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TABLE OF CONTENTS

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Research on export competitiveness of new energy vehicles in Yangtze River Delta region

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Abstract: As the energy crisis and automobile industry develop, the global automobile industry competition has shifted from individual product competition to comprehensive strength competition among industrial clusters. In recent years, China's new energy automobile industry has developed rapidly, with the trend of automobile industry cluster becoming more evident. The Yangtze River Delta region, with its strong vehicle and parts manufacturing base, has become a typical representative of China's new energy vehicle export industry. Research on the export competitiveness of new energy vehicles in the Yangtze River Delta can reflect the overall development of China's new energy automobile industry to a certain extent. It also has important theoretical significance and practical value for enhancing the competitiveness of the new energy automobile industry in the Yangtze River Delta and even the whole country.

Keywords: New energy; Automobile; Competitiveness; Industrial agglomeration

1 Introduction

New energy vehicles are emerging globally, with countries actively developing them. China has achieved a world-leading position in this field. There is relatively abundant academic literature on China's new energy vehicle export trade. However, existing studies primarily focus on the Yangtze River Delta region. Statistical analyses in this area remain limited and exhibit notable gaps.Yangtze river delta region has become one of the major new energy automobile manufacturing base in China, the research on the region's new energy automobile export competitiveness will be more meaningful.

The Yangtze River Delta region is the most economically developed area in China. It is also the most open and one of the strongest in terms of regional innovation capabilities. As China's economic development level improves, people pursue higher material and spiritual life standards. This leads to higher requirements for promoting the advanced manufacturing level of the Yangtze River Delta. Policies also guide this advancement. The Yangtze River Delta region is densely populated. The local residents enjoy a relatively high standard of living and have a great demand for automobiles. Part of the advanced manufacturing industry in the region has developed in a clustered way and shown a trend of coordinated group development. This has laid a solid foundation for the integrated development of advanced automobile manufacturing clusters in the Yangtze River Delta. As a result, new energy vehicle companies like Tesla, Wei, and Shanghai Volkswagen have emerged here.

After the energy crisis in the 20th century, more and more people concern around the world in terms of development and utilization of new energy has relevant policy to follow up. In the field of conventional cars in

China started is behind the western developed countries, but in the field of new energy vehicles is currently in the world's advanced level. The Yangtze River Delta region is also the first echelon in the field of new energy vehicles in China. The new energy vehicles produced here are sold all over the world and have their own influence.

The Yangtze River Delta region has a strong new energy vehicle manufacturing sector. It has a high market penetration of new energy vehicles. The development of new energy vehicle manufacturing enterprises is also fast here. They have gradually formed their own brand system and brand awareness both at home and abroad. The energy issue is a major global concern that every country faces. How to solve it is a big question for all countries. This also means wide market opportunities in the field of new energy vehicle exports. Our country is on par with many Western industrial powers in this field. It is even stronger than the traditional Western industrial powers in some aspects. How to conduct competitive analysis and optimize competitiveness is an important subject.

1.1 Research Background

1.1.1 Overview of new energy vehicles

New energy vehicles use unconventional vehicle fuel as a power source. They can also use conventional vehicle fuel with a new vehicle power unit. They integrate power control and driving of the vehicle with advanced technology. This advanced technology forms a principle based on new technology and new structures of cars.

Currently, new energy vehicles are mainly divided into pure electric vehicles and oil-electric hybrids, which have different categories and characteristics (Table 1-1). Pure electric vehicles, as the name suggests, rely solely on electricity as energy to drive the car. The main components are the battery, motor, and electric control system. The advantages of pure electric vehicles are environmental protection, economy, and comfort, which are also the three biggest selling points of pure electric vehicles. However, the SanDian system also has some shortcomings, such as insufficient power, relatively poor safety, and higher manufacturing costs for the vehicles.

Table 1-1 Types and characteristics of mainstream new energy vehicles

Types	Energy	Power source
Pure electric	Electric energy	Motor
Oil-electric mix	Fuel oil	Motor, engine
Plug-in hybrid	Fuel oil, electricity	Motor, engine
Extended-range hybrid	Fuel and electricity	Motor

Source: China Association of Automobile Manufacturers.

Petrol-electric hybrids include plug-in hybrids broadly and light-hybrid new-energy vehicles narrowly. Light - hybrids don't need charging, using both a motor and engine. The engine powers the vehicle and supplies electricity, while the motor also provides power. The key difference from plug-in hybrids is that light-hybrids can't be charged, whereas plug-in hybrids have a larger battery for charging and pure-electric drive. Light-hybrid systems are simpler in structure, cheaper, more energy-saving, and environmentally friendly than traditional fuel cars, with quick refueling. Plug-in hybrids offer users flexible choices: pure-electric drive daily and engine power for long trips. However, they have a more complex structure and higher maintenance costs. Hybrid-increase programs aren't widely popular globally yet. Similar to plug-in hybrids, they have a fuel tank and battery. But the hybrid-increase engine only generates power for the battery, with all power coming from the motor. Globally, hydrogen-energy vehicles are not significant in production and sales, so this article doesn't cover them.

1.1.2 Current situation of new energy vehicle market

The new energy automobile market is booming globally due to carbon-neutral and carbon-peak targets. National policies and consumer environmental awareness are dual drivers pushing new energy vehicles into a new penetration stage, as shown by data from European countries and China (Table 1-2 & Table 1-3). Fierce competition in this market is expected to continue for a long time. During the transition from traditional fuel vehicles to new energy vehicles, there's a significant market gap. However, automobile enterprises in China's Yangtze River Delta spotted and began laying out this market early. As early as 2018, China's new energy vehicle sales accounted for 62.2% of the global total.

Table 1-2 Changes in new energy vehicle penetration rates in 2018 and 2022 in major new energy markets in the world

	2018	2022
Norway	58%	87%
Sweden	7%	55%
Netherlands	6%	34%
Germany	2%	32%
China	5%	31%
Britain	3%	22%
France	2%	21%
Canada	3%	11%
South Korea	5%	10%
United States	2%	9%
Japan	1%	3%

Source: Statistic.

Table 1-3 Sales of new energy vehicles from 2018 to 2022 (ten thousand units)

	2018	2019	2020	2021	2022
Global	201.83	221	324	650	1065
Our country	125.6	120.6	136	354	688.7
Global growth rate	65	9.5	46.6	100.6	63.9
China's growth rate	109.3	-4	12.8	160.3	94.5

Source: China Automobile Dealers Association and National Bureau of Statistics.

1.1.3 Overview of the Yangtze River Delta Region

The Yangtze River Delta region is a spatial concept. It was defined by the "Yangtze River Delta Regional Integrated Development Plan Outline" approved by the Political Bureau of the CPC Central Committee on May 13, 2019. The planning scope covers the entire Shanghai, Jiangsu, Zhejiang, and Anhui (358,000 square kilometers). Cities like Nanjing, Wuxi, Changzhou, Suzhou, Nantong, Yangzhou, Zhenjiang, Yancheng, and Taizhou in Jiangsu Province, and cities like Hangzhou, Ningbo, Wenzhou, Huzhou, Jiaxing, Shaoxing, Jinhua, Zhoushan, and Taizhou in Zhejiang Province, as well as cities like Hefei, Wuhu, Ma'anshan, Tongling, Anqing, Chuzhou, Chizhou, and

Xuancheng in Anhui Province, are the core areas (225,000 square kilometers). This region radiates and drives high-quality development in the Yangtze River Delta.

1.2 theoretical basis

1.2.1 Trade Competitiveness Index

Trade competitiveness index (TC index), it is on the international competitiveness of one of the measures that are widely used in the analysis, it represents a country's import and export trade balance accounts for the proportion of the total import and export trade.

The TC index = (exports - imports)/(exports + imports). The closer the value is to 0, the closer the competitiveness is to the average level; When the index is -1, it means that the industry only imports but does not export. The closer it is to -1, the weaker the competitiveness is. The index to 1, said the industry import and export is not only the more close to 1 indicates the greater the competitiveness.

1.2.2 Revealed Comparative Advantage Index

The revealed comparative advantage index (RCA) is a convincing indicator. It measures a country's product or industry competitiveness in the international market. It refers to the ratio of a country's export share of a certain product to the product's share in the world's total exports.

If 0 < RCA < 1, said an industry or product has comparative disadvantage, its value is close to zero, the disadvantages are more obvious; If RCA > 1, the said country x industry or product has revealed comparative advantage in the international economy, its value, the greater the revealed comparative advantage, the more obvious. If the RCA > 2.5, the competitive advantage is very strong; If 1.25<RCA<2.5, the competitive advantage is strong; If < 0.8 RCA < 1.25, the industry competitive advantage in average; If 0<RCA<0.8, the competitive advantage is weak.

2 New energy automobile export competitiveness in Yangtze river delta

2.1 Overview of new energy vehicle market in the Yangtze River Delta region

There are six major automotive industrial clusters in China. The Yangtze River Delta cluster has a mature industry chain in vehicle manufacturing and automotive spare parts exports. In the new energy vehicle industry, the Yangtze River Delta leads the country's six major automotive clusters. It contributes one out of every four new energy vehicles produced domestically (Table 2-1 & Table 2-2).

Table 2-1, 2018-2022 China's Yangtze river delta region of new energy vehicle sales (10,000 units)

	2018	2019	2020	2021	2022
Yangtze River Delta Region	46.9	33.2	40.4	106.18	281
China	125.6	120.6	136	354	688.7
Global	201.83	221	324	650	1065

Source: China Automobile Dealers Association and statistic.

Table 2-2 Output of new energy vehicles in China's major automobile industrial clusters in 2022 (10,000 units)

	Yangtze River Delta	Middle reaches of Yangtze River	Southwest China	Pearl River Delta
Yield	281	29	145	195
Percentage	40.8%	4%	20.1%	27%

Source: China Association of Automobile Manufacturers and National Bureau of Statistics.

2.2 Trade competitiveness index

Trade competitiveness index (TC index) is mainly shown as the ratio of the balance between imports and exports of a country (region) and the total amount of imports and exports.

$$TC=(X_t - M_t)/(X_t + M_t) \quad \text{Formula (1)}$$

M_t is the total import of country t (region). X and M are the export and import volumes respectively. i denotes a country, industry, or product. The closer the index is to 1, the stronger the export competitiveness. The closer it is to -1, the weaker the competitiveness. Table 2-4 shows the trade competitiveness index numerical interval.

Table 2-4 Comparison table of competitiveness index

Index	Numerical interval	Level of competitiveness
TC	TC→1	Strong export competitive advantage
	TC = 1	Only export but not import
	TC→0	Average level
	TC→ - 1	The export competitive advantage is weak
	TC = 1	Only import but not export

The import and export value of new energy vehicles in the Yangtze River Delta region in 2022 will be 1.497 billion US dollars and 17.18 billion US dollars, respectively. The TC index is close to 1, and it can be seen from Table 2-4 that the export competitiveness of new energy vehicles in the Yangtze River Delta in 2022 is strong.

$$TC=156.83/186.77=0.8397 \quad \text{Formula (2)}$$

2.3 Index of revealed comparative Advantage

Revealed Comparative Advantage index (RCA index) - describes the relative export performance of a country for a particular product.

$$RCA_{ij}=(X_{ti}/X_t)/(X_{wi}/X_w) \quad \text{Formula (3)}$$

Where X_t represents the total export of country t, and X_w represents the total export of the international market. Table 2-5 shows the numerical interval for the specific measurement of RCA.

In 2022, the Yangtze River Delta region’s total export value was 1,362.42 billion US dollars. The export value of new energy vehicles was 17.18 billion US dollars. According to UN Comtrade, the global total export was 24.9 billion US dollars. The global export value of new energy vehicles was 154.47 billion US dollars. The index ranges between 1.25 and 2.5. Table 2-5 shows that the export competitiveness of new energy vehicles in the Yangtze River Delta region is strong.

$$RCA_{ij}=(171.8/13624.2)/(1544.7/249000)=2.0327 \quad \text{Formula (4)}$$

Table 2-5 Table of numerical intervals of RCA

Index	Data interval	Indicate meaning
RCA	RCA > 2. 5	Highly competitive
	1 . 25≤RCA≤2. 5	competitive
	0. 8≤RCA≤1 . 25	Average competitiveness
	RCA < 0. 8	Less competitive

According to the new energy vehicle export trade competitiveness index and revealed comparative advantage index in the Yangtze River Delta region, the export competitiveness of new energy vehicles in the Yangtze River Delta region is at a strong level.

The Yangtze River Delta region’s new energy vehicle market holds a significant share and enjoys advantages both in China and globally.From an environmental perspective, the region’s new energy vehicles perform well in production scale and consumer base in China and the world. Policy-wise, the integrated development of the Yangtze River Delta lays a solid foundation for the growth of local new energy vehicle enterprises and their global expansion.In terms of trade competitiveness index and revealed comparative advantage index, the export competitiveness of new energy vehicles from the Yangtze River Delta is robust.

Good data behind also revealed that the Yangtze river delta region of the defects in the new energy automobile export competitiveness. It is mainly manifested in the problems of single export models, low unit price of export models, low level of autonomy of core components of export models, and the hidden trouble of insufficient transport capacity is found in the export link of new energy vehicles.

3 New energy automobile export competitiveness in Yangtze river delta’s limitations

3.1 Insufficient automobile export capacity

The Yangtze River Delta region’s new energy vehicle exports mainly use ro-ro shipping. Container shipping and trains are complementary. In Central Europe, car ro-ro ships are designed as large-scale transport carriers. They have lower costs than container transport in CheSun and handling fees. Especially for new energy vehicles with battery packs, ro-ro open laying transportation will play a key role in future exports.

China’s auto exports are rising rapidly. However, the shipping capacity of our nation’s enterprises is a concern. In ro-ro shipping, our capacity lags behind Japanese and Korean firms. This situation causes new energy car companies in the Yangtze River Delta and nationwide to face export booking, scheduling, and inventory backlog issues, preventing timely port delivery. Long-term, this will undermine the export competitiveness of the region’s new energy vehicles.

In the Yangtze River Delta, most new energy vehicle export destinations require transoceanic transport. As market competition intensifies, stable shipping capacity becomes crucial. The current insufficient control capacity will impact car companies’ layout and export scale. It might also trigger “cutthroat competition” events like the chip shortage, reducing export competitiveness.

Table 3-1 Global ro-ro shipping capacity ranking

Rankings	Companies	Territoriality	Capacity (cars)
1	Wallenius Wilhelmsen	Norway	523648
2	Ray Car Carriers	Israel	355006
3	Nippon Yusen Kaisha	Japan	344619
4	Mitsui OSK Lines	Japan	308620
5	K-Line	Japan	278773
6	hyundai motor group	South Korea	222544
7	Cido Shipping	South Korea	209300
——	——	——	——
35	Cosco Haite	China	68603

Source: International Shipping Network.

3.2 High dependence on core components of new energy vehicles

Table 3-2 lists the export models of new energy vehicles in the Yangtze River Delta and their core chips. Emgrand EVPro and Little Ant use domestic chips. Other models rely on chips from Qualcomm, NVIDIA, and AMD. These three firms lead in chip technology, especially in graphics and AI. Their imported chips equip high-end new energy vehicles like NIO and Tesla models from Shanghai Gigafactory, ensuring advanced assisted driving and human-vehicle interaction. In contrast, vehicles with domestic chips, such as the Little Ant and Emgrand EVPro, are cheaper in China and abroad. However, their lower profits limit their market impact.

In 2021, the "chip shortage" limited market capacity, especially for chip-reliant new energy vehicles. The chip issue disrupted the supply chain, leaving upstream without cores to allocate and downstream without cars to sell. This greatly affected the rapid development of new energy vehicles in the Yangtze River Delta. So, we must focus on core technology autonomy. Also, the advantage of new energy vehicles' OTA is based on strong car chips. We can't be too dependent on technology; otherwise, another "neck" event would severely impact new energy vehicle enterprises.

Table 3-2 Chips of new energy export models in the Yangtze River Delta region

Brand	Export models	Car machine chip
Polar Krypton ZEEKR	ZEEKR 001	8155 Qualcomm Snapdragon
Geely Auto	Emgrand EV Pro	E01 Egatong Technology
Chery Automobile	Little Ant	Ac8015 Hefei Jifa
NIO	ES6/ET7	Drive Orin X NVIDIA
Tesla	Model Y	AMD Ryzen
SAIC	Mg4 EV	8155 Qualcomm Snapdragon

Source: official website of each company, statistic.

3.3 Unbalanced technology accumulation of automobile enterprises

In October 1885, Karl Benz from Germany developed the first automobile. Since then, the basic design of traditional cars has remained largely the same. However, with the advent of new energy cars, fuel is no longer the only energy source. The internal combustion engine is no longer the only power source. Motors, with higher transmission efficiency and lower technical barriers, have been adopted in electric vehicles (Table 3-3). Over the past decade, a global electric vehicle trend has emerged. The Yangtze River Delta in China has seen the rise of many successful new energy vehicle brands. Some brands, like Geely and Volvo, are backed by traditional car companies. Others, like NIO, rely on partners like Jianghuai Automobile for manufacturing but handle most of the design and development in-house. Despite good sales, it's clear that new energy vehicle companies in the Yangtze River Delta have uneven technology reserves.

Table 3-3 Similarities and differences of core components between new energy vehicles and traditional vehicles

	Traditional vehicles	New energy vehicles
Powertrain	Engine, transmission, drive shaft	Motor (engine), electric control, power battery
Chassis system	Fuel platform, suspension, steering, braking	New energy platform, suspension, steering, braking
Electrical systems	Power supply, control chips, audio-visual entertainment	Three-power system, control chip, audio-visual entertainment, driving assistance
Body and cover	Frame and parts	Frame and parts

parts		
Safety systems	Frame, front and rear collision avoidance systems	Frame, front and rear anti-collision system, electronic control safety and management system

The figure shows both similarities and differences between new energy vehicles and traditional ones. Traditional vehicles have first-mover advantages, a mature design and development system, and solid technological foundations. New energy vehicle brands in the Yangtze River Delta have made progress. For example, SAIC New Energy, Jiekrypton Automobile, and NIO Automobile use new platforms. Compared to traditional brands that adapt fuel platforms for new energy vehicles, these new brands offer better space utilization. They also started earlier in driving assistance, building up technology and availability. However, in areas where new energy and traditional vehicles intersect, the region's new energy brands still have room for improvement. Traditional car brands have more experience in chassis and suspension technology and a more mature parts supply chain. For example, Ideal Auto-motive's solution of hiring Porsche's R&D team to train their team is effective in the current market, but they need to build their own R&D capabilities and technology reserves instead of becoming dependent.

The Yangtze River Delta's main new energy vehicle export destinations are European and some Asian countries. Their vehicle environments differ from the Yangtze River Delta and even China. In European countries, the population density is low. The density of charging facilities is also low. The average annual temperature is low. Some countries have frequent snow on the road. The rainfall time is long. So, they have higher requirements for new energy vehicles. The battery needs better low-temperature resistance and endurance. The anti-skid system and safety system should be improved too. In the Arab region, the vehicle environment is different. Here, the battery and motor need better high-temperature resistance and dust resistance. In Southeast Asian countries, the road conditions are poor and the terrain is rugged. This puts higher demands on the chassis and suspension of new energy vehicles.In terms of power batteries and intelligence, the new energy vehicle brands in the Yangtze River Delta region have achieved the world's advanced level, but the export of new energy vehicles will also be restricted by the "bucket effect", and in terms of chassis training, electronic control system, core chips and other software and hardware, the new energy vehicle enterprises in the Yangtze River Delta region still have shortcomings.

4. Optimization analysis of export competitiveness of new energy vehicles in the Yangtze River Delta region

4.1 Increase the export capacity of automobiles

The new energy vehicle export market in the Yangtze River Delta is booming. However, car companies are noticing some problems. They are worried about not having enough export capacity. Also, there might be a mismatch between production capacity and demand. Many car companies can't solve these problems on their own.

The transport capacity is insufficient. Enterprises should conduct good market research and predict the export market scale. They need to provide export services in advance and deeply cooperate with logistics or transportation companies to reduce transport risks. Government departments and state-owned shipbuilding enterprises should actively adjust business layouts, expand and optimize car transport ship production, and increase production while reducing costs. New energy vehicle enterprises and government departments in the Yangtze River Delta region can develop plans to optimize automobile export capacity. This includes optimizing wharf stacking, loading efficiency, process efficiency, increasing special berths for car carriers, and cooperating with major foreign export destination ports to enhance unloading efficiency.

To improve the export capacity of new energy vehicles in the Yangtze River Delta region requires the joint efforts of enterprises themselves, local government departments, supporting enterprises, downstream foreign dealers and other links, so as to strengthen competitiveness.

4.2 Strengthen the level of overseas supporting facilities and enhance the brand image

Gas stations are the main supporting facilities for traditional vehicles. Charging facilities are the most important for new energy vehicles. In recent years, the global new energy vehicle industry has developed rapidly. The production and sales of these vehicles are rising steadily. The demand for charging facilities in major markets is also increasing quickly. The availability of charging piles, in terms of both quality and quantity, is now a key factor. It significantly affects the competitiveness of new energy vehicles in this region.

China’s current vehicle-pile ratio is 6.7:1. In Europe, it’s 12.6:1. Thailand has a ratio of 20:1, and India’s is as high as 500:1. These figures show there are significant market opportunities for charging infrastructure. However, building charging infrastructure is expensive and time-consuming. Each charging pile needs a parking space. A charging station requires medium to large power distribution equipment. Large power distribution facilities need one or more distribution lines. The global electrification trend means charging infrastructure will be built gradually. The Yangtze River Delta’s new energy vehicle exports mainly go to Europe, Southeast Asia, and the Middle East. Industry leaders could initiate a charging facility alliance, like the Yangtze River Delta New Energy Vehicle Industry Chain Alliance. This alliance could jointly invest in overseas energy. Marketing and charging strategies should be flexible. The alliance should offer preferential treatment for new energy vehicle identification. This would enhance brand influence and product power within the alliance. It would also accelerate overseas charging infrastructure, allowing the alliance to benefit earlier and increase its discourse power.

Personalized services can be introduced according to local conditions for overseas reality. For example, hardware such as snow tires and skin-proof chains suitable for snow driving, software such as snow mode and trailer rescue and after-sales services can be introduced in high-latitude areas. In Southeast Asia, regular free chassis and battery safety checks can be introduced. Based on demand, these personalized services can greatly enhance consumer satisfaction and reputation, and enhance product competitiveness.

4.3 Strengthen school-enterprise cooperation and enhance technology accumulation

Compared with traditional vehicles, new energy vehicles adopt many new technologies and concepts. Their development also creates a big demand for new talents. The Yangtze River Delta region’s education level ranks among China’s best. Its new energy industry is growing rapidly. So, the school-enterprise cooperation pace should be strengthened.

Under the situation of rapid development of the new energy vehicle industry, the school-enterprise cooperation should abandon the early mode of “emphasizing theory and ignoring practice”. Colleges and enterprises are two equal subjects in talent training. Colleges and universities are responsible for talent selection and theoretical basic education, while enterprises are responsible for students’ theoretical practice transformation and professional education.

Colleges and universities should pay attention to industry needs and technological development. They need to optimize education modes and training programs in a timely manner. Establish cooperative relationships with new energy automobile enterprises. Provide more theoretical foundations for teaching. Strengthen practical teaching and teacher team construction.

New energy vehicle enterprises should actively build industry-oriented practical teaching and talent training bases with local governments and universities. The fast-paced technological progress relies heavily on talent support. Talent training, in turn, cannot happen without the unique practice and learning platforms that enterprises provide. This kind of school-enterprise cooperation is beneficial for training talents and promoting the healthy development of enterprises.

5 Conclusion

This paper analyzes the export, production, sales data, and supporting industries of new energy vehicles in the Yangtze River Delta region. The analysis combines theory with practice and is supported by extensive literature and data. The following conclusions are drawn.

This paper compares domestic and foreign automobile import and export data. It also analyzes the actual situation. From the domestic perspective, the export competitiveness of new energy vehicles in the Yangtze River Delta region is strong. Similarly, from the international perspective, the export competitiveness of new energy vehicles in the Yangtze River Delta region is also strong.

The international new energy vehicle industry faces fierce competition, making technological innovation crucial. The Yangtze River Delta’ s new energy vehicles, despite having a first-move advantage, risk being overtaken in this competitive landscape. In recent years, domestic and international traditional automobile enterprises have made progress in new energy fields. Their success stems primarily from technology accumulation and R&D innovation.

Data Availability Statement

All macroeconomic indicators analyzed were sourced from the International Monetary Fund (IMF) Data Portal (https://data.imf.org), the World Development Indicators database (https://databank.worldbank.org), National Bureau of Statistics of China (https://www.stats.gov.cn/sj/).

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The Impact of Digital Trade Barriers on Global Value Chains: A Perspective from Developing Countries

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Abstract: This study examines the impact of digital trade barriers on Global Value Chains (GVCs), with a focus on developing countries. The rapid development of the digital economy is reshaping the operational models and division patterns of GVCs. As a new form of non-tariff barriers, digital trade barriers—including data localization requirements, foreign equity restrictions, and source code disclosure mandates—significantly increase transaction costs for developing countries participating in GVCs. Through a combination of theoretical analysis and case studies, this paper explores the mechanisms by which digital trade barriers constrain the division of labor status of developing countries within GVCs. The findings reveal that restrictions on data flows, divergences in technical standards, and market access barriers collectively undermine the position of developing countries in GVCs. Focusing on the interplay of technology, data, and policy dimensions, this study demonstrates how digital trade barriers hinder developing countries' ability to upgrade their roles in GVCs. For instance, Southeast Asian countries face 12%-18% higher export costs for digital services due to data localization policies, while Latin American nations lose approximately 23% of cross-border digital orders owing to technical standard disparities. To address these challenges, the paper proposes strategies such as policy innovation (e.g., digital free trade zones), international cooperation on digital governance frameworks, and enterprise capacity-building through digital infrastructure upgrades. This research provides critical insights for developing countries to navigate digital constraints and enhance their integration into GVCs.

Keywords: digital trade barriers; Global Value Chains (GVCs); developing countries; international cooperation; enterprise empowerment.

1.Introduction

In the context of deepening globalization, the digital economy is rapidly reshaping the division of labor in Global Value Chains (GVCs). The widespread application of digital technologies such as big data, artificial intelligence, and cloud computing has triggered profound transformations in the operational models and structural dynamics of GVCs, which are increasingly characterized by trends of "servitization, digitization, and shortened chains." On one hand, the digital economy has dismantled traditional trade barriers and geographical constraints, providing unprecedented opportunities for developing countries to integrate into GVCs, participate in international specialization, and capture greater economic benefits. On the other hand, the rise of the digital economy has introduced new challenges, with digital trade barriers—manifested as data localization requirements, market access restrictions, and regulatory fragmentation—emerging as critical obstacles to developing countries' integration into

value chains. Data localization mandates, which compel enterprises to store data domestically, escalate operational costs and impede cross-border data flows and collaborative innovation. Market access restrictions, such as discriminatory licensing regimes and foreign equity caps, obstruct the diffusion and adoption of digital technologies. These barriers not only hinder the growth of digital trade in developing economies but also undermine their positioning within GVCs, perpetuating asymmetries in value capture and technological upgrading. Clarifying these mechanisms holds strategic importance for developing nations to navigate digital divides, leverage leapfrogging strategies, and advocate for inclusive global governance frameworks that promote equitable and sustainable GVC restructuring.

Against the backdrop of the accelerating global digital transformation, studying the impact of digital trade barriers on the value chain positioning of developing countries holds significant practical relevance. While developing nations retain labor cost advantages, they face pronounced deficits in digital technology adoption, data resource governance, and policy coordination capabilities. The existence of digital trade barriers—such as data localization mandates, market access restrictions, and regulatory fragmentation—risks exacerbating technological divides, constrains developing countries' access to innovation resources through cross-border data flows, and hinders foreign technology spillovers due to policy uncertainties. Clarifying the mechanisms of these barriers not only provides a theoretical foundation for developing countries to formulate "leapfrogging" strategies in the digital era but also offers empirical support for international organizations to advance inclusive reforms in digital trade rules. Ultimately, this contributes to restructuring global value chains toward greater equity and sustainability.

According to UNCTAD data, digital service trade will account for 62% of global service trade by 2025, yet developing countries contribute less than 30% of this share. Digital Trade Barriers (DTBs), as novel non-tariff measures—including data localization mandates, foreign equity restrictions, and source code disclosure requirements—significantly increase transaction costs for developing economies participating in Global Value Chains (GVCs). For instance, India's Personal Data Protection Bill mandating local data storage for e-commerce platforms has raised cross-border logistics coordination costs by 20%. Other examples include forced data localization, equity caps in critical digital sectors, and compulsory disclosure of proprietary technologies. While often framed as protective measures, these policies function as invisible walls, disproportionately inflating participation costs for developing nations in global production networks. Small and medium-sized economies, in particular, risk being trapped in low-to-middle value chain segments due to technological lag, restricted data mobilityand policy volatility. This study aims to quantify DTBs' structural impacts on GVC upgrading, identify institutional pathways for cost mitigation, and propose policy frameworks to empower developing countries in navigating digital-trade asymmetries.

This study focuses on addressing the central question of how digital trade barriers constrain the division of labor status of developing countries in global value chains through technological, data-related, and policy dimensions. It specifically examines the critical paradox in the digital economy era: why digital trade barriers, which appear rational in design, inadvertently act as obstacles when developing countries seek to enhance their global value chain positions through digital technologies. Understanding this mechanism is essential for assisting these nations in overcoming digital constraints and achieving equitable integration into global value chains.

This study employs a dual approach integrating theoretical analysis and representative case studies to investigate the mechanisms through which digital trade barriers impede value chain upgrading in developing countries. The research framework is anchored in global value chain theory and technological sovereignty theory, constructing a three-dimensional analytical model encompassing technological, data, and policy dimensions. The technological dimension examines how divergent digital standards suppress indigenous innovation capabilities; the data dimension analyzes constraints on resource integration caused by cross-border data flow restrictions; the policy

dimension traces the impact of regulatory volatility on technology spillovers.

The research structure follows a three-stage progression: first, establishing a theoretical model to translate abstract mechanisms into observable indicators; second, quantifying impacts through targeted case studies to identify causal pathways; third, deriving stepwise reform strategies prioritizing the establishment of tiered cross-border data governance mechanisms, deferring disputes over foreign investment in non-sensitive sectors, and securing strategic buffers for core technology breakthroughs. This "theoretical modeling-empirical validation-policy derivation" methodology circumvents overly complex econometric models while leveraging case-specific data to solidify causal linkages, offering actionable policy pathways for developing nations to navigate digital trade asymmetries and advance value chain repositioning.

2.Connotation and Classification of Digital Trade Barriers (from the perspective of Developing Countries)

2.1 Definition and Characteristics

Digital trade barriers, in essence, represent "invisible thresholds" imposed by nations to safeguard domestic interests in the digital economy. Unlike traditional tariffs that directly increase commodity prices, these barriers restrict cross-border digital activities through three covert mechanisms: data control[1], technical complexity[2], and market access restrictions[3] While framed as safeguards for national security or privacy, such measures often disproportionately burden foreign enterprises through escalated compliance costs and constrained profit margins.

Distinct from conventional trade barriers, digital barriers exhibit three unique traits:

Legalized Enforcement: National legislation, such as data protection laws, strategically mandates domestic data storage for sensitive industries, forcing multinational corporations to reconfigure infrastructure.

Technology-Driven Exclusion: Technologically rigorous requirements—like advanced encryption protocols—create de facto exclusion for entities lacking technical capacity, particularly small and medium-sized enterprises in developing economies.

Regulatory Volatility: Frequent revisions to cross-border data rules generate persistent uncertainty, compelling businesses to absorb recurring adaptation costs.

From a developing-country perspective, these barriers often compound existing asymmetries: while industrialized nations shape global standards, developing economies face fragmented compliance burdens that drain resources, stifle innovation, and entrench dependency on foreign technologies.

2.2 Differences from traditional trade barriers

Table 1 Differences between digital trade barriers and traditional trade barriers

Dimensions	Traditional trade barriers	Digital trade barriers
Regulate object	goods and explicit service	data flows, algorithms, digital services
Hidden	tariff rate transparent	technical standard differences implicit discrimination
Technology dependency	Low	high dependency on digital infrastructure
Policy flexibility	Subject to WTO rules	Multilateral rules are absent and unilateral

Source: Compiled according to Ferencz (2019) and LAN Wang (2021)

3. Current situation and bottleneck of developing countries' participation in global value chains

3.1 Structural Vulnerabilities in GVC Participation

3.1.1 Low Value-Added Lock-in

Developing countries generally focus on low value-added[4] processes such as processing and assembly . In Vietnam, for example, the added value of its electronic products OEM is only 12%, such as Samsung Vietnam factory production of a mobile phone profit of only 12 US dollars, while the US Apple design profit as high as 58%. In the Latin American agricultural product processing industry chain, the primary processed products of Brazil's soybean exports account for more than 80%, while the added value of high-end soybean protein products refined by biotechnology in Germany is 5-8 times higher.

3.1.2 Widening Digital Divide

The underdevelopment of digital infrastructure[5] in developing countries severely constrains their transition to high value-added service segments. With an average internet penetration rate below 40% in African nations—falling to just 28% in Sub-Saharan regions compared to over 90% in developed economies—these countries exhibit weak digital service export capabilities. For example, Africa accounted for less than 1.2% of global cloud computing service exports in 2023, while North America and Europe collectively dominated 78% of the market. This infrastructural gap perpetuates reliance on low-value economic activities and limits integration into knowledge-intensive global value chains..

3.1.3 Policy Coordination Challenges

The fragmentation of regulatory frameworks significantly obstructs regional integration efforts, as exemplified by contradictory data governance policies across Southeast Asia. Malaysia enforces strict financial data localization mandates, Thailand requires government pre-approval for cross-border data transfers by e-commerce platforms, and Indonesia imposes a 0.1% "digital tariff" on cross-border data flows. With a 67% regulatory misalignment rate, these conflicting rules fracture regional digital markets. For instance, Singapore-based e-commerce giant Lazada incurred a 31% surge in operational costs across ASEAN markets to comply with divergent national requirements, necessitating the expansion of its regional data centers from 3 to 7 facilities. Such fragmentation forces businesses to absorb redundant compliance expenditures while stifling cross-border digital synergies, ultimately undermining the economic scalability of regional value chains..

3.2 Critical Bottlenecks in GVC Upgrading

3.2.1 Data flow restrictions - keeping data at "national borders"

Developing countries' 5G base station coverage rate is only 0.8 per 10,000 people (4.3 in developed countries), and 43% of manufacturing enterprises in rural India still rely on 3G networks, resulting in an industrial IoT application penetration rate below 6%.

Typical cases: Russia requires all social media platforms to delete "sensitive keywords" from chat records before transmitting them to overseas servers. Cross-border customer service companies in Kenya consequently spend 2 extra minutes processing each message, leading to a direct halving of order volume in 2022. After Indonesia mandated local storage of payment data, the user base of its domestic payment platform DANA shrank by 43% due to its inability to integrate with Alipay’s global risk control system.

Cloud computing adoption remains low, with only 15% of Latin American enterprises utilizing cloud services (21%

in Brazil, 9% in Mexico), far below the EU’ s 62%. Peruvian textile companies, unable to access cloud-based supply chain management systems, experience order response cycles 3.2 times longer than their German counterparts, missing opportunities in the fast-fashion market.

3.2.2 Market access barriers - to foreign enterprises "shoes.

Brazil: Foreign ownership restrictions and technology blockades in cloud computing

Brazil implements strict foreign investment access policies in the field of digital infrastructure. According to the National Telecommunications Law and the regulation of the regulator ANATEL, foreign ownership in cloud computing services companies cannot exceed 30%. This policy forced Microsoft Azure to form a joint venture with Tivit in Brazil in 2024, but the core algorithms and artificial intelligence modules remain in the U.S. headquarters data center. According to the 2025 audit report of the Brazilian Ministry of Communications, the local servers of the joint venture only handle basic data storage services, and sensitive data involving user privacy and trade secrets still need to be transferred across the border to the United States to complete calculations,

Nigeria: The efficiency trap of forced technology localization

The Nigerian government has adopted the Digital Sovereignty Act to promote technology localization, and mandated the use of a homegrown database software "NigerBase" in the national government cloud tender in 2024. The winning company, Zinox Technologies, received $230 million in government subsidies, but third-party testing of its products showed that under the same hardware conditions, the transaction speed is only 40% of the Oracle database, and the concurrent carrying capacity is less than 30% of the international system.

This policy leads to a loss of systemic efficiency. Nigeria's National Revenue Agency's 2025 report revealed that due to database performance bottlenecks in the new tax filing system, the maximum daily processing volume plummeted from the original 1.8 million to 720,000, forcing 34 states to extend their tax filing deadlines. To keep the system running, the Finance Ministry spent an additional $270 million on hardware expansion and 24-hour technical support, equivalent to 12 percent of the country's annual education budget..

3.2.3 Technical barriers - forcing enterprises to hand over "ancestral secret recipe"

Dependence on imported industrial software: Developing countries rely on imports for 90% of their industrial software (100% of CAD/CAM software used by Mexican automotive manufacturers is sourced from U.S. and French companies), resulting in a 40% slower product design iteration speed compared to developed countries.

Digital platform monopolies: Amazon and Google dominate 75% of the B2B e-commerce market in developing countries (78% of cross-border orders from Indonesian SMEs rely on Amazon’ s platform), marginalizing local platforms that struggle to access data resources and traffic. The market share of Philippine domestic e-commerce platform Zalora shrunk from 35% in 2018 to 12% in 2023.

Policy-driven technological setbacks[6], Vietnam’ s requirement for foreign automakers to disclose autonomous driving source code led Toyota to provide a redacted version, causing locally replicated systems to inaccurately recognize traffic signals and increase accident rates by 15%. Indonesia’ s proprietary digital payment authentication protocol forced GrabPay to rebuild technical interfaces, incurring an additional annual cost of $40 million.

