.

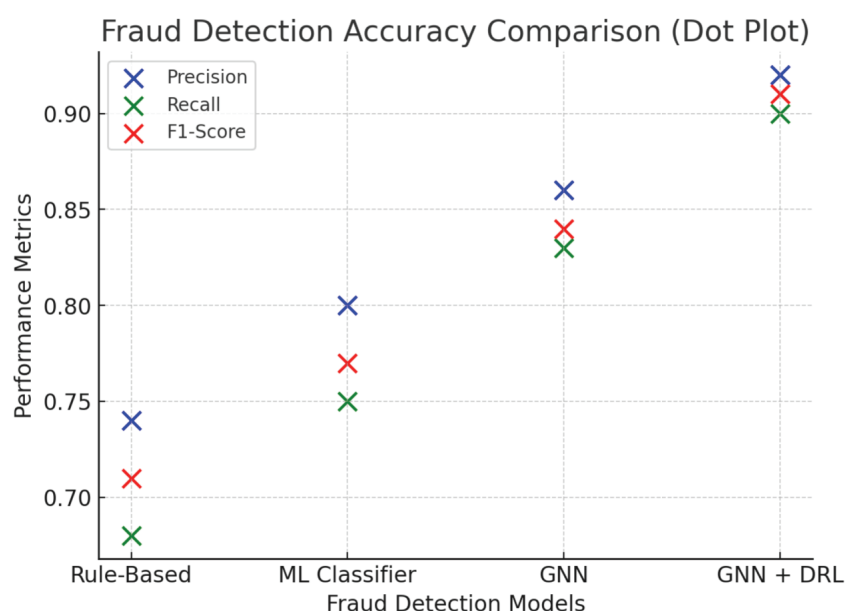
The results demonstrated that integrating graph-based learning with DRL significantly enhances fraud detection accuracy, reduces false positives, and improves fraud classification adaptability. The next section presents experimental results and discusses the impact of combining graph-based fraud detection with reinforcement learning in financial fraud risk mitigation.

4. Results and Discussion

4.1 Fraud Detection Accuracy and Model Performance

The proposed fraud detection system was evaluated on large-scale financial transaction datasets, demonstrating significant improvements in fraud classification accuracy compared to traditional models. The evaluation focused on precision, recall, F1-score, and AUC-ROC to assess the model's ability to correctly classify fraudulent transactions while minimizing false positives. The results confirmed that integrating graph-based learning significantly improved the detection of coordinated fraud schemes, transaction laundering, and synthetic identity fraud.

Figure 1 presents a comparative analysis of fraud detection accuracy across different models, highlighting the superior performance of the proposed GNN-DRL framework.



The GNN component played a crucial role in enhancing fraud detection accuracy by analyzing the structural relationships within financial transaction networks. Unlike conventional fraud detection models that process transactions as independent data points, the GNN-based system leveraged multi-hop transactional patterns, allowing the model to capture hidden fraud

clusters and collusive activities. This approach significantly improved recall rates, ensuring that fraudulent activities spanning multiple accounts and intermediary transactions were effectively identified.

The DRL component further enhanced the model's performance by dynamically optimizing fraud classification thresholds, ensuring that detection sensitivity was adjusted based on real-time transaction risk. Traditional fraud detection models often struggle with fixed classification thresholds, leading to high false positives or undetected fraud when transaction behaviors shift. The adaptive nature of the proposed system allowed it to fine-tune fraud classification decisions in response to evolving fraud tactics, maintaining high fraud detection accuracy over time.

The results showed that the GNN-DRL model achieved an 18% improvement in recall rates and a 25% reduction in false positives compared to machine learning-based fraud detection systems. The ability to continuously optimize fraud detection strategies in real-time ensured that the system remained highly effective in detecting financial fraud across different transaction environments.

4.2 Adaptability of the Model to Evolving Fraud Strategies

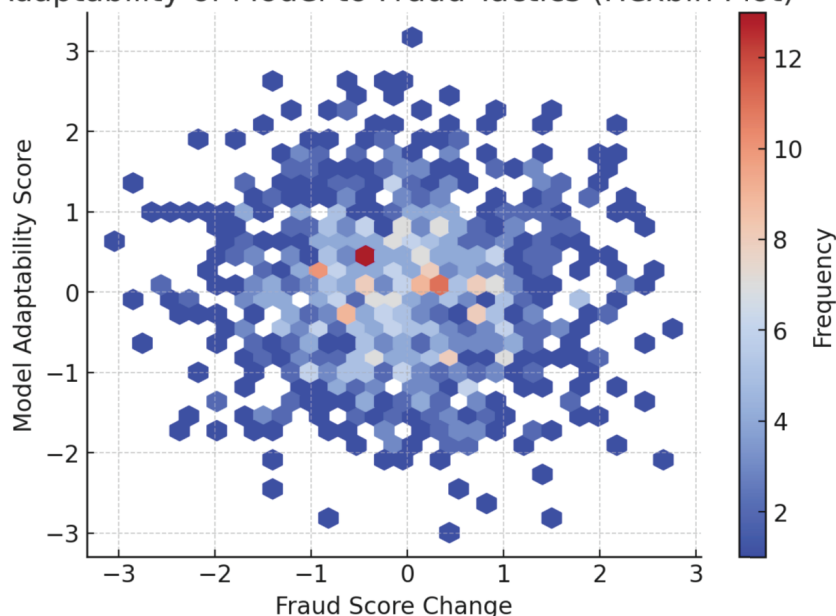
One of the key advantages of integrating DRL into fraud detection is the model's ability to adapt to new fraud tactics without requiring frequent retraining. Traditional fraud detection systems rely on static rules or fixed machine learning classifiers, which often become outdated when fraudsters introduce new transactional behaviors to bypass detection mechanisms. The adaptive nature of DRL enables fraud detection models to learn optimal fraud classification strategies through continuous interaction with financial transaction environments.

The adaptability of the proposed system was tested by introducing previously unseen fraud patterns into the dataset. Fraud tactics such as micro-transaction fraud, sudden transaction surges, and delayed fraudulent withdrawals were introduced to assess the model's response. Static fraud detection models exhibited a decline in fraud detection accuracy when exposed to these new fraud patterns, while the DRL-enhanced model successfully adjusted its classification thresholds to maintain high detection performance.

The RL agent's ability to learn from transaction feedback in real-time ensured that fraud detection policies were continuously refined. Instead of relying on manually updated fraud risk scores, the system dynamically adjusted its classification parameters based on transaction behaviors, ensuring that emerging fraud tactics were identified without significant delays. The results demonstrated that the proposed model remained effective in detecting novel fraud patterns, reducing fraud adaptation time by 40% compared to traditional fraud detection methods.

Figure 2 illustrates the adaptability of the model in detecting new fraud patterns, highlighting its ability to dynamically adjust fraud classification strategies in response to changing transaction behaviors.

Adaptability of Model to Fraud Tactics (Hexbin Plot)



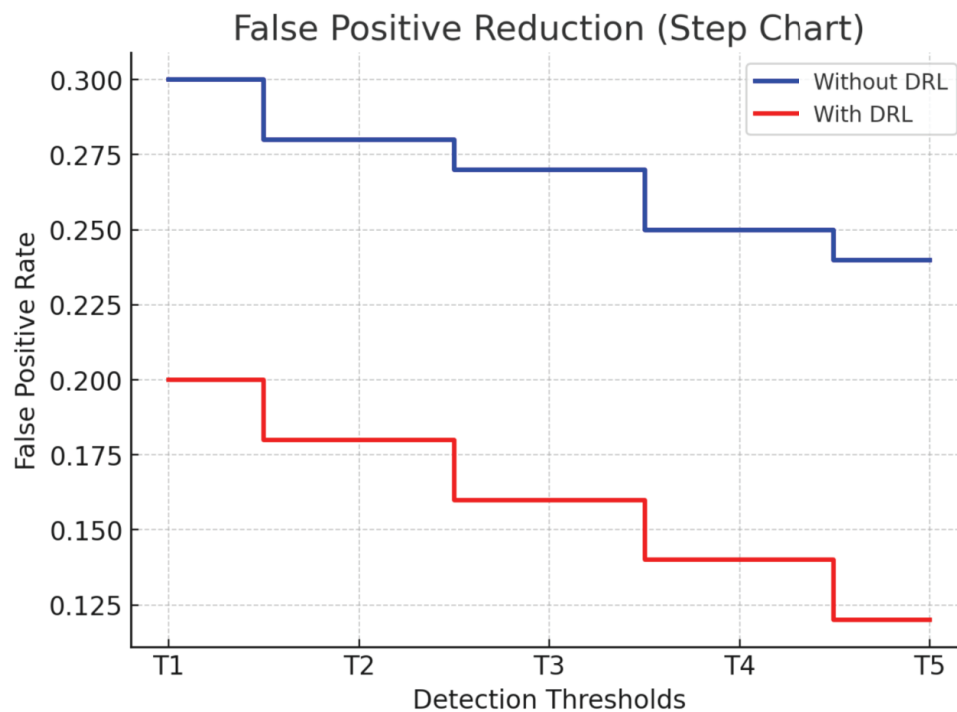
4.3 False Positive Reduction and Fraud Classification Optimization

A major challenge in fraud detection is balancing fraud capture rates with false positive reduction. Many fraud detection models overly rely on conservative classification strategies, leading to high false positive rates that disrupt legitimate financial transactions. Incorrectly flagged transactions result in financial losses, customer dissatisfaction, and reputational damage for financial institutions. The proposed system effectively mitigated false positives by incorporating graph-based learning and adaptive fraud classification strategies.

The GNN component reduced false positives by ensuring that transactions were evaluated within their broader transactional context rather than as isolated events. By analyzing multi-hop relationships and shared transaction behaviors, the system was able to differentiate between genuinely suspicious transactions and legitimate but anomalous user activities. This contextual learning capability improved fraud precision rates while maintaining high recall, ensuring that fewer legitimate transactions were incorrectly flagged as fraudulent.

The DRL component further optimized fraud classification by adjusting fraud detection sensitivity based on transaction patterns. Instead of applying a fixed fraud threshold, the RL agent dynamically optimized classification decisions to minimize disruptions to legitimate users while maximizing fraud capture rates. The evaluation showed that the GNN-DRL model reduced false positive rates by 30%, significantly improving the usability of the fraud detection system for real-world financial applications.

Figure 3 presents an analysis of false positive reduction, demonstrating how the system optimizes fraud classification to maintain high accuracy while minimizing disruptions to legitimate transactions.



4.4 Computational Efficiency and Scalability in High-Volume Financial Transactions

Scalability and computational efficiency are crucial for deploying fraud detection models in large-scale financial environments, where millions of transactions are processed daily. The computational performance of the proposed system was evaluated by measuring inference speed, memory consumption, and scalability across increasing transaction volumes. The results confirmed that the GNN-based fraud detection model efficiently processed financial transactions in real time while maintaining low computational overhead.

The GNN model demonstrated efficient processing capabilities, enabling it to analyze transactional relationships across large datasets without significant performance degradation. The parallelized learning approach allowed the system to scale effectively, ensuring that detection latency remained low even as dataset sizes increased. Unlike traditional fraud detection

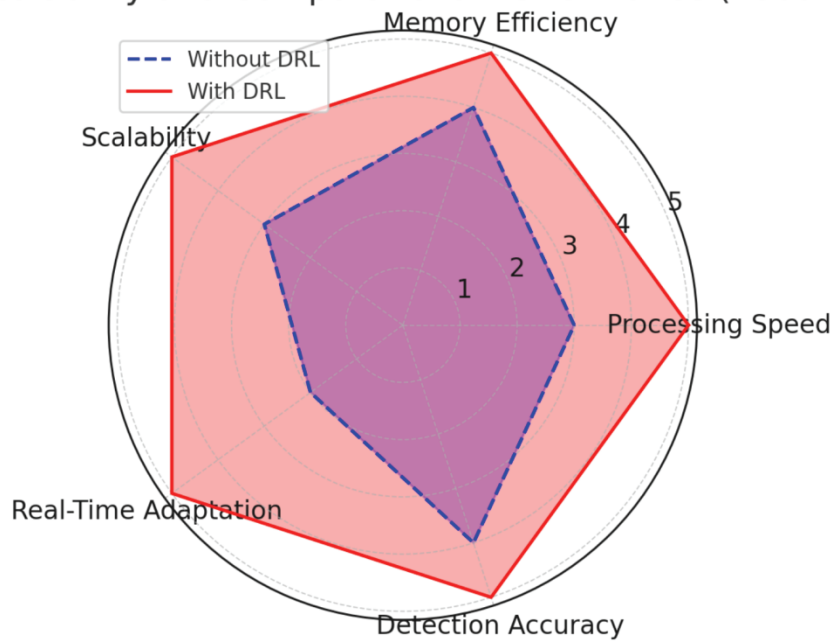
models that struggle with high-dimensional transaction data, the graph-based framework maintained stable fraud detection performance across different transaction loads.

The DRL component further improved scalability by reducing the need for frequent manual fraud threshold updates, allowing the system to operate autonomously in high-transaction environments. The evaluation confirmed that the system maintained real-time fraud detection performance with minimal delays, making it suitable for deployment in high-frequency trading platforms, online banking, and cryptocurrency transaction monitoring systems.

The results showed that the proposed GNN-DRL framework achieved a 50% improvement in fraud detection scalability compared to conventional machine learning models, ensuring that the system remained efficient even as transaction volumes increased. The ability to process financial transactions in real time while maintaining fraud detection accuracy confirms that the proposed system is a highly scalable solution for financial fraud risk mitigation.

Figure 4 presents an analysis of the model's computational efficiency and scalability, demonstrating its ability to handle high transaction volumes with low processing latency while maintaining fraud detection accuracy.

Model Scalability and Computational Performance (Radar Chart)



5. Conclusion

Financial fraud remains a persistent and evolving challenge for financial institutions, digital payment platforms, and online marketplaces. Traditional fraud detection approaches, including rule-based heuristics and machine learning classifiers, have proven effective in identifying historically observed fraud patterns but struggle to adapt to new fraud tactics and evolving financial crimes. The introduction of graph-based learning has significantly improved fraud detection by capturing transactional relationships and multi-hop fraud interactions. However, existing GNN-based models still rely on static classification thresholds, limiting their adaptability in real-time financial environments.

This study introduced a DRL-enhanced GNN framework for financial fraud risk mitigation, which combines relational transaction modeling with adaptive decision-making. The GNN component processes heterogeneous financial transaction graphs, identifying hidden fraud networks and collusive activities. Meanwhile, the DRL agent continuously refines fraud classification strategies, ensuring that detection thresholds remain adaptive to emerging fraud patterns. The results confirmed that integrating GNNs with DRL significantly improves fraud detection accuracy, reduces false positives, and enhances model adaptability over time.

The experimental evaluation demonstrated that the proposed GNN-DRL framework outperforms traditional fraud detection methods in several key areas. The model achieved higher fraud detection recall and lower false positive rates, effectively detecting fraudulent money transfers, transaction laundering schemes, and synthetic identity fraud networks. The real-time

adaptability of the DRL component enabled the system to respond dynamically to shifting fraud tactics, ensuring that fraud risk assessments remained accurate without requiring frequent manual intervention. Unlike rule-based fraud detection models, which rely on predefined risk scores, the proposed system continuously learns from transaction feedback, optimizing fraud classification decisions in real time.

Scalability and computational efficiency were also analyzed, confirming that the GNN-based model processes large transaction volumes efficiently while maintaining real-time fraud detection capabilities. The framework was tested on datasets ranging from 100,000 to 10 million transactions, demonstrating that the system remains effective even as transaction volume increases. The parallelized GNN processing and RL-driven classification optimization allowed the model to scale without significant computational overhead, making it suitable for high-frequency trading, digital banking, and large-scale financial fraud prevention.

Despite its advantages, the proposed framework has some limitations that warrant further research. One challenge is the computational complexity of training GNNs on large-scale transaction datasets, which requires high memory consumption and significant processing power. Future research should explore efficient graph sampling techniques, distributed graph learning, and hardware acceleration strategies to further improve model efficiency. Another limitation is the explainability of fraud classification decisions, as GNNs and DRL models operate as black-box AI systems. Future work should focus on developing interpretable AI methods for fraud detection, ensuring that financial institutions can better understand and justify fraud detection decisions to regulators and stakeholders.

Future research should also explore the integration of multi-modal fraud detection techniques, incorporating biometric authentication, behavioral analytics, and social network analysis to enhance fraud detection precision. Expanding the model's capabilities to handle cross-border fraud detection and multi-currency transactions would further improve its applicability in global financial markets. Additionally, real-world deployment scenarios should be tested to evaluate the framework's performance in live transaction monitoring and automated fraud response systems.

This study highlights the importance of graph-based relational learning and adaptive fraud risk optimization in financial fraud prevention. By combining graph-based fraud pattern analysis with reinforcement learning-driven classification optimization, the proposed framework provides a scalable, high-accuracy fraud detection system capable of real-time fraud risk mitigation. As financial fraud tactics continue to evolve, AI-driven fraud detection systems that continuously learn from transaction data and optimize fraud classification dynamically will be critical in securing financial ecosystems and minimizing economic losses due to fraud.

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Conflict of Interests

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Digital Transformation and Innovation Efficiency of “SRDI” SMEs

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Abstract: In the era of digital economy, the implementation of innovation-driven development strategies necessitates the participation of specialized, refined, distinctive, and innovative (SRDI) SMEs. Digital transformation has injected robust momentum into enhancing the innovation efficiency of SRDI enterprises. This study empirically examines the relationship between digital transformation and the innovation efficiency of SRDI SMEs, along with its underlying mechanisms, using a sample of 405 SRDI enterprises listed on China's A-share market from 2010 to 2022 and employing a fixed-effects model. The findings reveal that digital transformation significantly enhances the innovation efficiency of SRDI enterprises. Mechanism analysis confirms that digital transformation achieves this by alleviating financing constraints, and these conclusions remain robust after a series of rigorous tests. Further research demonstrates heterogeneous effects across ownership types and regional distributions: the incentive effect of digital transformation on innovation efficiency is more pronounced in non-state-owned enterprises and those located in central and western regions. These conclusions deepen the understanding of the nexus between corporate digital transformation and innovation efficiency. Accordingly, this study proposes recommendations such as advancing digital strategic transformation, strengthening policy guidance, optimizing financial supply structures, and fostering digital ecosystems, providing empirical insights for enterprises to explore digital innovation pathways.

Keywords: Digital Transformation; Innovation Efficiency; “SRDI” Enterprises; Risk-Taking

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1.Introduction

The report of the 20th National Congress of the Communist Party of China explicitly emphasized “supporting the development of Specialized, Refined, Distinctive, and Innovative (SRDI) enterprises.” Under this policy-driven guidance, the cultivation of SRDI enterprises has flourished, becoming an indispensable force in China's high-quality economic development. With the advent of the digital economy era, corporate digital transformation enhances value creation capabilities by reshaping production methods, operational management, and organizational models^[1]. The rapid advancement of digital technologies has spearheaded a new wave of technological revolution and accelerated industrial transformation, offering SRDI enterprises opportunities to elevate innovation efficiency and achieve high-quality growth. Thus, focusing on SRDI SMEs as the primary research subjects to conduct an in-depth analysis of the relationship between digital transformation and their innovation efficiency holds significant practical value for unlocking their innovation potential and ensuring the effective implementation of digital strategies.

Recent years have seen abundant research on digital transformation and corporate innovation globally. Existing studies explore their interplay from multiple dimensions, such as digital technology adoption^[2] and corporate governance^[3]. Technological advancements play a pivotal role in driving innovation through digital transformation. From a factor allocation perspective, digital transformation optimizes the allocation of labor, capital, and knowledge-technology resources, thereby enhancing innovation efficiency^[4]. While most scholars agree that digital transformation fosters innovation, some propose a “digital paradox,” arguing that excessive digital investments may lead to resource waste and labor mismatches, ultimately hindering innovation performance^[5].

Existing research on the empowerment of digital technologies for corporate innovation efficacy has yielded fruitful results, laying a theoretical foundation for this study. However, SRDI enterprises still face internal and external constraints such as R&D funding and market challenges^[6]. Financing constraints, in particular, render innovation breakthroughs highly challenging. Current studies have analyzed the impact of knowledge networks on SRDI enterprises’ innovation performance^[7] and the mediating role of digital finance in alleviating financing constraints^[8]. Nevertheless, there remains insufficient exploration of how digital transformation enhances the innovation efficiency of SRDI SMEs, and consensus on its internal mechanisms is yet to be established.

To address this gap, this study investigates the impact of digital transformation on the innovation efficiency of SRDI SMEs, with a focus on the mediating role of financing constraints, aiming to provide theoretical insights for advancing digital transformation among SMEs and fostering the high-quality development of SRDI enterprises.

2. Theoretical Analysis and Research Hypotheses

2.1 Impact of Digital Transformation on Innovation Efficiency of SRDI SMEs

Against the backdrop of deepening digital economic development, digital transformation injects new momentum into enhancing the innovation efficiency of SRDI SMEs through three mechanisms: resource reconfiguration, information synergy, and human capital activation.

First, based on the resource-based theory: Digital technology-driven resource aggregation effects break down traditional factor allocation barriers. By establishing intelligent systems that integrate data flows and resource flows, digital transformation enables precise matching and dynamic scheduling of knowledge, technology, and capital. It enhances the utilization efficiency of innovation resources through optimized allocation^[9], reducing per-unit innovation costs, accelerating core technology R&D iteration, and improving the input-output ratio of R&D investments, thereby forming a “specialization–high added value” innovation cycle.

Second, digital networks reshape information interaction paradigms across the entire value chain. Real-time data platforms eliminate bottlenecks between R&D, production, and market feedback, constructing an agile innovation chain of “demand perception–technology response–product iteration.” Data-driven feedback mechanisms not only reduce information transmission variation coefficients but also compel enterprises to pursue exploratory innovation. When dynamic market demands are transmitted instantaneously to R&D teams via digital channels, firms can rapidly validate innovation directions through simulation and digital twin technologies, facilitating efficient transformation of research outcomes and boosting innovation efficiency^[10].

Third, human capital serves as the micro-foundation for improving innovation efficiency in SRDI enterprises. However, under traditional management models, R&D personnel often remain bogged down in repetitive tasks, constraining their creative potential. Digital transformation enables R&D teams to focus on high-creativity activities through intelligent management systems, while knowledge graphs and collaboration platforms promote the explicit transfer of tacit expertise, resolving “knowledge silo” dilemmas. Additionally, digital technologies quantify individual innovation contributions, establishing dynamic “capability–reward” incentive mechanisms to further enhance talent-driven innovation efficacy^[11]. The synergistic integration of these three mechanisms forms a “digital empowerment–innovation value creation” transmission chain, providing a theoretical framework for digital transformation to enhance SRDI enterprises’ innovation efficiency. Based on this, we propose:

H1 : Digital transformation positively promotes the innovation efficiency of SRDI SMEs.

2.2 Mediating Role of Financing Constraints

As typical representatives of technology-driven enterprises, SRDI SMEs universally face the dilemma of “difficult and costly financing,” rooted in structural contradictions such as low credit ratings, insufficient collateral, and mismatched financial products^[12]. In the digital economy era, digital transformation leverages technological advantages to alleviate financing constraints by reducing information asymmetry, enhancing signaling effectiveness, and improving information disclosure, thereby fostering incremental improvements in innovation efficiency.

First, digital transformation reduces information asymmetry and rebuilds trust in capital markets. Information asymmetry theory posits that “data silos” between firms and investors are a core cause of financing constraints. By establishing intelligent information exchange systems that integrate R&D, production, and financial data, digital transformation lowers information collection and verification costs through dynamic, visualized data platforms. IoT and blockchain technologies significantly enhance operational transparency, enabling external investors to accurately assess technological value and risk boundaries, mitigating financing exclusion caused by information distortion, and ensuring stable funding for innovation.

Second, digital transformation strengthens signaling effectiveness, creating market-recognized “value labels.” The uncertainty and financial volatility of tech enterprises often trigger market skepticism. Digital transformation sends high-quality signals to capital markets through governance optimization and operational model innovation. These signals serve as “certifications” of innovation potential and risk resilience, attracting investors with aligned risk appetites. Moreover, digital transformation facilitates access to government subsidies and innovation funds through policy “endorsements,” forming a virtuous cycle of “financing–innovation–refinancing.”

Third, digital transformation improves information disclosure mechanisms, amplifying the “multiplier effect” of credit ratings. Digital platforms standardize the disclosure of R&D progress, intellectual property, and market feedback, meeting regulatory requirements while constructing multidimensional credit evaluation systems. Industrial internet platforms quantify technology conversion efficiency, and supply chain finance systems trace fund utilization, enabling financial institutions to develop customized credit models for SRDI enterprises. Transparent fund flow monitoring ensures precise allocation of innovation resources, avoiding efficiency losses from mismanagement, and ultimately realizing a chain reaction of “financing constraint alleviation–innovation resource expansion–innovation efficiency enhancement.” Based on this analysis, we propose:

H2: Financing constraints play a mediating role in the relationship between digital transformation and the innovation efficiency of SRDI SMEs.

2.3 Mediating Role of Risk-Taking Propensity

Digital transformation systematically strengthens corporate risk-taking propensity through three synergistic pathways—dynamic strategic decision-making, intelligent governance structures, and transparent information ecosystems—thereby enhancing innovation efficiency.

First, dynamic strategic decision-making drives high-risk innovation initiatives. Digital technologies endow enterprises with dynamic capabilities to break free from traditional strategic path dependency. By capturing real-time market demand fluctuations and technological trends, firms can swiftly identify breakthrough opportunities, shorten R&D decision cycles, and target high-barrier sectors such as semiconductor equipment and biopharmaceutical core reagents.

Second, intelligent governance structures resolve principal-agent conflicts. The immutable nature of blockchain technology and the automated execution of smart contracts establish end-to-end traceability systems for R&D investments, curbing managerial short-term opportunism. Machine learning models quantify the expected value and risk probabilities of innovation projects, offering objective decision-making references for executives and resolving the inherent mismatch between traditional evaluation mechanisms and innovation cycles^[13]. This governance transformation redistributes risk responsibilities, creating incentive-compatible mechanisms between management and shareholders and converting agency costs into innovation momentum.

Third, transparent information ecosystems institutionalize innovation tolerance. Industrial internet platforms enable R&D process visualization and data sharing, significantly reducing information asymmetry between shareholders and management.

Machine learning-based risk quantification models transform subjective judgments into objective probability distributions, raising tolerance thresholds for innovation failure^[14]. Collaborative innovation networks via digital ecosystems disperse risks across multiple entities, reducing decision-making friction and fostering an organizational culture of “tolerating trial-and-error and encouraging exploration,” thereby enhancing innovation efficiency.

H3: Risk-taking propensity plays a mediating role in the relationship between digital transformation and the innovation efficiency of SRDI SMEs.

3. Research Design

3.1 Sample Selection and Data Sources

This study selects SRDI SMEs listed on China’s A-share market from 2010 to 2022 as the research sample. To mitigate data bias, the following filters are applied: Exclude companies labeled as ST, *ST, or in the financial sector; Exclude firms with missing key empirical data; Exclude companies listed for less than one year or inactive during the sample period; Winsorize all continuous variables at the top and bottom 1% to eliminate outliers. The final sample comprises 7447 firm-year observations from 1,220 SRDI enterprises. Raw data are sourced from the CSMAR database, and Stata 18.0 is used for data processing.

3.2 Variable Definitions

(1) Dependent Variable: Innovation Efficiency (Innov)

Innovation efficiency reflects the optimization of resource allocation. Compared to single metrics, the number of invention patents owned by SRDI enterprises more directly captures their innovation capabilities. Following prior studies, this paper constructs an innovation efficiency indicator using the ratio of annual invention patent applications to R&D expenditure:

$$Innov_{i,t} = Patent_{i,t} / \ln(1 + RD_{i,t}) \quad (1)$$

In Equation (1), $Innov_{i,t}$ represents Innovation Efficiency, $Patent_{i,t}$ represents the total number of invention patent applications, $RD_{i,t}$ denotes R&D expenditure for firm i in year t . To address skewness, R&D expenditure is logarithmically transformed (after adding 1) before ratio calculation.