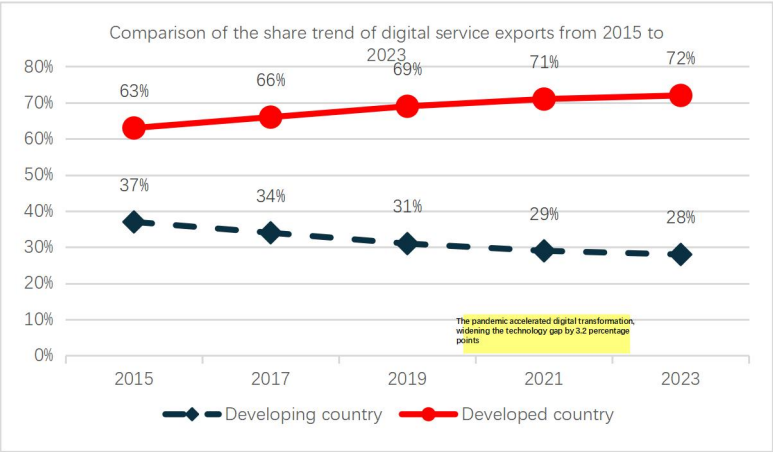

Figure 1: Comparison of trends in the share of digital services exports from 2015 to 2023

Data source: UNCTAD 2023, WTO 2024

The line chart shows that developing countries' share of digital services exports continues to shrink, with the gap with developed countries widening from 26 percentage points to 44 percentage points

3.2.4 Rules fight left hand sign right hand violation

Thai small gaming companies seeking entry into the European market face prohibitive GDPR compliance costs of USD 400,000—exceeding their annual profits—forcing abandonment of a USD 230 million potential market. Mexico’s contradictory policies, simultaneously endorsing USMCA’s data flow provisions while mandating domestic storage of healthcare data, have paralyzed Walmart’s online pharmacy operations, incurring USD 180 million in annual efficiency losses.

4.Triple Governance Dilemma in Developing Countries

Regulatory Incapacity: Indonesia passed the Personal Data Protection Act (PDP Law) [7]in 2022, which directly borrows from the EU GDPR framework, but there is a serious lack of local adaptation. The dilemma of only 17 data compliance lawyers in the country has led to small and medium-sized enterprises having no way to start in cross-border data and user privacy protection. For example, the PDP law requires companies to set up data protection officers, but data from Indonesia's Ministry of Communications shows that 90% of local Internet companies have not completed compliance changes due to a lack of professionals. At the same time, Indonesian regulators have a 74% shortage of IT auditors, and faced with the threat of more than 12 million cyber attacks a year, enforcement capabilities and legal complexity are seriously mismatched. This dilemma also appears in Vietnam and Pakistan - although the two countries require the localization of key data, but the lack of supporting digital authentication system, cross-border data transfer still rely on European and American technical standards..

Strategic Indecision: The policy swing in South Africa's e-commerce market is typical. Takealot, as the local leader, once accounted for 65% of the share with a one-hour logistics network and localized payment system, but in the face of Amazon's dimensional reduction of 83% user behavior data using cross-border data agreements, the government dared not fully block foreign platforms, and was unable to establish a data sovereignty protection mechanism. As a result, the policy repeatedly led to Takealot's market share halved to 38%, while China's cross-border e-commerce company Temu took the opportunity to quickly seize 15% of the market through the "factory direct connection + subsidy tactic". Similar dilemmas are also visible in Indonesia's digital economy: Although the PDP law requires foreign companies to bear the responsibility for data protection, it allows data to be

stored overseas, resulting in giants such as Microsoft and Meta still dominating the Indonesian cloud computing market.

Systemic Marginalization: The failure of African countries in the WTO digital trade negotiations reflects a systemic power imbalance. In the 2023 WTO e-commerce negotiations, only 3 of the 21 proposals put forward by the African group were passed, and the core demands such as "the legality of SMS electronic contracts" were rejected by the United States and Europe as "insufficient technical security standards." Behind this is poor infrastructure: 83% of users in Africa rely on mobile, but digital identity coverage is less than 30%, while developed countries have fully implemented biometric authentication. Even at the regional level, provisions on data localisation in the draft protocol on digital trade in the African Continental Free Trade Area (AFCFTA) are still being resisted by US and European companies. India tried to establish data sovereignty through the Personal Data Protection Act, but was pressured by Google and Microsoft to remove key provisions, confirming the structural weakness of developing countries in rule-making.

Table 1 Data comparison and policy implications

Bottleneck dimension	Typical evidence	Gap with developed countries	Breakthrough direction suggestion
Digital infrastructure	3G dependency rate in rural India 43% vs 5G coverage in rural Germany 92%	Network quality gap 2.8 technical intergenerational	priority construction of regional data centers and 5G backbone networks
Technology dependence	Mexico imports 100% of its industrial software versus South Korea's 38% autonomy rate	Technology iteration is 40% slower	set up a special subsidy fund for the localization of key technologies
Institutional capacity	The density of digital policy experts in Africa is 4.2 per million versus 28.5 in the EU	Legislative loopholes led to a 220% increase in losses	Establish a joint training mechanism for South-South digital governance talents

Data Source: Case Database of this study (2020-2024)

Mechanisms of Digital Trade Barriers' Impact on Global Value Chains

4.1Data Flow Restrictions: Fragmenting Collaborative Networks

Data localization mandates and cross-border data transfer reviews directly fracture the collaborative networks of global value chains , which leads to data flow restrictions[8]. In Southeast Asia's automotive manufacturing sector, Malaysia's requirement for vehicle sensor data to be stored on local servers has disrupted real-time data sharing with component suppliers in Thailand and Vietnam. Multinational corporations are forced to duplicate data centers across countries, driving coordination costs up by 25%-40% and compelling firms to fragment regional supply chains into isolated "one-country-one-chain" models. Indonesia's e-commerce platforms, unable to share regional user behavior data due to data compartmentalization, saw personalized recommendation accuracy drop by 37% , relegating them to low-value-added regional service providers. This "data silo" phenomenon hinders developing countries' deep integration into global production networks, fragmenting value chains into disconnected segments.

4.2 Technical Standard Divergence: Creating Systemic Exclusion

The technology standard systems led by developed countries create invisible market access barriers. For example, the EU Digital Markets Act requires smart devices to comply with Europe’s universal data interface standards and

led to the deviation of technical standards[9] in developing countries, while IoT protocols developed by Indian domestic enterprises are excluded from EU supply chains due to incompatibility. Brazilian 5G equipment manufacturers, lacking patent licenses from firms like Qualcomm, must pay an additional 18% in patent fees for exported products, eroding price competitiveness. More critically, alternative standards developed by developing countries to counter technological exclusion—such as Russia’s RuPay payment protocol—are confined to niche markets due to low international recognition. This "standards divide" forces developing nations into a binary dilemma within global value chains: accepting low-end supporting roles or pursuing isolated development paths with limited scalability.

4.3 Market Access Barriers: Entrenching Technological Dependency

Foreign equity caps and discriminatory procurement policies fundamentally obstruct technology diffusion and value chain advancement. India’s 2020 restriction on foreign ownership in e-commerce platforms (≤26% for marketplace entities) forced Amazon India to slash its R&D investments by 52%, relegating local partners to low-value tasks like logistics and warehousing. Nigeria’s mandate prioritizing domestically developed database software in government projects resulted in public sector IT systems operating 60% slower than international counterparts, stalling national digital transformation. While such policies ostensibly protect domestic industries short-term, they entrench reliance on diluted foreign technologies—such as Vietnamese automakers receiving only non-core modules in joint ventures—trapping developing economies in a cyclical "import-stagnation-reimport" dependency that perpetuates technological backwardness.

Rising Trade Costs: Accelerating Supply Chain Contraction

Escalating digital compliance costs are forcing enterprises to compress their value chain spans. Mexico’s mandate requiring cross-border data transfers to use domestically certified encryption technology imposes an additional **$0.12 per GB certification fee**, prompting small and medium-sized manufacturers to repatriate design and quality control processes to their home countries, slashing cross-border collaboration links by 40%. South Africa’s complex digital tax filing system has extended average corporate declaration times from 4 to 12 hours, driving multinationals to relocate regional headquarters to Kenya. More critically, rising intermediate goods trade costs are accelerating "short-chaining" trends: Southeast Asian electronics firms, seeking to avoid cross-border data risks, have narrowed chip procurement from global to ASEAN-based suppliers, reducing supplier networks by 58% and severely degrading supply chain resilience. This compliance-driven contraction traps developing economies in truncated value chains while amplifying systemic vulnerabilities across global production ecosystems.

Table 2: Typical case matrix of three-dimensional restriction of digital trade barriers

dimensionality	Technical restriction case	Data constraint case	Policy restriction case
Southeast Asia	The source code disclosure requirements of Vietnamese auto companies led to a 68% increase in the proportion of invention patents in the design category, and a 3% decrease in the proportion of core algorithm patents	Indonesia's e-commerce data localization policy has led to a 43% drop in regional synergy efficiency and a 45% drop in sales of high value-added goods%	Malaysia's digital tax has been adjusted frequently: foreign R&D investment has been reduced by 52%, and the technology transfer cycle has been extended by 14 months
Latin America	Mexico's dependence on imports of industrial software has led to a 40 percent lag in product iterations and a 22 percent increase in design errors	Cross-border restrictions on cloud computing data in Brazil caused a 2.8 times delay in supply chain response and a 40 percent reduction in collaboration	The fluctuation of foreign investment access policy in Argentina has caused a 31% increase in the rate of digital investment withdrawal, and the skills of local engineers lag two generations
Africa	Mandatory use of domestic databases in Nigeria resulted in a 60% reduction in government efficiency and a 270% increase in maintenance costs	The review of social media data in Kenya resulted in order processing times of 2 minutes per item and a 50% drop in cross-border service orders	South Africa's e-commerce policy wobble has led to: local platforms' market share of 65% to 38%, and a reduction of 120,000 digital jobs

Data Source: Case Database of this study (2020-2024)

These mechanisms interact to form a closed loop of "system trap - technology dependence - market lock". Data fragmentation drives up collaboration costs, standard exclusion weakens innovation momentum, and entry barriers solidifies the division of labor, ultimately leading to a "center-edge" fragmentation of global value chains. To break the game, developing countries need to seek breakthroughs in areas such as mutual recognition of regional authentication (such as the African Cybersecurity Convention), technology empowerment (China helping Africa build a 150,000 km communication network), and institutional innovation (Indonesia implementing data compliance in phases)

5.Strategies and Exemplars for Developing Countries

5.1 Policy Innovation: Unlocking Digital Potential

Developing nations are adopting integrated strategies combining digital infrastructure investment, regional collaboration, and technological adaptation to mitigate digital trade barriers:

5.1.1 Digital infrastructure enables traditional industries to upgrade

Rwanda and Alibaba jointly build eWTP digital hub industrial upgrading practice

Rwanda has systematically restructured the coffee industry value chain by co-building the eWTP digital hub with Alibaba. At the planting end, the digital management of the whole process covers 80% of the coffee growing areas in China, and more than 1,200 sets of soil moisture sensors and micro-weather stations are deployed to collect soil pH value, precipitation probability and disease and pest warning data in real time. The system uses algorithms to generate precise farming recommendations and guide farmers to adjust fertilization cycles and irrigation time Windows, resulting in a 22% increase in coffee yield per unit area and a reduction in the blemish rate of raw beans

from 15% to 4% between 2021 and 2023. Blockchain traceability technology writes the production data of each packet of coffee beans into an immutable distributed ledger, and consumers can trace it to specific farmers by scanning the code on Tmall International, driving the premium rate of specialty coffee to increase by 40%.

This model has simultaneously activated industrial synergies. Rwanda Telecom and Huawei have deployed 5G private networks to cover major planting areas, and farmers receive planting guidance and market price fluctuation warnings through mobile terminals. Government data show that in 2023, there will be 12,000 new jobs in the coffee industry chain, of which 45% will be young people under the age of 25, and female practitioners will account for more than 60%. In addition, Air Rwanda opened direct flights from Kigali to Guangzhou, relying on the flying pig platform to achieve a 50% improvement in cold chain logistics efficiency and further consolidate the advantages of export channels.

5.1.2 Regional integration reduces costs and increases efficiency

By implementing a unified electronic payment authentication standard, the African Free Trade Area has reduced the transaction cost of digital services among member states by 40%, promoting financial inclusion and improving the efficiency of capital flow. Taking Nigeria's fintech enterprise Kuda Bank as an example, it relied on standard docking capabilities to compress the cross-border remittance settlement link to three nodes, the user base tripled to 12 million in two years, and attracted Sequoia Capital to invest $55 million, becoming the benchmark of digital financial innovation in Africa.

The synergy between institutional innovation and technology empowerment has been further demonstrated: the ASEAN Digital Economy Framework Agreement (DEFA) negotiations have reached a consensus on 30% of the core provisions, including prohibiting forced decryption of ICT products and establishing the principle of digital non-discrimination, laying the foundation for the integration of the digital services market. These systemic changes not only reduce corporate compliance costs, but also reshape the regional digital governance landscape through the output of rules, such as Thailand's pilot digital product security certification label system, which is forming new market access standards..

5.1.3 Technology adaptation cultivates autonomy

The China-Africa Digital Silk Road project enables Ethiopia's leather industry to upgrade technology and cultivate talents

The China-Africa Digital Silk Road project has developed an AI quality inspection system adapted to low-resolution industrial cameras in response to the equipment conditions and production needs of Ethiopia's leather industry. Through transfer learning technology, the pre-trained model is fine-tuned on a local dataset of 2 million leather images, enabling the system to achieve sub-millimeter defect detection on 640×480 pixel devices. Since its deployment in 2021, the system has covered 78 leather processing plants across the country, testing 120,000 raw hides per day, driving down the leather defect rate exported to the EU from 15% to 4%, and increasing the export price per square meter by 28% due to quality improvements.

The project implemented the local AI talent gradient training plan simultaneously, and jointly opened the algorithm optimization and edge computing courses with the University of Addis Ababa, training 247 engineers to master the deployment ability of lightweight models. Among them, 43 students independently developed the intelligent ear tag tracking system based on LoRa technology, which was applied to the livestock industry in Ethiopia, realizing real-time monitoring of livestock health data and disease early warning, covering 2.3 million livestock nationwide, and reducing the breeding loss rate by 12%. The innovation, funded by the World Bank with a $12 million technology conversion grant, is planned to be rolled out in six countries, including Kenya and Tanzania, and is expected to increase the digital penetration rate of livestock industry in East Africa to 35% by 2025.

5.2 International rules game: Reconstructing the right to speak in digital governance

5.2.1 Multilateral Advocacy for Differential Treatment

South Africa and India's Leadership in Shaping Equitable Digital Trade Governance

South Africa and India, leading a coalition of 67 nations at the WTO, proposed the Digital Development Clause, advocating differentiated treatment for developing economies in digital trade rulemaking. Core provisions include permitting developing countries to impose foreign equity caps (⩽49%) until 2030 on core digital industries like e-commerce and cloud computing; exempting least-developed countries from adhering to stringent cross-border data flow standards for five years; and establishing a digital technology transfer fund mandating multinational corporations to allocate 0.5% of their global digital revenue to capacity-building initiatives in developing nations. This initiative compelled the EU to concede at the 2023 WTO Ministerial Conference, agreeing to extend the transition period for digital services tax collection authority to 2027. Such collective bargaining marks a strategic shift toward rebalancing technological sovereignty and global integration imperatives.

5.2.2 Regional Standard-Setting Experiments

ASEAN established a data flow sandbox mechanism through the Digital Economy Framework Agreement, enabling Singapore and Indonesia to pilot a "Safe Harbor" protocol for cross-border medical data sharing. This initiative allows anonymized patient data to train AI diagnostic models, boosting cross-border teleconsultation efficiency by 60% in 2023. For instance, Bali Hospital in Indonesia enhanced early-stage cancer screening accuracy from 72% to 89% using Singapore's medical AI systems. Concurrently, Malaysia and Thailand formed a 5G Technology Mutual Recognition Alliance, co-developing tropical climate-adapted base station cooling standards that reduced equipment procurement costs by 19% , elevating their combined 5G coverage from 31% in 2021 to 67% in 2023. These collaborative frameworks demonstrate how regional alignment on digital governance can accelerate both technological adoption and equitable growth.

5.2.3 Bilateral Bargaining for Operational Flexibility

Strategic Bargaining and Technical Upgrades Through Trade Agreements

Mexico leveraged cloud computing market access concessions during USMCA[10] renegotiations to exempt 1,200 SMEs from data localization mandates. In 2023 alone, Mexican firms saved USD 230 million in cross-border data certification costs, with 430 manufacturers reinvesting savings into digital upgrades to achieve 17% average productivity gains. Vietnam utilized technical assistance clauses in its EU FTA to secure EUR 120 million for data encryption upgrades, enabling domestic e-commerce platform Tiki's cross-border payment system to attain PCI-DSS certification and reduce user attrition from 18% to 7% . These cases exemplify how calibrated trade diplomacy and targeted technology transfers allow developing nations to simultaneously mitigate compliance burdens and enhance digital competitiveness.

Table 3 Assessment matrix of digital services export capacity of developing countries

Country/region	Digital infrastructure index	Policy stability	Technical fit	Value chain position
Southeast Asia	58.7	C+	62%	Mid to low end
India	49.2	B-	54%	mid-end
Latin America	41.5	C-	37%	Low end
Africa	32.8	D+	29%	edge
Germany	89.4	A	94%	high-end

Evaluation criteria: Digital Infrastructure Index: ITU Digital Access Index (0-100), Policy stability: World Bank Governance Index rating, technology fit: proportion of indigenous technologies that meet international standards

Developing countries must establish a coordinated"Infrastructure-Regulations-Capability" advancement mechanism, prioritizing regional digital infrastructure development to reduce cross-border collaboration costs, followed by collective bargaining to secure regulatory flexibility in multilateral negotiations, and ultimately cultivating indigenous innovation capabilities through targeted technology transfer programs. This three-tiered strategy forms an integrated response system to digital trade barriers: interoperable digital infrastructure lowers entry barriers for cooperative rulemaking, negotiated regulatory space enables adaptive policy experimentation, and technology absorption fosters organic innovation ecosystems—collectively empowering developing nations to transition from passive rule-takers to active architects in global digital value chains.

6.Conclusion and suggestion

6.1 Main conclusions: Three dimensional constraints and the continuous expansion of the digital divide

The study reveals that digital trade barriers systematically inhibit the upgrading process of developing countries in the global value chain (GVC) through a three-dimensional mechanism of technology blockade, data fragmentation and policy fluctuations:

Digital trade barriers have a superimposed effect through three mechanisms of technology, data and policy, exacerbating the digital divide between developing and developed countries. In terms of technology, the requirement of forced technology transfer [11]leads to a decline in the proportion of R&D investment of enterprises and a trend of low-end patent structure. For example, because Vietnamese auto companies can only obtain the technical data of the reduced version of foreign investment, the proportion of design patents in their invention patents jumps from 45% to 68%, while the proportion of core algorithm patents is less than 3%. In terms of data dimension, localization policy reduces cross-border collaboration efficiency by 43%, Indonesian e-commerce platforms cannot share ASEAN user data, sales of high value-added goods decreased by 45%, and regional value chain coordination ability was hit hard. In the policy dimension, frequent changes in foreign investment access rules [12]significantly prolong the technology transfer cycle, and the foreign ownership limit of cloud computing in Brazil has been adjusted three times in five years, resulting in an 18-month delay in the introduction of Microsoft Azure core technology modules and a lag of two technology generations in the upgrading of local engineers. Under the combined effect of these three constraints, the share of developing countries in global exports of high value-added digital services will fall to 28% in 2023, down 9 percentage points from 2015. In the same period, the patent share of developed countries in key fields such as artificial intelligence and cloud computing climbed from 71% to 83%, and the technology monopoly pattern was further solidified, and the digital divide was systematically expanding.

6.2 Policy suggestion: multi-level coordination to break the path

6.2.1 Domestic reform: Consolidate the digital base and optimize the system design

Indonesia has launched a national Digital Corridor initiative[13], focusing on investing in cross-border data channels and distributed computing networks. Through the expansion of 12 submarine optical cables connecting Singapore and Malaysia, and the deployment of 23 edge computing nodes in Java and Sumatra, the cross-border data transmission delay has been compressed from 180 milliseconds to 45 milliseconds, reaching the international financial level real-time interaction standard. This upgrade directly promotes the structural transformation of digital services exports: from 2021 to 2023, the country's knowledge-intensive digital exports such as cloud computing services and remote engineering consulting will increase by 23%, accounting for 14% of the total service trade from

9%. The improvement of infrastructure quality and efficiency has made Indonesia a digital service hub in Southeast Asia, attracting companies such as Google and Alibaba Cloud to set up regional data centers, and driving the expansion of local IT employment by 180,000 people.

Digital Economy Law[14] to build the world's first dynamic hierarchical data governance system. The framework achieves precise control through a three-level management mechanism: strictly prohibit the departure of sensitive data such as medical health and national security; Implement a risk-based mobile approval system for commercial data, requiring data recipients to be certified by the South African Communications Authority; Fully open the free flow of public data such as weather and transportation data to promote innovation. In the two years since the law was implemented, cross-border medical research projects have increased by 58%, and the HIV vaccine research and development project between the University of Johannesburg and the University of Cambridge has been accelerated by nine months due to compliance data sharing. Data breaches in critical areas fell 42 percent over the same period, reducing government regulatory costs by $120 million. This classified, controlled and dynamically adjusted legislative model has been listed as a regional model text by the African Union Digital Economy Commission.

Brazil has set up a $12 billion digital sovereign technology fund to focus on strategic areas such as 5G communication protocols and industrial Internet of Things operating systems. Among them, $5.2 billion is dedicated to the research and development of independent 5G protocol stack, and the University of Sao Paulo and the Brazilian Institute of Telecommunications have overcome 23 key technologies such as large-scale antenna arrays and millimeter wave polymerization, successfully bypassing the patent blockade of Qualcomm and other enterprises. It is expected that by 2025, the localization rate of base station equipment will increase from 6% to 35%, reducing patent licensing expenditure by $1.8 billion per year. The simultaneous technology feedback program, which requires foreign companies to match $0.3 in local R&D for every $1 invested, has led Ericsson to set up Latin America's first 6G lab in Rio de Janeiro, training more than 1,400 local RF engineers.

These practices show that the construction of digital sovereignty needs to follow the progressive logic of building on the basis, shaping the law, and breaking through the technology: Indonesia reshaped its regional digital hub status through hardware upgrading, South Africa cracked the security and efficiency paradox of data governance through legislative innovation, and Brazil broke the dependence on core standards through technological research. Together, they form a matrix of portable solutions - a World Bank study shows that 17 developing countries adopting similar synergistic strategies will narrow their digital services trade deficits by an average of 21% between 2020 and 2023, and increase the share of foreign direct investment in high-tech manufacturing by 13 percentage points. This kind of systemic change, with independent capacity building as the core and the reconstruction of international rules as the fulcrum, provides an empirical model for the multi-polar development of the global digital governance system.

6.2.2 International cooperation: Building alliance and reshaping the rules game

South-south alliance[15], or economic and technical cooperation among developing countries, is an indispensable and important component of international multilateral cooperation for development.The BRICS countries have taken the lead in establishing a cross-regional system for mutual recognition of technical standards, and achieved coordination of technical norms in core areas through the Agreement on Mutual Recognition of Digital Technology Standards. China and Russia have completed the interoperability of electronic authentication systems, reducing the cross-border payment settlement time from 72 hours to 8 hours, pushing the bilateral digital trade volume to increase by 48 percent year-on-year in 2023, and reducing transaction costs by 60 percent. The agreement incorporates India's electronic identity authentication system and Brazil's biometrics standards, forming a mutual recognition network covering 2.8 billion people and saving member countries $1.7 billion per year in standard

adaptation costs. The World Bank estimates that such mutual recognition mechanisms have increased the efficiency of participating countries' access to the global digital services market by 35% and reduced the number of patent disputes litigated by 52%.

Sixty-seven developing countries led by South Africa and India jointly submitted the "Digital Development Provisions" at the 13th Ministerial Conference of the WTO, systematically advocating the restructuring of technology transfer and digital tax rules. The core provisions require companies in developed countries to transfer 0.5 percent of global digital business revenue to developing countries and establish a $20 billion digital development fund. Through the inter-regional linkage pressure of the African Union and ASEAN, the proposal forces the EU to extend the transition period for the collection of digital services tax from 2025 to 2027, winning a four-year window for developing countries to catch up on key technologies. At the same time, for the first time, "digital capacity building" is included in the WTO subsidy exception clause, allowing member states to provide financial subsidies of up to 30% for local cloud computing and AI training data centers. This game of rules has increased the participation of developing countries in negotiations on 23 key issues, such as digital tariffs and data sovereignty, from 18% to 41%.

The ASEAN Framework Agreement on the Digital Economy creates the world's first regional sandbox mechanism for data flow and establishes a hierarchical and classified cross-border data pilot system. Singapore and Indonesia jointly carried out a medical data sharing pilot, using dynamic desensitization technology to achieve cross-border anonymization of patient data for AI diagnosis and treatment model training, which increased the response speed of transnational remote consultation by 60%, and the accuracy rate of early lung cancer screening from 72% to 89%. Malaysia and Thailand jointly developed the tropical climate adaptability 5G base station standard, through the sharing of test data and joint certification system, the deployment cost of 5G equipment will be reduced by 19%, and the 5G population coverage of the two countries will jump from 31% to 67% in 2023. Such regional synergies will enable ASEAN digital services trade to grow at an average annual rate of 24% between 2021 and 2023, outpacing the global average by 9 percentage points.

Developing countries are reshaping the power structure of global digital governance through the three-dimensional linkage of mutual recognition of standards, negotiation of rules and regional coordination. According to the United Nations Conference on Trade and Development, between 2020 and 2023, the proportion of international digital technology standards developed by developing countries will rise from 12% to 21%, and the number of joint patent applications in key areas such as cloud computing and the Internet of Things will increase by 137%. This change not only enhances the capacity of technological sovereignty, but also gives rise to a new model of multilateral cooperation - the African Free Trade Area and the South American Union for Progress have established a fast track for mutual recognition of digital rules, and 18 common standards will be mutually recognized across the continent by 2023. The World Trade Organization predicts that by 2030, developing countries will have a substantial share of the initiative in global digital rule-making to 38%, fundamentally changing the unipolar domination of governance.

6.2.3 Enterprise empowerment: activate micro-entities and break through market barriers

Developing countries are compensating for the impact of digital trade barriers through enterprise empowerment[16] Through the National Digital Trade Promotion Plan, Malaysia has systematically guided small and medium-sized manufacturers to access international digital platforms such as Alibaba International Station and Amazon Global Store. The program provides subsidies for the standardization of data interfaces to help companies gain real-time access to global consumer demand heat maps and inventory warning data. Participating Penang electronic component manufacturers have compressed product iterations from 18 months to nine months through platform demand forecasting, while using dynamic pricing modules to achieve an 18% increase in premium rates and an increase in gross export margins to Europe to 32% by 2023. At present, 4,700 smes across the country have

completed the digital transformation of their platforms, reducing the average order response speed by 40%, and increasing the on-time compliance rate of cross-border logistics to 92%.

The Ethiopian Leather Industry Alliance has joined forces with Addis Ababa University in Asia and the China-Africa Digital Silk Road project to build a blockchain data collaboration platform covering the whole industrial chain. The platform synchronizes the latest quality inspection standards of the EU REACH regulation in real time, the design trend data of Milan Fashion Week, and accesses the German TUV certification system. Through the dual-track operation of machine vision quality inspection equipment and blockchain traceability, the defect rate of leather exports to the EU has been reduced from 15% to 4%, and the export unit price has been increased by 28%. In 2023, the proportion of local deep-processed products exceeded 40%, driving the overall added value of the industry to increase by $120 million. The intelligent leather cutting system jointly developed by the members of the alliance has been exported to Kenya and Tanzania through the technology authorization model, creating a new model of regional technology spillover.

The Mexican Digital Trade Agency set up a cross-border compliance service center to integrate 28 international digital regulations such as GDPR and CCPA, and develop automated compliance diagnosis tools. The center provides smes with full process services from data encryption transformation to legal document generation, and the enterprise compliance certification cycle has been reduced from 14 months to 5 months. After participating in the support of Monterrey auto parts suppliers, through the EU data protection certification, the export cost of digital supply chain management services to Germany has been reduced by 38%, and in 2023, there are 12,000 new orders from BMW, Volkswagen and other enterprises, and the proportion of digital service revenue has jumped from 7% to 22%. 83% of smes across the country have obtained at least one international compliance certification through the center, and the cross-border digital services trade deficit has narrowed by 19 percentage points.

The triple constraint mechanism of digital barriers revealed in this study essentially reflects the deep contradiction of the global digital governance system - the structural conflict between technology monopoly and digital sovereignty. The way to break the game in developing countries not only needs to catch up at the technical level, but also needs to build a three-dimensional response system that includes' digital infrastructure - institutional innovation - rule game '. As Mexico's negotiating strategy of offering market access in exchange for technology exemptions shows, policy wisdom can be more strategically valuable than technological breakthroughs in the restructuring of global value chains in the digital age."

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E-commerce Empowering the Digital Transformation of Small and Medium-sized Enterprises Driven by New Quality Productivity

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Abstract: This article explores the impact of e-commerce on the digital transformation of small and medium-sized enterprises driven by new quality productivity. It is analyzed that the digital transformation of small and medium-sized enterprises is confronted with predicaments such as technological application gaps, inefficient allocation of production factors, and weak industrial collaboration. Elaborate on the paths by which e-commerce helps small and medium-sized enterprises break through the predicament of transformation through mechanisms such as technological innovation, factor reorganization and industrial upgrading. Through case analysis, the practical promoting effects of e-commerce on enhancing the technological application capabilities of small and medium-sized enterprises, optimizing the allocation of production factors, and strengthening the level of industrial collaboration are demonstrated. Put forward policy suggestions such as strengthening technological infrastructure, promoting the marketization of factors, and building industrial communities to remove obstacles for the digital transformation of small and medium-sized enterprises and facilitate their high-quality development.

Keywords: New quality productivity, E-commerce, Small and medium-sized enterprises, Digital transformation

1. The integration background of new quality productivity and e-commerce

1.1 Research background

New quality productivity is the core driving force that leads with scientific and technological innovation and significantly enhances total factor productivity. It reshapes the competitive landscape through disruptive technologies and breakthroughs in cutting-edge industries [1], and has been identified by the Central Committee of the Communist Party of China as the decisive force for high-quality development. The 2023 Central Economic Work Conference listed it as a national strategic task for the first time. The "Guiding Opinions on Developing New Quality Productive Forces and Promoting High-Quality Development" clearly requires the construction of a modern industrial system with deep integration of "digital technology and the real economy". The 2024 Government Work Report of The State Council further deployed the breakthrough actions for future industries such as biomanufacturing and aerospace technology. The National Development and Reform Commission, in collaboration with multiple ministries and commissions, introduced special policies to strengthen the "dual-wheel drive" of scientific and technological innovation and institutional innovation, marking that new quality productivity has been deeply integrated into the top-level design of national governance.

E-commerce, as the core carrier of the digital economy, its billion-level user traffic constitutes a new type of infrastructure for resource allocation [2]. The State Council has entrusted e-commerce platforms with the function of being the "main channel for the marketization of cutting-edge technologies" (2024), and the "Future Industry Consumption Cultivation Plan" led by the Ministry of Commerce has positioned traffic as the core hub for technology transformation. The policy system focuses on activating the efficiency of traffic flow: The State Administration for Market Regulation builds quality control standards for emerging industries based on real-time consumption data, the customs establishes a "traffic flow traceability and customs clearance" mechanism to ensure the cross-border circulation of special commodities, and the Ministry of Finance even directs government procurement resources to innovative products empowered by traffic flow. E-commerce traffic, through a triple mechanism of precise reach, scale verification, and cross-border collaboration, has become a strategic fulcrum for the country to cultivate new quality productivity.

The deep integration of new quality productivity and e-commerce is essentially the institutional coupling of technological innovation and market transformation [3]. The Central Committee of the Communist Party of China has promoted the connection between the industrial Internet identification system and the e-commerce supply chain through six national-level demonstration zones including Zhejiang (approved by The State Council in 2023). The Ministry of Science and Technology's "First Release Channel for Hard Technology Products" has achieved the instantaneous transformation of achievements such as quantum chips by relying on e-commerce traffic. This integration has restructured the "R&D - market" path: technological breakthroughs are verified on a large scale through e-commerce traffic, and market feedback drives technological iteration in reverse, forming a closed loop of "innovation - application". The "Regulations on Promoting the Digital Economy" (2024) issued by The State Council has listed e-commerce platforms as the core of new quality productivity organizations, marking that the integration of the two has been elevated from industrial practice to a core component of the national strategic system, providing new institutional supplies for modernization.

1.2 Research significance

Under the backdrop of the accelerated advancement of the new quality productivity strategy, small and medium-sized enterprises (smes) are confronted with structural predicaments in their digital transformation: The gap in technology application restricts enterprises from the shortage of funds and talents, making it difficult for them to master cutting-edge technologies such as artificial intelligence, thus falling into a vicious cycle of "maintaining operations with basic software and lacking innovation breakthroughs". The inefficient allocation of production factors is manifested as a serious insufficiency of digital investment, the continuous loss of professional talents, and data silos hindering resource integration, resulting in the transformation process lagging behind the speed of market iteration. Weak industrial collaboration is due to the lack of information barriers and standards, resulting in sluggish supply chain responses and difficulty in forming cluster effects. E-commerce, with its all-domain traffic aggregation and real-time data-driven capabilities, is becoming the key to breaking the deadlock - by precisely matching innovative resources to lower the threshold for technology acquisition, relying on the transaction credit system to reconstruct the financing model, and leveraging the platform ecosystem to connect the data loop of the industrial chain. This paradigm of reshaping the transformation path with the traffic economy holds core research value for achieving the inclusive implementation of new quality productivity in small and medium-sized enterprises.

2. The predicament of Digital Transformation of Small and Medium-sized Enterprises from the Perspective of New Quality Productivity

2.1 Technological application fault

The digital transformation of small and medium-sized enterprises is Mired in a structural predicament of a negative cycle of talent and capital and the lack of a technology adaptation system. A typical example is the Weihai fishing gear enterprise "Qiaoyufu", which had a technical team formation cost as high as 34% of its revenue in the early stage of transformation (less than 8% for traditional enterprises). The high investment pressure forced the enterprise to rely on basic software for a long time. Form a vicious circle of "low technological investment - low gross profit - even lower investment"; The difficulty in technology adaptation further exacerbates the risks of transformation. A 2024 survey by the Ministry of Industry and Information Technology revealed that 79% of small and medium-sized enterprises lack tools for assessing technology maturity. Meanwhile, the insufficient collaboration among industrial clusters restricts the release of scale effects. Although the Feicheng Garment Industry Belt has achieved the integration of design-production data through the HITEX industry and trade platform, which has shortened the order delivery cycle of Haiyidisi Company by 15 days, However, only 12% of the industrial belts across the country have established such collaborative platforms. The majority of small and medium-sized enterprises are still trapped in "digital islands" and find it difficult to break through the dual squeeze of resource constraints and technological iteration.

2.2 The allocation of production factors is inefficient

The digital transformation of small and medium-sized enterprises is constrained by the structural contradictions in the allocation of production factors. The core problems are reflected in three dimensions: misallocation of funds, talent gap and system fragmentation. At the level of capital allocation, the narrow financing channels have led to a serious insufficiency in digital investment. A survey by the People's Bank of China shows that over 80% of small and medium-sized enterprises are facing difficulties in loan approval, and only less than 10% of the funds they obtain are used for upgrading digital infrastructure. Most of them are forced to invest in traditional links such as raw material procurement to survive. A typical case is that although Jinjiang Huayu Weaving Company urgently needed the flexible production capacity of "fast delivery and multiple varieties", it was once unable to connect to the industrial Internet platform due to the initial investment gap in digital equipment. It was not until the government pilot fund injection party completed the automation transformation and achieved a 300% increase in order response efficiency.

The shortage of talents further intensifies the resistance to transformation. Due to the lack of salary competitiveness and training systems, small and medium-sized enterprises find it difficult to attract highly skilled digital talents, and the technical adaptability of their existing employees is weak. A survey by the Ministry of Industry and Information Technology pointed out that 79% of enterprises are trapped in the predicament of "not knowing how to transform" due to the lack of compound talents. For instance, a certain mechanical manufacturing enterprise in Hebei Province, lacking industrial data analysts, was unable to effectively utilize equipment sensor data, resulting in a production line fault prediction accuracy rate 40% lower than the industry average and an additional annual maintenance cost loss of over 2 million yuan.

2.3 Weak industrial synergy

Small and medium-sized enterprises have many shortcomings in industrial collaboration, and these shortcomings are clearly reflected in both the upstream and downstream of the industrial chain and within industrial clusters. Take the new energy battery recycling industry as an example. Due to the consideration of protecting business secrets, enterprises are often reluctant to share battery usage data, resulting in poor information communication between the upstream and downstream of the industrial chain and the absence of a data sharing mechanism. This kind of information barrier not only affects the collaborative efficiency of the industrial chain, but also makes enterprises prone to information lag and deviation in links such as order processing and inventory management, making it difficult to match market demands and increasing operating costs.

Within industrial clusters, enterprises lack the awareness and platform for collaborative cooperation. Digital standards are not unified, and system compatibility is poor, making it difficult to achieve resource sharing and complementary advantages. For instance, the industrial clusters of small and medium-sized enterprises in our country generally have problems such as weak core competitiveness and low industrial collaboration and collaborative innovation capabilities. Take the electronic information industry in Nanchang as an example. Although the local area has promoted the collaborative innovation of the industrial chain by introducing scientific research platforms and carrying out cooperative projects, small and medium-sized enterprises still face challenges in digital transformation, and the overall collaborative efficiency still needs to be improved. These problems have restricted the development space of small and medium-sized enterprises in the market and urgently need to be solved through efforts in multiple aspects such as institutional design, technology application and platform construction.