(2) Independent Variable: Digital Transformation Index (Dig)

Drawing on the methodology of Yu Miao et al^[15], this study adopts the Enterprise Digital Transformation Index (Dig) jointly released by the CSMAR database and East China Normal University in 2022. This index comprehensively evaluates six dimensions: strategic leadership, technology-driven practices, organizational empowerment, meso-environmental factors, digital outcomes, and application depth, providing a robust measure of corporate digital transformation.

(3) Mediating Variable: Financing Constraints (SA Index)

The SA Index, widely recognized for its exogeneity in assessing financing constraints, is selected as the proxy for financing constraints following Ju Xiaosheng et al^[16]. The formula is: $SA\ Index = -0.727 \times Size + 0.043 \times Size^2 - 0.04 \times Age$, where $Size$ is the natural logarithm of total assets, and Age represent the firm’s establishment years. The absolute value of the SA Index is used, with higher values indicating greater financing constraints.

(4) Control Variables

To ensure robustness, this study controls for variables identified in prior literature: Firm size ($Size$), Asset-liability ratio (Lev), Return on assets (ROA), Proportion of independent directors ($Indep$), Duality of roles ($Dual$), Board size ($Board$), Cash flow ratio, Equity balance ($Balance$). Fixed effects for individual firms ($Stock$), years ($Year$), and industries ($Industry$) are included to control unobserved heterogeneity. Detailed variable definitions are summarized in Table 1.

Table 1 Variable Definitions

Type	Symbol	Measurement
Dependent Variable	<i>Innov</i>	Natural logarithm of (Total invention patent applications / (R&D expenditure + 1))
Independent Variable	<i>Dig</i>	Digital Transformation Index from CSMAR Database
Mediating Variable	<i>SA</i>	Absolute value of the SA Index
	<i>RiskTap</i>	Frequency of myopic terms in annual MD&A reports

Type	Symbol	Measurement
Control Variables	<i>Size</i>	Natural logarithm of total assets
	<i>Lev</i>	Total liabilities divided by total assets
	<i>ROA</i>	Net profit divided by average total assets
	<i>Indep</i>	Number of independent directors divided by total board members
	<i>Dual</i>	Dummy variable: 1 if CEO and board chair roles are separate, 0 otherwise
	<i>Board</i>	Natural logarithm of the number of board members
	<i>Cashflow</i>	Net cash flow from operations divided by total assets
	<i>Balance</i>	Shareholding ratio of the 2nd to 5th largest shareholders relative to the largest shareholder
	<i>Stock</i>	Control for individual firm heterogeneity
	<i>Year</i>	Control for industry heterogeneity
	<i>Industry</i>	Control for time-specific trends

3.3 Model Construction

Building on the hypotheses proposed earlier and existing research, this study constructs the following baseline regression model:

$$Innov_{i,t} = \alpha_0 + \alpha_1 Dig_{i,t} + \sum \alpha_2 Control + \mu_i + \lambda_t + ind_j + \varepsilon_{it} \quad (2)$$

$$Med_{i,t} = b_0 + b_1 Dig_{i,t} + \sum b_2 Control + \mu_i + \lambda_t + ind_j + \varepsilon_{it} \quad (3)$$

$$Innov_{i,t} = \delta_0 + \delta_1 Dig_{i,t} + \delta_2 Med_{i,t} + \sum \delta_3 Control + \mu_i + \lambda_t + ind_j + \varepsilon_{it} \quad (4)$$

Where, *I* and *t* denote the firm and year, respectively. Dependent variable: *Innov* represents innovation efficiency. Independent variable: *Dig* is the digital transformation index. Mediating variable: *Med* denotes the mediator (financing constraints or risk-taking propensity), Control variables: Control includes all specified control. Firm fixed effects, Year fixed effects and Industry fixed effects are introduced into the model (μ_i , λ_t , and ind_j). ε_{it} is random error term.

4. Empirical Results Analysis

4.1 Descriptive Statistics

Descriptive statistics for key variables are presented in Table 2. The mean value of innovation efficiency (*Innov*) is 0.109, with a standard deviation of 0.078. Some firms reported zero patent applications during the study period, indicating significant dispersion in innovation efficiency across enterprises. The digital transformation index (*Digital*) has a maximum value of 6.401 and a mean of 1.393, reflecting substantial variation in digital maturity among sample firms. All other variables exhibit reasonable distributions.

Table 1 Descriptive Statistics

Variable	Mean	SD	Min	Max	Med	N
<i>Innov</i>	0.109	0.0780	0	0.641	0.110	8338
<i>Dig</i>	1.393	1.404	0.000	6.301	1.099	8338
<i>SA</i>	-3.761	0.241	-4.890	-3.033	-3.755	8338
<i>RiskTap</i>	0.133	0.148	0.000	5.405	0.096	8338
<i>Size</i>	21.380	0.808	19.160	26.390	21.300	8338
<i>Lev</i>	0.313	0.176	0.011	0.995	0.288	8338
<i>ROE</i>	0.059	0.141	-1.916	1.751	0.069	7447
<i>Indep</i>	38.140	5.536	14.291	75.000	37.500	8322
<i>Dual</i>	0.434	0.496	0.000	1.000	0.000	8338
<i>Board</i>	2.060	0.185	1.386	2.708	2.079	8322
<i>Cashflow</i>	0.042	0.068	-0.528	0.839	0.043	8338
<i>Balance</i>	0.882	0.639	0.014	4.000	0.715	8323

4.2 Baseline Regression Analysis

Table 3 reports the regression results. A stepwise regression approach is employed to analyze the relationship between digital transformation and innovation efficiency. Columns (1) to (4) show that the coefficient of Dig remains significantly positive at the 1% level after controlling for firm, year, industry fixed effects, and other covariates. These results preliminarily validate H1, confirming that digital transformation significantly enhances the innovation efficiency of SRDI SMEs.

Table. 3 Benchmark regression results

Variable	(1)	(2)	(3)	(4)
	Innov	Innov	Innov	Innov
dig	0.002*** (52.023)	0.001*** (8.026)	0.001*** (19.533)	0.001*** (5.369)
Size			0.021*** (19.830)	0.021*** (10.977)
Lev			0.002 (0.308)	-0.002 (-0.344)
ROE			0.030*** (5.073)	-0.000 (-0.019)
Indep			-0.000*** (-2.585)	0.000 (1.402)
Dual			0.003** (2.176)	0.001 (0.396)
Board			-0.002 (-0.439)	0.012* (1.676)
Cashflow			-0.010 (-0.819)	0.001 (0.053)
Balance2			0.001 (0.843)	-0.004 (-1.629)
Constant	0.035*** (22.066)	0.066*** (11.806)	-0.367*** (-14.201)	-0.410*** (-9.189)
Observations	29,750	7,437	6,757	6,588
R-squared	0.083	0.653	0.126	0.667
stock FE	NO	YES	NO	YES
Year FE	NO	YES	NO	YES

Note : * p<0.1, ** p<0.05, *** p<0.01, The data in parentheses are t-values.

4.3 Robustness Tests

Variable substitution: To address potential measurement biases, alternative proxies are used. The dependent variable is redefined as the natural logarithm of total granted patents divided by R&D expenditure (Innov_new) ; Following Wu Fei et al^[17], digital transformation (Dig_new) is measured using keyword frequencies from annual reports, focusing on foundational and applied technology adoption. Regression results in Table 4 (Columns 1–2) remain robust, with coefficients staying positive and significant.

Table 4 Replace the main variables

Variable	(1)	(2)
	Innov_new	Innov
Dig	0.00033** (2.261)	
Dig_new		0.004*** (4.724)
Constant	-0.257*** (-6.275)	-0.399*** (-9.621)
Control	YES	YES
Observations	6,365	6,973
R ²	0.635	0.653
Stock/Year/Industry	YES	YES

4.4 Endogeneity Treatment

To mitigate endogeneity, instrumental variable (IV) approaches are adopted. Drawing on Zhang Xuan et al^[18], two IVs are used: (1) the average digital transformation index of peer firms in the same city and industry (IV-list), and (2) the one-period lagged digital transformation index (IV-lag). The 2SLS results in Table 5 show no weak instrument or over-identification issues (Columns 1 and 3). After addressing endogeneity, the positive effect of digital transformation on innovation efficiency remains significant at the 1% level (Columns 2 and 4), confirming the robustness of baseline findings.

Table 5 IV test results

Variable	IV-lis		IV-lag	
	(1)	(2)	(3)	(4)
	Dig	Innov	Dig	Innov
Dig		0.001** (2.092)		0.002*** (3.127)
IV	0.382*** (22.449)		0.345*** (22.022)	
Control	YES	YES	YES	YES
Stock/Year/Industry	YES	YES	YES	YES
KP rk LM statistic	452.953		426.656	
KP rk Wald F statistic	503.958		484.956	
	(16.380)		(16.380)	
Observations	6,208	6,208	6,175	6,175
R ²		0.033		0.027

4.5 Mechanism Analysis

Innovation investment is a long-term and continuous process, accompanied by internal and external information asymmetry and unpredictable investment risks, in which financing constraints and corporate risk-taking tendencies hinder the progress

of innovation activities. Therefore, this paper takes financing constraint (SA) and enterprise risk-taking propensity (RiskTap) as mediating variables, and uses a step-by-step test method to verify the internal mechanism of financing constraint (SA) and enterprise risk-taking propensity (RiskTap) on the relationship between digital transformation and innovation efficiency of specialized, special and new SMEs, and the results are shown in Table 6.

Regression results indicate that in Column (2), the coefficient for the digital transformation index is -0.001, significant at the 5% level, demonstrating that digital transformation significantly alleviates financing constraints for SRDI enterprises. In Column (3), the coefficient for digital transformation remains 0.001, while the coefficient for financing constraints (SA) is -0.057, also significant and negative. These results further confirm the existence of a partial mediating effect, implying that SRDI SMEs improve their innovation efficiency by leveraging digital transformation to mitigate financing constraints, thereby validating Hypothesis H2.

Similarly, in Column (4), the coefficient for digital transformation is -0.001, significant and negative, indicating that digital transformation significantly enhances the risk-taking propensity of SRDI enterprises. In Column (5), the coefficient for digital transformation remains 0.001, while the coefficient for risk-taking propensity (RiskTap) is -0.019, significant and negative. This further supports the partial mediating effect, suggesting that SRDI SMEs enhance innovation efficiency by increasing their risk-taking propensity through digital transformation, thereby confirming Hypothesis H3.

Table6 The mechanism test results

Variables	(1)	(2)	(3)	(4)	(5)
	Innov	SA	Innov	RiskTap	Innov
SA			-0.057*** (-3.051)		
RiskTap					-0.019** (-2.098)
Dig	0.001*** (5.443)	-0.001*** (-4.589)	0.001*** (5.246)	-0.001** (-2.062)	0.001*** (5.448)
Constant	-0.392*** (-8.695)	-2.888*** (-88.577)	-0.558*** (-7.901)	0.187*** (2.696)	-0.388*** (-8.593)
Control	YES	YES	YES	YES	YES
Observations	6,444	6,481	6,444	6,455	6,418
R ²	0.668	0.985	0.669	0.671	0.668
Stock/Year/Industry	YES	YES	YES	YES	YES

4.6 Heterogeneity Analysis

The impact of digital transformation on innovation efficiency is often moderated by multiple factors. Enterprises with stronger reliance on digital technologies and more advanced digital infrastructure are better positioned to harness the positive innovation feedback from digital transformation. To explore the heterogeneous effects across different sample groups, this study conducts further analysis based on ownership type and industry attributes.

(1) Ownership Heterogeneity

Ownership type, as a critical classification criterion, influences corporate digital transformation. State-owned enterprises (SOEs) hold advantages in resources, talent, and policy support, enabling them to secure more direct government-backed resources for innovation activities compared to non-SOEs. Consequently, this study divides the sample into SOEs and non-SOEs for subgroup regression. Results in Columns (1) and (2) of Table 7 show that the coefficient for digital is higher and statistically significant at the 1% level for SOEs. This indicates that digital transformation exerts a more pronounced positive effect on innovation efficiency in SOEs relative to non-SOEs.

(2) Industry Heterogeneity

Given variations in technological R&D across industries, SRDI enterprises are categorized into manufacturing and non-manufacturing sectors. Regression results using Model (1) are reported in Columns (3) and (4) of Table 7. The coefficient for digital transformation in manufacturing firms is 0.085, significant at the 1% level, while the coefficient for non-manufacturing firms is 0.092, significant at the 5% level. Inter-group coefficient comparisons reveal that digital transformation drives more substantial improvements in innovation efficiency for manufacturing SRDI enterprises, likely due to their higher dependency on process innovation and technology-intensive operations.

Table 7 Heterogeneity test results

Variables	(1)	(2)	(3)	(4)
	Innov	Innov	Innov	Innov
	Non-SOE	SOE	Manufacturing	Non-manufacturing
dig	0.077*** (4.439)	0.111** (2.219)	0.085*** (4.867)	0.092** (2.245)
Constant	-0.397*** (-7.983)	-0.574*** (-4.079)	-0.394*** (-7.981)	-0.446*** (-3.739)
Control	YES	YES	YES	YES
Observations	5,619	738	5,550	1,033
R-squared	0.670	0.727	0.664	0.700
stock FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES

5. Conclusions and Policy Implications

5.1 Conclusions

This study empirically investigates the impact of digital transformation on the innovation efficiency of SRDI SMEs using panel data from A-share listed firms in China (2010–2022), with a focus on the mediating roles of financing constraints and risk-taking propensity. The findings reveal three key insights: Digital transformation significantly enhances the overall innovation efficiency of SRDI SMEs ; Financing constraints and risk-taking propensity partially mediate the relationship between digital transformation and innovation efficiency ; The innovation-enhancing effects of digital transformation exhibit significant heterogeneity across ownership types and industries, with stronger impacts observed in state-owned enterprises (SOEs) and manufacturing firms.

5.2 Policy Recommendations

Based on these findings, this study proposes the following targeted recommendations:

- (1) For SRDI Enterprises: Proactively integrate into the digital era by advancing transformation strategies. Establish efficient information exchange mechanisms and improve disclosure quality to alleviate financing constraints and secure funding foundations. Prioritize operational efficiency gains and innovation activation through digital tools, leveraging cost reduction and value creation to drive high-quality development.
- (2) For Policymakers: Design tailored support policies addressing the financing challenges faced by SRDI SMEs during digital transformation. Strengthen fiscal subsidies, tax incentives, and region-specific innovation incentives while enhancing regulatory frameworks to foster a robust digital ecosystem.
- (3) Systemic Enhancements: Develop comprehensive SRDI service platforms to streamline information flows and risk management. Strengthen intellectual property protection and institutionalize innovation-tolerant mechanisms (e.g., risk-sharing models, collaborative innovation networks) to amplify the risk-taking capacity of SRDI enterprises. Optimize external environments to maximize the role of digital transformation in boosting risk appetite, thereby accelerating breakthroughs in

core technologies and global value chain upgrading.

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Conflict of Interests

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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Research on the Influence of Enterprise ESG Performance on Green Technology Innovation Performance under Digital Transformation

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Abstract: With the acceleration of global digitalization process and the deepening integration of the concept of sustainable development, how the enterprise digital transformation affects the performance of enterprise ESG and green technology innovation has become an important issue of common concern to the academia and the industry. Taking China's A-share listed enterprises in 2013-2022 as the empirical research sample, the influence mechanism of enterprise ESG performance from the perspective of resource basis on the performance of green technology innovation is explored. The research shows that: (1) Enterprise ESG performance, and its three dimensions of environment, society and corporate governance have significantly promoted the improvement of enterprise green technology innovation performance, among which, environmental responsibility has a stronger role in promoting the green technology innovation performance. (2) Digital transformation positively regulates the promoting effect of enterprise ESG performance on the performance of green technology innovation. (3) Heterogeneity analysis shows that the ESG performance of enterprises with different property rights and industries has different effects on promoting green technology innovation performance, while the ESG performance of state-owned enterprises, manufacturing enterprises and non-heavy pollution enterprises has a stronger role in promoting green technology innovation performance. This study expands the related research on enterprise ESG performance, and provides more feasible solutions for enterprises to improve the performance of green technology innovation.

Keywords: Enterprise ESG Performance; Green Technology Innovation Performance; Digital Degree

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Introduction

In the context of global climate change and increasing pressure on resources and the environment, promoting green technology innovation has become a key path to achieve sustainable development. As the main body of economic activities, its environmental, social and governance (ESG) performance is closely related to the performance of green technology innovation. The ESG concept emphasizes that while pursuing economic benefits, enterprises both environmental protection, social responsibility and corporate governance, which is highly consistent with the goal of green technology innovation. In recent years, with the rise of the ESG investment concept and the improvement of the green financial system, the ESG performance of enterprises has been increasingly concerned by investors, regulators and all sectors of society. Good ESG performance not only helps enterprises to improve their brand image and reduce operational risks, but also brings more

financing opportunities and competitive advantages to enterprises, so as to promote the development of green technology innovation (Kamierczak M, 2022).

From a resource-based perspective, the better ESG performs, the more likely it are to actively search, acquire and integrate green technology innovation resources and carry out green technology innovation. However, the existing research on ESG performance and green technology innovation mechanism, mostly focus on strengthening environmental protection investment, ease financing constraints (Li, 2024) and improve risk bearing ability (Peng BaiChuan, 2024), etc., few research from the perspective of resource acquisition, solve the practical problems in the process of green technology innovation. Existing studies focus on the impact of ESG performance on corporate financial performance, but less on its mechanism of action on green technology innovation. In addition, the differential impact of different dimensions of ESG performance (environment, society and governance) on green technology innovation.

Existing research shows that the digital transformation has a significant impact on the performance of ESG, but the conclusions are different: Liu Fangyuan and Wu Yunlong (2024) proved that digital transformation can improve the environment and social responsibility; Wang Yinghuan and Guo Yongzhen (2023) found an “inverted U-shaped” relationship; Wang Haijun et al (2023) showed through quantitative analysis that every 1% increase of digital transformation can improve the performance of ESG by 0.096%. It is worth noting that existing research focuses on the direct correlation between digital transformation and ESG performance (Guo Shujuan and Yan Caifeng, 2024; Wang Jin et al., 2024), but ignores the regulatory role of the key situational variable, the degree of digitalization, on the “ESG-green technology innovation” relationship. Based on the dynamic capability theory, this paper discusses how the degree of digitalization can regulate the effect of ESG performance on the performance of green technology innovation.

Based on the above background, this study aims to explore the following core issues: How does enterprise ESG performance affect the performance of green art innovation? Is there any difference in the impact of different dimensions of enterprise ESG performance (environment, society, and governance) on green technology innovation performance? How the degree of internal digitalization adjusts the relationship between enterprise ESG performance and green technology innovation performance.

1.Theoretical analysis and research hypotheses

1.1 Enterprise ESG performance and green technology innovation performance

Enterprise green technology innovation performance is an important indicator to measure the output of green technology innovation enterprise green technology innovation, green technology innovation activity involves research and development, production and other links, need long-term capital, human resources and other resources and government and stakeholders have key resources and capacity (RanRong, 2023,2021), to improve enterprise green technology innovation performance, not only need sustainable development as the strategic goal, but also have the resources of green technology innovation (Yang Zhen and Wang Yue, 2024). ESG concept can guide the enterprise green transformation, green development into the enterprise production, management and financial management, help enterprises to form the sustainable development of resource allocation structure, increase investment in green technology innovation (Lin Binghong and Li Bingxiang, 2024), improve enterprise green technology innovation performance.

First, a company's ESG performance not only reflects the impact of organizational decisions on the environment and society but also maximizes the demonstration of sustainable development concepts (Xiao Hongjun, 2024). This means that companies focus on long-termism in their development, emphasizing collaboration between the company and the environment, society, and stakeholders. It also indicates that companies place greater emphasis on sustainable development in strategic decision-making and resource allocation (Yang Zhen and Wang Yue, 2024). From the perspective of responsibility fulfillment, a company's good ESG performance can send positive signals to the public, increase market attention, and thereby establish a favorable corporate image.

Secondly, good ESG performance represents that enterprises have taken active actions in environmental responsibility and social responsibility, to a certain extent, established the value symbiotic relationship between enterprises and multiple stakeholders, won the trust and support of government regulatory departments and stakeholders, and formed a reputation

advantage (Meng Mengmeng et al., 2023; Qiu Muyuan and Yin Hong, 2019), enterprise social responsibility can drive enterprise green innovation strategy (Xiao Hongjun, 2023), strengthen enterprise environmental investment, optimize resource structure, form green resource advantage, and enhance green innovation willingness (Li Huiyun et al., 2022).

Further, based on the basic view of natural resources, environmental performance (E) requires enterprises to reduce pollution and reduce carbon emissions, which will directly force enterprises to meet the needs of regulators and stakeholders through green technology innovation (such as clean production technology and recycling technology). Stakeholder theory states that improving employee well-being (e. g., safety training) and community relationships (S) can enhance internal cohesion, attract highly qualified talent, and indirectly promote innovation; and consumer environmental preferences may drive companies to develop green products. Agency theory points out that better internal governance (G) can avoid short-sighted management decisions and promote long-term investment in green technology. Based on the above analysis, the following assumptions are proposed:

H1: Good ESG performance helps enterprises to improve their green technology innovation performance.

H1a: The better the performance of enterprise environmental performance (E), the higher the performance of green technology innovation.

H1b: The better the good social performance (S) performance, the higher the green technology innovation performance.

H1c: The better the good governance performance (G) performance, the higher the green technology innovation performance.

1.2 Regulatory effect of digitalization degree

In the context of the enterprise digital transformation, digital application helps to the management of enterprise resources combination, including external resource acquisition, internal resource accumulation and stripping no value resources process, help enterprises to achieve competitive resources combination, for the development of the enterprise to build innovation pool, integrate resources for the enterprise to promote green technology innovation overweight power. With the development of digital economy, more and more enterprises have accelerated the pace of digital transformation. The power of digital technology has improved the speed of enterprise information acquisition and improved the efficiency of enterprise resource allocation (Wu Fei, 2021; Chen Dongmei, 2020).

Access resources is only one of the prerequisites for improving enterprise performance, and dynamic management of resources is the key to transforming resources into capabilities to improve enterprise performance (Sirmon et al., 2007; Sirmon et al., 2011). First, through digital transformation, enterprises can strengthen the resource allocation capacity and resource utilization efficiency, promote effective communication between departments, and realize the integration of internal and external resources of the organization (Amit R, HanX, 2017; Feng H, Wang F, Song G, et al, 2022). From the resource-based theory, the green innovation activities of enterprises rely on the effective use of resources, while digitalization can improve the efficiency of the use of resources and provide support for the green innovation of enterprises (Li Dehui, 2023). Based on the theory of resource arrangement, digitalization further enhances the dynamic capacity of enterprises, helps enterprises to improve the production process and optimize the allocation structure of elements (Lin Xin et al., 2023), so as to improve the operational efficiency and improve the utilization rate of resources (Fan Hongzhong et al., 2022).

The degree of digital transformation reduces innovation transaction costs (Wang Xiaohong et al., 2023). Companies with high levels of digitalization can reduce contract costs through technologies such as smart contracts, making ESG investments more efficiently converted into innovative outputs. At the same time, digital technology enhances data collection and analysis efficiency, accelerates capital turnover and knowledge sharing, and optimizes the allocation of production factors (Fan Hongzhong et al., 2022), creating a scale effect for green innovation. High-digitalization companies achieve real-time monitoring of energy consumption through technologies like the Internet of Things, directly guiding ESG performance improvements towards green technology research and development (Bai Fuping et al., 2023). Companies with high levels of digitalization improve corporate governance by increasing information transparency (Guo Shujuan and Yan Caifeng, 2024) and restructuring management frameworks (Wang Yinghuan and Guo Yongzhen, 2023).

Based on the above analysis, the following assumptions are proposed:

H2: The degree of digital transformation of enterprises strengthens the relationship between enterprise ESG performance and

green technology innovation performance.

2. Study design

2.1 Sample selection and data source

Take China's A-share listed companies from 2013 to 2022 as the initial sample, and make the following treatment: (1) excluding ST and * ST listed companies; (2) remove companies with missing data related to major research variables. After screening and matching, 4,464 A-share listed enterprises had A total sample size of 33,673. Among them, the green patent data of enterprises comes from the number of green patent applications of China Research Data Service Platform (CNRDS), and the relevant data of control variables comes from the National Tai'an (CSMAR) database.

2.2 Model setting

In order to verify the above assumptions, the following regression models are constructed: (1) assumptions of enterprise ESG and green technology innovation; (2) assumptions of the regulatory effect of digitalization degree on enterprise ESG performance and green technology innovation performance; specifically as follows:

$$\text{Green}_{i,t} = a_0 + a_1 \text{ESG}_{i,t} + a_2 \sum \text{Controls} + \sum \text{Industry} + \sum \text{Year} + \varepsilon_{i,t} \quad (1)$$

$$\text{Green}_{i,t} = t_0 + t_1 \text{ESG}_{i,t} + t_2 \text{ESG}_{i,t} \cdot \text{dig}_{i,t} + t_4 \sum \text{Controls} + \sum \text{Industry} + \sum \text{Year} + \varepsilon_{i,t} \quad (2)$$

In the above model, i represents the enterprise and t represents the time.

2.3 Variable selection and measurement

2.3.1 Interpreted variable: Green Innovation Performance (Green)

The performance data of green technology innovation is referred to the existing research, which is measured by the sum of the current number of green invention patent applications and the number of patent applications for green utility model (Xu Jianzhong and Wang Manman, 2019).

2.3.2 Interpretive Variables: Enterprise ESG Performance (ESG)

The measurement method of enterprise ESG performance, referring to the research of previous scholars, adopts the ESG score published by the third-party rating agency. In the process of robustness test, the ESG score published by Bloomberg Listed Company (PBESG) and CNRDS database (CNRDESG) plus 1 is used to measure the enterprise ESG performance.

2.3.3 Adjustment variables: degree of digital transformation (Dig)

In order to ensure the objectivity of the research method. Digital transformation data reference Tai'an (CSMAR) database of listed companies in Chinese digital transformation research database, including the strategy of listed companies, technology driven, organization can assign, enterprise digital achievements and application, the macro level of environmental support, etc., from the multidimensional enterprise digital transformation level. Therefore, the digital transformation index published in the National Tai'an (CSMAR) database was used to measure the degree of digital transformation.

2.3.4 Control variables

Control variables mainly include: 1) Firm Age (Age), which directly reflects the company's seniority and experience, influencing the resource endowment for green technology innovation; 2) Firm Size (Size), larger firms tend to be more rigid but have better resource advantages; 3) R&D Investment (RDinput), which directly affects the intensity of green technology innovation; 4) Debt-to-Asset Ratio (Lev); while also controlling for industry (Industry) and year (Year).

Specific variable definitions are shown in Table 1 below,

Table 1. Definitions of each variable

type of variable	Variable name	Specific definition	
explained variable	Green technology innovation performance	Green	Number of $\ln(1 + \text{green patent applications})$
explanatory variable	Enterprise ESG performance	ESG	The $\ln(1 + \text{ESG score})$

type of variable	Variable name	Specific definition	
regulated variable	Degree of digitization	Dig	CSMAR
controlled variable	scale	Size	Natural ln (1 + natural logarithm of total assets at the end of the year)
	asset-liability ratio	Lev	Total liabilities / total assets
	enterprise age	AGE	Enterprise listing years
	research input	RDinput	Source: Guotai An Database
	Enterprise nature	SOE	1 for state-owned enterprises and 0 for others

3. Empirical analysis

3.1 Descriptive statistical analysis

Table 2 presents the descriptive statistics of the main variables in this study. The mean value of corporate green technology innovation performance is 0.924, with a maximum of 7.782 and a minimum of 0. The maximum value for corporate ESG performance is 4.543, with a minimum of 3.628, and the sample mean is 4.303. It is evident that in recent years, many companies have begun to take effective measures to improve their ESG performance. The mean value of digitalization level is 3.599, with a standard deviation of 0.264, indicating significant differences in digitalization levels among companies. This further suggests that choosing differentiated levels of corporate digitalization as a contextual factor in the model for promoting corporate green technology innovation performance better aligns with the actual situation of each company.

In addition, the Pearson (Pearson) correlation analysis was conducted on the main variables, and the results showed that the correlation coefficient between all variables was less than 0.5, and there was no multicollinearity problem.