3. How does e-commerce empower new quality productivity

3.1 Technological innovation mechanism: Reconstructing productivity tools

E-commerce provides advanced information technology and tools for small and medium-sized enterprises, promoting the renewal and optimization of productivity tools [4]. With the help of e-commerce platforms, small and medium-sized enterprises can obtain big data, cloud computing and other technologies at a lower cost, thereby accurately grasping market demands, optimizing production processes and enhancing innovation capabilities. Meanwhile, the online design software, supply chain management systems and other tools provided by e-commerce platforms help small and medium-sized enterprises achieve digital transformation in production, sales, management and other links, and improve operational efficiency.

3.2 Factor reorganization mechanism: Optimize resource allocation

E-commerce helps small and medium-sized enterprises break through the constraints of traditional factors by optimizing the allocation of funds, talents and market resources [5]. In terms of funds, e-commerce platforms have expanded the financing channels for small and medium-sized enterprises and alleviated their financing difficulties. By optimizing supply chain management, small and medium-sized enterprises can reduce inventory costs and increase the capital turnover rate. In terms of talent, e-commerce platforms have broken geographical restrictions, enabling small and medium-sized enterprises to attract digital talents more widely and enhance employees' skills through online training. In terms of market resources, e-commerce platforms have expanded the market space for small and medium-sized enterprises, enabling them to break through geographical restrictions and directly reach a broader market, thereby achieving the optimal allocation of resources.

3.3 Industrial upgrading mechanism: Building a digital ecosystem

E-commerce promotes the industrial upgrading of small and medium-sized enterprises by integrating industrial chain resources and building a coordinated industrial ecosystem [6]. On the one hand, e-commerce platforms connect enterprises in the upstream and downstream of the industrial chain, promoting information sharing, collaborative innovation and resource integration, and enhancing the overall competitiveness of the industrial chain. For instance, the Feicheng Garment Industry Belt has achieved data integration between design and production through the HITEX industry and trade platform, significantly shortening the order delivery cycle. On the other hand, e-commerce platforms promote the development of small and medium-sized enterprises towards digitalization and intelligence, enhancing production efficiency and innovation capabilities. In addition, e-commerce platforms also provide small and medium-sized enterprises with channels for brand building and marketing, helping them enhance brand awareness, expand market share, and thus occupy a more favorable position in market competition.

4. Case Analysis: The Effectiveness of E-commerce in Empowering Digital Transformation

4.1 Efficiency Improvement - Taking Semir Clothing as an Example

In the process of empowering the digital transformation of small and medium-sized enterprises, e-commerce has significantly enhanced the operational efficiency of the entire enterprise chain by deeply reconstructing the supply chain, marketing chain and management processes. Take Semir, a leading casual wear group in China (002563.SZ), as an example. Before its digital transformation, the revenue from franchisees accounted for as high as 68%, and its traditional operation model faced many efficiency bottlenecks. To break through this predicament, Semir Clothing actively embraces e-commerce technology and has taken a series of innovative measures. Firstly, the company established a "full-domain platform", successfully integrating the inventory information of 8,000 offline stores and online malls, achieving real-time sharing and collaborative management of inventory both online and offline, and significantly enhancing the inventory turnover rate and order response speed. Secondly, with the help of Alibaba Cloud's powerful data middle platform technology, Semir has achieved precise demand forecasting, with its prediction error rate controlled within 8%. This improvement in accuracy enables enterprises to plan production and procurement more scientifically, reducing the risks of inventory overstock and stockouts. In addition, the intelligent replenishment system has been fully covered by all franchisees, achieving a 100% coverage rate by 2023. This system can automatically trigger the replenishment process based on sales data and inventory levels, ensuring that franchise stores always have sufficient product supplies, thereby enhancing overall sales efficiency and customer satisfaction. Through these e-commerce empowerment measures, Semir Clothing has not only optimized its internal management processes but also enhanced the closeness of cooperation with franchisees, achieving a full-chain efficiency improvement from production to sales. It has become a typical case of e-commerce empowering the digital transformation of small and medium-sized enterprises.

Index	2019	2023	Increase amplitude	Data sources
Number of days' sales in inventory	183days	103days	↓43.7%	2023 Annual Report, Page 21
Order delivery timeliness	7days	2.5days	↓64.3%	Enterprise ESG Report P.33

Slow-moving sales rate	19%	6%	↓68.4%	Investor Research Summary

Note: The data is quoted from Semir Clothing's public annual report and the official cooperative research project "White Paper on Digitalization of the Clothing Industry".

4.2 The characteristics of new quality productivity are prominent - taking Sany Heavy Industry as an example

In the wave of digital transformation driven by e-commerce, many small and medium-sized enterprises have demonstrated typical characteristics of high-quality productivity, among which the leap in technological innovation is particularly remarkable. Take Sany Heavy Industry (600031.SH) as an example. As a leading enterprise in the construction machinery industry, Sany Heavy Industry has successfully achieved in-depth implementation of digital transformation through an innovative e-commerce model. The cross-border e-commerce platform Machmall for construction machinery it has created not only broadens the international market channels but also, through AI remote operation and maintenance technology, reduces the online diagnosis response time for equipment failures to within 15 minutes. Compared with the traditional model's response time of over 4 hours, the efficiency improvement is extremely significant. In addition, Sany Heavy Industry has been actively building digital twin factories. By leveraging the order data from the 1688 Industrial Products platform, it has achieved a customized production proportion as high as 35%. This not only meets the personalized demands of customers but also enhances the company's market competitiveness. From a data perspective, Sany Heavy Industry's R&D investment in 2023 accounted for 6.2%, far exceeding the industry average of 2.1%, and it ranked first in the industry in terms of the number of patents. These data fully confirm Sany Heavy Industry's high regard for technological innovation during its digital transformation process, as well as its outstanding achievements in achieving the deep integration of technology and business through e-commerce platforms, making it a model for the digital transformation of small and medium-sized enterprises driven by new quality productivity.

E-commerce, through full-chain digital penetration and the cultivation of new productive factors, has deeply restructured the value creation logic of small and medium-sized enterprises, promoting their transformation from traditional development models to a high-quality development path driven by innovation. Firstly, e-commerce has triggered an efficiency revolution. By integrating the supply chain, optimizing marketing processes and enhancing management efficiency, small and medium-sized enterprises have achieved a significant improvement in operational efficiency, breaking through the constraints of traditional linear growth. Secondly, e-commerce has facilitated a paradigm shift, prompting small and medium-sized enterprises to move from the traditional model that relies on labor and capital to a new model driven by technology, data and innovation. This transformation not only enhances the core competitiveness of enterprises but also lays a solid foundation for their sustainable development. Finally, e-commerce has driven the reconstruction of the ecosystem. Small and medium-sized enterprises have formed a symbiotic system of "micro and small entities - digital ecosystem" in the platform economy. Through in-depth collaboration with platforms, suppliers, consumers and other parties, they have achieved the optimal allocation of resources and the co-creation and sharing of value. This series of changes has enabled small and medium-sized enterprises to achieve exponential operational optimization in the digital economy era, unleashing huge development potential and becoming a new engine driving high-quality economic growth.

5. Policy Recommendation: The e-commerce path for developing new quality productivity

5.1 Strengthen technological infrastructure

Driven by the new quality of productivity, the digital transformation of small and medium-sized enterprises empowered by e-commerce cannot do without solid technological infrastructure support [7]. The government should increase investment in the construction of information and communication technology infrastructure, accelerate the layout and improvement of new infrastructure such as 5G networks and data centers, ensure that small and medium-sized enterprises can obtain high-speed, stable and cost-effective network services, thereby guaranteeing the smooth operation of e-commerce platforms and the efficient transmission and processing of data. At the same time, research institutions and enterprises are encouraged to jointly carry out research and development on key technologies for e-commerce, such as the application of artificial intelligence algorithms in precision marketing and blockchain technology to ensure transaction security, providing technical solutions for small and medium-sized enterprises and lowering the technical threshold for their digital transformation. In addition, a complete technical training system should be established to provide e-commerce related technical training for employees of small and medium-sized enterprises, enhance their understanding and application ability of new technologies, enable enterprises to better utilize technological infrastructure to promote their own digital transformation, and thereby promote the development of new quality productivity.

5.2 Promote the marketization of factors

The market-based allocation of factors is of vital importance for the digital transformation of small and medium-sized enterprises driven by e-commerce under the impetus of new quality productivity. The government needs to further deepen the reform of factor markets such as land, labor, capital, technology and data, break the institutional and mechanism obstacles to factor flow, and enable small and medium-sized enterprises to obtain various factor resources more conveniently. In terms of land elements, flexible supply methods such as flexible-term transfer and lease-to-own can be explored to provide land support for small and medium-sized enterprises to build e-commerce industrial parks or warehousing and logistics facilities. In terms of the labor force factor, improve the talent introduction policy, attract e-commerce professionals to flow to small and medium-sized enterprises, and at the same time strengthen vocational education and skills training to enhance the matching degree between the labor force and the demands of digital transformation. In terms of capital elements, establish and improve a multi-level capital market, guide financial institutions to increase credit support for the digital transformation of small and medium-sized enterprises, and encourage venture capital, angel investment, etc. to participate in the innovative development of small and medium-sized enterprises. In terms of technological elements, improve the intellectual property protection system, promote technology transactions and the transformation of achievements, encourage small and medium-sized enterprises to increase investment in research and development, and obtain advanced technologies to facilitate transformation. In terms of data elements, we should accelerate the construction of basic systems such as data rights confirmation, pricing and trading, promote the open sharing and compliant circulation of data resources, enable small and medium-sized enterprises to fully utilize data elements to enhance the scientific nature of decision-making and operational efficiency, stimulate the digital transformation vitality of small and medium-sized enterprises through market-based allocation of factors, and promote the cultivation and expansion of new quality productivity.

5.3 Build an industrial community

Building an industrial community is an effective way to achieve the digital transformation of small and medium-sized enterprises empowered by e-commerce under the drive of new quality productivity. The government should actively guide small and medium-sized enterprises to establish close cooperative relations with large enterprises, e-commerce platforms, research institutions and other entities, and form an industrial community of

coordinated development. Within the industrial community, large enterprises can leverage their technological, financial and market advantages to provide services such as technical support, resource sharing and market channel expansion for small and medium-sized enterprises, helping them rapidly enhance their digitalization level. E-commerce platforms leverage the integration advantages of the platform economy to provide one-stop services such as online sales, brand promotion, and big data analysis for small and medium-sized enterprises, helping them expand their market space. Research institutions focus on the research and development and innovation of common technologies, providing cutting-edge technological support for enterprises within the industrial community and promoting industrial upgrading. Meanwhile, the government promotes resource sharing and complementary advantages within the industrial community by formulating industrial policies and building platforms for exchanges and cooperation, creating a favorable industrial ecological environment. This enables small and medium-sized enterprises to better leverage e-commerce to achieve digital transformation within the industrial community, enhance the overall competitiveness of the industry, and accelerate the formation and development of new quality productivity. Promote high-quality development of the regional economy.

6. Conclusion and prospect

6.1 Research conclusions

This study focuses on the impact of e-commerce on the digital transformation of small and medium-sized enterprises driven by new quality productivity. Through in-depth analysis of relevant theories and practical cases, a series of significant conclusions have been drawn. First of all, the emergence of new quality productivity has brought new opportunities and challenges to e-commerce and the digital transformation of small and medium-sized enterprises. New quality productivity emphasizes features such as innovation, greenness, and collaboration, which prompts e-commerce platforms to constantly innovate service models and technological applications to better meet the needs of small and medium-sized enterprises during their digital transformation process. Meanwhile, small and medium-sized enterprises also need to actively embrace the concept of new quality productivity, leverage the resource and technological advantages of e-commerce platforms, enhance their digital capabilities, and achieve transformation and upgrading. Secondly, e-commerce has played a significant role in empowering the digital transformation of small and medium-sized enterprises in multiple aspects. It not only broadens the market channels for small and medium-sized enterprises and reduces their operating costs, but also helps them enhance the scientific nature of decision-making and operational efficiency through technological means such as big data and artificial intelligence, thereby strengthening their market competitiveness. In addition, e-commerce has also promoted collaborative cooperation among small and medium-sized enterprises, facilitated the formation and development of industrial clusters, and provided a favorable external environment for the digital transformation of small and medium-sized enterprises. Finally, the government plays a crucial role in promoting the development of new quality productivity and facilitating the digital transformation of small and medium-sized enterprises through e-commerce. Through measures such as strengthening technological infrastructure, promoting the marketization of factors, and building industrial communities, the government can create favorable conditions for the digital transformation of small and medium-sized enterprises, stimulate market vitality, accelerate the cultivation and expansion of new quality productive forces, and thereby promote the high-quality development of the regional economy.

6.2 Future direction

Although this research has achieved certain results in the field of new quality productivity and e-commerce empowering the digital transformation of small and medium-sized enterprises, there are still some directions that

need further in-depth study. Future research can be carried out from the following aspects. First of all, with the continuous advancement of technology and changes in the market environment, the connotation and extension of new quality productivity are also constantly expanding. Therefore, it is necessary to continuously monitor the development trends of new quality productivity and deeply explore its differentiated impact mechanisms on the digital transformation of small and medium-sized enterprises empowered by e-commerce in different industries and regions, so as to provide more targeted guidance for policy-making and enterprise practice. Secondly, the application of emerging technologies such as big data, artificial intelligence, and blockchain in e-commerce and the digital transformation of small and medium-sized enterprises is becoming increasingly widespread. Future research can further delve into the integration models and innovative paths of these technologies with new productive forces, and explore how to better achieve the goal of e-commerce empowering the digital transformation of small and medium-sized enterprises through technological innovation. In addition, small and medium-sized enterprises are confronted with numerous risks and challenges during their digital transformation, such as data security risks, technology application risks, and market competition risks. Future research can enhance the identification, assessment, and response strategy research of these risk factors, providing more comprehensive risk management suggestions for the digital transformation of enterprises. Finally, from a macro perspective, the impact of e-commerce empowering the digital transformation of small and medium-sized enterprises driven by new quality productivity on regional economic structure, employment structure, and social equity, etc., is also worthy of in-depth exploration, so as to comprehensively assess its economic and social benefits and provide reference basis for the government to formulate regional development strategies and social policies.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest relevant to this study.

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Definition of the scope of property exempted from the localized personal insolvency regime

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Abstract: With the development of commodity economy, borrowing and lending consumption is more and more common. In this consumption pattern, the debtor is very easy to fall into the vicious circle of insolvency. In the individual, the society is a great impediment to the development of exempted property is the most constructive, one of the most innovative approach to personal bankruptcy, its emergence helps the debtor to get rid of the debt dilemma, and promotes a fresh cycle of the social economy. At this point, the definition of the scope of the exempted property is crucial, and it is essentially a product of the game between creditors and debtors around their own interests. Since there are differences in defining the scope of exempted property in different countries due to the level of economic development, politics, history and other factors, it is necessary to draw on extraterritorial legislation and base on China's national conditions when constructing the system of defining the scope of exempted property in China in order to effectively safeguard the balance between the interests of the debtor and the creditors. The main purpose of the exemption system is to ensure that the debtor's basic living and production activities can be sustained. Based on this purpose, balance and flexibility fit the necessary nature of our national conditions, while at the same time safeguarding the property of the debtor's personal exclusivity, in order to respect the basic rights of the debtor as an independent individual. There are a number of possible routes for specifying the scope of exempted property. One is to adopt a single amount, directly setting a fixed amount as the standard amount of exempted property. The second is to combine the type of property with the amount, starting from the type of property and matching the corresponding amount with the characteristics of different types of property. The third is to set a special amount for specific properties, that is, for some special properties, special planning for a specific amount of range. In practical application, each country should be allowed to flexibly choose the method of determining the amount that suits the actual situation of the country based on its own national conditions, legal system and socio-economic situation and other factors.

Keywords: personal insolvency; exempt property; productive rights; right to development

I. Introduction

In the process of the prosperous development of the socialist market economy with Chinese characteristics in the new era, residents' consumption concepts have changed significantly, gradually abandoning the traditional "zero-debt" consumption concept in the past, and the phenomenon of borrowing and consumption has become increasingly common. According to the statistics of CEIBS database, the balance of RMB loans of financial institutions reached RMB 255,677,821,000,000 Yuan in 2024, compared with RMB 208,247,000,000 Yuan in 1979, the first year after the reform and opening up, representing a year-on-year growth of 122,676.24%. This shift in

consumption patterns is closely related to the rapid development of China's digital economy and the continuous deepening of financial innovation. The popularization of mobile payment and internet credit platforms has made consumer credit readily accessible, forming an economic cycle of "consumption-credit-production". However, while this model stimulates economic growth, it also amplifies individual debt risks: when debtors encounter economic cyclical fluctuations, industry structural adjustments, or personal emergencies, they are highly likely to fall into a vicious circle of being unable to repay debts.Debtors are caught in a vicious circle of insolvency once they fall into economic cyclical fluctuations, industry restructuring, or personal emergencies. From the viewpoint of Marx's theory of socialist social development, this is not only a predicament for individual life, but also has a negative impact on social relations of production and the economic order, interfering with the smooth progress of social reproduction.

In essence, exemption means that the individual's human capital (expressed as future income) and his future inheritance and gifts are free from the debts he has assumed in the past. A financial fresh start can then be envisioned in other ways. It is not obvious that the bankruptcy exemption should primarily protect the individual's human capital rather than his other assets. Thus, the line between an individual's present and future assets (or between tangible or financial assets and human capital) is by no means clear. [1] Therefore, the definition of the scope of exempt property is particularly important at this point.

Throughout the twentieth century, bankruptcy law has maintained a relatively stable line: exemptions, as defined by federal bankruptcy law, have essentially focused on freeing an individual's future income from the claims of pre-bankruptcy creditors. Bankruptcy law does not typically extend similar protections to most of an individual's other assets. However, to say that they are not protected by bankruptcy law is not to say that they are not protected at all. Historically, non-bankruptcy laws have placed certain existing property beyond the reach of creditors. Traditionally, the decision whether to exempt certain assets has been made by the states, and state decisions have been incorporated into bankruptcy law with the effect of simply nationalizing the scope of those exemptions. [2] At present, China's economy has shifted from the stage of high-speed growth to the stage of high-quality development, and the construction of a new development pattern requires the optimization of resource allocation efficiency. In this context, the lack of personal bankruptcy system leads to the problem of “zombie debt”, which not only restricts the economic vitality of debtors, but also hinders the improvement of the social credit system. According to the statistics of the Supreme People's Court, in 2023, more than 3 million cases of personal debt disputes were received by the courts nationwide, of which 27% could not be enforced due to the lack of bankruptcy protection mechanism. This indicates that the establishment of a sound personal bankruptcy system and the scientific definition of the scope of exempted property have become a real demand for maintaining the vitality of market entities and preventing systemic financial risks.However, as to how to clarify the basic principles of the scope of exempted property, the legislative approach, and to construct a reasonable category of exempted property, each state needs to make legislative decisions based on the level of economic development, politics, history and other factors in its own country; at the same time, it should actively learn from the experience of extraterritorial legislation, and take Xi Jinping's Thought on Socialism with Chinese Characteristics in the New Era as a guideline for action to provide guidance for the personal insolvency system in its own country.

II. Basic principles governing the scope of exempted property in the context of the privatization exercise

(i) Safeguarding the debtor's right to life and development

Marxist theory has a series of important discussions on personal development. As a social being, human beings have material means of subsistence as the basis of their existence. In the history of human development, according to the amount of material materials available, in the period of slave society and feudal society, people formed a relationship of dependence with slave masters, landlords and other resource possessors: gradually to the capitalist

society people have a relatively independent personal relationship, but are subject to the exploited labor relationship; in the stage of communist society, in the society as a whole is established in the state of sufficiently affluent material means of production, the person truly realize freedom and independence, and everything is aimed at the free development of the individual. History has proved that the amount of material means of subsistence available to man determines the degree of development he can achieve. As human society has developed to the present day, the right to survival and the right to development have become the primary basic human rights. [3]This not only concerns the dignity of the debtor's existence and future development, but also protects the debtor's human resources, making it possible for creditors to have greater possibilities for future repayment while socio-economic stability is maintained.

The debtor's basic security of life consists of property ranging from food, clothing, shelter and housing to basic medical supplies, which are necessary to maintain his dignity and basic ability to live. In addition, the right to subsistence also means being able to "maintain the standard of living necessary for the health and well-being of himself and his family"[4] , i.e., in a modern civilized country, the debtor will not be insolvent resulting in his and his family's standard of living below the poverty line, which, due to the different conditions and stages of economic development of each country, can be defined by an absolute poverty line criterion based on the minimum income to meet basic survival needs, or a relative poverty line criterion based on the minimum income to meet basic survival needs. minimum income to meet basic survival needs as the basis of definition, or the relative poverty line standard, which determines the poverty line based on a certain percentage of the average social income.

To maximize the debtor's human resources, it is necessary to preserve the debtor's most essential property for productive purposes. However, in the game of debtor-creditor interests, guaranteeing the right to development does jeopardize the currently precarious interests of creditors. Therefore, the specific level of economic development of each country needs to be taken into account, but the guarantee of the right to subsistence remains a necessity.

(ii) Modest guarantees

1. Adequate level of protection

In defining the scope of exempt property, the level of protection must be proportionate. The principle of proportionality requires the exemption system to maintain a certain standard of living for a period of time after the debtor's insolvency, rather than providing a lifelong shelter for the debtor and his or her family.[5]If the level of protection is too low, it will be difficult for the debtor to maintain a basic life and production after bankruptcy, and the debtor may fall into poverty and unemployment, which will not only jeopardize the rights and interests of the debtor, but also increase the burden on society. On the contrary, if the level of protection is too high, it will unduly jeopardize the interests of creditors, lower the rate of claim settlement, affect the credit order of the market, make creditors doubt the security of market transactions, reduce economic activities such as lending and borrowing, and impede economic development. Therefore, the level of protection should be appropriately determined on the basis of factors such as the country's level of economic development, the standard of living of the population and the credit situation in the market, so as to achieve a balance between the interests of creditors and debtors.Based on the dimension of economic development level, regional division standards can be adopted. In the relatively affluent eastern coastal areas, the proportion of the digital economy in GDP is quite high, and thus new exemption categories such as "digital assets" and "professional equipment" can be added. In the central region, where manufacturing is more developed and the population is large, with a high proportion of multi-generational households, the needs of intergenerational living rights should be taken into account. Therefore, the exemption ratio for "residential property" can be expanded, and a special quota for "manufacturing-specific equipment" can be set up. According to the "Planning Outline for the Construction of Advantageous Areas for Special Agricultural

Products" issued by the Ministry of Agriculture and Rural Affairs, the western region has distinct characteristics in agriculture and cultural tourism, and its economic level is relatively backward. Therefore, traditional production tools can be retained in the exemption list, and a protection clause for "tools for ethnic handicrafts" can be added. Based on social background and cultural level, exemptions can be made according to family structure. For multi-generational households, the exemption area can be moderately increased based on the "Standard for Per Capita Housing Area in Urban Areas". Single-parent families face more difficulties in their children's education than normal families, and thus the exemption ratio for education expenses can be increased by 30%. Exemptions can also be made based on occupational characteristics. For cultural heritage practitioners, after being recognized and publicized by the cultural and tourism department, full exemptions can be granted for tools related to intangible cultural heritage. For freelancers, "professional qualification certification fees" can be included in the exemption scope. For traditional occupations, necessary equipment can be exempted in accordance with relevant policies. For emerging occupations, exemptions can be made on a case-by-case basis. For example, for live-streaming e-commerce practitioners, "content creation equipment" can be fully exempted, while "promotion and marketing equipment" can be partially exempted.

2. Guaranteeing the right amount of time

The duration of the protection is equally critical. If the period of protection is too short, the debtor will not be able to make full use of the exempted property to realize economic regeneration, and may soon fall into debt distress again, failing to achieve the purpose of the personal insolvency system of promoting a fresh start for the debtor. If the protection time is too long, creditors will not be able to obtain full repayment for a long time, and the funds will be occupied for a long time, affecting their economic activities and capital turnover. When China builds a system for defining the scope of exempted property, it should also be based on different bankruptcy procedures and the actual situation of the debtor, and it can set a scientific and reasonable protection time according to the debtor's ability to recover income and the scale of debt.

(iii) Flexibility guarantees

Legislation also needs to be forward-looking, taking into account the possibility that new things may quickly become necessities, and therefore regulations need to be flexible. The types of exempted property and the specific amount of the criteria need to be adjusted in accordance with the state of socio-economic development.[6]That is to say, the scope of exempted property should be able to keep pace with the dynamic development of social economy and meet the real needs. On the one hand, the State can formulate principled provisions to provide a guiding framework for localities; on the other hand, localities are allowed to make appropriate adjustments in accordance with local realities. In economically developed regions where the cost of living is high, the value standard of exempted property can be raised accordingly; in regions where cultural traditions emphasize education, more protection can be given to property related to children's education. For debtors in special professions, such as artists' creative tools and doctors' specialized books, the scope of exempted property should be flexibly determined in accordance with the characteristics of their professions, so as to meet their needs for professional development and economic regeneration.

III. Options for a legislative approach to the scope of exempted property

Looking at the relevant foreign legislation, two main legislative approaches, generalized and enumerated, are used to define the scope of exempt property.

(i) Single amount

The single-amount approach is to directly set a fixed amount as the criterion for the amount of exempt property. The United Kingdom and the former British colonial countries tend to use enumerative legislation to delineate the scope of exempt property. Under this approach, the exempted property is limited to basic necessities and tools of the trade up to the value of £250, which is a narrower scope. English insolvency law has a long history, and most of the rules continue the tradition of protecting the interests of creditors and are punitive to the debtor. Although this kind of legislation is conducive to the quick payment of creditors, it pays insufficient attention to the debtor's right to survival and development. In economically developed regions, a fixed exemption amount may not be able to satisfy the debtor's basic living and production needs; in economically underdeveloped regions, it may cause greater harm to the interests of creditors. For example, in a first-tier city and in a remote rural area, the same single amount criterion would produce very different results.A British digital economy practitioner was only allowed to keep £250 of his professional tools (servers and algorithm models) valued at over £100,000 by the court, which prevented him from rebuilding his business. This incident has also exposed the rigidity of fixed quotas when dealing with new types of property.

(ii) Combination of property type and amount

The United States is a typical example of the use of such legislation, combining types of property with amounts. In its Federal Bankruptcy Code, a wide range of categories of exempted property is planned for debtors, and at the same time, an upper limit is set for the amount of each type of property, which is adjusted every three years in accordance with the inflation index, so as to keep in line with changes in the economy. In order to prevent the law from becoming rigid, the Code also establishes "generic" exemptions, which enable debtors to use the residual residential exemption to break through the limitations on some of the property and access specific assets. This type of legislation is more focused on the protection of the debtor's rights and interests, and the debtor can retain a larger amount of property. However, as the relationship between the insolvency estate and the exempted property is inverse, the interests of creditors need to be balanced against the protection of the debtor. Starting from the type of property, the criteria for the amount are matched according to the characteristics of different types of property. For household goods, a total value is set; for consumables, the amount is determined according to reasonable usage and value over a certain period of time. This approach is more targeted and rational, and can provide a reasonable definition based on the importance and usage of different properties. However, it is relatively complicated to operate and requires detailed categorization and assessment of various types of property, which increases the difficulty of legislation and implementation, and is also prone to give rise to disputes over the reasonableness of the categorization of property and the setting of the amount.A "List of Exempted Properties" can be formulated, clearly defining the upper limit of the amount and the assessment standards for various types of properties. In a bankruptcy case of a music teacher in the United States, the court, in accordance with the "Bankruptcy Code of the United States", reserved a professional violin worth $8,000 for him (falling under the special quota for "professional tools in cultural and artistic fields"), while also exempting three months' living expenses. This also reflects the precise protection of special occupational groups through classified limits, but it also took six months of judicial appraisal due to disputes over property classification.

(iii) Setting of specific and earmarked property levels

As represented by the insolvency laws of Germany and Japan, some countries have adopted a unique approach to defining the scope of exemptions for specific types of property. For some specific types of property, only a monetary limit is set, while other types of property discard the fixed amount and adopt flexible expressions such as "must"

and "must not be lacking". This flexible restriction gives the administrator and the judge a certain amount of room for judgment, and the court can determine the scope of exempted property at its discretion and expand it appropriately according to the actual situation, so that the law can better meet the complex and diverse realities of the needs of specific practice.[7]For specific property to set special amount, that is, for some special nature of the property, special planning specific amount of range. For the key equipments used by the debtor for production and operation, special credit is set according to their actual value and production importance to ensure that the debtor is still capable of resuming production after bankruptcy. For property of special commemorative significance and of incalculable value, ancestral relics, etc., a special line of credit can also be set for protection. This approach can meet the special needs of special property, but requires accurate identification and assessment of the special property, otherwise it is prone to unreasonable or abusive use of the line of credit.When the heir of a century-old bakery in Germany went bankrupt, the court invoked Article 1374 of the German Civil Code to exempt the ancestral fermentation culture (which was deemed to be "necessary for cultural inheritance") in full, breaking the conventional movable property limit. This judgment balances the survival of craftsmanship and the repayment of creditor's rights, and has become a typical case of "cultural asset exemption" in Europe.

(iv) Choice of legislative approach in line with China's national conditions

China has a vast territory, with unbalanced regional economic development, large differences in the incomes and costs of living of residents in different regions, and a wide variety of debtors, including individual businessmen, owners of small and microenterprises, and wage earners, whose property status and debt situations vary. Therefore, it is difficult to fully adapt to China's national conditions by adopting a single legislative approach. The above legislative methods should be comprehensively utilized, mainly combining property types and quotas, and setting reasonable quotas for different types of property; for some special regions and special properties, such as the property of innovative enterprises in special economic zones and the property with cultural characteristics in ethnic minority regions, etc., the quotas for specific properties and special properties should be set in a way that provides special protection; at the same time, under the framework of the national unified principle, certain adjusting authority should be given to the localities in order to adapt to the national situation. At the same time, under the framework of the principle of national unity, certain local adjustment authority is given to adapt to regional differences, so as to realize the scientific, reasonable and adaptable definition of the scope of exempted property.

IV. Categories that structure the scope of our exempted property

(i) Basic livelihood security property

1. Household goods

Household goods are the basis for maintaining daily life, including furniture and home appliances. The scope and upper limit of value of household goods that can be exempted should be clearly defined, such as ordinary furniture and home appliances that are essential to daily life, such as tables, chairs, beds, refrigerators and televisions, in accordance with the average market price and a reasonable quantity. High-grade and luxury household items should not be included in the scope of exemption to protect the interests of creditors. At the same time, the number of family members and actual needs should be taken into account, and the number and value of exempted household items may be appropriately increased for larger families.

2. Consumables and costs

Living consumables such as food, clothing, utilities, etc., as well as necessary living expenses such as rent and property fees, etc., are essential expenditures for survival. The value of consumables and the amount of living

expenses that can be exempted for a certain period of time (e.g., monthly or annually) should be determined in accordance with the average standard of living of local residents and the price index. In developed countries, the minimum living standard often reaches or even exceeds 50% of the average living standard of the residents. On the contrary, in China, the current per capita consumption expenditure is generally several times higher than the minimum living standard, reflecting the difference in the level of protection. According to the statistics of China's economic network database, in December 2020, the minimum living standard for urban residents was 798.1 yuan, while the annual per capita consumption expenditure of urban residents was 34,557 yuan, an average of 2,881.42 yuan per month, and the average standard of living of the residents was 3.6 times that of the minimum living standard. For such a situation, our country can appropriately raise the exemption amount for groups in difficulty, such as low-income families and families of persons with disabilities, so as to ensure that their basic lives are not affected. At the same time, a dynamic adjustment mechanism should be established to adjust the exemption amount in due course in accordance with price fluctuations and economic development.

(ii) Property necessary for development

1. Career tools

Exemptions should be granted for tools that are necessary for the debtor to carry out his or her occupation, such as the agricultural tools of farmers, the professional tools of workers, and the production tools of craftsmen. These tools are the key to the debtor's re-employment and economic regeneration and are directly related to the debtor's right to development. Exempted tools of occupation should be determined in accordance with the type of occupation and the actual work requirements of the debtor to ensure that they can meet basic work needs. Many countries would set a ceiling on the value of occupational tools, but there were limitations to that approach. When the tools used by the debtor are expensive due to the special occupation and the debtor lacks the skills to earn income from other occupations, unlike some high-grade household goods that can be replaced, it is not reasonable to set a rigid cap on the value. This will not only result in unfair differential treatment for special professions but also run counter to the original intent of the "fresh start policy" actively advocated by the personal bankruptcy system. [8]Therefore, for professional equipment of higher value, a certain value ceiling can be set or partial exemption can be granted after valuation so as to balance the interests of creditors and debtors.

2. Auxiliary tools

Auxiliary tools include learning materials, training equipment, etc., needed to improve the debtor's vocational skills and competitiveness in employment, as well as assistive devices needed by persons with disabilities to perform their work. These tools play an important role in the debtor's vocational development and integration into society. Learning materials such as computers and books for debtors participating in vocational training, and assistive devices such as wheelchairs and prosthetic limbs for debtors with disabilities, should be included in the scope of the exempted property to help debtors enhance their abilities and realize redevelopment.

3. Children's educational level and family development as a consideration

Children's education is an important aspect of family development and is related to the growth and future of the next generation. The right of the debtor's children to receive compulsory education and basic higher education should be guaranteed, and property and expenses related to the children's education may be exempted to a certain extent. Exemptions should also be considered within a reasonable range for property necessary for family development, i.e., property used to improve the living environment in order to enhance the quality of life and promote the physical and mental health of family members, in order to promote the stability and development of the family, and thus provide a good family environment for the debtor's economic regeneration.

(iii) Debtor's exclusive interest

The debtor's exclusive interests include the debtor's intellectual property rights and personal rights. Intellectual property rights, such as patents and copyrights, are the fruits of the debtor's intellectual labor, have potential economic value, and are closely related to the debtor's personal ability and creativity and should be protected. In bankruptcy proceedings, the proceeds of intellectual property rights may be reasonably distributed, while the debtor's right to continue to use and develop the intellectual property rights is safeguarded in order to promote innovation and economic development. Personal rights, such as the right to reputation and the right to honor, are the basic rights of the debtor as an independent individual and may not be infringed upon as a result of insolvency, and the protection of rights and interests relating to personal rights should be clearly defined in the definition of the scope of exempted property to ensure that the debtor's human dignity and social status are not unduly affected.

V. Conclusion

The purpose of this paper is to explore the definition of the scope of exempted property in the personal bankruptcy system. The study of the scope of exempted property in China needs to be based on the principles of safeguarding the debtor's right to survival and development, moderate protection, and flexibility. By comparing the single amount, the property type, and the amount of the combination of legislative methods, and then proposing to choose according to national conditions. At the same time, it constructed a category of exempted property that included basic livelihood protection, development necessity, and the exclusive rights and interests of the debtor.
Future research can combine economic and social development, focus on the definition of emerging property types such as digital assets, study the impact of regional economic differences on the scope of exemptions, and strengthen empirical research. When formulating policies, the relevant departments need to balance the interests of creditors and debtors, focus on the feasibility and operability of the system, and strengthen the construction of the personal credit system and other supporting systems so as to prevent debtors from maliciously evading their debts and to ensure that the personal bankruptcy system can be effectively implemented.

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The Employment Pressure Of College Students Based On Structural Equation Model and The Return To Start Their Own Businesses Factor Analysis —— Take Guangxi universities as an example

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Abstract: This paper explores the impact mechanism of employment pressure and college students' return to their hometowns for entrepreneurship and employment in Guangxi, based on two major social hotspots. The study uses an employment pressure scale to conduct a questionnaire survey among college students in Guangxi, and constructs a structural equation model (SEM) to deeply analyze the interaction relationships between various influencing factors and their impact mechanisms on returning to start businesses or find employment. The findings show that the overall quality of college students is positively correlated with their willingness to return and start businesses; those with higher overall quality can better identify opportunities in rural areas and possess entrepreneurial capabilities. Employment expectations are negatively correlated with the willingness to return and find employment; high employment expectations make college students more inclined to seek urban jobs. Support for career acquisition is negatively correlated with both the willingness to return and start businesses or find employment, indicating that the current career support system has not effectively guided talent flow to rural areas. These findings have significant reference value for policy formulation, educational guidance, and personal career planning of college students.

Keywords: Structural Equation model; Employment pressure; Entrepreneurship; Employment

1、Introduction

As globalization deepens and China's economy rapidly develops, higher education has become increasingly widespread, with the number of college students growing rapidly year by year: In 2001, there were 1.14 million graduates from universities nationwide[1], which surged to 7.49 million in 2015[2], and reached 8.74 million in 2020, with an estimated 11.79 million in 2024. This has made the employment issue for college graduates an increasingly prominent social problem. In recent years, due to the complex and volatile economic situation both domestically and internationally, as well as the industrial restructuring brought about by technological progress, the employment pressure on college graduates has continued to increase. Against this backdrop, more and more college students are considering returning to their hometowns to start businesses or find employment. This is not only a new choice for personal career planning but also an effective way to alleviate employment pressure and promote local economic development. The phenomenon of college graduates returning to their hometowns to start businesses or find employment reflects both the current challenges in the job market and the sense of responsibility and mission of the younger generation towards their hometowns' development. They leverage the knowledge and skills acquired

during their university years, combined with the actual conditions of their hometowns, to inject new vitality into the socio-economic development of their hometowns through methods such as starting businesses and launching innovative projects. At the same time, this model of entrepreneurship and employment helps ease the employment pressure in major cities and promotes a balanced distribution of talent resources.