Table 2 Descriptive statistics of samples

variable		sample capacity	mean	standard error	least value	crest value
Enterprise ESG performance	ESG	32,815	4.303	0.0766	3.628	4.543
Environmental performance	E	32,815	4.115	0.126	3.416	4.566
social responsibility	S	32,815	4.317	0.147	0	4.615
corporate governance	G	32,815	4.373	0.105	3.025	4.605
Green technology innovation performance	Green	32,815	0.924	1.226	0	7.782
Digitization degree	Dig	32,815	3.599	0.264	3.107	4.395
scale	Size	32,809	3.149	0.0622	2.808	3.472
asset-liability ratio	Lev	32,747	0.429	0.214	0.00797	1.957
enterprise age	AGE	32,801	10.36	7.914	0	32
research input	RDinput	32,815	2.618	4.703	0	23.73

3.2 Analysis of the regression results

3.2.1 Enterprise ESG performance and green technology innovation performance

Table 3 reports the results of the regression analysis of enterprise ESG performance on green technology innovation performance. As shown in column (2), after controlling for the influence of other variables on green technology innovation performance, the regression coefficient of enterprise ESG performance on green technology innovation performance is 1.186 and significantly positive at the 1% level ($p < 0.01$), assuming H1 is supported. In addition, from the perspective of control variables, enterprise size, age and R & D investment have a significant positive impact on the green technology innovation of enterprises, which also shows that enterprises with good background can actively respond to the national two-carbon policy

and carry out green technology innovation.

Considering the ESG score, environmental performance (Environmental) mainly evaluates the positive measures taken by the enterprise in environmental protection; social responsibility performance (Social) reflects the responsibility of stakeholders and has more legitimacy and reputation advantages; corporate governance performance (Governance) mainly evaluates the overall strategic planning and internal management level of the enterprise, and good corporate governance ability will enhance the technological innovation level of the enterprise (Feng Genfu and Wen Jun, 2008). Based on the above analysis, ESG is divided into three dimensions to test the impact of different dimensions on the performance of green technology innovation of enterprises. Table 3 column (3) (4) (5) regression results show that environmental protection (E), social responsibility (S), corporate governance ability (G) to the regression coefficient of green technology innovation performance of 1.039, 0.329, 0.316 respectively, and all at 1% level is positive ($p < 0.01$), in addition, the environmental responsibility of green technology innovation performance is stronger. Suppose H1, H1a, H1b, and H1c were verified.

Table 3 Enterprise ESG performance and green technology innovation performance

variable name	(1)	(2)	(3)	(4)	(5)
	Green	Green	Green	Green	Green
ESG	2.611*** (32.136)	1.186*** (15.618)			
E			1.039*** (22.471)		
S				0.329*** (8.168)	
G					0.316*** (5.829)
Size		10.601*** (84.826)	10.550*** (86.762)	11.030*** (91.037)	11.100*** (91.820)
Lev		0.175*** (5.414)	0.059* (1.887)	0.071** (2.255)	0.119*** (3.578)
AGE		0.003*** (3.112)	0.002* (1.926)	0.002* (1.908)	0.001 (1.072)
RDinput		-0.004** (-2.373)	-0.002 (-1.370)	-0.004** (-2.232)	-0.004** (-2.299)
Constant	-10.889*** (-30.481)	-37.911*** (-90.125)	-36.982*** (-96.977)	-35.508*** (-93.097)	-35.782*** (-87.592)
Industry	YES	YES	YES	YES	YES
year	YES	YES	YES	YES	YES
Observations	32,815	32,734	32,734	32,734	32,734
R-squared	0.216	0.408	0.412	0.405	0.404

Note: t-statistics in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$; unless otherwise specified, the following tables are the same.

3.2.3 Test of regulatory effect

The regulatory mechanism test is shown in Table 4, which tests the regulation effect of redundant resources and the

dual regulation mechanism of digital and redundant resources successively. Column (1), (2) test the degree of digital transformation, column (2), the enterprise digital transformation degree and ESG performance interaction of the enterprise green technology innovation performance regression coefficient of 2.330, verify the hypothesis H2, namely the enterprise digital transformation degree strengthen enterprise ESG performance and green technology innovation performance.

Table 4: Test of regulatory effects

VARIABLES	(1)	(2)
	c_Green	c_Green
c_lnESG	1.186*** (15.618)	1.167*** (15.390)
c_lnESG*Indigg		2.330*** (9.022)
lnsize1	10.601*** (84.826)	10.579*** (84.738)
Lev	0.175*** (5.414)	0.172*** (5.302)
AGE	0.003*** (3.112)	0.002** (2.237)
RD1	-0.004** (-2.373)	-0.004** (-2.449)
Constant	-33.725*** (-86.224)	-33.666*** (-86.167)
Observations	32,734	32,734
R-squared	0.408	0.409

t-statistics in parentheses ; *** p<0.01, ** p<0.05, * p<0.1

3.3 Robustness Test

Considering the diversity of ESG rating indicators, this paper uses the ESG score published by Bloomberg listed companies and CNRD database plus 1 natural logarithm to remeasure the ESG performance of the enterprise, replace the original explanatory variable Huasheng ESG score, and regress the samples. In Table 5-8, columns (1) and (3), respectively, the estimated coefficients of Bloomberg ESG (PBESG) and CNRD database ESG (CNRDESG) were 1.707 and 0.426, respectively, which passed the 1% confidence level significance test. In addition, after the addition of control variables, the estimated coefficient of Bloomberg ESG (PBESG) and CNRD database ESG (CNRDESG) was 0.642 and 0.238, respectively, and was significantly positive at the 1% confidence level, indicating that the change of explanatory variables still has a significant positive impact of ESG performance on the enterprise green technology innovation, the regression results are basically consistent with the regression results of the above benchmark results, indicating that the main effect results are robust.

Table 5 Results of the robustness tests for replacing the ESG metric

VARIABLES	(1)	(2)	(3)	(4)
	Green	Green	Green	Green
CNRDESG			0.642*** (32.810)	0.238*** (13.525)
PBESG	1.707*** (30.608)	0.426*** (7.768)		
lnsize1		13.329***		10.912***

	(1)	(2)	(3)	(4)
VARIABLES	Green	Green	Green	Green
		(50.405)		(90.427)
Lev		-0.096		0.041
		(-1.443)		(1.311)
AGE		-0.000		0.001
		(-0.182)		(0.768)
RDinput		-0.000		0.000***
		(-0.230)		(3.627)
Constant	-4.972***	-42.897***	-1.801***	-34.509***
	(-21.962)	(-55.313)	(-16.295)	(-92.675)
Observations	11,075	11,068	32,815	32,734
R-squared	0.360	0.498	0.217	0.407

t-statistics in parentheses ; *** p<0.01, ** p<0.05, * p<0.1

3.4 Heterogeneity analysis

(1) Property property rights analysis

Based on the important impact of enterprise property rights on enterprise environmental performance, social performance and corporate governance performance (Li Yuee et al., 2018; Liu Xinji, Zhu Menglan, 2018), the sample enterprises are further divided into two sample groups according to the nature of state-owned enterprises and non-state-owned enterprises (Li Jinglin et al., 2024), and discuss the differences between ESG performance and green technology innovation performance under the nature of enterprise property rights.

Column (1) and (2) in Table 6 show that the regression coefficient of ESG performance of green technology innovation performance is 1.310, which is significantly higher than that of non-state-owned enterprises, and is significantly positive at 1% ($p < 0.01$), indicating that ESG performance of state-owned enterprises has a stronger role in promoting green technology innovation performance. First of all, state-owned enterprises, as the market subject, are not only the pillar of the national economy, but also the support of the national strategy. Compared with non-state-owned enterprises, they pay social benefits more attention while pursuing economic benefits. Secondly, the state-owned nature of state-owned enterprises makes it easier for them to obtain the support of stakeholders, and coupled with their good ESG performance, it is more convenient to obtain government subsidies or financial support from investors, which further strengthens their role in promoting green technology innovation.

Table 6 Test of heterogeneity of property rights

	(1)	(2)
	state-owned enterprises	Non-state-owned enterprises
VARIABLES	Green	Green
ESG	1.310***	0.984***
	(8.859)	(11.263)
size	12.744***	8.853***
	(58.117)	(56.157)
Lev	-0.147**	0.396***
	(-2.435)	(10.371)

VARIABLES	(1)	(2)
	state-owned enterprises	Non-state-owned enterprises
	Green	Green
AGE	0.001	0.003***
	(0.534)	(3.092)
RDinput	0.325***	0.025***
	(16.497)	(7.297)
Constant	-45.440***	-31.402***
	(-61.213)	(-59.072)
Observations	10,441	21,993
R-squared	0.520	0.356

t-statistics in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

(2) Analysis of sub-industry nature

Previous studies have found that the industry in which an enterprise operates will have an important impact on the environmental performance (Wang Jianming, 2008), social performance and environmental governance (Xu Dongyan et al., 2020). Therefore, this study further put the enterprise industry by manufacturing and non-manufacturing and heavy pollution and non-heavy pollution industry, Table 5-11 column (1), (2) shows that the influence of manufacturing ESG performance on green technology innovation coefficient is 1.425, higher than the non-manufacturing enterprise group coefficient of 1.284, and in the 1% confidence level is positive ($p < 0.01$). Analysis of the reasons: First of all, the manufacturing industry itself has a high technical content and a good foundation for technological innovation. Under the policy drive and strict environmental regulation, enterprises actively respond to national policies and increase investment in green technology research and development. Secondly, the technology content of non-manufacturing enterprises is relatively low, the technology foundation is weak, and lack the foundation and conditions for green technology innovation. With the deepening of green development, non-manufacturing enterprises also need to strengthen green technology innovation to realize the green transformation of the whole industry.

Further, this paper categorizes listed company samples into heavily polluting industries and non-heavily polluting industries based on industry characteristics. Columns (3) and (4) in Table 5-11 show that the coefficient of ESG performance for heavily polluting companies on green technology innovation is 0.612, significantly lower than the coefficient of 1.402 for non-heavily polluting companies, and it is significantly positive at the 1% confidence level ($p < 0.01$). The reasons may lie in: heavily polluting industries typically rely on traditional production technologies and energy structures, with highly specialized equipment and technology, lacking relevant technical reserves and R&D capabilities, making technological transformation difficult and facing talent shortages. In contrast, non-heavily polluting industries (such as high-tech manufacturing) have less pollution during production processes, lower technical barriers and cost pressures for green technology innovation, and are more likely to receive policy support and market recognition, thus having greater motivation to increase investment in green technology innovation.

Table 7 tests of heterogeneity by sector

VARIABLES	(1)	(2)	(3)	(4)
	manufacturing industry	non-manufacturing industry	Heavy pollution	Non-heavy pollution
	Green	Green	Green	Green
ESG	1.480***	0.790***	0.513**	1.059***
	(14.617)	(5.432)	(2.289)	(11.527)

VARIABLES	(1)	(2)	(3)	(4)
	manufacturing industry	non-manufacturing industry	Heavy pollution	Non-heavy pollution
	Green	Green	Green	Green
size	10.523*** (61.289)	6.669*** (33.852)	11.706*** (35.848)	7.369*** (53.146)
Lev	0.647*** (15.354)	-0.346*** (-5.732)	0.041 (0.452)	0.151*** (3.949)
AGE	-0.006*** (-5.168)	-0.016*** (-11.751)	-0.010*** (-4.430)	-0.006*** (-6.438)
RDinput	0.013*** (5.178)	0.031*** (8.379)	-0.011** (-2.129)	0.030*** (13.637)
Constant	-38.722*** (-67.343)	-23.640*** (-33.941)	-38.434*** (-35.498)	-27.027*** (-56.727)
Observations	21,613	11,121	3,431	29,303
R-squared	0.272	0.165	0.385	0.168

t-statistics in parentheses ; *** p<0.01, ** p<0.05, * p<0.1

4. Conclusions and revelation

4.1 Study Conclusions

This study takes the a-share listed companies from 2013 to 2022 and empirically test the relationship between ESG performance and green technology innovation performance. The research results of this paper show that: first, good ESG performance is conducive to the improvement of green technology innovation performance. From the perspective of enterprise ESG performance, enterprise environmental responsibility has a stronger effect on the improvement of green technology innovation performance; second, digital transformation positively regulates the promotion of enterprise ESG performance on green technology innovation performance. Third, the heterogeneity analysis shows that the ESG performance of state-owned enterprises, manufacturing enterprises and non-heavy pollution industries plays a stronger role in promoting the performance of green technology innovation.

4.2 Management implications

Based on the empirical analysis of China's A-share listed companies, this study provides important inspiration for the formulation of enterprise sustainable development strategy and digital transformation practice:

(1) Strengthen ESG management and focus on environmental responsibility to drive green innovation. The study has found that ESG performance (especially environmental responsibility fulfillment) has significantly promoted green technology innovation. Enterprises should systematically optimize the ESG management system and bring environmental governance into the core of their strategy, such as upgrading cleaner production technology, carbon footprint tracking and other means to transform ESG investment into green innovation competitiveness. For manufacturing and state-owned enterprises (with a more significant effect), a differentiated ESG technology roadmap can be developed in light of industry characteristics.

(2) Deepen the digital transformation and enable ESG resource transformation efficiency. Digital transformation is a key lever to amplify the innovation effect of ESG. Enterprises need to accelerate the application of the Internet of Things, big data and other technologies, build an intelligent environment management system to reduce the cost of green research and development (such as real-time monitoring of energy consumption), and integrate supply chain resources through digital platform to promote ESG data sharing and collaborative innovation. Non-heavy pollution industries can focus on the layout

of digital green product design, while heavy pollution industries need to strengthen the intelligent transformation of pollution control technology.

(3) Classified measures were taken to optimize the collaborative path between ESG and digitalization. Heterogeneity analysis shows that the ESG innovation effect of state-owned enterprises and manufacturing industry is more prominent. State-owned enterprises can take the advantages of resource integration to build industry-level ESG digital ecology; manufacturing enterprises should focus on production process digitalization and green process innovation; non-heavy polluting enterprises can explore ESG-oriented digital service mode (such as carbon asset management platform). Management needs to regularly evaluate the synergies between digitization and ESG and dynamically adjust resource allocation.