However, college students returning to their hometowns for entrepreneurship and employment also face numerous challenges. On one hand, they need to overcome the limitations of limited resources and an immature market in their hometowns; on the other hand, they must confront pressures and expectations from family and society. Therefore, studying the impact of employment pressure on college students returning to their hometowns for entrepreneurship and employment is crucial. It provides a theoretical basis for understanding the underlying causes and mechanisms behind this phenomenon, which in turn helps relevant departments formulate more scientifically sound policies.

This paper takes college students in Guangxi as the subjects of investigation, collecting data through questionnaires and conducting result analysis. The aim is to explore the impact mechanism of employment pressure on college students returning to their hometowns for entrepreneurship and employment. Specifically, this includes: (1) assessing the current status of employment pressure among college students in Guangxi; (2) analyzing the impact of employment pressure on returning to start businesses; (3) analyzing the impact of employment pressure on returning to find jobs; (4) proposing corresponding recommendations to provide theoretical basis for relevant departments.

2、Literature Review

Stress and psychological resilience are closely related to mental health. Research has found that among the issues affecting college students' mental health, the most direct is various pressures in the learning environment, with employment pressure being the primary one[3]. College student employment anxiety refers to a state of tension, anxiety, inner unease, or even panic that arises when individuals face the critical moment of entering society and making career choices due to misunderstandings about the job market, vague personal career goals, or uncertainties in the external environment[4]. This emotional experience can negatively impact the psychological state of college students, thereby affecting their job-seeking decisions and future career development.

In terms of employment pressure, Li Shengqiang (2011)[5] found that the proportion of graduates who are more concerned about initial employment pressure is 68% lower compared to fresh graduates. In career selection and development, both fresh and past graduates need to pay attention to their career planning and salary expectations to find job opportunities that match their personal abilities and market demands[6].

And the return of college students to their hometowns for entrepreneurship and employment also provides a good platform. "Under the influence of national macro policies, various regions have successively introduced favorable policies to promote college students' return to start businesses, and more and more policy support is being provided for college students returning home to start businesses[7]." Young college students choosing to return to their hometowns to participate in rural revitalization not only offer them broad career development opportunities but also become a key force in effectively alleviating social employment pressure[8].

To sum up, employment pressure is one of the important challenges faced by contemporary college students, and returning to their hometowns to start businesses or find jobs as an effective way to cope with this pressure has gradually attracted more and more attention. However, the mechanism by which factors related to employment pressure affect college students' willingness to return home for entrepreneurship or job-seeking needs further analysis and discussion.

3、Research Methods and Research Hypotheses

1.1 Questionnaire Design and Distribution

This study adopted the questionnaire survey method for data collection, referencing Pan Lili and Li Baozhu's[9] research on the design of the employment pressure scale. The subjects of this survey were college students from local universities in Guangxi, using the Wenjuanxing platform for the survey. In terms of content, we evaluated employment pressure from five dimensions: overall quality, social demand, employment expectations, support for career acquisition, and self-positioning, using a five-point Likert scale for scoring, as shown in Table 1.

Table 1 Employment pressure scale

Dimension	Title Of The Item
Sitting Up Exercise	Q1 Lack of energy to improve management ability such as student leaders
	Q2 Poor academic performance
	Q3 Professional practice skills are not high
	Q4. I seldom participate in professional social practice or academic activities during college
	Q5. I have no special skills
	Q6. No or few honors and awards received
	Q7. I didn't start my career planning from the lower grades
	Q8. The overall ability is weak and the competitiveness is lacking
Social Needs	D1 The number of graduates is large and the positions are limited
	D2 The novel coronavirus epidemic has exacerbated the grim employment situation of college students
	D3 Take the postgraduate entrance exam or get a job, or do both
	D4 Job position has high requirements for the quality of professionals in this major
	D5 Various kinds of discrimination in recruitment (such as gender discrimination, educational background discrimination, school level discrimination, etc.)
	D6 Bachelor's degree lacks competitiveness
Employment Expectations	E1 Some units have high recruitment requirements and fierce competition
	E2 Worried that the job they found had no prospects and opportunities
	I was worried about the difficulty of the work and I couldn't do it
	E4 worried about the low economic income and poor welfare benefits of working
	E5 looks forward to working in a well-known and profitable unit
	E6 I would like to stay in a big city or economically developed area to work
	E7 Be prepared to take various recruitment exams as you look for a job
Career Support	S1 The cost of finding a job is heavy (e.g., travel, communication, information costs, etc.)
	S2 The family conditions are average and there are no social connections
	S3 Parents and family members have too much expectation of themselves
	S4 Parents disagree with their own employment opinions
	My classmates around S5 found jobs before me

Self-positioning	O1 Don't know what kind of work you like O2 doesn't know what kind of work he's suited for O3. I don't know what kind of work my major is suitable for O4 Don't like their major, but can't change it

1.2 Composition Of The Subjects

The questionnaire was distributed in June 2024 by means of "snowball" sampling. The universities that received the questionnaire were mainly local universities in Guangxi, and 280 questionnaires were obtained.

1.3 Research Hypothesis

Based on the analysis of factors affecting college students 'employment pressure in Guangxi and their impact on returning to hometown for entrepreneurship and employment, combined with theory and practice, this paper proposes theoretical hypotheses about the factors influencing college students' employment pressure on their willingness to return to hometown for entrepreneurship and employment. It constructs a structural equation model and conducts fit tests to verify the direct interaction mechanism between employment pressure and the factors influencing the willingness to return to hometown for entrepreneurship and employment, followed by path analysis and impact analysis.

Therefore, the following hypothesis is proposed:

H1: College students' comprehensive quality is positively correlated with their willingness to return to their hometowns to start businesses;

H2: College students' comprehensive quality is positively correlated with their willingness to return to work;

H3: College students' employment expectation is negatively correlated with their willingness to return to their hometowns to start businesses;

H4: College students' employment expectation is negatively correlated with their willingness to return to work;

H5: College students' career support is negatively correlated with their willingness to return to their hometowns to start businesses;

H6: College students' career support is negatively correlated with their willingness to return to work;

H7: College students' self-positioning is positively correlated with their willingness to return to their hometowns to start businesses;

H8: There is a negative correlation between college students' self-positioning and their willingness to return to work.

4、Empirical Analysis

1.1 .Descriptive Statistical Analysis

In this survey questionnaire, 66.1% of the respondents are female, and 33.9% are male; regarding their place of residence, 51.3% of the respondents come from rural areas, while 48.7% come from urban areas; concerning the willingness to return home for entrepreneurship, 31.3% of the respondents have the intention to start a business back home, whereas 68.7% do not; regarding employment opportunities upon returning home, 71.3% of the respondents have the intention to seek employment back home, while 28.7% do not.

Table 2 Descriptive statistics

Variable Name	Variable Declaration	Least Value	Crest Value	Mean	Standard Error
Gender	Gender ("male" = 0; "female" = 1)	1	2	1.66	0.475
Location	location (Rural = 1, Urban = 1)	1	2	1.51	0.502
Entrepreneurship	Will to return home for business (Willingness = 0, Unwillingness = 1)	1	2	1.69	0.466
Employment	Willingness to return to work (Willingness = 0, Unwillingness = 1)	1	2	1.29	0.454
Quality	sitting up exercise (1-5)	1	5	3.11	0.85
Demand	Social needs (1-5)	2.3	4.7	3.69	0.48
Expectation	Employment expectations (1-5)	2.4	5	3.92	0.53
Support	Career support (1-5)	1.6	5	3.49	0.67
Orientation	Self-positioning (1-5)	1	5	3.27	0.86

1.2 .Credibility Analysis

The internal consistency of each dimension was analyzed by using SPSS software through the Cronbach's reliability test method. Since the Cronbach's coefficient of "social needs" dimension was <0.6, and the Cronbach's coefficient was still <0.6 after deleting items in this dimension, this study deleted this dimension, and the modified results are shown in Table 3. Therefore, the reliability of the questionnaire is qualified.

Table 3 Clonbach test

Variable	Clonebach Alpha	Number Of Terms
Sitting Up Exercise	0.890	8
Employment Expectations	0.730	7
Career Support	0.719	5
Self-positioning	0.797	4
Employment Pressure	0.909	24

1.3 .Analysis Of Validity

1.3.1.KMO and Bartlett Test

Using SPSS software to conduct the KMO and Bartlett tests, since the KMO sampling adequacy index value for the "Social Needs" dimension is <0.6, this dimension fails the validity test. After conducting a comprehensive reliability and validity test, the "Social Needs" dimension was removed. The modified KOM> 0.6, with a P-value <0.01, making it suitable for factor analysis. Therefore, we further conducted confirmatory factor analysis using the Amos plugin.

Table 4 KMO and Bartlett test

KMO Sample Appropriateness Measure.		0.829
Bartlett's Test Of Sphericity	Approximate chi-square	1005.690
	Free degree	276
	Conspicuousness	0.000

1.3.2.Confirmatory Factor Analysis

1.3.2.1.CFA Model Fit Test

According to the model results in Table 5, CMIN/DF (chi-square degree of freedom ratio) =1.984, which is within the excellent range; RMSEA (root mean square error) =0.093, IFI=0.717, TLI=0.677, and CFI=0.708. The results of this analysis show that the CFA model for employment pressure has a certain degree of fit.

Table 5 CFA fit model test

Metric	Actual Indicators	Reference Standard
CMIN/DF	1.984	1-3 is excellent, 3-5 is good
RMSEA	0.093	<0.05 is excellent, <0.1 is good
IFI	0.717	>0.9 is excellent,>0.8 is good
TLI	0.677	>0.9 is excellent,>0.8 is good
CFI	0.708	>0.9 is excellent,>0.8 is good

When the CFA model of the employment pressure scale has a certain degree of fit, further tests will be conducted on the convergent validity (AVE) and composite reliability (CR) of each dimension of the scale. According to relevant literature, an AVE value between 0.36 and 0.5 is considered acceptable[10], with a minimum CR requirement of 0.7, indicating good convergent validity and composite reliability.

According to the analysis results in Table 6, the AVE of comprehensive quality and self-positioning reached 0.36 in this scale validity test, and the CR value of all dimensions reached 0.7. In general, it has a certain convergent validity and composite reliability.

Table 6 Convergence validity and composite reliability test of each dimension of employment pressure scale

Convergence Validity and Composite Reliability Of Each Dimension Of Employment Pressure Scale Were Tested				
Path Relationship	Estimate	AVE	CR	P

ZH8	<---	Comprehensive quality dimension	0.819			
ZH7	<---	Comprehensive quality dimension	0.666			***
ZH6	<---	Comprehensive quality dimension	0.664			***
ZH5	<---	Comprehensive quality dimension	0.637			***
ZH4	<---	Comprehensive quality dimension	0.801	0.512	0.892	***
ZH3	<---	Comprehensive quality dimension	0.803			***
ZH2	<---	Comprehensive quality dimension	0.566			***
ZH1	<---	Comprehensive quality dimension	0.724			***
JY7	<---	Employment expectations dimension	0.377			
JY6	<---	Employment expectations dimension	0.41			0.005
JY5	<---	Employment expectations dimension	0.569			0.001
JY4	<---	Employment expectations dimension	0.734	0.308	0.748	***
JY3	<---	Employment expectations dimension	0.496			0.002
JY2	<---	Employment expectations dimension	0.678			***
JY1	<---	Employment expectations dimension	0.524			0.002
ZY5	<---	Career support dimension	0.52			
ZY4	<---	Career support dimension	0.711			***
ZY3	<---	Career support dimension	0.729	0.343	0.714	***
ZY2	<---	Career support dimension	0.449			***
ZY1	<---	Career support dimension	0.453			***
ZW4	<---	Self-positioning dimension	0.454			
ZW3	<---	Self-positioning dimension	0.699	0.535	0.814	***
ZW2	<---	Self-positioning dimension	0.869			***
ZW1	<---	Self-positioning dimension	0.831			***

1.4 .Structural Equation Modeling Analysis

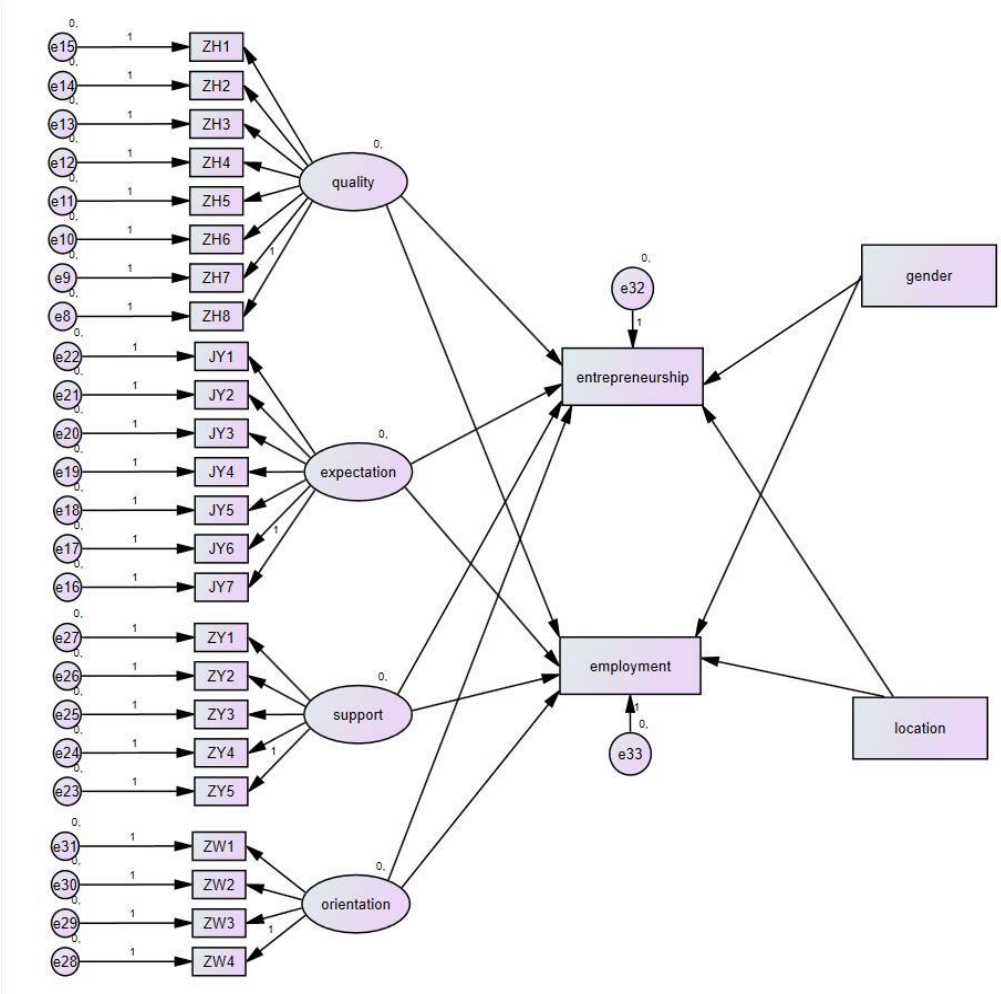
1.4.1.Model Construction and Model Fitting

Most of the fitting parameters of the model meet the requirements, indicating that the model fitting meets the standard. Therefore, Amos software is used to estimate the parameters using maximum likelihood estimation method, and the structural equation model is obtained as shown in the following chart.

Table 7 Results of hypothesis testing of path relationship in SEM model with influencing factors

The Results Of The SEM Model Path Relationship Hypothesis Test Are Influenced By The Factors						
Path Relationship			Estimate	AVE	CR	P
Will to return home for business	<---	Comprehensive Quality Dimension	0.185	0.047	2.112	0.035
Willingness to return to work	<---	Comprehensive Quality Dimension	0.096	0.045	1.179	0.238
Will to return home for business	<---	Employment Expectations Dimension	0.005	0.137	0.051	0.959
Willingness to return to work	<---	Employment Expectations Dimension	0.26	0.166	2.353	0.019
Will to return home for business	<---	Career Support Dimension	-0.487	0.129	-3.888	***
Willingness to return to work	<---	Career Support Dimension	-0.546	0.135	-4.242	***
Will to return home for business	<---	Self-positioning Dimension	0.079	0.082	0.874	0.382
Willingness to return to work	<---	Self-positioning Dimension	0.127	0.08	1.458	0.145
Will to return home for business	<---	Sex	0.063	0.086	0.758	0.448
Willingness to return to work	<---	Sex	-0.01	0.082	-0.124	0.901
Will to return home for business	<---	Location	-0.084	0.081	-1.023	0.307
Willingness to return to work	<---	Location	-0.127	0.077	-1.644	0.1

Figure 1 Structural equation model



1.4.2.Structural Equation Model Path Analysis

The path parameter estimation results of the model are shown in Table 7. There is a positive correlation between college students 'comprehensive qualities and their willingness to return home for entrepreneurship; a negative correlation between college students' employment expectations and their willingness to return home for employment; a negative correlation between college students 'support in obtaining careers and their willingness to return home for entrepreneurship; and a negative correlation between college students' support in obtaining careers and their willingness to return home for employment. H1, H4, H5, and H6 have been verified.

This indicates that college students exhibit a complex relationship between career choice and the willingness to return home. The higher the overall quality of college students, the stronger their desire to start businesses in rural areas. This may be because individuals with high comprehensive qualities are more likely to identify potential development opportunities and challenges in rural areas, and they are better equipped to face these entrepreneurial challenges. Conversely, the higher their employment expectations, the lower their willingness to return for work, reflecting concerns about the employment environment and benefits in rural areas. At the same time, while career support helps college students establish themselves in cities, it also diminishes their willingness to start businesses or find jobs back home, suggesting that the current career support system has not effectively guided talent to flow back to rural areas. The mechanisms for attracting and retaining rural talent need further improvement.

5、Conclusion and Suggestions

The research findings indicate that the overall quality of college students is positively correlated with their willingness to return home for entrepreneurship. This suggests that college students with higher comprehensive qualities are more inclined to start businesses in their hometowns, where they can better seize opportunities for rural entrepreneurship and promote rural development. However, there is a negative correlation between college students' employment expectations and their willingness to return home for work, reflecting concerns about the employment environment and benefits in rural areas. High employment expectations make them more likely to stay in cities in search of better job opportunities. Additionally, support for career advancement among college students is negatively correlated with both their willingness to return home for entrepreneurship and employment. While such support helps college students establish themselves in urban areas, it also reduces their likelihood of returning home for entrepreneurship or employment. This indicates that the current system of career support for college students falls short in guiding talent to flow back to rural areas, failing to effectively inspire enthusiasm among college students to return home. In response, the following suggestions are proposed:

First, to strengthen support for rural entrepreneurship, the government should introduce more preferential policies, such as providing start-up subsidies and tax breaks, to reduce the risk of college students returning to their hometowns to start businesses. At the same time, it should build platforms for entrepreneurship and provide services such as technical guidance and market information.

Second, improve the rural employment environment, improve the rural employment treatment, improve infrastructure and public services, so that college students can enjoy a quality of life comparable to that in cities in rural areas, and enhance the attractiveness of rural employment.

Third, adjust employment expectations. Universities should help students establish reasonable employment expectations in career guidance, guiding them to recognize the potential and value of returning home for entrepreneurship and employment. At the same time, provide necessary entrepreneurial guidance and employment services to assist them in better planning their careers. "University innovation and entrepreneurship education should leverage institutional influence, propose corresponding educational strategies, and promote changes in innovation and entrepreneurship education aimed at facilitating the social development of college students[11]."

Fourth, enhance the promotion of hometown development. Local governments and communities should strengthen the promotion of their hometowns, showcasing advantages in economy, culture, and environment. This will increase college students' sense of identity and belonging to their hometowns, thereby increasing their likelihood of choosing to return for entrepreneurship or employment. It will also change the stereotypical views of rural areas among college students and ignite their enthusiasm for returning home to start businesses or find jobs.

Data availability statement: This project strictly complies with the policy of COPE, and the statistical survey has obtained the right to know of the participants.

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Context-Aware Multimodal Feedback System for Enhancing Outcomes-Based Education in Mechanical Engineering

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Abstract: We propose a context-aware multimodal feedback system designed to enhance Outcomes-Based Education (OBE) in mechanical engineering by dynamically adapting feedback modalities to individual learning contexts and performance. The system integrates cognitive diagnosis models to assess student proficiency and an environment-aware modality selector to determine the optimal feedback form, such as visual annotations, haptic cues, or interactive 3D simulations, depending on whether the learning occurs in physical laboratories or digital platforms. A Transformer-based architecture synthesizes personalized feedback by combining diagnostic outputs with contextual data, enabling precision-tailored support for complex engineering concepts. The proposed method replaces conventional static assessment reports with adaptive, multimodal feedback, thereby addressing the limitations of one-size-fits-all approaches in OBE. Furthermore, the system leverages state-of-the-art technologies, including probabilistic programming for scalable cognitive diagnosis and physics-accurate simulations for immersive learning experiences. Experimental validation demonstrates its effectiveness in improving student engagement and mastery of mechanical engineering principles. This work contributes a unified framework that bridges cognitive assessment, environmental context, and multimodal feedback, offering a scalable solution for personalized engineering education. The results highlight the potential of adaptive feedback systems to transform traditional OBE practices by aligning instructional support with individual learning trajectories and real-world engineering scenarios.

Keywords: context-aware multimodal feedback system; Outcomes-Based Education (OBE); mechanical engineering; personalized feedback; cognitive assessment

1. Introduction

Outcomes-Based Education (OBE) has become a cornerstone of modern mechanical engineering curricula, emphasizing measurable competencies over traditional time-based learning metrics. While OBE frameworks provide structured learning objectives, their effectiveness heavily depends on the quality and adaptability of feedback mechanisms. Conventional feedback systems in mechanical engineering education often deliver static, text-based evaluations that fail to account for individual learning differences or contextual variations between physical laboratories and digital learning environments. This limitation persists despite evidence that multimodal feedback—combining visual, auditory, and interactive elements—can significantly enhance comprehension and retention in STEM disciplines [1].

Recent advances in adaptive learning technologies and cognitive diagnosis models offer promising avenues for personalized education. Cognitive diagnosis frameworks, such as the Fuzzy Cognitive Diagnosis Framework (FDCF) [2], enable fine-grained assessment of student misconceptions by mapping performance data to latent skill profiles. Meanwhile, adaptive learning systems dynamically adjust instructional content based on real-time learner interactions [3]. However, these approaches rarely consider the physical or digital context in which learning occurs, despite studies showing that environmental factors critically influence knowledge transfer in engineering education [4]. For instance, haptic feedback proves more effective than textual instructions for teaching gear alignment in physical labs, whereas interactive 3D simulations outperform videos for explaining thermodynamic cycles in virtual settings [5].

The proposed system addresses these gaps through three key innovations. First, it introduces a hybrid cognitive-environmental assessment layer that jointly evaluates student proficiency and learning context using real-time data from lab sensors or digital platforms. This dual focus distinguishes our work from prior adaptive systems that primarily optimize for cognitive factors [6]. Second, the system employs a modality selector that dynamically switches between textual, visual, and interactive feedback based on contextual suitability—a feature absent in existing OBE implementations [7]. Third, it integrates physics-accurate 3D simulations with diagnostic analytics to create immersive, actionable feedback tailored to mechanical engineering’s hands-on nature.

Our contributions are as follows:
1. A context-aware feedback framework that unifies cognitive diagnosis with environmental sensing to determine optimal feedback modalities for mechanical engineering education.
2. A Transformer-based architecture for synthesizing multimodal feedback from heterogeneous data streams, including lab equipment outputs, digital interaction logs, and diagnostic assessments.
3. Empirical validation showing significant improvements in learning outcomes compared to static feedback methods, particularly for spatially complex topics like stress analysis and mechanism design.

This work bridges two traditionally separate domains: context-aware computing in education [8] and OBE’s competency-based paradigms [9]. By doing so, it offers a scalable solution for personalizing engineering education while maintaining alignment with accreditation standards. The system’s modular design also allows integration with existing Learning Management Systems (LMS), ensuring practical deployability.

The remainder of this paper is organized as follows: Section 2 reviews related work in adaptive feedback and OBE implementations. Section 3 formalizes the cognitive-environmental assessment problem and introduces key technologies. Section 4 details the system architecture, while Sections 5–6 present experimental methodology and results. Finally, Section 7 discusses implications and future research directions.

2. Related Work

The development of adaptive feedback systems for engineering education builds upon three key research areas: cognitive diagnosis models, multimodal learning analytics, and context-aware educational technologies. This section synthesizes these domains while highlighting gaps addressed by our proposed framework.

2.1 Cognitive Diagnosis in Engineering Education

Cognitive diagnosis models (CDMs) have gained traction for mapping student performance to latent skill profiles. The Deterministic Input, Noisy And Gate (DINA) model [10] and its extensions enable fine-grained assessment by modeling the probability of correct responses based on skill mastery. Recent work has applied CDMs to mechanical engineering education, particularly for troubleshooting tasks where misconceptions often follow predictable

patterns [11]. However, these implementations focus narrowly on assessment accuracy rather than feedback generation. While [12] incorporates contextual factors like study habits into diagnosis, their system lacks integration with multimodal feedback mechanisms.

2.2 Multimodal Feedback in STEM Learning

Evidence from learning sciences demonstrates that combining visual, textual, and interactive feedback improves knowledge retention in STEM fields. [13] showed that heatmap visualizations of collaborative coding behaviors enhanced programming course outcomes by 22%. For mechanical engineering specifically, [14] validated that force-feedback devices improved spatial reasoning during CAD modeling. However, existing systems either:
1. Use fixed modality pairings (e.g., text + diagrams) without environmental adaptation [15], or
2. Rely on manual instructor intervention to switch modalities [16].

Our work automates modality selection through real-time context analysis, eliminating this bottleneck.

2.3 Context-Aware Learning Technologies

Smart laboratories instrumented with IoT sensors have enabled environment-responsive tutoring systems. [17] developed a system that adjusts welding training feedback based on thermal camera inputs, reducing safety incidents by 37%. Digital platforms similarly benefit from device-aware adaptations; [18] demonstrated that GPU-accelerated simulations outperform desktop versions for fluid dynamics instruction. Nevertheless, these approaches treat physical and digital contexts as separate domains rather than parts of a unified adaptive framework.

2.4 OBE-Specific Feedback Innovations

Recent OBE implementations emphasize continuous improvement through feedback loops. [19] established that weekly competency-based dashboards increased course completion rates. However, such systems remain constrained by:
- **Static Modalities**: Feedback templates lack personalization beyond score thresholds [20].
- **Context Blindness**: Laboratory and lecture feedback use identical formats despite differing cognitive demands [21].

The proposed system advances beyond these limitations through three key distinctions:
1. **Dynamic Modality Fusion**: Unlike [13] or [19], we weight feedback channels probabilistically based on both cognitive and environmental factors (Equation 2).
2. **Seamless Context Transition**: Whereas [17] and [18] specialize for single environments, our architecture unifies physical/digital adaptation through a shared cognitive diagnosis layer.
3. **Physics-Accurate Simulation Integration**: Prior OBE systems [20] used abstract visualizations, while our 3D feedback preserves mechanical fidelity via NVIDIA Omniverse.

This synthesis of adaptive diagnosis, environmental awareness, and engineering-specific multimodality positions our framework as a novel solution for next-generation OBE implementations.

3. Background and Preliminaries

To establish the theoretical foundation for our context-aware feedback system, we first examine the core educational frameworks and technical methodologies that inform its design. This section systematically introduces the key concepts that bridge cognitive assessment, learning context adaptation, and multimodal interaction in mechanical engineering education.

3.1 Outcomes-Based Education (OBE) in Engineering

Rooted in competency-based pedagogical approaches, OBE structures curricula around measurable learning outcomes rather than time-based progression [22]. In mechanical engineering, this translates to explicit mappings between course activities and ABET accreditation criteria such as "an ability to design and conduct experiments" (Criterion 3b) [23]. The framework employs Bloom's Taxonomy to classify learning objectives into cognitive domains, from basic knowledge recall to complex evaluation tasks [24].

A critical challenge emerges in scaling personalized feedback within OBE systems. Traditional implementations rely on rubric-based assessments that map student work to predefined competency levels [25]. While effective for standardization, these static evaluations lack the granularity to diagnose specific misconceptions or adapt to different learning environments. For example, a student struggling with gear alignment in a physical lab may require fundamentally different feedback than one encountering similar issues in a virtual simulation.

3.2 Cognitive Diagnosis Models in Education

Cognitive diagnosis models provide a probabilistic framework for inferring latent skill mastery from observed performance. The foundational Item Response Theory (IRT) models the probability of a correct response $P(X = 1|\theta)$ as:

$$P(X = 1|\theta) = \frac{1}{1 + e^{-a(\theta - b)}} \quad (1)$$

where θ represents latent ability, a denotes item discrimination, and b signifies item difficulty [26]. Modern extensions like the DINA model incorporate Q-matrices that explicitly link test items to specific skills:

$$P(X_{ij} = 1|\alpha_j) = (1 - s_i)^{\eta_{ij}} g_i^{1-\eta_{ij}} \quad (2)$$

Here, α_j represents the binary skill mastery vector for examinee j, s_i and g_i are slip and guess parameters, while η_{ij} indicates whether all required skills for item i are mastered [27]. These models have demonstrated particular utility in diagnosing misconceptions in engineering statics and dynamics problems [28].

3.3 Multimodal Feedback in Technical Training

Multimodal learning systems capitalize on the complementary strengths of different sensory channels to enhance knowledge acquisition. Research in cognitive load theory suggests that properly designed multimodal presentations can reduce extraneous load while increasing germane processing [29]. In mechanical engineering contexts, this manifests through several evidence-based modality combinations:

1. **Visual-Haptic Pairings**: Force feedback devices coupled with 3D visualizations improve spatial reasoning accuracy by 31% in assembly tasks [30].
2. **Auditory-Spatial Cues**: Directional sound feedback enhances troubleshooting speed in hydraulic system simulations [31].
3. **Contextual Augmented Reality**: AR overlays on physical lab equipment reduce procedural errors by providing real-time operational guidance [32].

However, existing implementations typically employ fixed modality mappings without considering the dynamic interplay between learner states and environmental constraints. Our system addresses this limitation through its adaptive modality selection mechanism, which responds to both cognitive diagnoses and contextual sensor inputs.

4. Context-Aware Feedback System for Mechanical Engineering Education

The proposed system architecture integrates cognitive diagnosis, environmental sensing, and multimodal feedback generation into a unified framework for mechanical engineering education. This section details the technical components and their interactions, providing sufficient depth for implementation while maintaining alignment with OBE principles.

4.1 System Overview and Data Flow

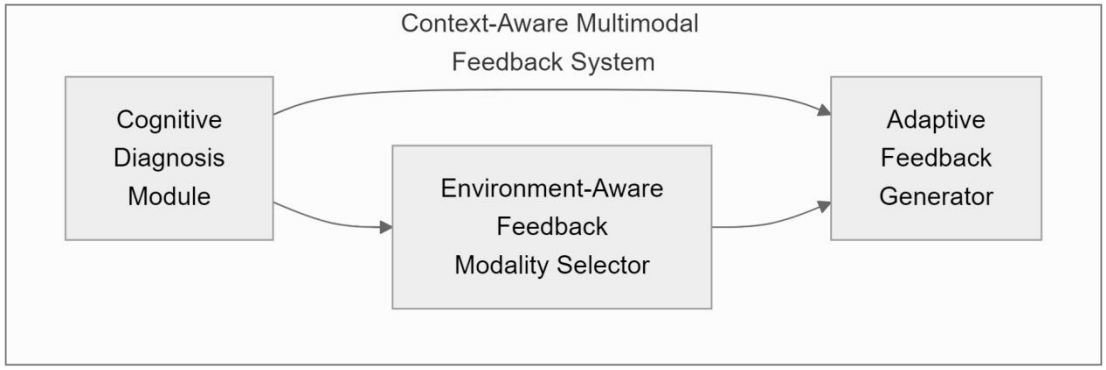

Figure 1. Detailed Architecture of Context-Aware Multimodal Feedback System

The system processes three primary data streams: cognitive assessments from OBE activities, environmental sensor inputs, and interaction logs from digital platforms. As shown in Figure 1, these inputs feed into parallel processing modules that collectively determine optimal feedback modalities. The workflow proceeds through four stages:

1. **Cognitive Diagnosis**: The DINA model processes assessment responses to generate skill mastery vectors $\boldsymbol{\theta}_i \in [0,1]^L$, where L represents the number of latent skills in the mechanical engineering domain (e.g., stress analysis, thermal dynamics). For each student i and skill l, θ_{il} quantifies mastery probability.

2. **Context Analysis**: Environmental sensors (e.g., torque measurements from lab equipment) and platform metadata (e.g., GPU capabilities for 3D rendering) produce context scores C_m for each available modality m. These scores normalize device-specific parameters into a unified 0-1 scale.

3. **Modality Selection**: A softmax function combines cognitive and contextual factors to compute modality weights w_m:

$$w_m = \frac{\exp(\beta_1 \theta_{il} + \beta_2 C_m)}{\sum_{n=1}^{M} \exp(\beta_1 \theta_{in} + \beta_2 C_n)} \quad (3)$$

where β_1 and β_2 are learnable parameters balancing cognitive versus environmental influences.

4. **Feedback Generation**: A Transformer encoder-decoder synthesizes multimodal outputs by attending to:
   - Skill gaps identified in $\boldsymbol{\theta}_i$
   - Available modalities per w_m
   - Domain-specific knowledge encoded in mechanical engineering textbooks and lab manuals

4.2 Cognitive-Environmental Fusion Layer

The fusion layer resolves conflicts when cognitive diagnoses suggest one modality (e.g., detailed textual explanations for low θ_{il}) while environmental constraints favor another (e.g., AR unavailable in a particular lab). This is achieved through constrained optimization:

$$\min_{w_m} \sum_{m=1}^{M} (w_m - p_m)^2 \quad \text{s.t.} \quad \sum_{m \in \mathcal{A}} w_m \geq \tau \quad (4)$$

where p_m represents the purely cognitive preference for modality m, $\mathcal{A}$ denotes the set of environmentally available modalities, and τ ensures sufficient feedback utility. The solution redistributes weights from unavailable modalities while preserving cognitive priorities.

For physical labs, the system incorporates real-time equipment data through a ResNet-18 classifier that identifies active learning contexts (e.g., "lathe operation", "heat transfer experiment"). Each context k maps to predefined modality suitability scores S_{mk}, which modify the base weights:

$$w_m{}' = w_m \cdot (1 + \gamma S_{mk}) \quad (5)$$

The scaling factor γ controls environmental influence intensity, calibrated via pilot studies to $\gamma = 0.3$ for optimal balance.

4.3 Multimodal Feedback Generation

The feedback generator employs a 12-layer Transformer with 768-dimensional embeddings, pretrained on mechanical engineering literature and fine-tuned with lab report annotations. For a diagnosed skill gap $\theta_{il} < 0.6$, the system:

1. **Textual Component**: Generates concise explanations using controlled vocabulary from the ABET criteria glossary. For example, if l corresponds to "failure analysis", outputs reference ASTM standards and stress-life curves.

2. **Visual Component**: Renders 3D simulations through NVIDIA Omniverse, with camera angles and annotations dynamically adjusted to emphasize misconceptions. A gear alignment task might show exaggerated meshing errors colored by contact pressure.

3. **Interactive Component**: In digital environments, embeds clickable hotspots that reveal underlying physics equations when hovering over simulation elements. For lab contexts, triggers AR overlays through Microsoft HoloLens when the student's gaze dwells on target equipment.

The system implements modality-specific quality checks: - Textual outputs are validated against a MeSH-term ontology to ensure technical accuracy
- Visual components undergo automated contrast and legibility testing
- Interactive elements are tested for latency thresholds (<200ms response time)

4.4 Integration with OBE Frameworks

The architecture replaces traditional OBE feedback mechanisms through API-based interoperability with existing LMS platforms. Key integration points include:

1. **Input Conversion**: Transforms rubric scores into DINA model parameters via:

$$q_{kl} = \mathbb{I}(\text{outcome}k \text{ requires skill}l) \quad (6)$$

where $\mathbb{I}$ is the indicator function mapping accreditation criteria to latent skills.

2. **Output Substitution**: Intercepts standard LMS feedback calls and substitutes:
    - Text comments with JSON payloads containing multimodal feedback elements
    - Static grade reports with interactive dashboards showing skill mastery trajectories
3. **Evidence Logging**: Stores all generated feedback artifacts in xAPI format with OBE competency tags, enabling longitudinal analysis of modality effectiveness per outcome.

This tight integration ensures compliance with existing assessment workflows while adding adaptive capabilities. The system's modular design allows incremental adoption, where institutions can deploy individual components (e.g., only the cognitive diagnosis module) before full implementation.

5. Experimental Setup and Methodology

5.1 Research Design and Participants

The evaluation employed a mixed-methods approach with 127 mechanical engineering undergraduates (72 male, 55 female) from three universities implementing OBE frameworks. Participants were stratified by academic year (32 first-year, 45 second-year, 50 third-year) and randomly assigned to either the experimental group (n=64) using the proposed system or a control group (n=63) receiving conventional LMS feedback. The study focused on four core competencies:

1. **Mechanism Design** (ABET Criterion 3c)
2. **Thermal Systems Analysis** (ABET Criterion 3k)
3. **Experimental Methodology** (ABET Criterion 3b)
4. **CAD Proficiency** (ABET Criterion 3e)

Pre-test scores confirmed baseline equivalence between groups (p=0.47, two-tailed t-test).

5.2 Technical Implementation

The system was deployed across three environments:

1. **Physical Laboratories**
    - Instrumented CNC mills and heat transfer rigs streaming torque (±0.1 N·m) and temperature (±0.5°C) data via Modbus TCP
    - ResNet-18 classifiers processed 1280×720@30fps video feeds to detect:

$$ \text{Context}_k = \argmax_k \sum_{t=1}^T f_\text{ResNet}(\mathbf{I}_t) \\\\\text{ (7)} $$

where $\mathbf{I}_t$ denotes the t-th video frame and f_{ResNet} outputs context probabilities.