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Conflict of Interests

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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The Path Mechanism of Government Behavior Promoting the Construction of Innovation Chain of Leading Enterprises

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Abstract: Promoting the construction of innovation chains in leading enterprises has become a crucial focus in China's new development stage. The government plays a pivotal guiding role in advancing this process. Based on government behavior theory, this study conducts an in-depth analysis of the representative case where Hefei municipal government facilitated BOE's innovation chain development, aiming to reveal the impact mechanisms of governmental actions on the formation of innovation chains in technology-leading enterprises. The findings demonstrate that: First, the construction of innovation chains in leading enterprises encompasses three dimensions - formation of internal links, establishment of external links, and creation of interconnected relationships between internal and external components. Second, the government constitutes the core driving force through three empowerment mechanisms: strategic guidance, innovation resource allocation, and institutional environment optimization. Third, key mediating factors include the government's role as chain coordinator, industry-academia collaborative projects, and digital innovation platform development. These conclusions provide theoretical foundations and practical pathways for optimizing governmental innovation chain governance models and improving industrial innovation chain cultivation mechanisms, contributing to both academic research and policy-making in innovation ecosystem development.

Keywords: Government Behavior; Construction of Leading Enterprise Innovation Chain; Path Mechanism; Case Study

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1.Introduction

As primary drivers of market economic activities, enterprises constitute pivotal forces in propelling technological innovation. Within the new developmental paradigm, China's innovation-driven development strategy is undergoing profound transformation, marked by a critical transition of its innovation system from scale expansion to quality enhancement. Serving as cornerstone entities within the national innovation ecosystem, leading enterprises have assumed increasingly vital roles in the global technology competition landscape. These enterprises not only possess proprietary control over core technologies but also function as benchmark leaders in international industrial competition, with their developmental trajectories directly determining the progress and efficacy of national innovation initiatives^[1]. The high-quality evolution of innovation chains in leading enterprises has emerged as a strategic imperative for leveraging scientific innovation to catalyze industrial advancement and cultivate next-generation productive forces in the new era^[2]. However, confronted with evolving global economic and political dynamics, China faces "chain fragmentation" risks in critical technology domains due to

innovation inadequacies. The misalignment between technological innovation outputs and industrial demands has hindered the manufacturing sector's ascent within global value chains. Fundamentally, the operational discontinuities in innovation chains and coordination failures across industrial ecosystems stem from inefficiencies in translating knowledge innovations into practical applications^[3]. Disruptions in inter-phase connectivity not only impede the continuity of innovation processes but also significantly degrade the operational efficiency of holistic innovation systems^[4]. The contemporary open innovation paradigm has fundamentally reconfigured the competitive logic of leading enterprises, manifesting in three transformative dimensions: Competitive Entity Evolution: Shift from individual firms to value chain ecosystems, progressing toward business ecosystem architectures; Innovation Paradigm Transition: Replacement of closed proprietary innovation models with open innovation systems emphasizing multilateral collaboration; Organizational Architecture Restructuring: Transformation from decentralized internal resource dependency to chain-structured innovation frameworks centered on leading enterprises as pivotal nodes. Under policy mandates to strengthen national strategic technological capabilities, constructing efficient innovation chains for leading enterprises has become an urgent priority for industrial modernization, bearing profound implications for realizing innovation-driven development strategies.

Although the current government has strongly promoted the innovative development of the transformation of scientific and technological achievements^[5], existing research has shown that local governments, as important guiding entities in the innovation chain, possess the ability to command and coordinate the forces and resources of all aspects of society^[6], and play a crucial role in constructing the innovation chain of leading enterprises and promoting the sound development of the innovation chain of leading enterprises^[7]. However, relevant research on issues such as the government's behavior patterns, effects, and the mechanisms by which the government promotes the construction of the innovation chain of leading enterprises remains insufficient. Clarifying the path of how government behavior constructs the innovation chain of leading enterprises is an important question that this study needs to answer.

Therefore, in order to address the above issues and make up for the deficiencies of existing theories, this study takes leading enterprises as the research subject and explores the path of how government behavior constructs the innovation chain of leading enterprises. This is conducive to giving play to the functions of an effective government, strengthening the status of leading enterprises as the main body of innovation, and promoting the effective formation of the innovation chain. To explore the path of how government behavior constructs the innovation chain of leading enterprises, this paper conducts research from the following three aspects: First, it analyzes the relevant research on the innovation chain of leading enterprises and the collaborative innovation between the government's guidance and the innovation chain of leading enterprises; Second, it explores the path mechanism of how government behavior constructs the innovation chain of leading enterprises by combining practical cases; Finally, it summarizes the research conclusions of this paper, and puts forward management implications and policy suggestions, providing theoretical support for accelerating the construction of the innovation chain of leading enterprises, and also providing useful inspiration for local governments to formulate relevant industrial policies.

2. Literature review

2.1 Leading enterprise innovation chain

The existing literature still shows insufficient systematic research on the innovation chain of leading enterprises, and a relatively unified definition has not yet been formed. A leading enterprise is an enterprise that has a significantly leading position in a certain industry or field and is a leader in the industry that can lead the progress of industrial technology and achieve breakthroughs in key and core technologies^[8]. The innovation of leading enterprises covers the whole process from new scientific discoveries to the industrialization of high technologies^[9], involving innovative activities with chronological correlations such as basic research, applied research, technological development, and industrialization. The sequential collection of all these activities can be represented by an innovation chain^[10]. Regarding the definition of the innovation chain of leading enterprises, some scholars define the innovation chain of leading enterprises as a process in which, with leading enterprises as the main body and around the common innovation goals, various innovation entities couple innovation resources through a certain relationship to generate value-added^[1]; some research also believes that the innovation chain of leading enterprises is a hybrid organization composed of actors adhering to different institutional logics. Although there are

differences in the conceptual definitions of the innovation chain of leading enterprises in the academic community, relevant research highlights the leading role of leading enterprises in the innovation chain, and it is unanimously believed that as the leaders of the innovation chain, leading enterprises can achieve the value-added of the innovation chain of leading enterprises only through collaborative innovation with multiple entities of industry, university, research institute, and application such as universities, scientific research institutions, customers, and suppliers^[11]. Therefore, based on the existing research, this paper defines the construction of the innovation chain of leading enterprises as a process in which leading enterprises, as the main enterprises of the innovation chain, play a leading role. Through the formation of the chain connection relationship between the internal and external links of the innovation chain, the innovation needs are further met, and multiple innovation entities divide labor and cooperate to form a process of innovation value-added.

Some scholars have conducted preliminary explorations on the models and structures of the innovation chain of leading enterprises based on specific case analyses. Scholars such as Yang Zhong^[12] summarized the characteristics of the innovation chain of leading enterprises in different situations from the perspectives of the structure and operation of the innovation chain, and refined four models of the innovation chain of leading enterprises, namely: the “symbiotic open type”, the “linear open type”, the “symbiotic aggregative type”, and the “linear aggregative type”. Xu Sen and Sun Jiayi^[13] used the qualitative meta-analysis method to construct a “4×4” classification of innovation chain models, dividing 30 Chinese leading enterprises into three grades with a total of 12 innovation chain models. Scholars Shao Jiyou and Sheng Zhiyun^[14] conducted a case study on the operation of Huawei’s innovation chain and found that the construction of Huawei’s innovation chain presented a nested structure. Some other scholars have found that under the operation mechanism of the innovation chain of state-owned leading enterprises, there are relationships of conflict, dislocation, consistency, and complementarity between institutional logics, which affect the core attributes of the innovation chain^[7].

2.2 The government guides the collaborative innovation of the leading enterprise innovation chain

When the government intervenes in the innovation activities within the innovation chain in different ways, its mechanisms of action and effects also differ accordingly. Therefore, the influence of government behavior on innovation activities has always been at the center of research by scholars both at home and abroad. Currently, scholars mainly hold the view that the government’s role in the innovation chain of leading enterprises is shifting from a “dominant” one to a “guiding” and “connecting” one, and is transitioning from being institution-driven to market-driven^[6]. Scholars like Song Jian et al. believe that tax preference policies can significantly enhance the innovation capabilities at all links of an enterprise’s innovation chain, and the government should be encouraged to further increase the intensity of tax preferences for enterprises^[15]. Scholars such as Yang Zhong believe that the central government plays a leading role in the operation of the innovation chain of state-owned leading enterprises^[7]. Some studies have pointed out that the government’s formulation of innovation policies, as well as its support and participation, play an important facilitating role in the innovation input, innovation output, and transformation of technological achievements within the innovation chain^[16-17]. Most of these studies contend that there are inherent flaws in the market mechanism, necessitating the government’s participation in innovation activities to make up for the market’s failure in allocating innovation resources. Hong et al.^[18] and Greco et al.^[19] have pointed out that the government’s presiding over and participating in the research and development of basic knowledge and common technologies creates a favorable knowledge environment for enterprises to carry out commercial and practical research and development activities, which is conducive to the formation of the innovation chain. Throughout the process of the government guiding the collaborative innovation of the innovation chain of leading enterprises, the government should assume the role of an “architect”, leveraging the “pioneer” demonstration effect of leading enterprises to drive other enterprises to generate a “following effect”, thereby promoting the collaborative innovation of the entire innovation chain of leading enterprises^[20].

In conclusion, scholars have currently conducted exploratory research on theories such as the construction of the innovation chain of leading enterprises and the collaborative innovation of the innovation chain of leading enterprises guided by the government, laying a solid theoretical foundation for this study. However, there are still the following aspects that require further exploration: Firstly, there is a lack of dimensional analysis of government behavior. Most existing studies start from a macro perspective, exploring the relationships and behaviors among various independent participants within a large system,

without attempting to distinguish the government from other entities, thus failing to clarify the specific role played by the government. Secondly, as the dominant force in the innovation chain of leading enterprises, the “black box” of how leading enterprises organize the collaborative innovation among the innovation entities from industry, academia, research institutions, and users has not been opened yet. Although scholars have conducted relevant research on the collaborative innovation among industry, academia, and research institutions, there is still a lack of analysis of the construction path of the innovation chain of leading enterprises.

3.The path mechanism and influence effect of government behavior on the construction of innovation chain of leading enterprises

3.1 Construction of leading enterprise innovation chain

The innovation chain of leading enterprises is a whole-chain, multi-subject, and multi-link collaborative innovation system constructed by leading enterprises in the process of promoting technological research and development, achievement transformation, and industrial application, spanning from basic research to industrialization and commercialization. Its core is to organically integrate innovation elements such as knowledge, technology, capital, and talent, forming an innovation activity process from original innovation to industrial application, so as to achieve technological breakthroughs, product iterations, and industrial upgrades. This paper argues that the innovation chain of leading enterprises has a structure formed by the chain connection relationship between internal and external links. It is manifested in that the leading enterprise, as a whole, is the leader of the entire macro innovation chain. At the same time, the leading enterprise has built a relatively independent and complete micro innovation chain internally. The multi-level participants in the internal system, following the logic of specialized division of labor, dominate the innovation activities at each link of the innovation chain. In the basic research stage, it is mainly the BOE Laboratory that participates, conducting basic research and development of semiconductor display technology, providing the theoretical knowledge required for technological innovation, investing in applied basic research, and assisting downstream departments in technological development; the product research and development center interfaces with the laboratory, absorbs the results of basic research and development, and transforms them into product technologies; in the stages of technological development and industrialization, the product trial production department completes the product trial production to realize new products or services, and the marketing department provides product marketing services. In the external links, the leading enterprise, through constructing a supply-demand coordination and matching system for internal and external technological innovation resources, establishes a resource adaptation mechanism according to the characteristics of task requirements during the process of internal subjects dominating innovation activities at each stage, systematically screens external subjects with special resource endowments to integrate into the innovation network, and forms a task-oriented collaborative innovation model. External participants show significant characteristics of phased embedding in the innovation chain on the entire macro innovation chain. Specifically, in the links of basic research and applied research, academic organizations represented by universities and scientific research institutions achieve innovation collaboration through forms such as establishing joint laboratories with the BOE Research and Development Center and setting up scientific research strategic alliances, so as to achieve complementary innovation capabilities and innovation demands. Judging from the distribution law of the innovation chain, academic organizations are more deeply embedded in the basic research link, while industrial subjects such as customers (demand-oriented relationship), suppliers (production complementary relationship), and competitors (competitive cooperation relationship) are mainly concentrated in the stages of technological development and industrialization. This subject embedding model based on the differentiation of innovation links not only ensures that each innovation subject can focus its capabilities in its advantageous fields but also promotes the continuous leap of technological innovation in the BOE innovation chain through the effective integration of specialized resource endowments.

As a leading enterprise in the semiconductor display industry, the successful construction of BOE's innovation chain is inseparable from the support of the government's strategic planning and effective measures. Specifically, the Hefei Municipal Government has clarified the direction for the overall development of the semiconductor display industry through top-level design and promoted the organic combination and interaction between the knowledge innovation system and the economic

system with the help of a series of innovation policies and strategic plans.

Optimizing the orientation of strategic planning, innovation resources, and the innovation institutional environment is not only an inevitable requirement for improving the overall effectiveness of the national innovation system but also the main working line for the government to implement the innovation-driven development strategy in the coming period. In the process of driving the formation of BOE's innovation chain, the Hefei Municipal Government has not only carried out in-depth strategic planning and effective innovation guidance but also paid special attention to the possible problem of insufficient resources in the innovation chain. To this end, the government has taken a variety of measures to enhance the capabilities of the innovation chain, including but not limited to the injection of human resources, scientific and technological resources, and financial resources. These measures have greatly enriched and improved the various resources required by the innovation chain. In addition, in order to create a more favorable development environment for BOE's innovation chain, the Hefei Municipal Government has actively committed to creating a fair competitive market environment, broadening financing channels, and continuously optimizing the business environment, thus providing a more complete institutional guarantee. Such a series of actions have effectively supported the growth and development of BOE's innovation chain. Therefore, this paper argues that government behavior promotes the construction of the innovation chain of leading enterprises through strategic guidance empowerment, innovation resource empowerment, and institutional environment empowerment.

3.1.1 Strategic guidance empowerment:

The government conducts strategic planning and innovation guidance for the innovation chain of leading enterprises. According to the local market environment, the government precisely provides innovation guidance for the innovation chain of leading enterprises through relevant strategic planning. Leading enterprises should actively comply with the guidance of national industrial policies and play a leading role in the entire industry. In the case, Hefei's home appliance industry has long occupied a leading position in the country, gathering many related enterprises and accumulating rich technologies, resources, and market shares. However, restricted by factors such as relatively backward production technology, especially the shortage of screen supply, the further development of the home appliance industry has been restricted. The development path of the traditional home appliance industry is not sufficient to support Hefei's long-term development, and it is necessary to implement an innovation-driven development strategy. In response to this situation, the Hefei Municipal Government has introduced a series of policy measures aimed at strongly supporting the breakthrough and upgrading of new display industry technologies and actively attracting related enterprises to settle in, so as to promote the overall prosperity and development of the home appliance industry. For example, "in terms of industrial development, the Hefei Municipal Government is clearly aware that the development path of the traditional home appliance industry is not sufficient to support Hefei's long-term development, and it is necessary to implement an innovation-driven development strategy to develop the strategic emerging industry - the new display industry." Therefore, based on the above analysis, the government's active strategic planning and innovation guidance for the industry where leading enterprises are located helps to accelerate the development of the innovation chain of leading enterprises. Thus, this study believes that the government's strategic guidance empowerment, that is, strategic planning and innovation guidance, is a prerequisite for the construction of the innovation chain of leading enterprises.

3.1.2 Innovation resource empowerment:

It refers to the behaviors of providing human resources, scientific and technological resources, financial resources, etc. through direct or indirect means. Existing research has shown that the government's scientific and technological innovation policies are an important guarantee for the rational allocation of innovation resources and the improvement of enterprise innovation performance^[21]. Hefei is one of the four major science and education bases in the country and has unique element advantages such as science and technology and talent. For example, the University of Science and Technology of China and BOE jointly established a joint laboratory to train high-end talents in fields such as display technology and materials science in a targeted manner. Moreover, the government has introduced a number of talent introduction policies, trained high-end technical talents, and guided enterprises to connect with universities to jointly train professionals with relevant majors. The government has also actively mobilized scientific and technological resources, including introducing advanced technologies, supporting key technological breakthroughs, and promoting the transformation of scientific and technological achievements.

On the basis of gathering scientific and technological resources, Hefei continues to promote the transformation of scientific and technological innovation achievements into real productive forces, and the “big scientific and technological achievement transformation model” has been selected as a national typical case. The Hefei Municipal Government has increased the investment in financial resources through policy measures such as financial subsidies and tax preferences, thereby stimulating the innovation vitality of leading enterprises. These investments not only provide the necessary financial support for the construction of the innovation chain of leading enterprises but also reduce the research and development costs of enterprises, making enterprises more willing and capable of carrying out research and development innovation activities. The Hefei Municipal Government has guided and encouraged BOE to increase innovation investment through a series of policy measures, such as setting up research and development innovation funds and providing research and development innovation tax preferences. These policy measures not only improve the self-research and development innovation capabilities of leading enterprises but also promote the construction of the innovation chain of leading enterprises. Research and development innovation investment enables enterprises to introduce advanced technologies, equipment, and talents, carry out research and development and innovation of cutting-edge technologies, and thus promote technological breakthroughs and upgrades in the industry. This is particularly important for leading enterprises because they need to maintain technological leadership and market competitiveness. Based on the above case analysis, the government’s active provision of human resources, scientific and technological resources, and financial resources can provide various innovation resources for the innovation chain of leading enterprises, facilitate the smooth progress of innovation activities, and thus completely construct the innovation chain of leading enterprises. Therefore, this study believes that the government’s innovation resource empowerment, that is, providing human resources, scientific and technological resources, and financial resources, is a necessary condition for the construction of the innovation chain of leading enterprises.

3.1.3 Institutional environment empowerment:

The government improves the market economic system, creates a more fair and open market environment for enterprises, broadens financing channels, and optimizes the business environment, attracting more innovation subjects to join the innovation chain of leading enterprises and providing the empowerment behavior of the institutional environment required for the construction of the innovation chain of leading enterprises. A good innovation market environment is an important guarantee for promoting the cultivation and development of scientific and technological talents, the germination and expansion of innovation subjects, the implementation and transformation of innovation achievements, and the deep integration of the innovation chain and the industrial chain and the feedback to scientific and technological innovation^[22]. Optimizing the institutional environment of the innovation chain of leading enterprises and endowing it with a good innovation environment can effectively promote the construction of the innovation chain of leading enterprises. The Hefei Municipal Government can effectively provide the required institutional environment for the innovation chain of leading enterprises by broadening financing channels, increasing financing methods, and creating a good business environment. For example, “the Hefei Municipal Government has created a new model of government investment and investment attraction, explored and adhered to a new path that conforms to its own development positioning. It has directly invested in strategic emerging industries that conform to the industrial development direction and national policy orientation by adopting models such as equity investment and follow-up investment, giving full play to the leverage role of state-owned capital, leveraging social capital to follow the investment, and forming an investment attraction model of investment driving attraction and state-owned capital leading the investment.” Based on the above case analysis, the government’s provision of a good market environment, broadening of financing channels, and optimization of the business environment for leading enterprises are conducive to the construction of the innovation chain of leading enterprises. Therefore, this study believes that the government’s institutional environment empowerment, that is, creating a fair competitive market environment, broadening financing channels, and optimizing the business environment, is an important guarantee for the construction of the innovation chain of leading enterprises.

3.2 The path mechanism of government behavior on the construction of innovation chain of leading enterprises

The above analysis shows that government behavior plays a promoting role in the construction of the innovation chain of leading enterprises. To clarify how government behavior promotes the construction of the innovation chain of leading enterprises, based on an in-depth analysis of case materials and combined with relevant literatures on government behavior and the innovation chain of leading enterprises, this paper analyzes the path mechanism by which government behavior promotes the construction of the innovation chain of leading enterprises. The following are its construction mechanism and specific practical paths:

Government behavior helps to promote relevant government personnel to play the function of the chain leader. Through policy innovation and institutional design, the Hefei Municipal Government identifies the orientation of strategic goals, actively explores and deepens the “chain leader system” of the industrial chain, promotes the deep integration of the industrial chain and the innovation chain through systematic reforms, and has formed the “Hefei Model” with a national demonstration effect. The core of the chain leader system in Hefei lies in the model of “government guidance + market-oriented operation”. To promote the construction of the innovation chain of leading enterprises, Hefei City has explored the “chain leader” system of the industrial chain, and designed a series of institutional plans with the goals of strengthening, supplementing, consolidating, and extending the chain. Moreover, the chain leader is not only the leader of the industrial chain but also the leader of the innovation chain. Due to the complex process of the formation of the innovation chain, the innovation chain of leading enterprises requires the main leaders of the Hefei Municipal Government to play the function of the chain leader. The chain leader guides the construction of the innovation chain of leading enterprises. As the leader of the innovation chain of leading enterprises, the main leaders of the Hefei Municipal Government, as the chain leaders of the innovation chain, should cooperate closely with the main enterprises of the innovation chain, that is, the leading enterprises, divide the work reasonably, jointly improve the overall efficiency of the innovation chain of leading enterprises, and maximize the jointly created value. Focusing on BOE’s core business, the Hefei Municipal Government plays its function as the chain leader, introduces upstream and downstream enterprises through “chain-based investment attraction”, forms an industrial cluster, and further promotes the formation of BOE’s innovation chain. For example, after introducing BOE, the Hefei Municipal Government attracted enterprises such as Corning and the Rainbow Group, as well as key material suppliers such as Jiangfeng Electronics, forming an all-industry innovation chain ecosystem covering “chips, screens, and terminals”. This model enables BOE to obtain local supporting support, shortens the supply chain cost, and accelerates technological collaborative innovation. Therefore, this study believes that playing the function of the chain leader plays a mediating role between government behavior and the construction of the innovation chain of leading enterprises.

Government policies are an important driving force for promoting industry-university-research cooperation^[23]. Through policy design, resource supply, and institutional innovation, government behavior systematically promotes leading enterprises to carry out joint project cooperation with universities, scientific research institutions, and enterprises on the chain, forms a closed loop of the innovation chain of “basic research - applied research - technological development - industrialization”, and further promotes the construction and development of the innovation chain of leading enterprises. Industry-university joint project cooperation enables enterprises to share the latest technological achievements and R&D experience, thus promoting technological exchanges and cooperation. Such exchanges and cooperation help leading enterprises obtain more innovation resources and technical support and promote the formation and development of their innovation chains. Existing research has shown that jointly building industry-university consortia and increasing the openness of industry-university cooperation can effectively improve enterprise innovation performance^[24-25]. And industry-university joint project cooperation enables enterprises and universities/scientific research institutions to jointly carry out R&D and innovation activities and achieve collaborative innovation. This collaborative innovation helps leading enterprises break through technical bottlenecks and enhance their independent innovation capabilities, thus promoting the efficient operation of the innovation chain of leading enterprises. Therefore, this study believes that industry-university joint project cooperation plays a mediating role between government behavior and the construction of the innovation chain of leading enterprises.

The digital innovation platform refers to a new type of platform that uses digital technology to integrate innovation resources, provide innovation services, and promote exchanges and cooperation among innovation subjects. By setting up special funds

for digital innovation platforms, optimizing the innovation environment, etc., the government guides and encourages leading enterprises and other innovation subjects to jointly build digital innovation platforms, improves the innovation capabilities and service levels of the platforms, and promotes the digital transformation of enterprises. At the same time, the government also provides all-round support and guarantees for the construction of digital innovation platforms by independently building digital cooperation platforms and providing technical support. The digital innovation platform, by integrating innovation resources, including talents, technologies, funds, information, etc., provides leading enterprises with rich innovation elements. These elements are the foundation for the construction of the innovation chain of leading enterprises and help leading enterprises carry out activities such as R&D of cutting-edge technologies, product innovation, and market expansion. The digital innovation platform promotes mutual benefit and win-win results between leading enterprises and other innovation subjects by constructing an open, shared, and collaborative innovation ecosystem. The government has introduced a number of talent policies, introduced core technical talents in the new display industry, and built a digital exchange and cooperation platform to guide enterprises to cooperate with universities to train professionals with relevant majors. The Hefei Municipal Government has promulgated policies to actively promote the construction of major experimental infrastructure and build a basic R&D platform for digital technology to ensure that leading enterprises can form close cooperative relationships with other enterprises, universities, scientific research institutions, etc., and jointly promote the construction and development of the innovation chain of leading enterprises. Therefore, this study believes that the construction of the digital innovation platform plays a mediating role between government behavior and the construction of the innovation chain of leading enterprises.

4. Conclusions and implications

4.1 Research conclusions

Based on the existing research and from the perspective of government behavior, through the combination of case studies, the following findings are obtained: (1) The innovation chain of leading enterprises has a structure formed by the chain connection relationship between internal and external links. Manifested as a whole, the leading enterprise is the leader of the entire macro innovation chain. At the same time, the leading enterprise has built a relatively independent and complete micro innovation chain internally. The multi-level participants in the internal system, following the logic of specialized division of labor, dominate the innovation activities at each link of the innovation chain. In the external innovation system, the leading enterprise, by constructing a supply-demand coordination and matching system for internal and external technological innovation resources, establishes a resource adaptation mechanism according to the characteristics of task requirements during the process of internal subjects dominating innovation activities at each stage, systematically screens external subjects with special resource endowments to integrate into the innovation network, and forms a task-oriented collaborative innovation model. External participants show significant characteristics of phased embedding in the innovation chain on the entire macro innovation chain. (2) To achieve industrial upgrading and accelerate the formation of the innovation chain, the government's actions must be strategic, that is, various means considering time and place should be adopted under the conditions of clear goals and principles. Government behavior mainly promotes the construction of the innovation chain of leading enterprises through behaviors such as strategic guidance empowerment, innovation resource empowerment, and institutional environment empowerment. Strategic guidance empowerment is a prerequisite for the formation of the innovation chain of leading enterprises. Innovation resource empowerment can provide resource guarantees for the innovation chain of leading enterprises, and the government's institutional environment empowerment is an important guarantee for the construction of the innovation chain of leading enterprises. (3) Playing the function of the chain leader, industry-university joint project cooperation, and the construction of the digital innovation platform all play a mediating role in the process of government behavior promoting the construction of the innovation chain of leading enterprises. Through the case exploration of the Hefei Municipal Government's promotion of the construction of the innovation chain of leading enterprises, this paper reveals the specific mechanism of the construction of the innovation chain of leading enterprises, enriches the research perspective of the innovation chain of leading enterprises, and can provide a reference for other local governments to realize the transformation of functions, promote the construction of the innovation chain of leading enterprises, and further promote high-quality economic growth.

4.2 Management Inspiration

First, local governments should construct a trinity empowerment system of “strategy-resource-institution” to enhance the empowerment ability of government behavior, precisely support leading enterprises in high-tech industries, and improve the government’s strategic guidance ability. They should formulate medium- and long-term strategic plans for local industrial innovation, clarify the goal orientation and the boundaries of rights and responsibilities at each stage of the innovation chain, and strengthen the leveraging role of innovation resources in technological innovation research and development. At the same time, improve the intellectual property protection system and the fault-tolerance mechanism, and establish a market-oriented evaluation system for innovation achievements to ensure the adaptability of the institutional environment.

Second, the innovation chain of leading enterprises should establish a collaborative innovation optimization system to strengthen the internal and external collaborative innovation capabilities. To promote the formation of the chain connection relationship between the internal and external links of the innovation chain, it is recommended to set up a special fund for basic research to enhance the participation of universities and scientific research institutions, implement the “industry-university-research-application” joint project cooperation plan, and promote the precise docking between research entities and industrial needs. The government should play the role of the main enterprise of the chain and establish the responsibility system of the main enterprise of the chain, endow leading enterprises with the right to allocate innovation resources, and construct a digital collaborative innovation platform that includes innovation entities such as scientific research institutions, suppliers, and customers. The government should issue management measures for the innovation of leading enterprises, improve the knowledge sharing and benefit distribution mechanism, and explore a value co-creation model of “risk sharing and benefit sharing”.

4.3 Research deficiencies and future prospects

Firstly, the influence mechanism of government behavior on the construction of the innovation chain of leading enterprises in this paper is an exploratory research result. In the future, it is possible to construct an index system to collect relevant data and conduct a quantitative study on the relationship between government behavior and the construction of the innovation chain of leading enterprises. Secondly, the single-case study in this paper has inherent limitations. Although a single-case study can provide in-depth analysis of complex phenomena, and this paper conducts a multi-dimensional analysis based on reliable data on the typical sample of BOE, due to the particularity of the individual case situation, the generalizability of the research conclusions should be further tested. Finally, this study has explored the practice of the successful case where the Hefei Municipal Government has boosted BOE’s innovation chain. However, it is undeniable that there are many practices of unsuccessful cases in reality, which leads to limitations in this study in distinguishing between successful and unsuccessful cases. Future research can attempt to select more cases of local governments promoting the construction of the innovation chain of leading enterprises for study, so as to supplement the existing research conclusions.