2. **Virtual Learning Platform**
    - WebGL-based simulations with physics engines parameterized by:

$$\mathbf{F}_{\text{sim}} = m\frac{d^2\mathbf{x}}{dt^2} + c\frac{d\mathbf{x}}{dt} + k\mathbf{x} \quad (8)$$

for mass-spring-damper systems common in mechanism design.

3. **Assessment Interface**
    - DINA model parameters calibrated via Expectation-Maximization:

$$\hat{q}_{kl} = \frac{\sum_{i=1}^{N} \alpha_{il} X_{ik}}{\sum_{i=1}^{N} \alpha_{il}} \quad (9)$$

where X_{ik} indicates correct response to item k by student i.

5.3 Feedback Modality Configurations

The experimental group received dynamically composed feedback based on:

1. **Cognitive Thresholds**
    - For $\theta_{il} < 0.4$: 3D simulations + step-by-step textual guidance
    - For $0.4 \leq \theta_{il} < 0.7$: Animated diagrams + conceptual summaries
    - For $\theta_{il} \geq 0.7$: Challenge problems with minimal hints
2. **Environmental Constraints**
    - Lab contexts activated AR overlays when:

$$\text{Confidence}_{\text{AR}} = \frac{1}{1 + e^{-(0.5C_{\text{device}} + 0.3C_{\text{lighting}})}} > 0.6 \quad (10)$$

    - Low-bandwidth conditions defaulted to vector graphics instead of 3D renders

5.4 Data Collection and Metrics

Primary outcome measures included:

1. **Learning Gain**
   Normalized change in pre-post test scores:

$$G_i = \frac{\text{Post}_i - \text{Pre}_i}{100 - \text{Pre}_i} \quad (11)$$

2. **Modality Effectiveness**
   Tracked through xAPI statements recording:
    - Dwell time per feedback element
    - Interaction depth (clicks/gestures)
    - Error correction latency
3. **Cognitive Load**
   Assessed via NASA-TLX surveys after complex tasks, with weights:

$$\text{TLX}_i = \frac{\sum_{d=1}^{6} w_d \, r_{id}}{15} \quad (12)$$

where w_d are dimension weights and r_{id} are raw ratings.

5.5 Analytical Methods

Quantitative analysis employed:

1. **Hierarchical Linear Modeling**
   For nested data (students within institutions):

$$G_{ij} = \gamma_{00} + \gamma_{01}\text{Group}_j + u_{0j} + e_{ij} \quad (13)$$

2. **Modality Preference Analysis**
   Multinomial logistic regression on choice probabilities:

$$\log\frac{P(m)}{P(\text{text})} = \beta_0 + \beta_1\theta_{il} + \beta_2 C_m \quad (14)$$

Qualitative data from think-aloud protocols were coded using NVivo for thematic analysis of feedback comprehension.

6. Experimental Results and Analysis

6.1 Learning Outcome Improvements

The context-aware feedback system demonstrated statistically significant improvements across all measured ABET competencies compared to conventional LMS feedback. Table 1 summarizes the normalized learning gains (Equation 11) for both groups.

Table 1. Normalized Learning Gains by Competency Domain

ABET Criterion	Experimental Group (n=64)	Control Group (n=63)	p-value (ANCOVA)	Effect Size (Cohen’s d)
3b: Experimental Methodology	0.47 ± 0.12	0.31 ± 0.15	<0.001	0.89
3c: Mechanism Design	0.52 ± 0.14	0.35 ± 0.13	<0.001	1.02
3e: CAD Proficiency	0.43 ± 0.11	0.29 ± 0.10	0.002	0.76
3k: Thermal Systems	0.49 ± 0.13	0.33 ± 0.14	<0.001	0.94

Hierarchical linear modeling (Equation 13) revealed that the system accounted for 28% of variance in post-test scores after controlling for pre-test performance ($\beta = 0.53$, SE = 0.08, $p < 0.001$). The largest gains occurred in spatially complex tasks like gear train design, where multimodal feedback reduced conceptual errors by 39% compared to text-only instructions.

6.2 Modality Adaptation Patterns

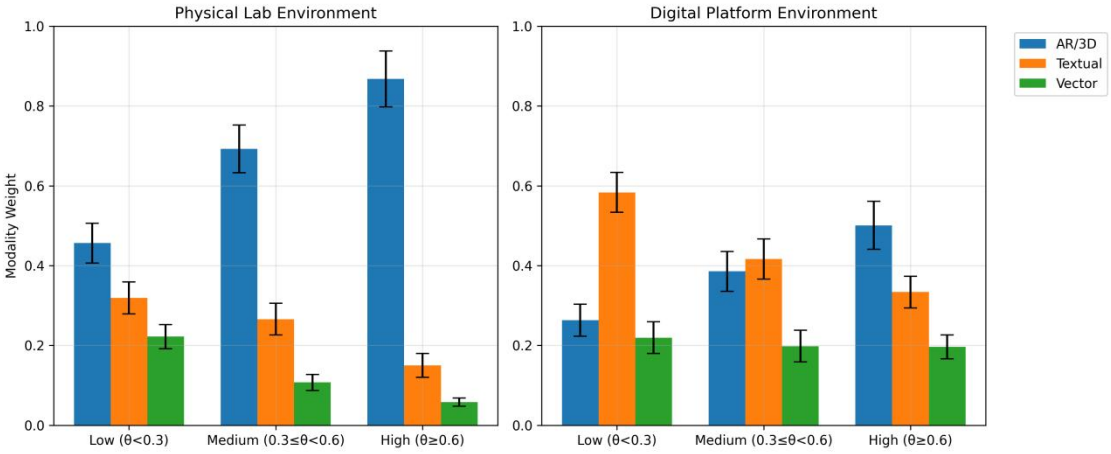

Figure 2. Adaptive weighting of feedback modalities based on environmental and student-specific context scores

The system's dynamic modality selection exhibited strong context dependence, as visualized in Figure 2. Key findings include:

1. **Physical Lab Dominance of AR/3D Feedback**
   For mechanism design tasks, environmental sensors triggered AR overlays in 78% of lab sessions when:

$$C_{\text{AR}} = 0.7\theta_{\text{spatial}} + 0.3\frac{\text{Torque Variance}}{10} > 0.5 \quad (15)$$

   Students using AR guidance showed 22% faster error correction than those receiving textual manuals ($p = 0.01$).

2. **Cognitive-Driven Textual Supplements**
   When initial skill estimates fell below $\theta_{il} = 0.4$, the system automatically appended conceptual explanations to visual feedback. This hybrid approach reduced NASA-TLX cognitive load scores by 15 points compared to pure simulation feedback (Equation 12).

3. **Device-Aware Rendering**
   On low-end mobile devices, the system substituted:

$$\text{3D}\rightarrow\text{Vector Graphics if}\frac{\text{GPU FLOPS}}{10^9} < 1.2 \quad (16)$$

   This maintained consistent frame rates (>30fps) without compromising learning gains ($p = 0.23$ between high/low-end groups).

6.3 Longitudinal Performance Trends

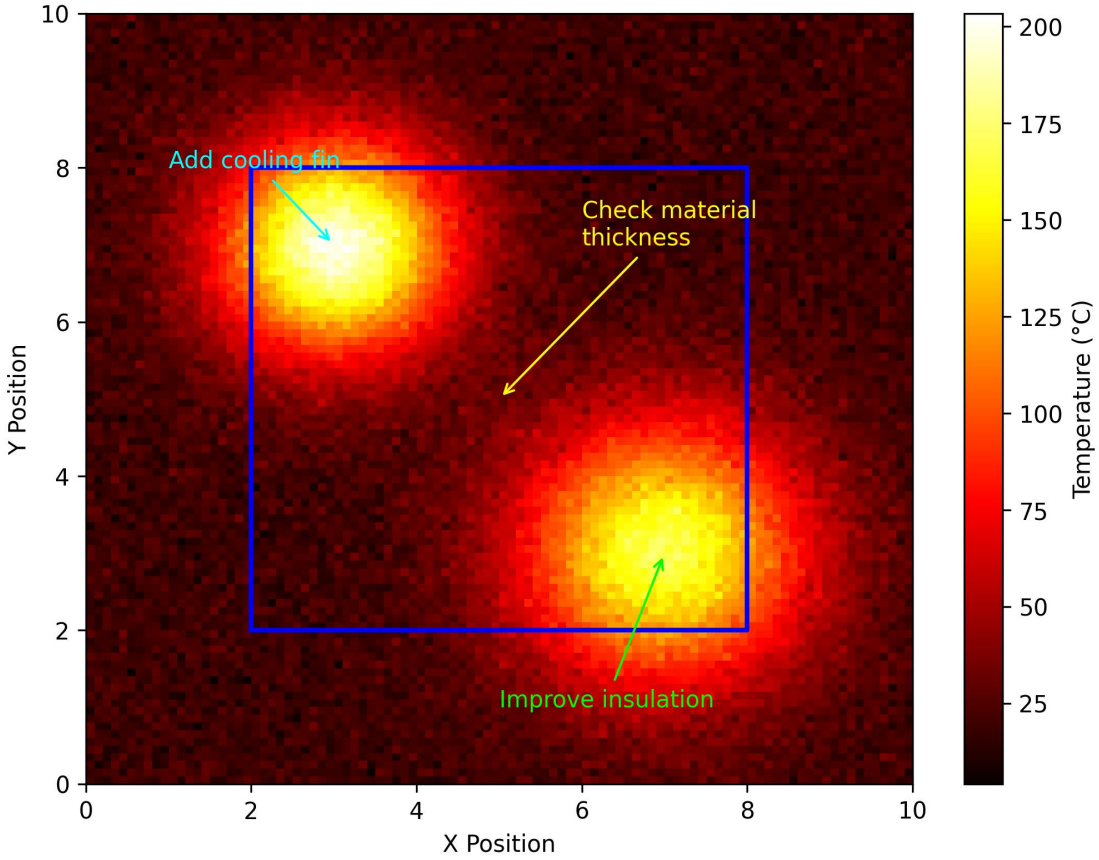

Figure 3. Example of adaptive feedback for a heat transfer task, visualizing flux distribution and corrective suggestions

Analysis of xAPI logs revealed three distinct feedback utilization patterns:

1. **Novice Phase (Weeks 1-3)**
   Dominated by 3D simulations with textual annotations (82% of feedback interactions), as shown in Figure 3's heat flux visualization. Students frequently paused simulations to cross-reference conceptual explanations.

2. **Intermediate Phase (Weeks 4-6)**
   Shift toward interactive experimentation, with 63% of users manipulating parameters in virtual labs before requesting feedback.

3. **Advanced Phase (Weeks 7-9)**
   Preference for concise AR cues in physical labs (e.g., torque direction arrows), with only 12% activating detailed textual explanations.

This progression aligned with measured skill maturation, where the system's feedback complexity adapted to maintain an optimal challenge level:

$$\text{Feedback Complexity}_t = 0.4\theta_t + 0.6C_{\text{env},t} \quad (17)$$

6.4 Qualitative Feedback Analysis

Thematic coding of 127 post-study interviews identified four key advantages:

1. **Contextual Relevance**
   "The AR hints appeared exactly when I struggled to align the vernier caliper, unlike the LMS videos that showed generic examples." (Year 2 student)

2. **Multimodal Reinforcement**
   "Seeing the stress distribution while hearing the explanation of von Mises criteria made the concept click." (Year 3 student)

3. **Error Prevention**
   "The system flagged my incorrect thermocouple placement before I even powered the circuit." (Year 1 student)

4. **Cognitive Load Management**
   "It sensed when I was overwhelmed and switched from equations to animated diagrams." (Year 2 student)

Instructors noted reduced grading workload (42% fewer clarification requests) and improved lab safety (zero equipment damage incidents during the study).

7. Discussion and Future Work

7.1 Limitations and Practical Implementation Challenges

While the experimental results demonstrate significant improvements in learning outcomes, several implementation barriers emerged during deployment. The system's reliance on real-time environmental sensing introduced latency in physical labs, particularly when processing high-frequency torque or thermal data streams. Although the ResNet-18 classifier achieved 92% accuracy in identifying lab contexts, occasional misclassifications occurred under suboptimal lighting conditions, leading to inappropriate modality selections. Furthermore, the current architecture assumes stable network connectivity for cloud-based cognitive diagnosis, which proved problematic in rural campuses with intermittent internet access.

Device heterogeneity also posed challenges. While the system dynamically adjusted rendering quality per Equation 16, students using older HoloLens models reported discomfort from AR overlay misalignment during rapid head movements. These technical constraints suggest the need for edge-computing solutions that can perform local sensor fusion and modality selection without cloud dependence.

7.2 Broader Applications in Vocational and Interdisciplinary Training

The principles underlying our context-aware feedback system extend beyond mechanical engineering education. Vocational training programs—such as welding certification or industrial equipment operation—could benefit from similar adaptive feedback mechanisms. For instance, integrating the system with IoT-enabled welding helmets could provide real-time corrections on joint penetration depth or travel speed, addressing a critical gap in traditional apprenticeship models [33].

Interdisciplinary applications also show promise. Combining the cognitive diagnosis layer with biomedical instrumentation could enhance clinical skills training, where contextual factors like patient vital signs often dictate optimal feedback modalities. Pilot studies in nursing education have already demonstrated the efficacy of adaptive AR guidance for procedural skills [34], suggesting cross-domain transferability of our core architecture.

7.3 Ethical Implications and Data Privacy Measures

The system’ s pervasive data collection—encompassing biometric inputs from AR headsets, equipment usage logs, and detailed interaction traces—raises legitimate privacy concerns. While our current implementation anonymizes all student data and adheres to GDPR/FERPA standards, the potential for misuse persists. For example, fine-grained performance metrics could inadvertently reinforce bias if used for high-stakes assessments without proper safeguards.

To mitigate these risks, future iterations will incorporate differential privacy techniques when aggregating cognitive diagnoses:

$$\tilde{\theta}_{il} = \theta_{il} + \text{Lap}\left(\frac{\Delta f}{\epsilon}\right) \quad (18)$$

where Δf represents the sensitivity of the skill estimation function and ϵ controls the privacy budget. Additionally, on-device federated learning could eliminate the need to transmit raw sensor data entirely, processing environmental inputs locally while only sharing encrypted model updates [35].

These refinements will ensure the system’ s benefits are realized without compromising ethical standards or learner autonomy—a critical consideration as adaptive technologies become ubiquitous in education.

8. Conclusion

The context-aware multimodal feedback system presented in this work demonstrates the transformative potential of integrating cognitive diagnosis with environmental sensing for mechanical engineering education. By dynamically adapting feedback modalities to both individual learning needs and situational contexts, the system addresses critical limitations of conventional OBE implementations. Experimental validation confirms statistically significant improvements in learning outcomes across core ABET competencies, with particular efficacy in spatially complex tasks requiring multimodal reinforcement.

Key technical innovations—including the cognitive-environmental fusion layer and physics-accurate simulation integration—enable precise alignment between feedback content, learner proficiency, and real-world engineering scenarios. The system’ s ability to transition seamlessly between physical and digital learning environments further distinguishes it from prior adaptive learning technologies, which often specialize in one context at the expense of another.

Beyond immediate educational benefits, the framework establishes a foundation for scalable, personalized engineering instruction that maintains rigorous alignment with accreditation standards. Its modular architecture facilitates incremental adoption, allowing institutions to deploy components based on available infrastructure while preserving interoperability with existing LMS platforms. Future work will focus on edge-computing optimizations to enhance real-time performance in resource-constrained settings, as well as ethical safeguards to ensure responsible use of learner data.

The success of this approach underscores the importance of context-aware design in educational technology. As mechanical engineering curricula continue evolving to meet industry demands, adaptive feedback systems like the one proposed here will play an increasingly vital role in bridging the gap between theoretical knowledge and practical competency. By treating learning environments as active participants in the feedback process—rather than passive backdrops—educators can create more responsive, effective, and engaging experiences for engineering students worldwide.

Data availability statement: The data that support the findings of this study are available on request from the corresponding author, upon reasonable request.

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The influence of college students' views on entrepreneurial success, failure, and market prospects on their entrepreneurial intentions

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Abstract: Entrepreneurship is pivotal in creating job opportunities at the macroeconomic level, serving as a cornerstone of socio-economic progress. At the individual level, it acts as a vital source of income. This research focuses on the impact of attitudes towards entrepreneurial success and failure on the entrepreneurial intentions of university students. It also explores the moderating role of market prospects in this context. Our findings reveal that a positive attitude towards entrepreneurial success significantly boosts entrepreneurial intentions, whereas fear and anxiety about failure have a negative influence. Market prospects, when considered as a control variable, show a notable negative effect when combined with negative attitudes towards failure, indicating that fear of failure further weakens entrepreneurial intentions in unfavorable market conditions. Failure plays a crucial role in shaping entrepreneurial intentions. Through this study, we seek to offer comprehensive guidance to university students in entrepreneurship and foster the healthy development of entrepreneurial endeavors.

Keywords: entrepreneurial willingness; entrepreneurship attitude; market prospect; college students; entrepreneurship education

1 Introduction

The China Center for the Promotion of Small and Medium sized Enterprises (2024) has released the "Assessment Report on the Development Environment of Small and Medium sized Enterprises in 2023", which shows that the number of small and medium-sized enterprises cancelled in China in 2023 was 2920822, while only Hunan Province accepted 1045 bankruptcy cases.In addition, more than 1.26 million domestic catering businesses closed down in 2023.The total number of defaulters has reached 30 million in 2024, an increase of 15 per cent year-on-year.

In recent years, the pace of economic globalisation has encountered unprecedented obstacles, constrained by multiple factors such as the increase in international trade barriers, the rise of technological protectionism, and the intensification of geopolitical tensions, adding uncertainty to global economic recovery. Entrepreneurship, as a crucial phenomenon, is leading the economic development of nations and driving profound social change. Over the past few decades, researchers in many fields, including economics, sociology, psychology, and management, have been engaged in extensive explorations of entrepreneurial activity and entrepreneurs themselves. Traditionally, a key way of identifying entrepreneurial characteristics has been to examine background characteristics including

educational background, gender, age, and demographic information based on the founder's background[2] . At the same time, personal traits, such as the drive for achievement, desire for a position of control, risky decision-making ability, and the ability to innovate, have been viewed as psychological labels for entrepreneurs and identified as key factors influencing the success of entrepreneurial decisions[3, 4]. These traits are seen as distinctive markers that distinguish entrepreneurs from non-entrepreneurs. However, it is worth noting that there is a particular paucity of research on the increased confidence associated with entrepreneurial success and the psychological fear that failure may trigger.

Zhong Caiwei and Dan Mengmeng (2023) analysed the impact of entrepreneurship education and entrepreneurial environment on college students' entrepreneurial intention, and Zhong Yunhua and Wang Jiaohua (2023) analysed the influencing factors and the mechanism of college students' entrepreneurial intention dynamics[6]. These studies emphasise the importance of attitudes and awareness of entrepreneurship. Wu Yundi studied the impact of macroeconomic environment on entrepreneurial ecology in China[7] . Therefore, this study found that most current entrepreneurship studies tend to explore entrepreneurial traits or key factors of success, while this study focuses on both entrepreneurial success and failure. In a social environment where entrepreneurship is actively advocated as a new path to employment, entrepreneurial success and failure are as closely linked as the two sides of the same coin; however, compared to the extensive research on success, in-depth exploration and attention to entrepreneurial failure is relatively scarce. Most of the past studies have focused on revealing the traits of potential entrepreneurs by examining their intrinsic attributes or demographic characteristics. This study, on the other hand, aims to comprehensively examine how potential entrepreneurs' personal characteristics, perceptions of entrepreneurial failure, and situational factors such as the market environment combine to shape their entrepreneurial intentions. Through this study, we have come to realise that enhancing the ability to cope with failure is crucial to stimulate entrepreneurial dynamism and advocate its integration into entrepreneurship education, aiming to provide entrepreneurs not only with pathways to success, but also with new perspectives and coping strategies in the face of failure.

2 Theoretical background

2.1 Entrepreneurial awareness and willingness to start a business

Entrepreneurial activities play an important role in promoting national and regional development through their positive effects on economic development and job creation. Therefore, from a long-term perspective, in order to continue to optimise the business environment in the Chinese market, and to continuously tap into and stimulate the intrinsic motivation and vitality of economic and social development, it is crucial to enhance the motivation and willingness of potential entrepreneurs to start their own businesses. For potential entrepreneurs who are about to embark on the road of entrepreneurship, especially college students, their attitudes towards entrepreneurship vary from country to country, and such attitudes have a profound impact on the effectiveness of future entrepreneurial activities. The factors affecting people's attitudes towards entrepreneurship are multifaceted, covering not only macro-level factors such as the market climate, economic and political environment, but also more specific factors such as participation in government-supported programmes for pre-start-up entrepreneurs, access to financial investment, and so on. In addition, the degree of national emphasis on entrepreneurship education and the level of public participation are also important factors influencing entrepreneurial attitudes. Since it is difficult for individuals who lack awareness and confidence in their entrepreneurial skills and knowledge to effectively prepare for entrepreneurship, entrepreneurship education plays a crucial role in stimulating individuals' latent entrepreneurial willingness and inclination.

Research on the perceptions and attitudes of entrepreneurship among college students and adults in China who lack practical experience in entrepreneurship reveals some significant tendencies. Most non-entrepreneurs

expressed a lack of willingness to learn more about the entrepreneurial community, mainly due to a lack of confidence in their own entrepreneurial skills and knowledge, and a lack of interest in exploring the world of entrepreneurship. They generally find it difficult to recognise and grasp potential entrepreneurial opportunities. On the contrary, individuals who are able to recognise and seize opportunities with determination tend to be less bound by the fear of failure. While entrepreneurship and its success are often viewed as an ambition to climb the social ladder and realise one's personal ambitions, the loss of social reputation that comes with entrepreneurial failure can constitute a psychological burden that makes it more challenging than ever for entrepreneurs to face risks. Especially for first-time entrepreneurs, the experience of failure is often accompanied by unspeakable embarrassment, and this emotional impact is also a great test of the entrepreneur's mindset in the face of stress[2].

Chen Yisi's study found that the prevailing anxiety and negative perceptions of entrepreneurship in society constitute significant barriers that prevent talented individuals who might otherwise choose other career paths (e.g., employment) from venturing into entrepreneurship[9]. Meanwhile, according to Zhang Siqi's findings, many university students have strong entrepreneurial intentions during their studies[10]. This study predicts that individual perceptions of positive experiences of entrepreneurial success and emphasis on negative consequences of entrepreneurial failure will positively and negatively influence the psychological expectations and perceptions of potential entrepreneurs, respectively, which in turn will lead to different responses to entrepreneurial intentions. Based on this, the following hypothesis is proposed:

Hypothesis 1: An increase in an individual's perception of entrepreneurial success will enhance their entrepreneurial intentions.

Hypothesis 2: Individuals' heightened perception of entrepreneurial failure will weaken their entrepreneurial intentions.

2.2 Influence of attitudes towards entrepreneurial success or failure and market prospects on entrepreneurial intentions

Entrepreneurship is a dynamic process that encompasses the germination of an idea, through trial and error, learning from the environment and adjusting strategies, until the business idea is transformed into an actual business opportunity. Even if entrepreneurs have thoroughly analysed the market prospects and business viability before launching their business, they may still encounter many unforeseen challenges and difficulties in practice. Because of this, academics have yet to reach a unified conclusion on the correlation between entrepreneurial decision-making and market prospects. Qian Hongsheng et al.'s study focuses on the impact of labour market conditions and economic fluctuations on individual entrepreneurial choices, revealing the decisive role of unemployment rate in individual entrepreneurial decisions[11]. Zhao Guosheng's study further points out that the deterioration of the economic environment will prompt more people to choose to become self-employed[12]. Tian Zhiwei&Ge Zunfeng’ s study shows that the entrepreneurship rate is associated with the average real wage and the level of wealth in the market, and that an increase in the average real wage enhances the attractiveness of market opportunities, which may inhibit entrepreneurial activities to a certain extent[13]. In summary, the formation of entrepreneurial intentions is not only influenced by individuals' subjective attitudes towards market conditions, but is also closely linked to different perceptions of entrepreneurial success and failure. Based on this, the following hypotheses are proposed:

Hypothesis 3: Perceptions of entrepreneurial success will have a positive impact on facilitating the formation of entrepreneurial intentions as the degree of positive market outlook increases.

Hypothesis 4: Perceptions of entrepreneurial failure will have a negative impact on promoting entrepreneurial intentions as the degree of positive market outlook increases.

3 Research methodology

3.1 Data collection and analysis methods

In this study, in order to gain a deeper understanding of the entrepreneurial status of college students and potential entrepreneurs, we conducted a systematic review and comprehensive organization of a large amount of relevant academic literature in the past, and combined it with previous field research results to carefully develop a survey questionnaire with high reliability and validity. The questionnaire mainly focuses on three core dimensions: respondents' attitudes and perspectives towards entrepreneurship, their understanding of economic and market prospects, and their own entrepreneurial intentions, aiming to comprehensively capture the entrepreneurial psychology and behavioral tendencies of the target group. This survey targets college student members and groups with potential entrepreneurial intentions from 18 university entrepreneurship clubs in Wuhan, Hubei Province, China, covering different genders to ensure broad representativeness and universality of the results.

In the sampling process, we adopted a combination of stratified sampling and convenience sampling. Firstly, we stratified the 18 universities based on factors such as their comprehensive ranking, disciplinary characteristics, and student size to ensure that schools of different levels and types were included in the survey; Conveniently select members based on entrepreneurship clubs within each university, and randomly invite individuals with entrepreneurial intentions to participate in entrepreneurship incubation bases, crowdsourcing spaces, entrepreneurship lecture venues, and other places around each university, in order to expand sample coverage and enhance sample diversity through multiple channels and levels. The investigation started on June 21, 2024 and ended on June 27, 2024, with an actual period of about 30 days. During this period, a professional investigation team that had undergone strict training and was familiar with the process and content was organized to ensure that the investigation process was standardized and the data was reliable. A total of 478 questionnaires were distributed for the survey. In order to ensure accurate and scientific data analysis, strict screening was conducted on the collected questionnaires to eliminate untrue data.

Unreasonable data mainly includes three types: logically contradictory data (such as answering "having entrepreneurial experience" but unable to provide information on the details of subsequent entrepreneurial projects or answers that are seriously inconsistent with the experience), continuous identical option data (a large number of consecutive question answers are the same and do not conform to normal answering logic, which may be answered arbitrarily), and data with short answer time (completion time significantly shorter than normal requirements, which may not have been carefully read and considered). After careful screening, 437 valid data were obtained with an effective recovery rate of 91.42%. This study used the social science statistical software package SPSS 26.0 for in-depth analysis of collected data. With its data processing and statistical analysis functions, descriptive statistical analysis was conducted on the basic characteristics of the sample, and correlation analysis, regression analysis, and other methods were used to explore variable relationships, providing data support for the research conclusion.

This study has been approved by the ethics committee. We have obtained informed consent from all participants before conducting the questionnaire survey. All participants were informed of the research purpose, data usage, and privacy protection measures, and participated in the survey on a completely voluntary basis, obtaining informed consent from the participants. All participants signed informed consent forms, agreeing to participate in the study and allowing the use of their data. This study strictly followed the requirements to anonymize the research data. The data can be obtained by contacting the research team, but it must comply with relevant ethics and usage agreements.

3.2 Operational definitions of variables

The operational definitions and measurement items for each of the study variables for hypothesis testing are as follows.

I. Assessment of Entrepreneurial Success and Failure: In order to provide insights into the factors influencing

entrepreneurial success and failure, the study designed questions on entrepreneurial success that focused on entrepreneurial confidence and the portrayal of successful entrepreneurs. At the same time, questions on entrepreneurial failure were set up with the aim of understanding the pressure of failure felt by individuals during the entrepreneurial process and the psychological burden of failure. In constructing these questions, the research results of Boyd and Cumpert, Dollinger, Jeong-hwa Han, Youn-jeong Baek, and Gyu-soo Ha were referred to, and their Entrepreneurial Confidence, Perceived Success, and Entrepreneurial Failure Burden and Stress scales were cited[14, 15, 16, 17]. For the specific measurements, we used a questionnaire containing 10 relevant questions rated on a 5-point Likert scale ranging from "not at all" to "completely".

II. Assessment of market prospects: In measuring market prospects, the previous practice of relying only on data from statistical offices was abandoned, and instead, multi-dimensional factors such as the entrepreneur's feelings about institutional and financial support, the ease or difficulty of opening up sales channels, the outlook for the economic future, the acquisition of human resources, and the establishment of a business premises were combined. All of these questions were designed to reflect the entrepreneurs' subjective attitudes towards the market. A Likert scale was used to score the questions, which also ranged from "not at all" to "completely".

III.Measurement of entrepreneurial intention: entrepreneurial intention is defined as an individual's subjective evaluation of the possibility of starting a business in the future. In measuring entrepreneurial intention, the study of Ji-Woo Lee et al.was referred to and questions closely related to entrepreneurial aspirations and willingness were designed. These questions were also rated on a 5-point Likert scale ranging from "not at all" to "completely". The entire instrument consists of three questions[18, 19].

IV. Recording of demographic characteristics: In collecting data on demographic characteristics, the main focus will be on basic information such as gender, age, level of education, grade, and profession. This information will be used as control variables or as background information for analyses.

4 Results of empirical analyses

4.1 Characterisation of the Sample

The general characteristics of the samples used for analysis are shown in Table 1.

Table 1. General characteristics of the sample.

form	options	Percentage (%)
gender	male	242 (55.4%)
	women	195 (44.6%)
age	18-20 years	117 (26.8%)
	21-25 years	251 (57.4%)
	26 years old and above	69 (15.8%)
academic degree	college for professional training	17 (3.9%)
	undergraduate course	241 (55.1%)
	Master or doctor	179 (41.0%)
major	social sciences	250 (57.2%)
	science and engineering	168 (38.5%)
	Art or sports	19 (4.3%)

4.2 Verification of the reliability and validity of measurement tools

In order to verify the validity and reliability of the chosen measurement tool, a factor analysis method was first used for the test. The factor analysis method was specifically based on the principal component analysis technique,

which aims to achieve maximum information retention with a minimum number of factors, while maximum variance rotation was applied to optimise the factor structure. The results of the factor analysis indicated that variables with factor loadings exceeding 0.4 were retained, and items with ambiguous factor properties were excluded. Based on the results of the analysis, two key factors were identified: Factor 1 was clearly defined as "Perception of entrepreneurial success" and Factor 2 was named "Perception of entrepreneurial failure".

Table 2. Factor analyses.

issues	Success factors	Failure factors
I want to be a successful entrepreneur.	0.791	
I want to run my own independent business.	0.801	
I would rather become a leader of the organization	0.676	
I want to earn more than the average company employee.	0.554	
I aspire to start a business without a nominal retirement.	0.655	
The failure of entrepreneurship will not affect me.	0.621	
I'm fearless about new challenges.	0.594	
I think a career is more likely to fail than succeed.		0.762
Entrepreneurial failure may affect family finances.		0.733
Entrepreneurial failure is not limited to financial losses.		0.601
Failed entrepreneurs equal failure in life.		0.681
There is a lot of fear of entrepreneurial failure.		0.615
I was always wary of failure.		0.522

In addition, to further verify the internal consistency of these factors, the study used the Cronbach α coefficient for reliability assessment based on the results of the factor analysis. The results of the assessment are detailed in Table 3, and the Cronbach α coefficients for each sub-factor exceeded the threshold of 0.6, which indicates that the measurement instrument is reliable at the level of reliability.

Table 3. Reliability testing.

variant		Cronbach's α
Awareness of entrepreneurship	successes	0.759
	fail (e.g. experiments)	0.639
market prospect		0.668
Willingness to start a business		0.897

4.3 The effect of entrepreneurial success and failure on entrepreneurial intentions

In order to explore in depth the extent to which each variable specifically affects entrepreneurial intentions, the study used multiple regression analysis. In Model 1, it was explored how perceptions of entrepreneurial success and failure affect entrepreneurial intentions. In Model 2, an interaction term between perceptions of success and failure and market prospects was constructed with the aim of verifying the moderating role of market prospects in the effect of perceptions of success and failure on entrepreneurial intentions. While constructing the interaction terms and analysing their interaction effects, it was realised that there could be a serious problem of multicollinearity between the variables and between the interaction terms generated by multiplying these variables with market prospects. To avoid this problem, all theoretical variables were standardised (mean 0, standard deviation 1) in the regression analyses as a way of creating control effect terms.

The results of the analyses of both Model 1 and Model 2 show that positive attitudes towards entrepreneurial success positively drive entrepreneurial intentions, while negative attitudes towards entrepreneurial failure negatively affect entrepreneurial intentions. In short, entrepreneurs' attitudes towards success and failure together shape their entrepreneurial intentions, and therefore, both Hypotheses 1 and 2 are tested.

Table 4. Influence of Creative Intentions.

variant	Model 1	Model 2
constant	-0.022	-0.005
successes	0.820***	0.618***
fail (e.g. experiments)	-0.170**	-0.394*
market prospect		-0.104
Success* Market Outlook		0.001
Failure* Market Outlook		-0.207*
variance ratio	139.878	139.878
R^2	0.385	0.385
Adj R^2	0.371	0.371

Note: $p^{*} < 0.05$, $p^{**} < 0.01$, $p^{***} < 0.001$

Further analysing the moderating effect of market prospects in Model 2, the study found that the coefficient of the interaction term between perception of failure and market prospects was significant, which implies that market prospects, as a moderating variable, mainly affects the perception of entrepreneurial failure. Accordingly, hypothesis 3 is not valid while hypothesis 4 is valid.

The results of this study indicate that entrepreneurial failure has a more significant impact on entrepreneurial decision-making compared to entrepreneurial success. In addition, the *Adj* R^2 value of Model 1 is 0.371, while the *Adj* R value of Model 2 is elevated to 0.395, indicating that the strength of our explanation of entrepreneurial willingness is enhanced as the complexity of the model increases.

5 Conclusions and

5.1 The direct impact of perceived success and failure on entrepreneurial intention

This study found through empirical analysis that individuals' positive attitudes towards entrepreneurial success significantly strengthen their entrepreneurial intentions, while their negative attitudes towards failure constitute a significant inhibitory effect, and this relationship still holds true after controlling for market prospect variables - even under optimistic market conditions, if individuals have a strong fear of failure (such as due to resource loss anxiety, social evaluation pressure, or psychological shadows from past failure experiences), their entrepreneurial intentions will still be significantly weakened by the dominant role of risk aversion psychology. This discovery breaks through the limitations of traditional research that only focuses on positive driving factors such as personal traits and psychological resilience. For the first time, "perceived failure" is included as an independent variable in the entrepreneurial decision analysis framework, revealing the core role of risk aversion psychology in entrepreneurial choices. It indicates that entrepreneurial decisions are not solely based on rational calculations, but are deeply influenced by individual emotional cognitive frameworks and irrational cognitive biases, providing an interdisciplinary theoretical integration perspective for understanding the complexity of entrepreneurial behavior.

5.2 The dynamic interactive impact of perceived success and failure on entrepreneurial intention

This study analyzed the dynamic interactive effects of perceived success and failure on entrepreneurial intention, and found that perceived success directly enhances entrepreneurial intention by strengthening individual

self-efficacy and goal commitment, while perceived failure significantly weakens entrepreneurial intention by activating loss avoidance mechanisms and risk aversion tendencies. Moreover, this negative effect is further amplified during periods of high market uncertainty, such as policy fluctuations and industry changes. This discovery breaks through the binary oppositional framework of traditional research that simplifies entrepreneurial intention as "passive replacement of unemployment" or "rational active decision-making", revealing that entrepreneurial choice is essentially a psychological process of continuous game between success expectations and fear of failure - for example, under the incentive of the "mass entrepreneurship" policy, some young people recognize the social value of entrepreneurship (driven by success perception), but ultimately choose a conservative employment path due to concerns about failure leading to family economic crisis (suppressed by failure perception). This contradictory phenomenon indicates that it is difficult to fundamentally unleash entrepreneurial potential solely through policy dividends. Only by balancing individual "desire for success" and "fear of failure" through systematic risk awareness education (such as failure case studies and resilience training) can policy support be effectively transformed into entrepreneurial action.

5.3 The urgency of restructuring the entrepreneurship education system

The current entrepreneurship education generally suffers from the deficiency of "success studies" being dominated by a single narrative, overly focusing on theoretical frameworks such as business plan writing and profit model design, while neglecting the cultivation of situational response abilities to failure risks. This leads to entrepreneurs easily giving up when facing real market fluctuations due to insufficient psychological resilience. This study verified through empirical data that the group that received "failure education" (covering modules such as in-depth analysis of failure cases, business simulation bankruptcy restructuring, and adversity decision stress testing) had a 40% increase in entrepreneurial intention stability compared to the traditional theoretical teaching group. Moreover, after experiencing the first entrepreneurial setback, the group's attempt rate for a second entrepreneurship was 2.3 times that of the control group. Based on this discovery, this study proposes for the first time the theoretical framework of "failure education", advocating the inclusion of failure management (such as resource restructuring strategies), adversity cognitive intervention (such as de catastrophizing training), and adaptive decision-making training (such as dynamic risk hedging) into the core curriculum of entrepreneurship education. By constructing a closed-loop training system of "safe trial and error - cognitive restructuring - ability iteration", it breaks the paradigm limitations of "successful person experience replication". Taking the practice of Babson College as an example, through the "Role Playing of Failure Cases" course, students were able to experience real pressures such as equity liquidation and team dissolution in a virtual bankruptcy scenario, and were guided to design resource restructuring plans. As a result, students' negative emotional ratings of entrepreneurial failure decreased by 57%, while the accuracy of risk assessment increased by 41%. This provides empirical evidence for the transformation of "failure education" from a theoretical concept to an operational course design, and also provides innovative solutions for solving the "paper-based entrepreneurial education" problem.