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From Repression to Performance: An Autoethnographic Account of a Chinese Young Gay Man

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Abstract: The inherent tension between traditional ethics and sexual identity among young gay men in Chinese culture has constructed the unique living condition of them. Based on autoethnography, this paper traces a life course focusing on identity negotiation mechanisms of a young gay in multiple fields including family, workplace, school, and online communities. This transformation not only reflects the gradual adjustment of traditional ethics in Chinese modernization, but also provides a reference for understanding the adaptability of minority groups in China.

Keywords: Young Gay Man; Coming Out; Autoethnography

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1.Introduction

This article explicates my entire process from confirming my sexual orientation in high school to fully coming out. The purpose of this study is to explore how a Chinese young gay man resists the pressure of traditional culture and family, and to analyze what factors prompted this change, as well as the differences in my coming out strategies in various situations, and whether my experience is representative of young gay community in China.

2.Theoretical Framework : Dramaturgical Approach

Goffman is the founder of dramaturgical theory, and his contribution lies in the first systematic and theoretical application of the metaphor of drama, re-examining social life from this unique perspective. Performance, stage crew, region, discordant roles, off-stage communication, and impression management are the six major components of dramaturgical theory. Goffman points out that society is a stage where people, whether intentionally or unintentionally, use certain techniques to make others form an impression that they hope they will have, and make this impression serve their own purposes^[1]. Within the dramaturgical theory, front stage and back stage are two spatial elements that coexist in the dramatic system . The performance of an individual at a specific time presents a certain situation to the audience, which requires the use of standardized, rule-based settings and props. Goffman refers to this area of performance as the front stage. The back stage is the part of the stage that is not seen by the audience and is restricted to the audience and outsiders. The back stage is usually adjacent to the front stage, but they are distinct from each other. On the front stage, people present their socialized selves, while in the back stage, people present the spontaneous, most essential parts of themselves. Goffman believes that sociologists should observe how people transition from the back stage to the front stage

3. Methodology: Autoethnography

As a postmodern research paradigm, autoethnography is a research style and writing form that connects the individual with culture, examining the self within the socio-cultural context^[2]. In other words, autoethnography emphasizes the subjectivity of “I,” exploring the relationship between the individual and the cultural and social structure they are situated within through personal narratives. In essence, autoethnography is reflective and serves as a powerful tool for critically examining social power and discursive practices^{[3][4]}.

Evocative narrative is also known as personal narrative, and it is a method that researchers tell stories about their academic identity and personal characteristics by focusing on the everyday events they have personally experienced^[5]. Evocation refers to the purpose of a work contains expression and discussion, rather than the representativeness emphasized by traditional social research. Evocative narratives typically use first-person writing, with the author positioning themselves as the subject of study, thus transcending the separation between the researcher and the subject of study in traditional social research^[6].

In this article, “I” possess a dual identity as both a researcher and the subject of research. Through first-person narration and a review of my own life journey, I focus on issues commonly encountered by young gay men, such as identity and coming out. The aim is to convey the voice of a young Chinese gay man to the readers, broadening the depth and breadth of international scholars’ research perspectives on Chinese young gay men.

4. The story of “I”

4.1 Repression: Who am I?

4.1.1 Self-doubt and Stigma

I was born in a rural area of central China. Even as a child in elementary school, I felt different from others, often having better relationships with girls. At that time, I was too young to have any concept of sexual orientation. It wasn’t until junior high school, when I got access to the internet, that I became aware of the fact that some boys like other boys. However, I didn’t consider myself gay at that time. It was during high school that I truly began to contemplate my sexual orientation. At the beginning of my freshman year, I noticed my attention would linger on male classmates. There was a part of me that doubted myself, questioning if I was truly gay and if there was something wrong with me. At the same time, my classmates had negative comments about gay, such as “disgusting” and “sick,” which made it even harder for me to identify as gay. In this way, I was equated with disgusting and sick. And finally the scene came when I was under much pressure.

From the perspective of dramaturgy, I did not yet have a clear sense of role as a child, and my frontstage performance differed from social expectations, while the backstage was still a period of exploration. In junior high school, I came into contact with the Internet and learned about homosexuality, but I had not yet self-identified with it. Considering the social stigmatization of homosexuality, it led me to hide my true self in the foreground to avoid being labeled negatively. This internal and external conflict exemplifies the role conflict and impression management strategies in dramaturgy.

4.1.2 The dual pressure from culture and family

After confirming my sexual orientation, a period of repression followed. The sources of stress can be mainly divided into two parts: on one hand, the cultural tradition of in China, and on the other hand, my family situation. From the perspective of cultural tradition, the most obvious constraints on individuals may be the ideas of the unity of family and state, familism, and the family-centered approach. Filial piety holds an important position in traditional Chinese culture, as the saying goes, “governing the world with filial piety.”. It is in this context of mainstream culture that I decided to temporarily conceal my homosexual identity. From the perspective of family circumstances, I am the only son in my family, and the responsibility of continuing the family lineage naturally falls on me. Undoubtedly, this has put a lot of pressure on me. I told my mother several times that I do not want to get married, but she didn’t approve, it is under the dual influence of cultural tradition and family circumstance that I choose to remain silent, thereby also placing myself in repression.

4.2 Coming out: Declaration in various fields

4.2.1 Peer group field: Start with good friends

I began to consider coming out after starting college, feeling that I had gained freedom. During freshman military training, I

came out to two female classmates from high school who were my best friends at that time. They did not discriminate or look down on me. We often gathered together, and I would share my romantic life with them.

Entering college meant breaking away from my old community and gaining a new arena to reconstruct my social role, providing a more forgiving frontstage with less stigmatizing pressures from before. I chose to come out to two high school friends who belonged to a trusted backstage where I could more safely show my true self without fear of negative judgment.

4.2.2 Family field: Multiple aspects of parental reactions

After coming out to my friends, the next question that haunted me was when to come out to my parents? This issue was like a nightmare, causing me anxiety. At that time, I searched online for information about coming out to parents and I always could see a tip that one should wait until they are financially independent before coming out. Back then, I frequently self-depreciated, thinking that even finding a job after college graduation was a challenge, let alone achieving financial independence. So, should I still come out? Between being true to myself and breaking the filial piety, I felt as if there was a force tearing me apart. During the summer after college graduation, under immense psychological pressure, I came out to them. Later, due to psychological issues, I saw a doctor, and my mother found out that the unimaginable pressure I had been under. Now, my parents have completely different attitudes towards my sexual orientation; my father rarely mentions it, while my mother expresses complete respect and support.

My journey of coming out presents the role collapse and reconstruction in the family theater, revealing the deep dilemma faced by sexual minorities in the core kinship network, breaking the performance without financial independence, leading the audience in the family stage into a role perception crisis. The turning point is the incident of the psychiatrist's visit to the doctor, where the intervention of the medical authority reconfigures the rules of the performance, prompting the mother to change from a moral judge to a collaborator in the performance, and reconstructing the discourse of the family theater.

4.2.3 The workplace field: the game between professional identity and sexual identity

Between my graduation from university in 2020 and my enrollment in graduate school in 2024, I had several jobs. I worked as a teacher in a kindergarten, and considering the risks of coming out, such as parents may claim that a gay teacher could corrupt children. I initially did not share this with my colleagues. However, one day on the way home from work, while chatting with a colleague, I mentioned that I would not get married, and she immediately asked if I was gay. At that moment, I admitted it, and she told me she wouldn't spread the word. Later, I joined a foreign trade company where everyone was preoccupied with their own work, and there was no need for me to disclose my sexual orientation. I didn't stay long at the foreign trade company before leaving. Finally, I went to educational institution, where I also initially kept quiet. Later, considering that my colleagues were around the same age and more open-minded, I posted a status on my social media feed, setting the leadership as invisible, which implied that I am gay.

My coming out strategies in different professional fields can be seen as a dynamic process of absolute cover-up, strategic cover-up to partial disclosure. Parents have high moral expectations of kindergarten teachers, at which point they are a demanding audience, and I chose to completely conceal my sexual identity by compressing my sexuality into the background to ensure moral impeccability in my frontstage performance. The foreign trade workplace is a depersonalized stage, where my colleagues are the functional audience, focusing only on performance and output rather than personal identity. I follow the irrelevance principle, where sexual identity is completely removed from the front stage performance and becomes a private matter that does not need to be mentioned. In the hosting organization, the younger colleagues constituted a subculture-friendly audience that was more inclusive of sexual minority issues. At this point I planted sexual identity cues in the foreground to screen out allied audiences while maintaining informational ambiguity for conservative audiences.

4.2.4 School field: From the clandestine to the public

During my undergraduate studies, I adopted a completely different coming-out strategy compared to my graduate school. In my undergraduate years, I adhered to a "don't ask, don't tell" policy with my classmates. Unlike in high school, the connections with classmates were not as close, I didn't tell anyone in my class. I only came out to two friends from other departments who I was close with, and they both respected me greatly. Interestingly, my classmate and roommate once asked me if I was gay over dinner, and I nodded. He even said he had long suspected that I was. When I reached graduate school,

whether to come out to my classmates was a concern that troubled me at the beginning of my first year. Especially during casual conversations with classmates, when I heard the remark that all homosexuals have AIDS, I realized that coming out could potentially harm me. However, after coming out to my parents and receiving respect and support from my mother, I wanted to face myself honestly. Being gay is a very important part of my life, and I couldn't possibly hide this aspect of myself throughout my three years of graduate school. I first shared articles about sexual minorities on my social media, then posted photos of myself with my then-boyfriend, and finally chose to publicly come out during some presentation in class.

The shift in my coming out strategy from undergraduate to graduate student is essentially a dynamic assessment and scenario-based adjustment of audience and performance risk, reflecting the complexity of managing the boundaries between the foreground and background in performance. The weak connectivity of the undergraduate class constitutes a low-pressure performance field, so I adopted the strategy of "don't ask, don't tell", placing sexual identity in the background to maintain the image of the class by avoiding any hints of sexual orientation. In graduate school, I did not return to the limited invisibility of my undergraduate studies in the face of a potentially prejudiced audience, but rather reconstructed the foreground through staged performances. My mother's support dissolved the traditional impediment of filial pressure. I was able to import more backstage authenticity into the school field, forming a source of confidence in coming out.

4.3 Performance: The Daily Practice of Queer Identity

4.3.1 Reconstruction of body symbols

After coming out, especially after receiving my mother's support, I went from feeling ashamed of my sexual identity to feeling proud of it. I began to wear rainbow badges on my backpack and started to customize T-shirts with slogans about sexual identity at Taobao stores. These practices are based on my strong identification and are also a rebellion against traditional gender binaries.

Rainbow badges and slogan T-shirts as symbols constitute what Goffman describes as "front stage performance props". These symbols are not only declarations of self-identity, but also signals of alliance to the outside world, attracting potential supporters and screening hostile audiences.

4.3.2 Self-presentation in cyberspace

Not long after coming out to my parents, I publicly shared my sexual orientation on my WeChat Moments, and my friends thought I was very brave. Since then, I have shared stories I've created with gay themes or shared my life insights. I have also met many members of the LGBTQ community on social platforms, which has made me feel less lonely.

Self-presentation in cyberspace can be seen as a "real virtual performance". When I express my sexual identity on the Internet, I go through a process: the first step is to understand the expectations of the potential audience. When presenting myself online, I need to consider different groups of viewers, such as family members, friends, coworkers, or strangers. For example, one might be more discreet in a circle of friends and more open in a specialized sexual minority community. The second step is self-reflection to determine the role I want to play and express who I am through the role of the creator. The third step is to choose a role that balances the expectations of others with the needs of the self. Keeping a low profile in family groups while openly supporting affirmative action on Twitter.

Conclusion

This article uses autoethnographic and Goffman's dramaturgical framework to outline the trajectory of a young Chinese gay man from identity repression to public performance. This journey is not only an exposure of private experience, but can also be seen as a slice of the situation of sexual minorities in contemporary China. Under the concepts of "being honest" and "being true to myself", I chose to come out under the cultural tradition of filial piety and the pressure of family succession. My coming out strategy varies according to different fields and can be summarized as a gradient exposure process of impression management. What can be seen is that my journey is common among members of the gay community and also reflects individualized differences. It should be noted that the choice of whether or not to come out should be based on one's own reality.

Of course, there are inherent limitations in using autoethnography as a research methodology, and describing my own experience alone cannot encompass the full sample of young gay men. And it should be noted that this review of my life

course is a process of actively sifting through information, making it difficult to be completely objective, and I have not included all the details from repression to performance. However, no one knows me better than I do, I have tried to be as objective as possible in the writing process, but still have an emotional bent. Therefore, this paper can be regarded as a new attempt to understand the cultural connotations and behavioral motives behind a young gay man's journey from repressing to accepting through writing of the process. This paper can provide useful reference for scholars to study young gay men in China and enrich the research methodology of sexual minority studies.

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Conflict of Interests

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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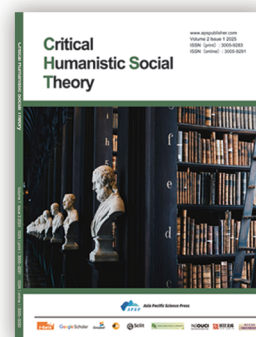
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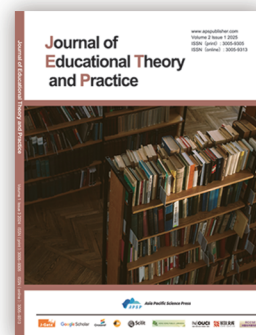
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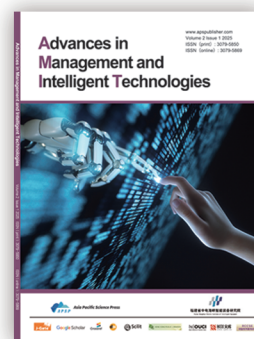
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