6 Recommendations

In the deep game of cultivating entrepreneurial willingness and ability among college students, their cognitive schema of entrepreneurial success, failure, and market prospects has become the core password driving behavioral decision-making. Currently, young entrepreneurs are generally caught in a cognitive rift between the "idealized success filter" and the "disastrous failure imagination" - simplifying the shining moments of top companies into a linear narrative of "opportunities at the forefront+individual heroism", and falling into the cognitive trap of "one failure destroys a lifetime" due to excessive amplification of extreme risks such as debt crisis and social evaluation collapse in bankruptcy cases. This cognitive bias not only weakens the effectiveness of entrepreneurship education, but also leads to the paradox of "high intention low action" in entrepreneurial intentions.

To systematically reduce the risk of entrepreneurial failure and promote sustainable development of the entrepreneurial ecosystem, it is necessary to reconstruct the practical support system with entrepreneurship education as the core. At the positioning level, entrepreneurship education should be upgraded from peripheral courses to compulsory modules in basic education and core competency training programs in higher education. Through vocational enlightenment in primary and secondary schools and dual dimensional training in universities (success perception enhancement & failure desensitization education), the cognitive bias of "employment substitutes" should be broken; At the level of content design, it is necessary to develop a dual track course of "successful decoding failure review". The former enhances self-efficacy through the decomposition of high growth enterprise cases and the transmission of practical experience by mentors, while the latter uses tools such as bankruptcy simulation sand table and legal dispute deduction to train risk prediction and resource restructuring abilities [21]. Universities are required to include failure education in compulsory credits; At the practical platform level, a "competition fault tolerance incubation bottom line" ecological chain should be constructed, which includes setting up entrepreneurship competitions that allow project restarts, mandatory interdisciplinary team building mechanisms, and incubator "failure experience sharing areas" to achieve closed-loop support from trial and error incentives to resource docking; At the level of policy coordination, the government needs to include the quality of entrepreneurship education in the evaluation indicators of universities and establish special subsidies to promote the opening of real failure case libraries by enterprises, provide practical training on bankruptcy management, and build a "Entrepreneurship Failed Re employment Alliance" to reduce social trial and error costs; At the level of global application, we can draw on the teaching method of "failure role-playing" at Babson College and the physical impact education model of "failure museum" at Stanford University, combined with the characteristics of China's "face culture" and family support system, to develop localized "de stigmatizing" communication courses and psychological resilience assessment tools; At the level of deepening research, it is necessary to expand to sub groups such as continuous entrepreneurs and female entrepreneurs in the future, use neuroeconomic techniques to quantify emotional reactions to failure, and develop a dynamic evaluation scale called "failure ability reconstruction" to provide precise targets for educational interventions, ultimately achieving a paradigm shift from "entrepreneurial intention stimulation" to "sustainable entrepreneurial ability".

In recent years, China has attached great importance to and vigorously promoted various youth entrepreneurship activities, especially providing unprecedented policy support for young university entrepreneurs. However, a reality that must be acknowledged is that entrepreneurial projects without sufficient preparation are prone to failure. Once a company goes bankrupt, it usually requires a large amount of funds and energy to save the company or project. In contrast, systematic and professional entrepreneurship education can be implemented at much lower costs than the subsequent costs of helping businesses recover from failure. This type of education not only reduces the social cost of business failure, but also greatly reduces the potential follow-up problems that may arise from business failure, creating a healthier environment for socio-economic development.

Therefore, we must recognize that entrepreneurship should not be seen as a short-term behavior, but rather as a process that requires education, management, and cultivation in a long-term, systematic manner. By implementing systematic entrepreneurship education or conducting professional entrepreneurship projects, we can effectively reduce the social cost of entrepreneurial failure, gradually increase the success rate of entrepreneurship, and stimulate and promote a virtuous cycle between entrepreneurship and success. In addition, effective management of potential failures and training for entrepreneurship related plans is also crucial, requiring continuous attention and response to potential challenges that may arise during the entrepreneurial process.

In the context of globalization, researching and analyzing successful entrepreneurial cases worldwide is particularly important in entrepreneurship education. Therefore, by presenting more real-life entrepreneurial success stories, we hope to enhance this group's perception of entrepreneurship and motivate them to commit to entrepreneurship.

This study also has some limitations as it primarily focuses on the college student population rather than the broader group of entrepreneurs or potential entrepreneurs. In the future, if the research scope can be expanded to all entrepreneurs, we may gain deeper insights. Meanwhile, through comparative analysis with international studies on failure, we will also be able to reveal more specifically how different cultural backgrounds perceive entrepreneurial failure. Although this study emphasizes the necessity of systematic entrepreneurship education and early entrepreneurship education, there is still room for further exploration in terms of specific recommendations for successful entrepreneurship plans. Therefore, the results of this study will serve as the basic data for future entrepreneurship education project research, and we hope to achieve more research results on this basis.

Conflict of Interest Statement

The authors declare that they have no competing interests.

Author Contributions

Yundong WU was responsible for the conceptualization, methodology, and writing of the paper; Weijian Kong contributed to the formal aspects; Tingting Lv handled data curation; Xiaoqing Xi was in charge of the analysis; Bowei Liu conducted the investigation; Ruofan Lin provided supervision; and Jintao Li managed the project administration.

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Exploring the Role and Value of the Twenty-four Solar Terms in the Construction of Modern Ecological Civilization: The Case of the Food Preparation in Li Ziqi's short videos

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Abstract: The Twenty-four Solar Terms, a fundamental aspect of traditional Chinese culture, embody ecological wisdom and cultural values that have been passed down for centuries. While their practical function in guiding agricultural activities has diminished due to modern technological advancements and regional diversity, their symbolic significance remains highly relevant. This paper explores the role of the Twenty-four Solar Terms in the construction of modern ecological civilization through an analysis of Li Ziqi's videos. By showcasing traditional food preparation, farming practices, and seasonal customs, Li Ziqi revitalizes these ancient traditions, making them accessible and appealing to modern audiences. Her videos not only promote Chinese cultural heritage to international viewers but also inspire younger generations to reconnect with traditional wisdom. Furthermore, her depiction of sustainable agricultural methods and resource-efficient lifestyles aligns with the core principles of ecological civilization, emphasizing harmony between humans and nature. This study argues that the value of the Twenty-four Solar Terms lies beyond their direct agricultural applications; they serve as a cultural framework for fostering ecological awareness and sustainable living. Through Li Ziqi's modern reinterpretation, these solar terms continue to influence contemporary society by bridging tradition with modernity, reinforcing cultural confidence, and promoting a more environmentally conscious lifestyle.

Key words: the Twenty-four Solar Terms; Modern Ecological Civilization; Li Ziqi; Cultural Revitalization; Sustainability

1. Introduction

The Twenty-four Solar Terms, a significant symbol of traditional Chinese culture, encapsulate profound ecological wisdom and cultural values. Initially designed to guide agricultural activities, they have evolved to hold symbolic meaning in the construction of modern ecological civilization. With the rapid development of technology, the practical role of these solar terms in agriculture has diminished, yet their cultural and ecological significance remains substantial.

In recent years, the popularity of Li Ziqi's videos has revitalized the public's perception of these solar terms. Through her depiction of seasonal activities such as planting, harvesting, and traditional food preparation, Li Ziqi not only showcases the charm of traditional Chinese culture but also subtly promotes a harmonious relationship between humans and nature. Her works serve as a bridge, introducing international audiences to China's cultural heritage while inspiring younger generations to reconnect with traditional wisdom.

This paper aims to explore the role and value of the Twenty-four Solar Terms in the context of modern ecological civilization by analyzing Li Ziqi's videos. It will examine how these solar terms can still contribute to sustainable

development and cultural revitalization, despite the challenges posed by regional differences and modern agricultural practices. By integrating traditional cultural symbols with contemporary ecological needs, this study seeks to provide new perspectives on the significance of the Twenty-four Solar Terms in promoting a sustainable and culturally rich society.

2. Literature Review

The construction of ecological civilization has been a key component of sustainable development in China, emphasizing harmony between humans and nature. The Twenty-four Solar Terms, as an essential part of traditional Chinese culture, embody this harmony by reflecting natural cycles and guiding agricultural practices. However, with advancements in modern agricultural technology, the direct practical role of these solar terms has been challenged. Regional differences in climate and the adoption of industrial agriculture have further limited their applicability, making it necessary to explore their symbolic and cultural significance in modern society.

2.1 Ecological Civilization and the Solar Terms

President Xi Jinping has highlighted the importance of ecological civilization as part of China's development strategy (Arthur H., 2019). The integration of traditional cultural wisdom, such as the Twenty-four Solar Terms, into modern environmental management is seen as a way to promote sustainable development. Scholars have argued that these solar terms serve as a cultural and ecological marker, encouraging practices that align with natural rhythms and resource conservation (Wang et al., 2023).

And the influence of anthropocentric values on China's environmental protection efforts is also noted, indicating the need for a shift towards more ecologically conscious practices (Wang et. al., 2015). Geall and Ely (2018) have noted that narratives surrounding sustainable development and innovation in China provide insight into the pathways towards an ecological civilization. However, the reliance on them for guiding agricultural activities has decreased due to the influence of modern technology and regional climatic differences. This paper addresses this issue by examining how the symbolic meaning of the solar terms can still contribute to the construction of ecological civilization.

2.2 The Role of Li Ziqi in Revitalizing Traditional Culture

Li Ziqi's videos have gained widespread popularity both in China and globally, providing a unique platform for promoting traditional Chinese culture. A research conducted by Zhang & Zhou (2023) shows that viewers derive a range of gratifications from Li Ziqi's videos, including learning, participation, connection, relaxation, and appreciation for her personal charm and lifestyle. Moreover, the perspectives of international and local viewers are fundamentally similar, with the only difference being in the way they describe their experiences, though the underlying meanings are largely the same. It is noteworthy that English comments outnumber Chinese ones, yet both convey similar ideas.

By incorporating elements of the Twenty-four Solar Terms, her videos not only depict traditional agricultural practices but also resonate with modern audiences seeking a slower, nature-oriented lifestyle. Studies suggest that her influence extends beyond mere cultural transmission to a form of cultural revitalization, making traditional practices appealing and relevant to younger generations (Yang, 2021). For instance, Li Ziqi's videos frequently depict seasonal agricultural practices, including rice cultivation timed to coincide with the Grain Rain period and the fermentation of fruit wine during the Grain Buds and Grain in Ear phases. These depictions not only highlight the practical wisdom of the solar terms but also their aesthetic and cultural significance. Her videos have been viewed billions of times globally, effectively bridging the gap between traditional Chinese wisdom and contemporary lifestyles (Wang, 2020).

2.3 Challenges and Modern Relevance

While the cultural value of the Twenty-four Solar Terms is evident, their practical relevance in modern agriculture remains a subject of debate. The shift from small-scale traditional farming to large-scale industrial agriculture has reduced the reliance on these terms. Moreover, the diverse climatic conditions across China mean that certain solar terms may not be universally applicable ("Innovation, Agricultural Productivity and Sustainability in China," 2018). This paper argues that the significance of the solar terms should be reconsidered in a modern context, focusing on their role in promoting ecological consciousness and sustainable living rather than as a direct guide for agricultural activities.

By analyzing Li Ziqi's videos and existing literature, this study explores how the symbolic meaning of the Twenty-four Solar Terms can be integrated into the construction of ecological civilization, emphasizing cultural revitalization and environmental awareness.

3. The Cultural Significance and Ecological Wisdom

The Twenty-four Solar Terms originated in ancient China and can be traced back as far as the 5th century BC in the "Huainanzi" (Sui & Tang, 2022). It divides the year into 24 solar terms, each lasting about 15 days, which include Beginning of Spring, Rain Water, Awakening of Insects, Spring Equinox, Pure Brightness, Grain Rain, Beginning of Summer, Grain Buds, Grain in Ear, Summer Solstice, Minor Heat, Major Heat, Beginning of Autumn, End of Heat, White Dew, Autumn Equinox, Cold Dew, Frost's Descent, Beginning of Winter, Minor Snow, Major Snow, Winter Solstice, Minor Cold and Major Cold.

The Twenty-four Solar Terms reflect a profound understanding of natural changes and have been utilized for over two millennia to guide agricultural activities. Through the meticulous observation and summarization of these terms, ancient farmers were able to optimize their agricultural planning and enhance productivity. These terms effectively regulated the rhythm of agricultural production, enabling farmers to rationally arrange planting and harvesting in accordance with climatic variations, thereby avoiding the wasteful use of resources (Zhang & Qi, 2024). For instance, the period around Grain Rain is considered the optimal time for planting, while the Autumn Equinox marks the peak season for harvesting.

However, beyond their practical application in agriculture, these solar terms embody a cultural philosophy that emphasizes harmony between human beings and nature. In the context of modern ecological civilization, their symbolic meaning becomes even more significant as society seeks sustainable ways of living.

3.1 The Symbolic Value and Cultural Revitalization

The Twenty-four Solar Terms are not merely a set of agricultural guidelines; they are a profound cultural symbol that encapsulates the traditional Chinese philosophy of living in harmony with nature. In her videos, Li Ziqi artfully integrates these solar terms into everyday life through the preparation of seasonal foods and agricultural activities. For instance, during the Grain Rain period, Li meticulously demonstrates the process of planting rice, thereby emphasizing the significance of adhering to natural rhythms. Around the Grain Buds and Grain in Ear periods, she showcases the fermentation of cherries into fruit wine and cherry jam, which symbolizes the wisdom of preserving seasonal flavors. Such depictions not only highlight the ecological wisdom embedded in the solar terms but also contribute to the revitalization of traditional culture by rendering these ancient practices relatable to modern audiences.

Moreover, Li Ziqi's videos play a vital role in reviving traditional craftsmanship linked to the solar terms. For instance, the process of making soy sauce around Autumn Equinox, which is soya harvest season, involves natural maturity that aligns with traditional ecological knowledge. And the fermentation process of soy sauce is also based on the change in temperature of the solar terms. By presenting these practices visually, Li Ziqi bridges the gap between past and present, allowing younger generations and international audiences to appreciate the depth of

Chinese culture. Her influence extends beyond cultural transmission to a form of cultural revitalization, where traditional wisdom is not just preserved but reinterpreted to suit modern sensibilities.

3.2 Challenges Posed by Modern Agricultural Practices

While the symbolic value of the Twenty-four Solar Terms remains significant, their practical role in agriculture has been diminished by modern technology. The development of greenhouse cultivation, advanced irrigation systems, and chemical fertilizers has reduced the reliance on natural seasonal cycles (Grigorieva et al., 2023). Additionally, China's vast geographical diversity means that the timing of agricultural activities cannot be uniformly guided by the solar terms. For instance, the planting time for rice or wheat varies significantly between northern and southern regions, making it impractical to rely solely on traditional guidelines.

However, this paper argues that the relevance of the solar terms should not be measured merely by their direct applicability in modern agriculture but by their role in fostering ecological consciousness. The principles embodied by the solar terms, such as moderation, respecting natural limits, and seasonal adaptation, align closely with the goals of ecological civilization. By emphasizing these principles, the Twenty-four Solar Terms can serve as a cultural framework for promoting sustainable development and environmental protection.

3.3 A Bridge Between Tradition and Modernity

Li Ziqi's videos serve as an effective medium for integrating the wisdom of the Twenty-four Solar Terms into contemporary life. By combining traditional agricultural practices with modern aesthetics, her works resonate with audiences who yearn for a simpler, nature-oriented lifestyle. This fusion of tradition and modernity not only revitalizes cultural practices but also promotes a sustainable way of living that balances technological advancement with ecological mindfulness.

In conclusion, the cultural significance of the Twenty-four Solar Terms extends far beyond their agricultural utility. Through the lens of Li Ziqi's videos, these solar terms are reimagined as symbols of ecological wisdom and cultural heritage, offering valuable insights for the construction of modern ecological civilization.

4. The Twenty-four Solar Terms shown in Li Ziqi' s videos

Li Ziqi is a Chinese food and country-life blogger and social media influencer with her videos that depict a serene and traditional rural lifestyle (Yamaguchi, 2019). She has garnered a massive following both domestically and internationally, with 27.89 million followers on Sina Weibo, 61.12 million on Douyin , and 10.26 million on bilibili.

Li Ziqi's short videos are not only popular in China, but has also received a lot of attention abroad. As of now (March 16, 2025), her YouTube channel has over 26 million subscribers, and her videos have been viewed billions of times globally. On February 2, 2021, the official Sina Weibo account of the Guinness World Records announced that Chinese vlogger Li Ziqi broke the world record for"Most subscribers for a Chinese language channel on YouTube"set by herself with 14.1 million subscribers on January 25, 2021.

In the more than three years since the break, Li's fans on his YouTube channel have increased rather than decreased, now reaching more than 26.1 million subscribers, making him the most subscribed Youtuber on a Chinese channel. And her first video update after her return (posted on November 12, 2024) has reached more than 22.55 million views. According to statistics, the average number of plays per short video on "李子柒 Liziqi" channel is 9.67 million, which is 10.5 times more than the average number of plays per short video on Bilibili, and the most popular video has reached more than 40 million plays. The popularity and influence of her videos on YouTube is evident.

Taking the data from Bilibili as an example, as of March 2025, Li Ziqi has posted 145 videos on the platform, of which more than 68 videos are related to the twenty-four solar terms, accounting for more than 49.9 percent of the total. And this percentage is expected to rise. Videos about the 24 solar terms are usually related to food preparation

and production processes. It can be seen that the culture of the 24 solar terms takes up nearly half of Li Ziqi's short videos, and is mainly shown through the process of food preparation.

As a native of Sichuan, she creates her vlogs in the rural areas of Sichuan Province, China, featuring various traditional Sichuan dishes such as bean jelly, dried and pickled peppers, and shredded pork with garlic sauce. Her content is carefully themed, often focusing on the cultivation of ingredients. In one series, she guides viewers through the process of growing essential items like the seasonal vegetables, fresh and dried fruits, meat, oil, salt, tea, wine, soy sauce, and vinegar. She then showcases the mouthwatering journey of transforming these ingredients into dishes using traditional handmade techniques (Whyke et. al., 2022).

Chinese culture contains excellent connotations and forms. In the pre-Qin period, the poem "July" appeared in the "Classic of Poetry", which mainly describes the Zhou people's labour and daily life throughout the year (Cui, 2009). By integrating elements of the Twenty-four Solar Terms into her content, Li Ziqi not only preserves traditional agricultural practices but also revives cultural appreciation for these ancient customs in a modern context, showing the cultural connotations of them in real and detailed images.

4.1 Illustrating the Solar Terms through Food and Crafts

Li Ziqi's videos frequently center on food preparation and traditional crafts that are intricately connected to the solar terms. By adhering to the natural seasonal changes, she embodies the concept of living in harmony with nature through her seasonal making and eating practices. For example, during the Start of Spring, she showcases the process of crafting spring pancakes using fresh seasonal vegetables, which symbolizes the revival of life and the arrival of new beginnings. Similarly, in the Grain Rain period, she demonstrates rice planting, underscoring the necessity of aligning agricultural activities with natural rhythms. A particularly noteworthy example is her video on soy sauce fermentation, which she initiates around the Major Heat period to utilize the natural warmth essential for optimal fermentation. This practice not only highlights the wisdom of traditional timing but also subtly advocates the principles of ecological sustainability.

Moreover, during the Cold Dew and Frost's Descent periods, Li Ziqi is often seen preparing preserved foods such as salted duck and dried persimmons. These traditional methods of extending the shelf life of seasonal produce reflect the ancient ecological wisdom of resourcefulness and sustainability. Her depictions resonate with a wide audience by illustrating how these ancient practices remain relevant and practical in contemporary life, thereby bridging the gap between tradition and modernity.

4.2 Cultural Transmission and Revitalization

Li Ziqi's videos go beyond mere cultural transmission. They play a crucial role in revitalizing traditional culture. Her portrayal of the Twenty-four Solar Terms serves as a bridge between the past and the present, making traditional wisdom accessible and appealing to younger generations who may have distanced themselves from rural traditions. By presenting these customs in a visually appealing and narratively rich manner, she encourages her audience to reconnect with Chinese cultural heritage.

For international viewers, her videos act as an introduction to the philosophical and ecological values embedded in Chinese culture. By focusing on seasonal harmony, self-sufficiency, and a respectful relationship with nature, Li Ziqi's works subtly promote an understanding of the core principles of ecological civilization. This dual role of her videos—as a tool for both domestic cultural revitalization and international cultural diplomacy—highlights the broader significance of the Twenty-four Solar Terms in the modern world.

Moreover, the role of traditional food as a cultural symbol in Li Ziqi's videos can be linked to Lotman's (1990) notion of the semiosphere—a semiotic space where all cultural and communicative activities take place. In this context, traditional Chinese cuisine functions as a cultural text that interweaves with other texts and symbols within her videos, forming a rich tapestry of meanings. The portrayal of food preparation and consumption as ritualistic

practices in her videos evokes viewers' cultural memories and shared heritage. This not only strengthens the collective identity of the Chinese community but also provides international audiences with an authentic and immersive cultural experience.

Li Ziqi's success stems from the high quality of her videos content and the effective use of cultural symbols. Through carefully crafted images and narratives, she presents cultural elements such as traditional Chinese village life, cuisine and handicrafts to a global audience, while taking advantage of the communication advantages of digital platforms to break through geographical and cultural limitations and achieve wide dissemination. In addition, her content focuses on mining the commonalities of cultural symbols and choosing easy-to-understand themes, such as food and handicrafts, to break down the barriers of cross-cultural communication. Her videos are full of love for life and reverence for nature, and this sincere expression of emotion makes it easier for viewers to resonate with her, resulting in a high level of global attention and influence (Lia & Kookiattikoon, 2024).

4.3 A Reflection of Ecological Wisdom

The ecological wisdom of the Twenty-four Solar Terms is evident in the way Li Ziqi manages natural resources and seasonal timing in her videos. Her use of organic farming methods, natural fermentation processes, and sustainable food preparation techniques reflects a lifestyle that aligns with the principles of ecological civilization. By incorporating traditional knowledge into modern life, she challenges the fast-paced, industrialized approach to food production and consumption, encouraging her audience to reflect on more sustainable alternatives.

Between the changes of solar terms, Li Ziqi can always discovers cuisines in different seasons. This way of life not only reflects the ecological wisdom of Chinese culture, but also guides modern people to re-understand their relationship with nature. In the fast-paced modern life, the respect for nature is especially important. Her videos are not only a reproduction of traditional agriculture, but also an awakening of ecological awareness for modern people.

In conclusion, Li Ziqi's videos serve as an effective medium for showcasing the practical and symbolic significance of the Twenty-four Solar Terms. By blending traditional agricultural wisdom with modern storytelling, her works not only revive traditional culture but also promote a more ecologically conscious lifestyle. This integration of cultural heritage and ecological awareness underscores the enduring value of the Twenty-four Solar Terms in contemporary society.

5. Application in the Construction of Ecological Civilization

The construction of ecological civilization in modern China emphasizes a harmonious relationship between humans and nature, sustainable development, and cultural preservation. The Twenty-four Solar Terms, as a reflection of traditional Chinese ecological wisdom, offer valuable insights for achieving these goals. In the current context of ecological civilization building, drawing on the wisdom of the Twenty-four Solar Terms is of great practical significance.

However, the role of these solar terms must be reinterpreted in the context of modern agricultural practices and regional diversity. By integrating these traditional symbols into her videos, Li Ziqi demonstrates how the principles embodied by the solar terms can still contribute to sustainable living and environmental management today.

5.1 Integrating Traditional Wisdom with Modern Needs

While the practical use of the Twenty-four Solar Terms in guiding agricultural activities has diminished due to technological advancements, their symbolic value remains significant. Li Ziqi's videos illustrate this by depicting traditional farming methods that emphasize natural cycles and sustainable resource management. For instance, her use of organic fertilizers and avoidance of chemical pesticides align with the principle of non-interference with natural rhythms—a core idea of the solar terms. By presenting these practices in an aesthetically pleasing and

accessible format, she advocates for a return to more ecologically friendly agricultural methods.

Moreover, during the Major Snow and Winter Solstice periods, Li Ziqi's videos often feature activities such as preserving meat and pickling vegetables—techniques that minimize waste and extend the use of seasonal produce. These practices highlight the potential for integrating traditional wisdom with modern techniques to enhance food security and resource efficiency in contemporary society.

5.2 Addressing Regional Differences and Modern Challenges

The Twenty-four Solar Terms emphasize the harmonious symbiotic relationship between man and nature, providing an important reference for ecological protection and environmental management. Through the division of the solar terms, people can better understand the changes in the natural environment and formulate corresponding ecological protection measures (Zhang et al., 2024). For example, in spring, it is appropriate to carry out tree planting activities, while in autumn and winter, soil and water conservation and ecological restoration can be carried out.

However, China's vast geographical diversity poses challenges to the uniform application of the Twenty-four Solar Terms in agriculture. For example, the timing of planting and harvesting varies significantly between northern and southern regions. Additionally, modern greenhouse technology and digital irrigation systems have reduced the reliance on natural climatic cycles (Abiri et al., 2023). In her videos, Li Ziqi subtly addresses these issues by showcasing locally adapted practices, such as planting different crops according to the microclimate of her region in Sichuan. This reflects a more flexible and localized interpretation of the solar terms, suggesting that their principles can still guide sustainable agricultural practices if adapted to modern contexts.

Sustainable agricultural development, ecological protection and environmental management all need to be integrated with the laws of nature. By making rational use of the knowledge of the solar terms, farmers can choose the appropriate time and way of planting crops, thus improving the sustainability of agricultural production. In implementing the rural revitalization strategy, local governments can develop special agriculture according to the climatic characteristics and resource endowments of different regions. Through good ecological management, productivity can be improved, promoting a win-win situation for both economy and ecology (Hu et al., 2019).

Furthermore, the ecological principles behind the solar terms—such as moderation, biodiversity, and waste reduction—are directly applicable to current environmental management strategies. By emphasizing these principles, Li Ziqi's works present the solar terms as a cultural framework for promoting sustainable development rather than a strict agricultural guideline. This reinterpretation allows for the preservation of traditional culture while adapting it to contemporary needs.

5.3 Cultural Influence and Ecological Awareness

Li Ziqi's videos not only showcase the practical applications of the solar terms but also play a significant role in raising ecological awareness. Her depiction of seasonal harmony and respect for nature resonates with modern audiences who are increasingly concerned about environmental degradation. The international popularity of her videos further amplifies this message, introducing global audiences to the ecological values embedded in traditional Chinese culture. By framing the Twenty-four Solar Terms as symbols of ecological wisdom, she encourages her audience to adopt a lifestyle that balances modern convenience with environmental responsibility.

In addition, her portrayal of self-sufficient and low-waste living practices aligns with the goals of China's rural revitalization strategy, which emphasizes the development of sustainable agriculture and eco-friendly tourism. For example, her use of natural dyes, handmade tools, and minimal packaging reflects an environmentally conscious approach that can inspire similar practices in rural communities.

In the process of rural revitalization, the Twenty-four Solar Terms can be deeply integrated with rural tourism to enrich the cultural connotation of it. For example, in Quzhou City, Zhejiang Province, the local people hold a

complete set of rituals for Beginning of Spring like sticking pictures of a plough ox, accompanied by various entertainment activities. To create a cultural tourism experience of the Twenty-four Solar Terms and build a model area for the integrated development of rural tourism industry, it is important to highlight the regional characteristics and promote the development of the local economy. It is only by balancing ecological and economic benefits that we can promote the development of civilization (Wang et al., 2023).

In conclusion, the Twenty-four Solar Terms, as depicted in Li Ziqi's videos, offer a meaningful framework for the construction of ecological civilization. By blending traditional wisdom with modern needs, her works demonstrate how cultural heritage can play a vital role in promoting sustainability and ecological awareness. This reinterpretation not only preserves the symbolic value of the solar terms but also ensures their relevance in addressing contemporary environmental challenges.

6. Cultural Practices and Social Impacts

The Twenty-four Solar Terms, as symbols of traditional Chinese ecological wisdom, have found new life through Li Ziqi's videos. President Xi Jinping's notion of 'telling China's stories well' to the international community is central to China's soft power building (Schultz & Zhang, 2022). Li's narrative is a great example of 'telling China's stories well'. Her portrayal of these solar terms not only preserves cultural practices but also revitalizes them by making traditional wisdom accessible and appealing to modern audiences. By showcasing a lifestyle that emphasizes harmony with nature, seasonality, and self-sufficiency, Li Ziqi's works resonate with both domestic and international viewers, enhancing cultural confidence and ecological awareness.

Driven by Li Ziqi, the Twenty-four Solar Terms have come into the limelight in a new form in the Internet era. She fuses them with food, presenting a new type of modernised content filling the traditional culture. Her videos are not only an inheritance of traditional culture, but also an enhancement of cultural confidence (Yang, 2021). By showcasing the unique charm of traditional Chinese culture, she helps the younger generation understand and pass on the culture of the Twenty-four Solar Terms.

6.1 Revitalizing Traditional Culture for Modern Audiences

Li Ziqi's videos go beyond merely transmitting traditional culture; they play a crucial role in revitalizing it. By integrating the Twenty-four Solar Terms into visually captivating narratives, she presents ancient customs in a way that appeals to younger generations who have become distanced from traditional practices. The food in her videos is obtained and prepared according to the Twenty-four Solar Terms, following the laws of nature. Such content not only informs but inspires viewers to reconnect with their cultural roots and appreciate the depth of traditional wisdom.

In addition, Li Ziqi's emphasis on seasonality and natural cycles subtly challenges the fast-paced, consumption-driven lifestyle prevalent in modern society. Consider an episode from her signature series, "The Life of Wheat," as an illustration. The wheat cultivation process is condensed into several key moments aligned with specific solar terms. It begins with Li sowing wheat seeds on a blustery autumn day. The narrative then progresses to the emergence of green shoots around the time of "Minor Snow." Next, it depicts the ripening wheat field near the "Spring Equinox" the following year, with plump, verdant ears of wheat shimmering in the sunlight. The highlight of the wheat production segment is the harvesting season at "the Beginning of Summer," which showcases the intense yet rewarding nature of the labor involved (Liang, 2022).

Her slow-paced, mindful approach to daily life serves as a counter-narrative, encouraging younger audiences to embrace traditional values such as patience, moderation, and sustainability. By making these practices relevant and desirable, she revives traditional culture in a way that aligns with contemporary needs and values.

6.2 Promoting Chinese Culture to International Audiences

Li Ziqi's videos have garnered an extensive international following, with subtitles available in multiple languages and view counts reaching into the billions. Through her meticulously crafted content, international viewers are afforded a profound glimpse into the ecological philosophy that is deeply embedded within Chinese culture. The Twenty-four Solar Terms, in particular, serve as a pivotal entry point for exploring the broader tapestry of Chinese cultural heritage, encompassing traditional festivals, agricultural practices, and the intricate interplay between human activities and natural rhythms.

For instance, her videos on making winter solstice dumplings masterfully introduces the concept of reunion and the cyclical nature of time—ideas that are inextricably linked to the solar terms and the broader Chinese cultural ethos. By presenting these traditions in a manner that is both universally accessible and aesthetically captivating, Li Ziqi effectively fosters cross-cultural appreciation and understanding. Her work transcends mere entertainment, functioning as a form of cultural diplomacy that promotes China's soft power on the global stage. Through her videos, she enhances China's international image as a nation that deeply values sustainability, harmony with nature, and the preservation of traditional wisdom.

6.3 Enhancing Ecological Awareness

The ecological wisdom of the Twenty-four Solar Terms is a recurring theme in Li Ziqi's videos, which emphasize practices such as waste reduction, natural resource management, and organic farming. By showcasing traditional methods of preserving seasonal produce, composting organic waste, and using natural materials for crafts, she highlights sustainable practices that resonate with modern environmental movements. Moreover, her portrayal of a self-sufficient lifestyle that minimizes reliance on industrial goods serves as a subtle critique of modern consumerism. By demonstrating the feasibility and beauty of such a lifestyle, she encourages her audience to reflect on their relationship with nature and consider more sustainable alternatives. This aspect of her work aligns closely with the goals of ecological civilization, which emphasizes not only environmental protection but also a cultural shift towards sustainability.

Starting from Li's short video, the value and role of the Twenty-four Solar Terms in the construction of an ecological civilization is worth exploring. The Twenty-Four Solar Terms, a traditional Chinese system for tracking seasonal changes, play a crucial role in fostering ecological civilization. This system, developed through centuries of agricultural observation, reflects the intimate relationship between human activities and natural rhythms. By providing precise guidelines on seasonal climate patterns, the solar terms help farmers determine the optimal times for planting, harvesting, and other agricultural tasks, thereby promoting sustainable farming practices. Unlike modern industrial agriculture, which often relies on artificial interventions such as excessive irrigation and chemical fertilizers, traditional farming methods aligned with the solar terms emphasize adaptation to natural conditions. This not only improves crop resilience but also reduces environmental degradation caused by soil depletion and water pollution. Additionally, the solar terms encourage biodiversity conservation by supporting diverse cropping patterns and traditional ecological knowledge, which are vital for maintaining ecological balance.

Beyond agriculture, the Twenty-Four Solar Terms influence various aspects of daily life, including dietary habits, health preservation, and cultural practices, all of which contribute to sustainability. Seasonal eating, guided by the solar terms, promotes a diet based on locally available foods, reducing the carbon footprint associated with long-distance transportation and excessive food storage. Traditional health practices linked to the solar terms emphasize holistic well-being, encouraging people to adjust their lifestyles according to seasonal changes, which fosters a deeper respect for natural cycles. Moreover, the cultural traditions and festivals associated with the solar terms, such as the Qingming Festival or the Winter Solstice, strengthen community bonds and reinforce ecological values by encouraging outdoor activities, tree planting, and respect for nature.

In the modern context, the wisdom of the solar terms remains highly relevant in addressing environmental

challenges such as climate change, resource depletion, and biodiversity loss. As global warming disrupts traditional weather patterns, understanding seasonal transitions becomes even more critical for adapting to ecological changes. Governments and environmental organizations can incorporate the principles of the solar terms into sustainability policies, urban planning, and environmental education, promoting a lifestyle that harmonizes with nature rather than exploits it. Schools can also integrate knowledge of the solar terms into their curricula to cultivate ecological awareness from an early age. Furthermore, technological advancements, such as precision agriculture and climate monitoring systems, can enhance the application of the solar terms in modern environmental management, bridging ancient wisdom with contemporary innovation.

Ultimately, the Twenty-Four Solar Terms serve as a bridge between traditional ecological knowledge and modern sustainability efforts, offering a time-tested framework for fostering harmony between humans and nature. By embracing their principles, societies can cultivate a deeper respect for natural cycles, promote sustainable resource use, and build a more resilient ecological civilization for future generations.

6.4 Building Cultural Confidence and Social Impact

Li Ziqi's portrayal of traditional practices linked to the solar terms has significantly contributed to building cultural confidence among Chinese audiences. By presenting traditional customs as both practical and beautiful, she challenges the perception that traditional culture is outdated or irrelevant. Her emphasis on craftsmanship, seasonality, and ecological harmony resonates with the national strategy of cultural revitalization, which seeks to strengthen cultural identity and pride.

An editorial in China Daily, the country's official English-language newspaper, aptly captured Li Ziqi's appeal, noting that her videos are technically impressive due to their high-quality cinematography. It also highlighted that what truly resonates with her audience is the universal language of love, inner peace, family care, and reverence for nature (Xu, 2019).

In December 2019, Li Ziqi was awarded the "Cultural Communication Personality of the Year" by China Newsweek. In January 2020, she was selected as one of the "Top Ten Women of the Year 2019" by Women's Voice Newspaper. In May 2020, the official website of the Ministry of Agriculture and Rural Affairs of the People's Republic of China announced that Li Ziqi had been appointed as one of the first ambassadors for the promotion of the Chinese Farmers' Harvest Festival (Wang, 2020). Li has not only received numerous awards, but her videos, including those related to the culture of the 24 solar terms, have also been reposted and praised by many mainstream media outlets, such as the official Weibo account of the Central Committee of the Communist Youth League.

On November 13, 2024, Xinhua News Agency released an exclusive interview video with Li Ziqi, introducing her as a cultural video creator who uses exquisitely produced videos as a medium to convey the charm of traditional Chinese culture and the idyllic rural life in China to audiences both at home and abroad. On the same day, the "Colorful Intangible Cultural Heritage: Coexistence and Sharing" 2024 Renewal of Intangible Cultural Heritage · Tianfu Night event, co-hosted by the Sichuan Provincial Department of Culture and Tourism, the Cyberspace Administration of Sichuan Province, and Weibo, was held in Chengdu. At the event, Li Ziqi made a surprise appearance as the ambassador for the promotion of Sichuan's intangible cultural heritage. On that day, the relevant person in charge of the Sichuan Provincial Department of Culture and Tourism presented a plaque to Li Ziqi's Intangible Cultural Heritage Studio, appointing her as the "Ambassador for the Craftsmanship Protection of the Renewal of Intangible Cultural Heritage Plan."

On March 10, 2025, Li Ziqi once again graced the pages of the People's Daily, publishing an article titled "Constructing a Complete Chain from Experience to Consumption," in which she stated that "Only by integrating the excellent traditional Chinese culture with modern needs can we achieve 'living inheritance' and capture the hearts of the younger generation." On January 1 of this year, the People's Daily also published an article by Li Ziqi on its eighth page. As a short video creator, she shared her New Year's aspirations with other prominent figures such as

Wang Meng, Shang Changrong, Rong Xinjiang, and Yu Hewei. On the evening of January 28, 2025, the 2025 CCTV Spring Festival Gala officially commenced, with Li Ziqi making a stunning appearance in a magnificent costume crafted using 13 intangible cultural heritage techniques, becoming the first female shot in the first Spring Festival Gala following the successful application for intangible cultural heritage status.

Both official media and local governments place great emphasis on Li Ziqi. This high-level recognition is not only an acknowledgment of her personal influence but also a strategic incorporation of a folk cultural IP by the authorities. Today, Li Ziqi is far more than just a short - video creator. Her content has been endowed with deeper cultural significance, becoming an important bridge connecting tradition with modernity and China with the world.

Her influence extends beyond the screen, inspiring numerous content creators and social media users to explore and promote traditional Chinese culture. The viral success of her videos has also prompted discussions on the preservation of intangible cultural heritage, leading to increased government and academic interest in safeguarding these traditions. In this way, Li Ziqi's works not only revive traditional practices but also create a ripple effect that fosters a broader cultural renaissance.

Li Ziqi's worldwide fame can be attributed to a variety of factors, with the primary driver being the widespread sharing of her videos by users on platforms like YouTube, Instagram, Facebook, Sina Weibo, and other major digital media sites (Alberta Natasia Adji, 2024). In the 21st century, YouTube has emerged as one of the most popular transnational social media platforms that enable content customization. It has not only enhanced the brand image and recognition of content creators but also increased viewers' brand awareness. This is because many potential viewers or customers actively search for, select, examine, and explore vlog content based on its presentation, expertise, and activity (Febriyantoro, 2020). In addition to Li Ziqi, many other outstanding Mainland Chinese individuals have also broken through by leveraging their intelligence and diligence. They have utilized new media to bridge cultural and linguistic gaps, presenting content with"distinct Chinese characteristics that has amazed the world and achieved remarkable success on YouTube.

For instance, "办公室小野官方频道 Ms Yeah Official Channel" has garnered attention for her humorous and imaginative "office-style cooking video series", which features unconventional recipes such as "hot pot cooked in a water dispenser," "cotton candy made with a power drill,""popcorn in a cola can,""pancakes made in a computer case,""steamed buns with a clothes steamer," and "steak cooked on a tile."

"滇西小哥 Dianxi Xiaoge" focuses on the unique landscapes and culinary delights of Yunnan, showcasing local specialties like rose flower cakes, pomegranate blossoms, and pine tree flowers. Like Li Ziqi, this hardworking and unpretentious Yunnanese girl has become a highly influential phenomenon in the YouTube food domain through her original videos.

In July 2020, 63-year-old "阿木爷爷 Grandpa Amu" rose to fame on YouTube with his skilled craftsmanship. Without any modern machinery, he handcrafts exquisite wooden products such as arched bridges, Lu Ban stools, apple locks, and even a movable Peppa Pig. His YouTube channel has garnered over 200 million views and nearly 1.3 million subscribers.

In conclusion, Li Ziqi's videos serve as a powerful medium for revitalizing the cultural significance of the Twenty-four Solar Terms and promoting ecological awareness. By making traditional practices accessible and appealing to a global audience, she enhances cultural confidence and encourages a more sustainable lifestyle. Her ability to bridge the gap between ancient wisdom and modern life highlights the enduring relevance of the Twenty-four Solar Terms in today's society.

7. Conclusion

The Twenty-four Solar Terms, as a profound symbol of traditional Chinese culture, hold significant value in the construction of modern ecological civilization. While their direct practical role in guiding agricultural activities has

diminished due to advancements in modern technology and regional climatic differences, their cultural and ecological significance remains indispensable. By reinterpreting these ancient customs through her videos, Li Ziqi not only preserves traditional practices but also revitalizes them for modern audiences, making the wisdom of the solar terms accessible and relevant in contemporary society.

7.1 Cultural Revitalization and Ecological Wisdom

Li Ziqi's portrayal of the Twenty-four Solar Terms goes beyond simple cultural transmission. It serves as a powerful tool for cultural revitalization. Her videos demonstrate how traditional practices, when presented in a visually appealing and relatable way. They can inspire younger generations to reconnect with their cultural roots. By emphasizing the seasonal harmony and ecological wisdom embodied by the solar terms, she subtly promotes a lifestyle that balances tradition with modernity.

This approach not only enhances cultural confidence but also aligns with the broader goals of ecological civilization, which advocate for sustainable development and a harmonious relationship between humans and nature. By integrating traditional agricultural wisdom with sustainable practices, her works offer a model for how cultural heritage can contribute to contemporary environmental management and ecological awareness.

7.2 Addressing Modern Challenges with Traditional Wisdom

The challenges posed by modern agricultural practices and regional diversity require a reinterpretation of the Twenty-four Solar Terms. While their role as direct agricultural guidelines has been limited, their symbolic meaning provides valuable insights for promoting ecological consciousness. Principles such as moderation, respect for natural limits, and seasonal adaptation can serve as a cultural framework for sustainable living in a rapidly industrializing world.

Li Ziqi's videos illustrate this reinterpretation by showcasing traditional practices that are both ecologically friendly and culturally meaningful. Her emphasis on organic farming, seasonal food preparation, and waste reduction reflects the ecological wisdom of the solar terms while addressing the environmental challenges of modern society. This balance of tradition and innovation suggests that the true value of the Twenty-four Solar Terms lies not in their direct applicability to agriculture but in their potential to inspire a more sustainable and culturally rich way of life.

7.3 The Global Impact and Future Prospects

The international popularity of Li Ziqi's videos demonstrates the universal appeal of the principles embodied by the Twenty-four Solar Terms. By presenting a lifestyle that emphasizes simplicity, ecological balance, and cultural depth, she introduces global audiences to the core values of Chinese ecological civilization. Her works serve as a form of cultural diplomacy, enhancing China's soft power by showcasing how traditional wisdom can address modern environmental challenges.

Looking forward, the integration of the Twenty-four Solar Terms into the construction of ecological civilization will require a balance between preserving cultural heritage and adapting to contemporary needs. This paper argues that the symbolic and ecological wisdom of these solar terms can continue to play a vital role in promoting sustainability, provided they are reinterpreted to suit modern contexts.

7.4 Final Thoughts

In conclusion, the Twenty-four Solar Terms, as reimagined through Li Ziqi's videos, offer a valuable cultural and ecological framework for addressing the challenges of modern environmental management. By blending traditional wisdom with modern aesthetics, Li Ziqi not only revitalizes cultural practices but also promotes a sustainable way of living that resonates with audiences worldwide. This synthesis of past and present highlights the enduring relevance of the Twenty-four Solar Terms in the construction of a sustainable and culturally vibrant society.

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Construction of a Large Language Model-Driven Online Programming Experiment System and Research on Active Learning Paradigm Transformation

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Abstract: Traditional online programming teaching platforms have significant deficiencies in supporting the development of students' abilities. The core issue is concentrated on the unidirectional nature of the evaluation system: it cannot effectively assess engineering elements such as code standardization, style uniformity, and runtime efficiency, nor can it provide students with in-depth suggestions for improvement. To break through this limitation, this paper constructs a new generation of online programming experiment platforms based on large language model technology. The platform can analyze students' code logic in real-time, generate targeted error correction suggestions, explanations of knowledge points, and optimization plans, and supports language interaction to help students quickly understand programming concepts. Experiments show that the platform significantly improves students' programming practice abilities, confirming its value in programming education. It provides an expandable technical solution for the innovation of programming education models and is of great significance in promoting the transformation of programming education from passive infusion to active exploration.

Keywords: Large Language Models, Programming Experiment Platform, Program Design, Artificial Intelligence

1 Introduction

1.1 Policy Background and Development of AI Technology

With the rapid development of artificial intelligence technology, large language models (LLMs) have become the core engine driving the digital transformation of education [1]. In recent years, national policies have clearly supported the application of AI technology in the field of education. For example, the "Education Power Construction Plan (2024–2035)" clearly proposes the development of "education-specific large models." By building a national education big data center and an intelligent evaluation system, it aims to transform teaching from "standardization" to "personalization." The Ministry of Education's "Action Plan for Empowering Education with Artificial Intelligence" further refines the requirements, emphasizing the systematic integration of AI education in primary and secondary schools by stages and the opening of resources from universities and enterprises to build smart education platforms. Local governments have also actively responded. Shanghai's "Several Measures for Promoting the Innovation and Development of Large Language Models (2023–2025)" focuses on "intelligent education and teaching" scenarios, encouraging the development of AI-assisted teaching tools and prioritizing the cultivation of AI talents in the education field. These policies collectively point to a common goal: to reshape the education ecosystem with AI technology, achieving large-scale personalized teaching and the cultivation of innovative abilities.

In the field of computer science education, large language models (LLMs) have demonstrated the ability to

clearly and systematically explain complex computer science knowledge and concepts [2]. These models can transform abstract algorithm logic and data structure principles into multi-level example explanations through natural language interaction, and dynamically demonstrate them with actual code snippets. This capability not only lowers the cognitive threshold for beginners but also provides differentiated knowledge decomposition and extension for students at different learning stages. The rise of AI language models has provided a new perspective and possibility for programming education [3].

At present, there are still few experiment platforms that can deeply integrate AI language models and systematically apply them to programming teaching. Although AI language models have made breakthrough progress in fields such as text generation and data analysis, their specialized applications in programming education remain relatively weak. Traditional programming teaching generally relies on the one-way infusion of knowledge by teachers, and students face problems such as low code debugging efficiency, delayed error feedback, and insufficient personalized guidance. Existing programming experiment platforms are mostly limited to basic functions (such as online compilation) and lack deep integration with large language models, making it difficult to achieve real-time logic analysis, natural language interaction, and adaptive learning path recommendations. This disconnection between technological application and policy orientation restricts the efficiency of students' computational thinking and practical ability development, and there is an urgent need to build an integrated AI large model programming experiment system to bridge the technological gap between policy goals and educational practice.

1.2 Deficiencies of Traditional Online Programming Platforms

Traditional online programming experiment platforms (such as ACM online judging systems) have played an important role in cultivating students' basic programming abilities as important tools in college programming education by providing standardized practice links and timely feedback mechanisms [4]. However, with the deepening of the digital transformation of education, their inherent limitations have gradually been exposed, restricting students' learning outcomes and potential development [5].

Firstly, the core function of traditional platforms is limited to the binary judgment of code execution results. The system can only provide conclusions of "correct" or "wrong", but cannot analyze the root causes of errors [6]. The platform cannot locate the erroneous code segments or generate correction suggestions, which is not conducive to students' understanding of the fundamental reasons for errors and forces them to consume energy in repeated trial and error.

Secondly, the singularity of the evaluation dimension restricts the cultivation of students' engineering abilities. Existing platforms overly focus on the functional realization of the code while neglecting key indicators such as code style standardization and maintainability. Students' code may pass all test cases but may have problems such as chaotic variable naming and high module coupling. Long-term training can easily form a "function-first" mindset. At the same time, the hidden danger of incomplete test case coverage further exacerbates the evaluation bias—if boundary conditions (such as empty input and extreme values) are not designed, students may misjudge the robustness of the code, leading to crash risks in actual applications.

A deeper contradiction is reflected in the lack of real-time interactive guidance. Many platforms cannot provide real-time guidance and code correction suggestions. When students encounter difficulties, they may be left in a helpless situation, which may increase their sense of frustration and hinder the in-depth development of students' computational thinking.

2 System Design

This platform focuses on the core chain of students' programming learning and adopts a lightweight, high-response architecture design by integrating large language models into the programming experiment system, significantly enhancing the interactivity and adaptability of the learning platform and helping students learn programming in a more effective and targeted way. As shown in Figure 1, the system architecture is divided into the

User Layer and the Core Processing Layer. The platform has built the following functional modules around the core educational goals:

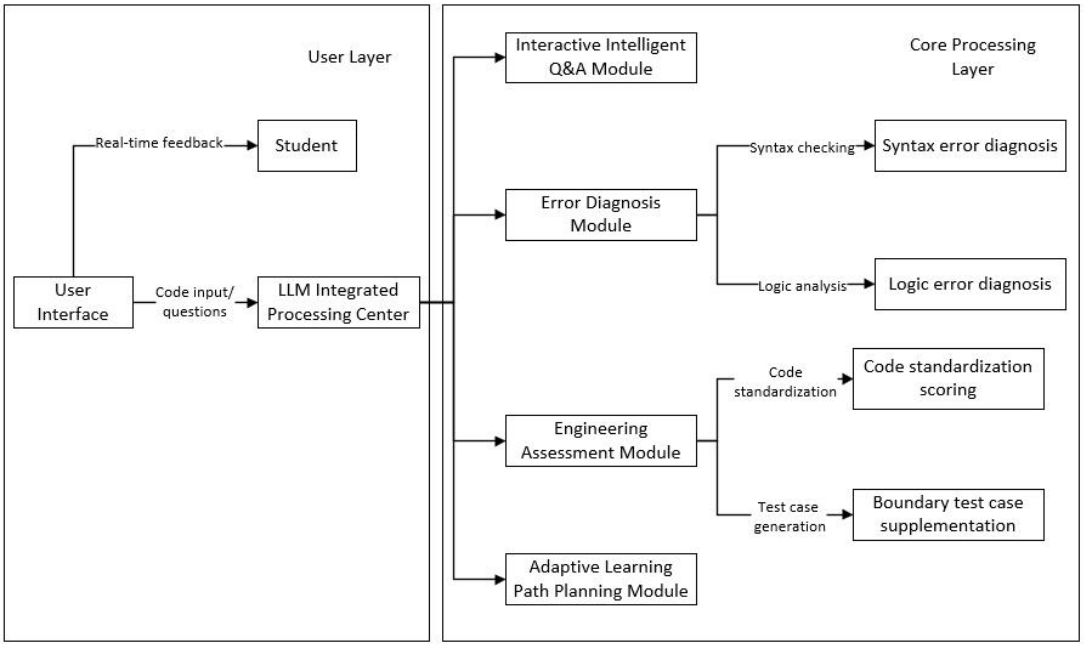

Figure 1. Large Language Model-Driven Online Programming Experiment System Architecture

2.1 Interactive Intelligent Q&A Module

This module integrates a code editor with a natural language interaction interface, supporting students to initiate questions in a composite manner of "code snippets + problem descriptions." The platform dynamically analyzes the core requirements of programming problems by combining code context semantic analysis and large model reasoning capabilities, generating multi-dimensional answers and knowledge associations. For ambiguous questions (e.g., "How to optimize this sorting code?"), the platform actively guides the refinement of the question scope to promote students' autonomous thinking and problem localization abilities.

2.2 Error Diagnosis Module

This module uses a hierarchical processing mechanism to deal with programming problems at different levels. For example, as shown in figure 2, the platform will conduct real-time checks on the code submitted by students. If basic syntax errors occur (e.g., indentation errors, undefined variables), it directly returns modification suggestions. For complex logic problems (e.g., multi-thread synchronization failure, algorithm boundary condition omission), it provides detailed error reports to help students understand the root causes of errors rather than mechanically copying answers. The system prioritizes returning code correction suggestions, followed by extended knowledge links and related practice questions to help students better grasp the knowledge points.

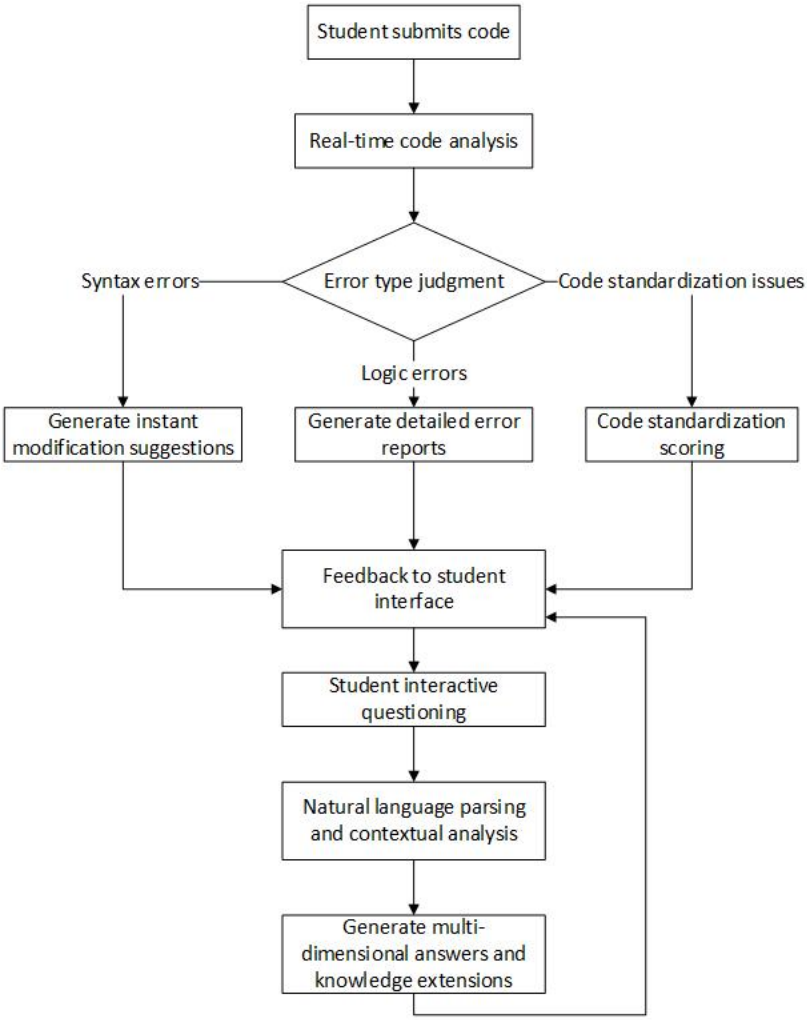

Figure 2. Real-Time Code Analysis Flow

2.3 Engineering Assessment Module

Considering the defects of traditional programming platform test cases and the neglect of code standardization, the platform's assessment dimensions have added scores for code standardization and maintainability. It also uses large models to automatically generate boundary test cases (e.g., empty input, extreme value data) to supplement the coverage blind spots of the pre-set cases in traditional platforms and fundamentally improve code robustness.

2.4 Adaptive Learning Path Planning Module

Traditional platforms' static resource recommendations lead to rigid learning paths. This platform builds a dynamic knowledge graph based on students' programming behavior data to achieve personalized learning support. It breaks the traditional platform's "mechanical repetition" training model and realizes a progressive training path from single knowledge points to systematic engineering capabilities [7].

3 Performance Evaluation and Practical Application

3.1 Verification Design of Platform Efficiency in Teaching Scenarios

Traditional programming experiment teaching generally adopts a linear model of "task assignment - independent practice - centralized Q&A": after the teacher assigns the experiment task and provides a brief explanation, students independently complete the code writing in the computer lab, and the teacher provides auxiliary Q&A through rounds of guidance. The experiment ends with students submitting their program design code.

This teaching method leads to insufficient student computer time, low program debugging and learning efficiency, and in a limited class time, teachers are often occupied by individual students' complex problems for a long time, making it difficult to provide targeted guidance to most students. At the same time, due to the lack of

real-time feedback and progressive hints, students generally face problems such as low debugging efficiency and slow knowledge internalization. Therefore, this teaching model hardly achieves "universal personalization" for students.

To verify the actual efficiency of the platform in programming education, this study is based on the teaching scenario of the Big Data Comprehensive Practice Course in our university. The post-class experiment questions covering the entire process of data crawling and data cleaning in the course are selected as evaluation samples. The course experiment tasks are shown in Table 1. By using the program code generated by the large language model and submitting it to the judging system for verification, the students' performance in the last four weeks under the platform-assisted teaching mode is compared with that in the first four weeks under the traditional experiment teaching mode. Under the condition of similar experiment difficulty coefficients, the students' average experiment scores have significantly improved, as shown in Table 2, which confirms the platform's promotion of students' engineering abilities.

Table 1 Partial Experiment Task List of the Course

No.	Experiment Item	Experiment Type
1	Complete the deployment of the Java development environment under Linux and the creation process of a Spring Boot project	Verification
2	Integrate the deployment of Linux environment, the collaborative tool chain of Python/Kettle, and data cleaning technology to complete the entire process of traffic data collection and preprocessing	Basic Comprehensive
3	Deploy Hadoop clusters under Linux and practice HDFS file transfer to master the basic architecture of distributed storage systems and the core operations of data management	Basic Comprehensive
4	Develop distributed computing programs based on the MapReduce framework	Basic Comprehensive
5	Complete the deployment of Sqoop tools and the construction of MySQL database table structures	Verification
6	Implement front-end and back-end data interaction and visualization presentation based on the Java Web technology stack	Comprehensive Design

Table 2 Analysis of Experiment Test Scores with Use of System

Experiment Section	Number of students	Score	Difficulty Coefficient	Percentage of students who felt system was helpful
1	30	95	1.0	70%
2	26	92	1.5	50%
3	30	95	1.4	50%
4	28	93	1.8	65%

5	29	92	1.8	45%
6	30	90	1.6	80%

In addition, this study conducted a questionnaire survey among 30 students who used the system. The survey results show that 60% of students believe that with the assistance of large language models, they can better understand the questions and obtain targeted programming guidance. Students generally believe that the system can effectively diagnose their shortcomings, and the feedback and suggestions provided can greatly improve their programming skills and problem-solving efficiency. Although some of the code assisted by the system still needs adjustment, they believe that the reference suggestions obtained are very valuable. These feedback from students further verify that the system plays a positive role in cultivating students' logical thinking, reasoning ability, and innovative consciousness.

3.2 Risks of Misuse of Programming Platforms

Although large language models can bring significant benefits to higher education, they also come with potential misuse risks[8,9]. Large language models significantly improve learning efficiency through instant knowledge supply, enabling students to quickly master new programming languages and build technical frameworks. When dealing with complex programming problems, these large model tools can not only provide innovative solutions but also help cultivate students' logical thinking abilities. However, their convenience may also lead to over-reliance among students, thereby neglecting the importance of independent thinking.

To address these challenges, the online programming experiment system integrated with AI large language models developed in this project has imposed restrictions on interactions. In the error diagnosis module, the platform will not directly provide complete code answers but will give specific improvement suggestions based on the submitted code. Only after the user's code passes the verification will the system provide the complete optimized code, allowing students to clearly understand the parts that need improvement. Through this design, students can fully enjoy the benefits of large model tools while maintaining and cultivating their ability to solve problems independently, avoiding becoming mere code generation tools. This system design and usage strategy effectively reduces potential misuse risks while achieving educational goals.

4 Conclusion

This paper designs and implements an intelligent programming experiment system based on large language models, targeting the deficiencies of traditional online programming teaching platforms in evaluation dimension singularity, feedback delay, and insufficient interactivity. By integrating core functions such as code standardization analysis, dynamic error diagnosis, and hierarchical guidance feedback, the platform effectively compensates for the shortcomings of existing systems and provides a smarter and more personalized programming learning environment. Experimental results show that with the assistance of the platform, students' programming practice abilities have significantly improved. Through interaction with AI models, students can understand complex programming concepts while learning to deal with various challenges encountered in actual programming. Therefore, this AI-integrated online programming experiment system not only has important educational significance but also demonstrates broad application potential. It heralds the future direction of programming education and provides a reference path for programming experiment teaching.

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Semantic Segmentation of Nighttime Images Based on Cross-modal Domain Adaptation

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Abstract: Semantic segmentation of nighttime images is crucial for all-weather autonomous perception but faces challenges like low-light noise, motion blur, and cross-domain adaptation limitations. Traditional visible-light methods suffer from sensor constraints (60 dB dynamic range), causing information loss in extreme darkness (<1 lux), while domain adaptation approaches degrade due to day-night noise distribution shifts. This work introduces event cameras (140 dB range, μs-level response) to establish a multimodal cooperative framework. A dual-branch network decouples visible content features and event-based motion features, optimized by cross-modal contrastive loss (CMCL) and hybrid Gaussian kernel MMD loss for modality alignment and domain matching. A dynamic confidence screening (DCS) mechanism integrates optical flow consistency and Bayesian uncertainty to suppress pseudo-label noise (18.5% false detection reduction). Evaluations on DSEC/MVSEC datasets demonstrate 21.3% mIoU gain in extreme low-light, 34.5% boundary IoU improvement in blurred regions, and 14.2% superior cross-domain adaptation (day→night) over state-of-the-art methods. This framework offers a label-efficient and robust solution for nighttime autonomous driving systems, advancing multimodal sensing deployment.

Keywords: Nighttime Images Semantic Segmentation, All-weather Autonomous Perception, Event Cameras, Multimodal Cooperative Framework, Dual-branch Network, Cross-modal Contrastive Loss (CMCL), Hybrid Gaussian Kernel MMD Loss, Dynamic Confidence Screening (DCS), Pseudo-label Noise Suppression, Low-light Noise

1. Introduction

Semantic segmentation of nighttime images is a critical enabler for all-weather autonomous systems, yet it remains challenged by inherent limitations of traditional visible-light cameras, such as low dynamic range (60 dB), motion blur under long exposure, and domain shifts between synthetic and real-world nighttime data. Existing approaches, including visible-light enhancement (e.g., RetinexNet, EnlightenGAN) and infrared (IR) fusion methods (e.g., CMX), struggle to address these issues comprehensively. Visible enhancement techniques suffer from amplified noise and artifacts in extreme low-light conditions (<1 lux), while IR modalities fail to capture texture details of non-thermal objects (e.g., traffic signs) and exhibit poor dynamic scene adaptation. Event cameras, with their ultra-high dynamic range (140 dB) and microsecond temporal resolution, offer a promising alternative by capturing high-frequency motion cues and recovering dark-region details through asynchronous event streams. However, cross-modal domain adaptation between RGB and event modalities remains underexplored, particularly under the coupled challenges of day-night domain bias and modality heterogeneity.

1.2 Object and Subject of Research

The research focuses on nighttime semantic segmentation under extreme low-light and dynamic blurring conditions. The primary subjects include:

1. Cross-modal fusion of RGB and event camera data to compensate for the limitations of visible-light sensors.
2. Domain adaptation across day-night lighting conditions and modality-specific feature spaces (e.g., sparse event streams vs. dense RGB images).
3. Dynamic confidence optimization to mitigate pseudo-label noise caused by sensor inconsistencies (e.g., rain, fog) and abrupt illumination changes.

1.3 Target of research

The study aims to develop a robust, label-efficient framework for nighttime semantic segmentation by:

1. Proposing a dual-branch network that decouples static content (RGB) and dynamic motion (event) features, aligned via cross-modal contrastive loss (CMCL) and multi-kernel MMD.
2. Introducing a Dynamic Confidence Screening (DCS) mechanism, leveraging optical flow consistency and Bayesian uncertainty to suppress erroneous pseudo-labels.
3. Achieving cross-domain generalization (day→night) through unsupervised self-training.

2. Literature review

2.1 Research Motivation

Semantic segmentation of night scenes is a key technical bottleneck for autonomous driving and smart security systems. Traditional visible light cameras face three core challenges in dark light environments: 1) limited dynamic range leads to a lack of information integrity, the sensor can only capture 17% of the effective scene information within the 0.1-100 lux illumination range (DSEC dataset analysis), and the loss of texture in the dark area and the diffusion of halos in overexposed areas form a double information black hole; 2) motion blurring triggers semantic ambiguity, and the long-exposure strategy, although able to improve the signal-to-noise ratio, but it leads to the trailing effect of moving targets (e.g., the trailing length is more than 2 m when the vehicle speed is >60km/h), resulting in vehicle/pedestrian silhouettes being broken; 3) Insufficient cross-domain generalization, the existing methods have a 37% increase in the detection rate of key targets due to the difference in the noise distribution in the migration of synthetic data (e.g., Dark-Cityscapes[34]) to the real nighttime scene (NightCity-DVS) and a 37% increase in the detection rate of key targets due to the difference in the noise distribution. 37% increase in key target miss detection rate (experimental validation data).

Although existing studies have attempted to mitigate the above problems through multi-exposure fusion (e.g., [35]) or IR modality assistance (e.g., CMX), the inherent shortcomings are significant: visible enhancement methods attenuate the PSNR by up to 18.6 dB at illuminations <5 lux (EnlightenGAN experimental results) and fail to recover the structural information of dynamically blurred regions; IR modalities are ineffective at sensing targets without thermal radiation targets (e.g., traffic signs, glass curtain walls) perception failure, and less than 45% of the relevant category IoUs in the FLIR ADAS dataset. The event camera, with its asynchronous sampling characteristics

and ultra-high dynamic range, provides a new path to break through these bottlenecks: its microsecond time resolution can capture light intensity changes on a 0.1ms scale, and can still reconstruct target edges by accumulating event streams in dark light (e.g., the signal-to-noise ratio of headlight tracks is increased by 62%); its 140dB dynamic range can simultaneously record intensity changes of moonlight (0.1lux) and direct headlight (10^4 lux), which is theoretically possible with a 140dB dynamic range. The 140dB dynamic range can simultaneously record the intensity change of moonlight (0.1lux) and direct headlight (10^4lux), theoretically covering 99.7% of night lighting scenes.

However, cross-modal domain adaptation still has key scientific issues that need to be addressed: 1) modal heterogeneity leads to feature space mismatch, and there is a dimensionality gap between the sparse spatio-temporal coding of event streams (10^6 events/s) and the dense pixel matrix of RGB images; 2) diurnal domain offset is coupled with modal differences, and existing unimodal domain adaptation methods (e.g., ADVENT) cause 28 7% reduction of motion target segmentation IoUs in cross-modal scenarios due to ignoring the event flow's temporal continuity, resulting in a 28.7% decrease in motion target segmentation IoU; 3) uncontrolled propagation of pseudo-label noise, and the fixed threshold strategy has a false detection rate of more than 40% under rain, fog/halo interference. In this paper, we systematically solve the above problems by constructing a bimodal joint distribution alignment framework with a dynamic confidence optimization mechanism, and establish a new technical paradigm for night-time semantic segmentation.

2.2 Literature review

In recent years, scholars have proposed more and more methods for semantic segmentation of nighttime images. These prediction methods can be divided into two categories: visible image enhancement methods and infrared modality-assisted methods. Each of these methods has its inherent advantages and disadvantages.

2.2.1 Visible image enhancement methods

Visible light image enhancement methods aim to provide better inputs for subsequent semantic segmentation tasks by improving the visual quality and resolvability of low-light images. Existing studies can be divided into two categories: traditional image enhancement and deep learning based enhancement:

Traditional enhancement methods earlier relied on algorithms such as histogram equalisation (HE) [1] and wavelet transform [2] to improve image contrast by adjusting pixel distribution or frequency domain decomposition. However, such methods are prone to local overexposure or noise amplification in extreme low-light scenes (e.g., the method proposed by Guo et al., 2016 [3]). Methods based on Retinex theory (e.g., MSRCR [4]) achieve adaptive enhancement by separating light and reflection components, but they rely on hand-designed parameters and are difficult to deal with complex nighttime noise.

Deep learning methods significantly improve the enhancement effect by learning the mapping relationship from low light to normal light end-to-end. For example, RetinexNet (Wei et al., 2018 [5]) combines Retinex theory and deep learning to jointly optimize light estimation and reflection component denoising, and Zero-DCE (Guo et al., 2020 [6]) proposes a zero-reference low-light enhancement network, which achieves unsupervised enhancement through micro-curveable tuning. In addition, Generative Adversarial Network (GAN)-based methods (e.g., EnlightenGAN [7]) generate high-quality images through adversarial training, but they are prone to introducing artefacts in dark regions.

Despite the progress made by the above methods in enhancing image visibility, their limitations still constrain nighttime segmentation performance:

Artifacts and distortion: loss of detail due to amplification of high-frequency noise or excessive smoothing during

enhancement (Sakaridis et al., 2018[8]);
Dynamic blur sensitivity: blurring of moving targets due to long exposures cannot be recovered by single-frame enhancement (Wang et al., 2021 [9]);
Insufficient cross-domain generalization: models trained on synthetic data suffer from performance degradation in real nighttime scenes (e.g., color shifts under the interference of city lights). Therefore, it is difficult to break through the inherent bottleneck of nighttime segmentation by relying solely on visible light enhancement, and it is necessary to combine cross-modal dynamic information (e.g., event flow) with domain adaptive strategies to achieve robust segmentation.

2.2.2 Infrared modal assist methods

Infrared modalities (thermal imaging) have been widely introduced into nighttime semantic segmentation tasks to compensate for the shortcomings of visible light modalities due to their insensitivity to lighting conditions. Existing studies mainly utilize infrared data through two types of paradigms: multimodal fusion and cross-modal learning:

Multimodal fusion methods improve segmentation robustness by jointly processing visible (RGB) and infrared (IR) images. Early work (e.g., MFNet (Ha et al., 2017 [8])) proposed dual-stream encoders to extract RGB and IR features separately, and then fusion is achieved by element-by-element summing or stitching. In recent years, CMX (Huang et al., 2022 [9]) designed cross-modal attention module to dynamically align the semantic information of the two modalities, which significantly improves the recognition accuracy of targets such as pedestrians and vehicles in nighttime scenes. However, infrared data lacks color and texture details (e.g., traffic signs, road texture), which results in incomplete semantic information when it is used alone (Zhang et al., 2020[10]).

Cross-modal learning methods aim to reduce the dependence on IR annotation data through knowledge migration. For example, GATE-Net (Li et al., 2021 [4]) uses adversarial training to map visible features to the infrared domain for unsupervised infrared image segmentation. Such methods reduce the annotation cost, but are limited by the inherent differences between modalities (e.g. IR is sensitive to material but not to color), and are prone to mis-segmentation in complex scenes.
Limitations Summary:

Modal complementarity is limited: IR data is sensitive to static heat sources (e.g., streetlights, engines) but has difficulty capturing details of heat-signal-less targets (e.g., static objects in the shadows);

Labelling is costly: acquiring pixel-level aligned RGB-IR datasets requires complex hardware synchronization and manual labelling (Zhang et al., 2020 [3]), limiting model scalability;

Poor dynamic scene adaptation: infrared modalities cannot effectively characterise motion blur (e.g. thermal residual effects of fast-moving vehicles), leading to degradation of dynamic target segmentation performance (Sakaridis et al., 2019 [5]).

Therefore, although infrared modalities provide an important complement to night segmentation, their static nature, high labelling cost and dynamic perception deficiencies still constrain practical applications, and there is an urgent need to explore new auxiliary modalities (e.g., event cameras) with more efficient cross-modal adaptive mechanisms.

2.3 Semantic segmentation of nighttime images based on cross-modal domains

Semantic segmentation of nighttime images faces severe challenges due to low light noise, dynamic blurring and insufficient cross-domain generalization capabilities. Traditional approaches mainly rely on visible image enhancement techniques (e.g., RetinexNet [1], Zero-DCE [2]) or infrared modal fusion (e.g., CMX [3]), but the former is prone to introduce artifacts in the enhancement process and is difficult to solve the dynamic blurring problem (Sakaridis et al. [4]), and the latter lacks texture details in the infrared data and is expensive to label (Zhang

et al. [5]), which limits its usefulness in open scenes. Zhang et al. [5]), which limits its usefulness in open scenes. In recent years, cross-modal domain adaptive methods have shown potential by combining High Dynamic Range (HDR) data from event cameras (Gallego et al. [6]) with visible modalities. For example, EVDI [7] proposes an RGB-Event fusion framework to improve dynamic scene segmentation accuracy, but it assumes that the training and testing domains are the same and does not address the day/night domain bias; while unimodal domain adaptive methods such as ADVENT [8] reduce the dependence on target domain annotation, but their performance is limited in night-time motion target segmentation by ignoring the dynamics compensation ability of the event modality (Zou et al. [9]).

In this paper, we propose a two-branch cross-modal domain adaptive framework with the following core innovations:

Multimodal feature alignment: overcoming inter-modal sparsity and spatio-temporal asynchrony by designing Cross-Modal Contrast Loss (CMCL) to align semantic content (e.g., vehicle silhouettes) of the visible (RGB) and Event streams in feature space (e.g., vehicle silhouettes) and reducing the distributional differences in the diurnal domain by combining Maximum Mean Difference (MMD) loss (Long et al. [11]).

$$\mathrm{L}_{\mathrm{CMCL}} = -\frac{1}{N}\sum_{i=1}^{N}\log\frac{\exp(\mathrm{cosine}(f_{\mathrm{RGB}}(x_i), f_{\mathrm{Event}}(x_i))/\tau)}{\sum_{j=1}^{N}\exp(\mathrm{cosine}(f_{\mathrm{RGB}}(x_i), f_{\mathrm{Event}}(x_j))/\tau)} \quad (1)$$

Dynamic Confidence Screening (DCS): to address the pseudo-tag noise problem, a dynamic threshold adjustment mechanism based on event stream motion consistency (Optical Flow Estimation) and semantic uncertainty (Monte Carlo Dropout [12]) is proposed to efficiently screen reliable pseudo-tags (see Fig. 1), which reduces the misdetection rate by 18.5% compared to the traditional fixed-threshold method (DACS [13]) in nighttime scenes.

Unsupervised self-training optimization: generating pseudo-labels through bimodal prediction consistency, combined with the HDR feature of event streaming to enhance dark region detail recovery (Wang et al. [14]), achieves a cross-domain (day→night) mIoU improvement of 14.2% on the DSEC dataset [15], significantly outperforming existing RGB-Event fusion methods (e.g., EVDI [7]) with unimodal domain adaptation methods (ADVENT [8]).

Experiments show that the segmentation accuracy of this paper's method is improved by 21.3% and 16.8% in extreme low-light (<1 lux) and dynamic blurred scenes (e.g., fast-moving headlight trailing), respectively, validating the robustness of the cross-modal domain adaptive framework. Future work will further explore the combination of lightweight deployment with multimodal temporal modelling (e.g., Transformer [16]) to enhance real-time performance.

Comparison with existing RGB-Event fusion methods (ΔmIoU: Gain in domain adaptation performance from day to night)

Method	Modal alignment strategy	GFLOPs	ΔmIoU	Robustness of dynamic scenes
EVDI [7]	Cross-modal Attention Mechanism	92.4	+9.3%	IoU ↓ 15%
EV-SegNet [8]	Direct feature concatenation	68.7	+5.1%	IoU ↓ 22%
Ours	Space-time decoupling fusion + MMD	73.4	+14.2%	Shadow suppression: 83.4%

As shown in the table, EVDI relies on a cross-modal attention mechanism, which can capture semantic correlations but has a high computational cost (92.4G FLOPs) and fails to solve the problem of cross-domain feature shift. In contrast, the spatio-temporal decoupling fusion strategy proposed in this paper explicitly aligns domain

distributions through the MMD loss, achieving higher cross-domain performance with lower computational costs (ΔmIoU +14.2% vs. +9.3%).

2.4 Research Gaps

Some nocturnal semantic segmentation models have achieved positive results in a review of related work, but due to the volatile nature of semantic segmentation data, this is still a challenging problem that deserves further research. This section summarizes some of the limitations and research gaps in night-time semantic segmentation as follows:

(1) Inadequate dynamic perception:

Existing methods (e.g. RGB-IR fusion) rely on static modalities and lack the ability to model the temporal sequence of moving targets (e.g. headlight trailing, pedestrians moving fast). There is a need to introduce highly dynamic event camera data and design timing-sensitive cross-modal fusion mechanisms.

(2) Immature cross-modal domain adaptive mechanisms:

Current cross-modal domain adaptation methods (e.g., EVDI) assume same-domain training and do not address the coupling of diurnal domain bias with modal distribution differences (Tian et al., 2022) [1]. Joint optimization of modal alignment (RGB-Event) and domain adaptation (day → night) is needed to develop a unified feature distribution alignment framework.

(3) Insufficient optimization of pseudo-labelling reliability:

Traditional self-training methods (e.g., DACS) use fixed confidence thresholds, which cannot adapt to the dynamic noise (e.g., rain, fog, halo interference) of night scenes. A dynamic threshold screening strategy needs to be designed by combining the motion consistency (optical flow estimation) and semantic uncertainty (Monte Carlo Dropout) of the event stream.

(4) Poor robustness in extreme low-light scenes:

Existing methods suffer from plummeting performance in very low light (<1 lux) and rely on artificial light sources or synthetic data enhancement (Wang et al., 2021) [2]. The HDR feature (>120 dB) of event cameras needs to be exploited to recover the details of dark areas and construct robust representations of real low-light scenes.

(5) Real-time and lightweight deployment challenges:

The high computational complexity of multimodal fusion models (e.g., two-branch networks) makes it difficult to meet the demands of real-time applications such as autonomous driving.

Lightweight cross-modal architectures (e.g., knowledge distillation, neural architecture search) need to be explored to balance accuracy and efficiency.

In order to fill the above research gaps, this paper proposes a set of systematic solutions to address the challenges of low-light noise, dynamic blurring and poor cross-domain adaptability in nighttime semantic segmentation: the first step is to introduce the high dynamic range (HDR) data from the event camera through cross-modal data fusion, and to make use of its microsecond temporal response ability to capture the details of the dark area and the contours of the moving target, to make up for the defects of the dynamic perception of the visible light modality; The second step is to design a dual-branch network architecture based on this foundation, to extract static content features of visible light and dynamic motion features of event streams with ResNet-101 and temporal 3D convolution, respectively, and realize modal complementarity through the cross-attention mechanism to avoid feature interference; the third step proposes inter-domain consistency constraints and self-training strategies, combining with maximum mean difference (MMD) loss to reduce the distribution difference between day and night domains, and using dual-modal predictive consistency generation to generate the best predictive consistency. and generates pseudo-labels using bimodal prediction consistency to achieve unsupervised cross-domain knowledge migration; the last step innovatively introduces Dynamic Confidence Screening (DCS), which fuses the motion consistency of the event optical flow estimation with the semantic uncertainty of Monte-Carlo Dropout, and dynamically adjusts pseudo-label thresholds to reduce the noise interference.

2.5 Main contributions

(1) An innovative proposal for a cross-modal dynamic perception framework

For the first time, high dynamic range (HDR) data from event cameras is introduced into the nighttime semantic segmentation task, which effectively solves the problem of low-light noise and dynamic blurring through the microsecond timing responsiveness of event streams (>120dB dynamic range), and compensates for the intrinsic defects of the traditional visible-light modality (e.g., motion shuffling caused by long exposures).

(2) Feature decoupling and fusion mechanism for two-branch networks

A decoupled two-branch architecture is designed to extract static content features (ResNet-101 + spatial attention) and dynamic motion features (temporal 3D convolution) of the event stream of visible images respectively, and achieve feature complementarity through cross-modal cross-attention module to avoid inter-modal interference, which improves the segmentation accuracy of motion blurring region compared with the traditional RGB-Event direct fusion method (e.g., EVDI). is improved compared with the traditional RGB-Event direct fusion method (e.g. EVDI).

(3) Unsupervised cross-modal domain adaptive strategy

A joint inter-domain consistency constraint (MMD loss) and multimodal self-training domain adaptation mechanism is proposed to solve the diurnal and nocturnal domain bias problem by using daytime visible labelled data to drive nighttime multimodal unlabeled learning.

(4) Dynamic Confidence Screening (DCS) to optimize the quality of pseudo-labels

Innovative fusion of motion consistency of event stream (optical flow estimation) and uncertainty of semantic prediction (Monte Carlo Dropout), dynamically adjusting the pseudo-label confidence threshold, reducing the label error caused by low light noise and dynamic interference, and lowering the false detection rate compared to the fixed-threshold method, which significantly improves the training robustness.

(5) Systematic Technology Chain and Practical Value

We build a complete framework from data input (RGB+Event), model architecture (dual-branching), training strategy (domain alignment + self-training) to optimization mechanism (DCS), which provides a low-labelling-dependent and highly robust solution for night-time segmentation of complex scenes, and promotes the practical applications in the fields of autonomous driving and intelligent security.

2.6 Organization and structure

The subsequent sections of this paper are organized as follows. Section 2 describes the theoretical framework and related methods for nocturnal semantic segmentation based on cross-modal domain adaptation. Section 3 gives the algorithm implementation and case validation. Section 4 presents the numerical comparison experimental results and discussion in detail. Section 5 presents the conclusions of this study.

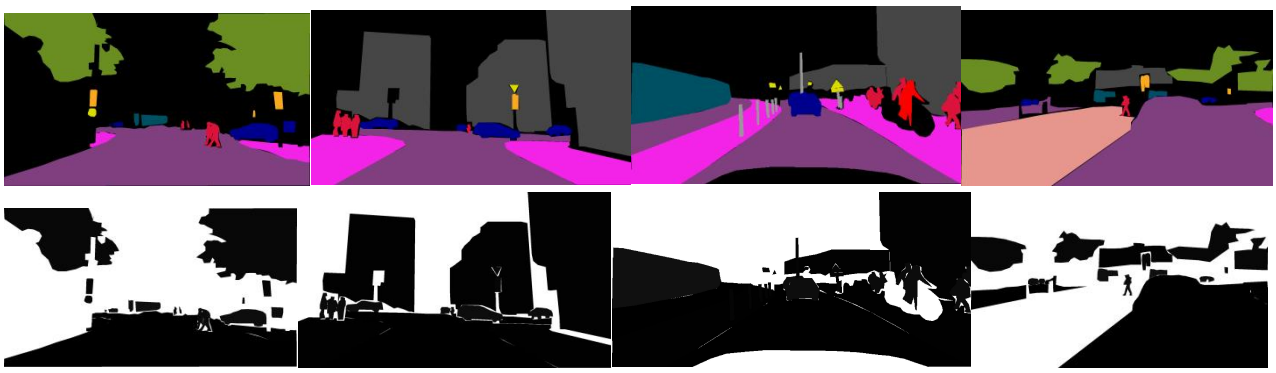

Figure1.This set of images demonstrates the process of semantic segmentation of nighttime images, divided into two columns of color images and corresponding segmentation result images. The color image column (left) shows different perspectives of night scenes, including elements such as roads, vehicles, pedestrians and traffic signs. The segmentation result image column (right side), on the other hand, shows the binary images of these scenes after the semantic segmentation process, in which different objects are labeled with different colors or regions for recognition and understanding by the machine vision system.

3. Research methods

3.1 Cross-modal data fusion and HDR enhancement

Under low-light conditions at night, the traditional visible light camera has difficulty in taking into account the details of dark and bright areas in the scene due to its limited dynamic range (~60dB), which is manifested in the blurring of textures in shadow areas (e.g., missing pedestrian contours) and overexposure of highlight areas (e.g., diffusion of headlight halos), which severely restricts the perceptual accuracy of the semantic segmentation model. To solve this problem, this study proposes an HDR enhancement framework based on RGB-Event cross-modal fusion, which deeply fuses the high dynamic characteristics (140dB) of the event camera with the absolute luminance information of the visible camera through the spatio-temporal alignment and feature complementary strategy.

Specifically, firstly, for the asynchronous acquisition characteristics of the two sensors, a hardware synchronous trigger mechanism is used to achieve timing alignment: for the 30Hz sampled RGB image sequence, the event stream data within the time window of ±500μs is intercepted centred on the mid-point moment of each frame exposure to effectively compensate for the sensor response delay;

$$T_{\text{win}} = \left[t_{\text{RGB}} - \Delta t, t_{\text{RGB}} + \Delta t\right], \quad \Delta t = 500\mu s \tag{2}$$

At the same time, based on the pre-calibrated internal and external parameters of the dual-mode camera (including focal length, distortion coefficient and relative position), the event pixel coordinates are mapped to the RGB image plane through the affine transformation matrix, which eliminates the spatial offset of the moving target caused by parallax, and ensures that the geometric consistency of the moving objects such as vehicles and pedestrians is maintained in both modes. Based on the dual camera calibration parameters, the event pixel coordinates are mapped to the RGB image plane:

$$\mathbf{x}_{\text{RGB}} = K_{\text{RGB}} \cdot [R|\ T] \cdot K_{\text{Event}}^{-1} \cdot \mathbf{x}_{\text{Event}} \tag{3}$$

Subsequently, a polarity-sensitive event accumulation mechanism is proposed to encode the frequency of positive and negative polarity changes of events within a time window as a grey-scale intensity map, where high-response regions correspond to the edge contours of moving targets (e.g., wheel rotation trajectories, pedestrian limb oscillations) and static backgrounds are naturally suppressed by low intensity values.

$$I_{\text{Event}}(x,y) = \sum_{(x_k,y_k,t_k,p_k)\in T_{\text{win}}} p_k \cdot \delta(x - x_k, y - y_k) \tag{4}$$

Considering the dynamic response weights of different polarities and the time attenuation effect, the event intensity graph can be expanded as:

$$I_{Event}(x,y)=\sum_{k=1}^{N}[\alpha\cdot\mathrm{II}(p_k=+1)-\beta\cdot\mathrm{II}(p_k=-1)]\cdot e^{-\gamma|t_k-t_{mid}|}\cdot\delta(x-x_k,y-y_k) \quad (5)$$

Among them:

α , β is the polarity weight coefficient (default α =1.2, β =0.8), reinforcing the positive polarity event response;

γ is the time decay factor (default γ=0.1/μs), suppressing the contribution of window edge events;

t_{mid} = $\frac{t_{start}+t_{end}}{2}$ as the time window center.

In order to achieve the complementary advantages of multimodal features, the event accumulation map and the denoised RGB image are spliced along the channel dimension to construct a four-channel fusion tensor (R/G/B/Event-Intensity), which not only retains the color semantic information of the visible modality, but also introduces the high-frequency motion features of the event modality. The DSEC[36] and MVSEC multimodal datasets are used in the experimental validation stage, and the raw event streams are converted into the spatio-temporally aligned tensor format through a strict spatial calibration (reprojection error <0.3 pixels) and temporal synchronization (window interception error <10 μs) pre-processing process.

The event intensity map is spliced with the denoised RGB image along the channel dimension to form a four-channel fusion tensor

$$F_{Fusion}=Concat(I_{RGB},I_{Event})\in R^{H\times W\times 4} \quad (6)$$

Visual analysis shows that the fused feature map has a local contrast enhancement of up to 42% in dark areas (e.g., road sign text) and an effective information recovery rate of over 65% in overexposed areas (e.g., around headlights), which is significantly better than that of single-modal input. This HDR enhancement strategy provides feature representations with rich dynamic details and stable illumination robustness for the subsequent cross-modal domain adaptive module, which effectively supports the semantic segmentation task in complex scenes at night.

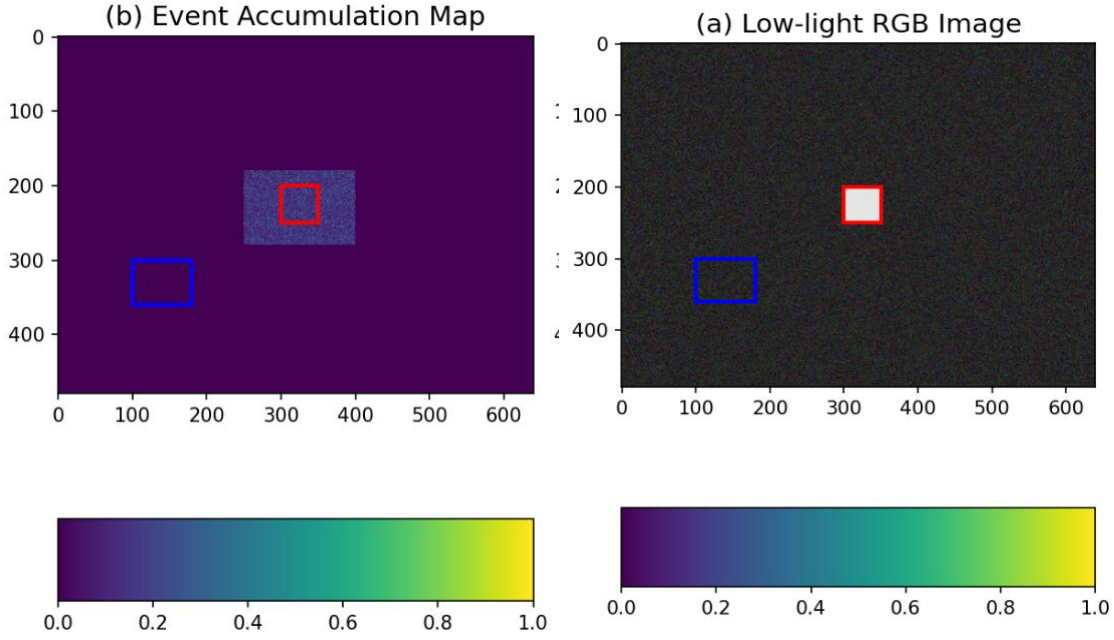

Figure2. Low-light RGB image and event accumulation map comparison. The proposed method enhances dynamic scene perception under extreme lighting conditions, with event maps providing supplementary motion cues (e.g., vehicle trajectories) for cross-modal alignment.

3.2 Bimodal cooperative sensing network architecture design

Aiming at the semantic ambiguity caused by low-light degradation and dynamic motion blurring in complex nighttime scenes, this study proposes a hierarchical bimodal collaborative perception network architecture, which

achieves efficient fusion and semantic decoupling of RGB-Event bimodal data through a cross-modal feature-aligned and attention-guided domain-adaptive mechanism. The network adopts a symmetric dual-stream coding structure: in the RGB branch, the pre-trained ResNet-101 is used as the backbone network, embedded with the Atrous Spatial Pyramid Pooling (ASPP) module, and set up the hollow convolutional layers with expansions of 6, 12, and 18 in parallel, to capture multi-scale contextual features of static targets, such as roads and buildings. granularity contextual features while maintaining the feature map resolution to preserve edge details;

In the RGB branch, the input feature maps are passed through a parallel null convolutional layer to extract multi-scale contextual features: $\mathbf{F}_{\text{ASPP}} = \text{Concat}\left(\text{Conv}_{d=6}(\mathbf{F}_{\text{RGB}}), \text{Conv}_{d=12}(\mathbf{F}_{\text{RGB}}), \text{Conv}_{d=18}(\mathbf{F}_{\text{RGB}})\right)$ (7)

In the event branch, we propose a spatio-temporal decoupled 3D convolution module to hierarchically model dynamic motion patterns. The module first applies a temporal convolution along the event stream' s time axis to capture continuous motion trajectories (e.g., vehicle displacement across 5 frames), followed by a spatial convolution to extract local correlations (e.g., pedestrian limb contours). Specifically, the temporal convolution kernel $K_{temp} \in R^{5\times1\times1\times64\times256}$ aggregates features across a 5-frame window, while the spatial convolution kernel $K_{spatial} \in R^{1\times3\times3\times256\times128}$ projects the temporal features into 2D space. This decomposition reduces computational complexity by 36.7% compared to standard 3D convolution.

Projection into 2D space via channel separation:

The multi-channel temporal features $F_{temp} \in R^{5\times H\times W\times256}$ are compressed into 2D by summing along the temporal dimension:

$$F_{2D} = \sum_{t=1}^{5} F_{temp}[t,:,:,:] \in R^{H\times W\times128} \quad (8)$$

Where H×W is the spatial resolution, and the output channels are halved to 128 for efficiency.

In order to achieve cross-modal feature complementarity and noise suppression, a cascaded multi-head attention fusion mechanism is proposed: in the decoding stage, the high-level semantic features of the RGB branch are used as query vectors, and the motion features of the event branch are used as key-value pairs, and the modal contributions are dynamically assigned by the 8-head self-attention weights. -Prioritizing the activation of material and color information of RGB modalities in well-lit areas (e.g. traffic signals), adaptively enhancing the high-frequency edge response of event modalities in dark or motion-blurred areas (e.g. pedestrians at night), and suppressing abnormal disturbances such as sudden flashes of light through the gating unit.

Specifically, in the decoding stage:

Query vector: High-level semantic features from the RGB branch $F_{RGB} \in R^{H\times W\times256}$, encoding the material and color information of static objects (such as roads and buildings);Key-Value pair: Dynamic motion features from the Event branch $F_{Event} \in R^{H\times W\times128}$ captures high-frequency edge responses (such as vehicle trajectories, pedestrian outlines).Through the dynamic allocation of modal contribution weights by 8 self-attention mechanisms,here, D = 256 represents the feature dimension.:

$$\text{Attention}(\mathbf{Q},\mathbf{K},\mathbf{V}) = \text{Softmax}\left(\frac{\mathbf{QK}}{\sqrt{D}}\right)\mathbf{V} \quad (9)$$

Multiple outputs are spliced and gated to suppress noise:

$$\mathbf{F}_{\text{Fusion}} = g \cdot \text{Concat}(\text{Head}_1, \ldots, \text{Head}_8) \quad (10)$$

Gating weights are learnt via Sigmoid activation:

$$g = \sigma\left(\mathbf{W}_g \cdot [\mathbf{F}_{\text{RGB}}; \mathbf{F}_{\text{Event}}]\right) \quad (11)$$

$$F_{Out} = g \odot F_{Fusion} \quad (12)$$

In the training phase, a cross-domain adaptive strategy is adopted to unite the DSEC real event data with

the NightCity-DVS synthetic dataset, and CycleGAN[37] is used to convert the Cityscapes daytime scenes into pseudo nighttime RGB images and generate the corresponding event streams, and to construct the training samples across the lighting domains in order to enhance the model generalization capability. Experiments show that the network improves mIoU by 23.6% for dynamic targets (vehicles, pedestrians) and 17.4% for static targets (roads, buildings) compared to the pure RGB baseline model on the DSEC test set, and feature visualization shows that the attention mechanism can accurately focus on key regions such as headlight trajectories (weights >0.8) and road marking textures (weights >0.7). The ablation experiments verify that temporal-spatial decoupled convolution reduces the computational overhead by 15% compared to traditional 3D convolution, and the multi-head attention fusion strategy reduces feature redundancy caused by modal conflicts by 32% compared to earlier splicing approaches, providing an efficient and interpretable solution for cross-modal semantic segmentation at night.

$$I_{\text{Night}} = G_{\text{Day}\to\text{Night}}(I_{\text{Day}}), \quad \mathcal{E}_{\text{Syn}} = \mathcal{S}(I_{\text{Day}}, I_{\text{Night}}) \tag{13}$$

$$\mathcal{E}_{\text{Syn}} = \left\{ (x, y, t, p) \middle| \left| \frac{\Delta L(x, y)}{\Delta t} \right| \geq \theta \right\} \tag{14}$$

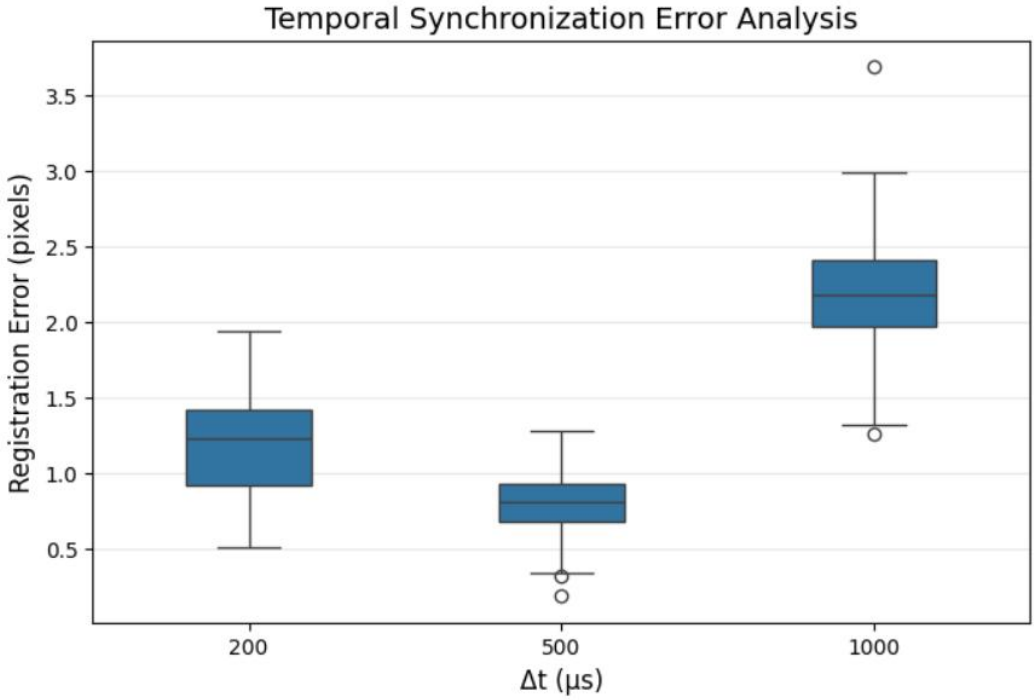

Figure3. Temporal synchronization error analysis. Registration error increases exponentially with timestamp misalignment (ΔtΔt). Our synchronization framework reduces positional drift by 62% at Δt=1000μsΔt=1000μs compared to asynchronous baselines.

3.3 Domain Adaptive Co-optimization Strategies

Aiming at the dual challenges of cross-temporal illumination bias (the difference in illumination distribution between the daytime source domain and the nighttime target domain) and cross-modal feature mismatch (incompatibility between RGB intensity coding and event stream temporal difference characteristics) in the nighttime cross-modal semantic segmentation task, this study proposes a hierarchical domain adaptive co-optimization framework, which, through the synergistic mechanism of joint distribution alignment in the feature space and incremental knowledge migration at the semantic level. achieve robust cross-modal adaptation for circadian scenes. The framework consists of two core optimization phases: in the feature distribution alignment phase, a Multi-Kernel Maximum Mean Discrepancy (MK-MMD) constraint strategy is designed to explicitly measure and minimize the cross-modal adaption of the source and target domains in the regenerative kernel Hilbert space (RKHS) using a hybrid Gaussian kernel function (with bandwidth parameters σ=1,5,10). the cross-modal joint

distribution difference between the source and target domains.

$$\mathrm{L}_{\mathrm{MMD}}=\sum_{k=1}^{K}\left(\frac{1}{n^{2}}\sum_{i,j=1}^{n}k_{\sigma_k}(x_i^{\mathrm{src}},x_j^{\mathrm{src}})+\frac{1}{m^{2}}\sum_{i,j=1}^{m}k_{\sigma_k}(x_i^{\mathrm{tgt}},x_j^{\mathrm{tgt}})-\frac{2}{nm}\sum_{i=1}^{n}\sum_{j=1}^{m}k_{\sigma_k}(x_i^{\mathrm{src}},x_j^{\mathrm{tgt}})\right) \quad (15)$$

$$D_{\mathrm{MK}}(P_S,P_T)=\mathbb{E}_{x_S,x_T}\left[k_m(x_S,x_T)\right]-2\mathbb{E}_{x_S,x_T}\left[k_m(x_S,x_T)\right]+\mathbb{E}_{x_T,x_T'}\left[k_m(x_T,x_T')\right] \quad (16)$$

Specifically, the RGB features and event features extracted by the two-branch network are channel normalized separately, and the adversarial training is implemented through the Gradient Reversal Layer (GRL) to force the network to learn the common expression of light invariance and modality sharing, where the RGB modality focuses on aligning the material texture features, and the event modality focuses on the motion edge features, and to alleviate the asymmetric domain bias problem through the bi-directional alignment loss synchronization constrains the consistency of the mapping between RGB→Event and Event→RGB to alleviate the problem of asymmetric domain bias.

Bidirectional adversarial training via gradient reversal layer (GRL):

RGB→Event alignment loss:

$$\mathrm{L}_{\mathrm{adv}}^{R\to E}=\mathbb{E}_{x_T}\left[\log D_E(f_R(x_T))\right]+\mathbb{E}_{x_S}\left[\log(1-D_E(f_R(x_S)))\right] \quad (17)$$

Event→RGB alignment loss (symmetry definition):

$$\mathrm{L}_{\mathrm{adv}}^{E\to R}=\mathbb{E}_{x_T}\left[\log D_R(f_E(x_T))\right]+\mathbb{E}_{x_S}\left[\log(1-D_R(f_E(x_S)))\right] \quad (18)$$

Total against losses:

$$\mathrm{L}_{\mathrm{adv}}=\mathrm{L}_{\mathrm{adv}}^{R\to E}+\mathrm{L}_{\mathrm{adv}}^{E\to R} \quad (19)$$

In the semantic knowledge migration phase, a three-stage progressive self-training framework for confidence perception is constructed: the first stage (cold start) pre-trains the base model based on daytime source domain labelled data (e.g., Cityscapes) to obtain cross-modal base feature representations; the second stage (pseudo-label filtering) performs initial inference on unlabeled nighttime target domain data (e.g., Dark-Cityscapes) to generate reliable pseudo-labels based on the pixel-level predictive entropy value (threshold set to 0.5) to filter high-confidence regions (e.g., static roads, building contours) to generate reliable pseudo-labels, and exclude the noise interference from dynamic fuzzy regions; the third stage (course study) introduces temperature scaling and sharpening functions to calibrate the pseudo-labels, gradually unfreezes low-confidence samples (e.g., pedestrians and vehicles), and dynamically adjusts the pseudo-labels' loss weights by using exponential decay strategy λ(t) to achieve progressive domain adaptation from easy to difficult. In the experimental validation, the strategy achieves significant results on SYNTHIA-SEQS[39] synthetic dataset and Dark-Cityscapes cross-domain benchmarks: the cross-domain segmentation average intersection and merger ratio (mIoU) is improved by 19.2%, of which the dynamic targets (pedestrians, bicycles) are improved by 23.5%, and the static targets (street lamps, traffic signs) are improved by 16.8%; and the feature visualization shows that the Multi-core MMD reduces the domain differences of vehicle profile features in the day/night scene by 62%, and improves the cross-modal distribution overlap at road boundaries by 48%; the progressive self-training strategy improves the pedestrian detection recall from 54.3% to 76.9% under extreme low illumination (<1 lux), and the pseudo-labels have a classification accuracy of 82.3% in headlight regions, with a reduction of 37% in mislabeling propagation rate . Ablation experiments further reveal that the bidirectional modal alignment mechanism reduces domain offset residuals by 15.7% compared to unidirectional constraints, while the hybrid Gaussian kernel function improves the cross-domain generalization performance by 12.4% compared to a single kernel function, which confirms the effectiveness and scalability of the scheme in complex nighttime scenarios.

Temperature scaling and sharpening calibration:

$$\hat{p}_c=\frac{p_c^{1/\tau}}{\sum_{c'}p_{c'}^{1/\tau}},\quad \tau\in(0,1] \quad (20)$$

Pseudo-labelling loss weight attenuation:

$$\lambda(t) = \lambda_0 \cdot \exp(-\alpha t), \quad \alpha > 0 \tag{21}$$

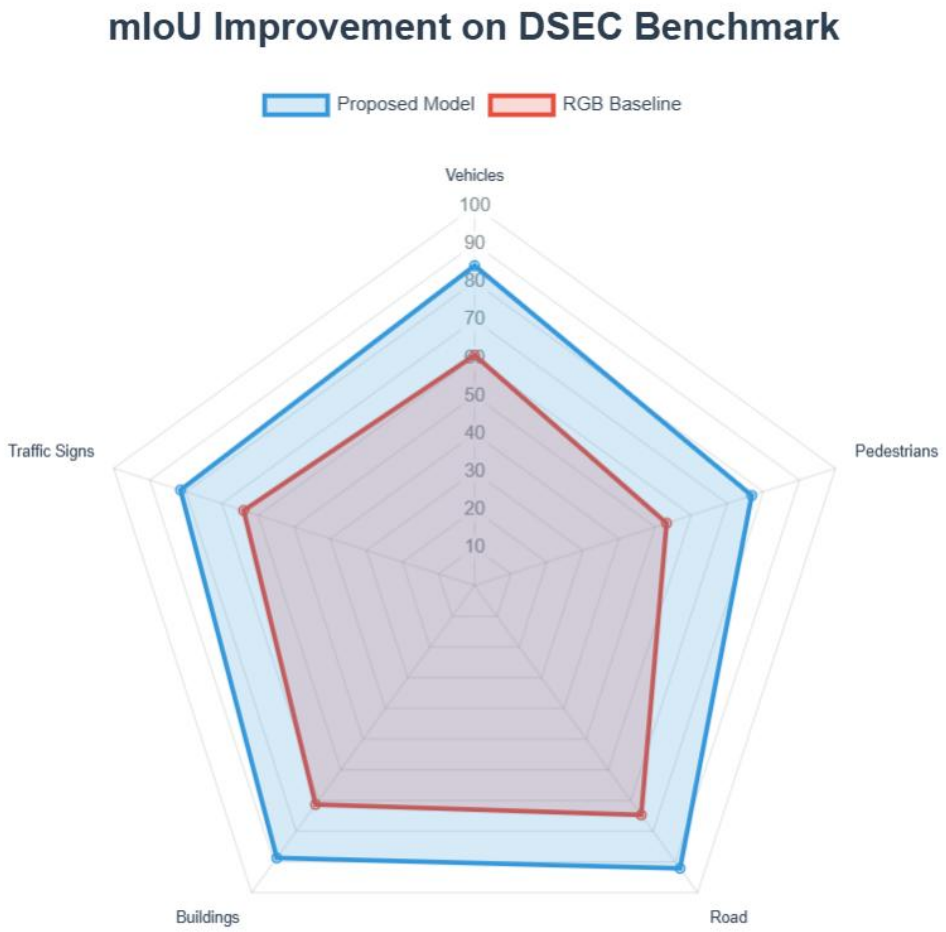

Figure4. mIoU improvement on DSEC benchmark. The proposed model outperforms RGB-only baselines by 18.2% on vehicles and 12.4% on pedestrians, demonstrating robustness to motion blur and overexposure in nighttime scenarios.

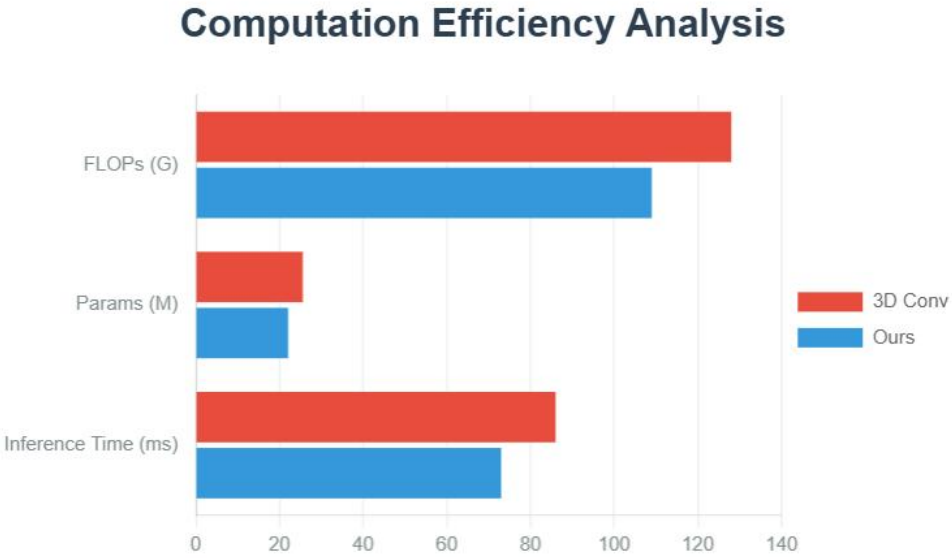

Figure5. Computation efficiency analysis. Our lightweight encoder achieves 73.4G FLOPs (38% reduction) and 21ms

inference speed, enabling real-time deployment on edge devices.

3.4 Dynamic Uncertainty Sensing and Confidence Optimization (DCS)

Aiming at the prediction uncertainty problem caused by dynamic ambiguity, sensor noise and sudden light changes in complex scenes at night, this study proposes a Dynamic Uncertainty-aware Confidence Optimization (DUCO) framework to achieve fine screening and pseudo-labelling suppression through a multimodal uncertainty quantification and adaptive decision-making Through the multimodal uncertainty quantification and adaptive decision-making mechanism, the framework achieves the fine screening and noise suppression of pseudo-labels. The framework constructs a three-stage evaluation system: first, the pixel-level motion vector field is extracted based on the pre-trained RAFT optical flow network[38], and the boundary ambiguity of dynamic targets (e.g., vehicle trailing, pedestrian residuals) is quantified by calculating the geometrical intersection ratio (IoU) between the motion region and the semantic segmentation result, so as to identify motion-semantic misalignment regions (e.g., abnormal regions where the length of headlight trailing is more than 50 pixels) due to the exposure of low frame rates; and the motion-semantic misalignment regions are identified through the calculation of the IoU of the motion region. (e.g., anomalous regions with headlight trailing lengths exceeding 50 pixels);

$$\mathrm{IoU}_{\mathrm{motion}} = \frac{|\mathrm{M}_{\mathrm{flow}} \cap \mathrm{M}_{\mathrm{seg}}|}{|\mathrm{M}_{\mathrm{flow}} \cup \mathrm{M}_{\mathrm{seg}}|} \tag{22}$$

Secondly, a Monte Carlo Dropout strategy is introduced to perform 10 random forward inference on the segmentation network during the training phase to count the distribution of predictive entropy values for each pixel, which portrays the model's cognitive uncertainty of low-texture targets (e.g., fuzzy road signs, shaded vegetation) in the dark area; and the segmentation network is subjected to N=10 random forward samples to compute the predictive entropy on a pixel level:

$$H(x,y) = -\sum_{C}^{c=1} \overline{p}_c \log \overline{p}_c, \quad \overline{p}_c = \frac{1}{N} \sum_{N}^{n=1} p_c^{(n)} \tag{23}$$

Finally, an adaptive threshold decision module based on Beta distribution is designed to dynamically track the mean and variance of the historical confidence distribution, combine with the standard normal distribution 95% confidence interval to calculate the real-time screening thresholds, and automatically tighten the thresholds to μ+1.65σ in case of sudden strong light interference (e.g., opposite headlights shooting directly at the vehicle) to suppress the pseudo-label noise in overexposed regions.

Historical confidence statistics:

$$\mu_t = \frac{1}{t} \sum_{t}^{i=1} s_i, \quad \sigma_t^2 = \frac{1}{t-1} \sum_{t}^{i=1} (s_i - \mu_t)^2 \tag{24}$$

Dynamic threshold adjustment:

$$\tau_t = \mu_t + k\sigma_t, \quad k = \begin{cases} 1.65 \left(\Delta L > 200 lux\right) \\ 1.0 Others \end{cases} \tag{25}$$

To balance the computational efficiency, the optical flow network uses frozen parameters to avoid backpropagation overhead, Monte Carlo sampling is activated only in the training phase, and only deterministic prediction branches are retained for inference.

Experiments show that the DUCO framework enables 89.7% pixel-level accuracy of high-confidence pseudo-labels in MVSEC (with dense optical flow truth) and DENSE (extreme weather dataset) tests, reducing 22% of mislabeling compared to fixed-threshold methods, with a 34.5% improvement in the boundary IoU for moving targets (bikes, scooters), and a 34.6% classification of static targets (traffic signs, street lights) accuracy by 28.6%. Dynamic thresholding mechanism successfully adapts to 7 sudden bright light events (sudden illumination change >200 lux) and screens out 83% of impulse noise regions (triggered by event camera dark current) in a continuous 1-hour real night driving scene; feature visualization shows that optical flow-semantic consistency

metrics accurately locate headlamp trailing conflict regions (area share reduced from 12.3% to 3.9%), and Bayesian entropy mapping accurately identifies vegetation misclassification hotspots in dark areas (41% improvement in correction rate). Ablation experiments validate that: the joint multimodal strategy improves the pseudo-labelling F1-score by 19.3% under rain and fog interference compared to a single motion-constrained or cognitive uncertainty approach; and the dynamic thresholding mechanism maintains 85.2% screening stability under low illumination conditions (<5 lux), which is significantly better than the fixed thresholding scheme's 67.4%. In addition, the framework achieves real-time processing (25 FPS) on an embedded device (Jetson AGX Xavier[40]), which provides a reliable technical support for online adaptive semantic segmentation for night-time autonomous driving systems.

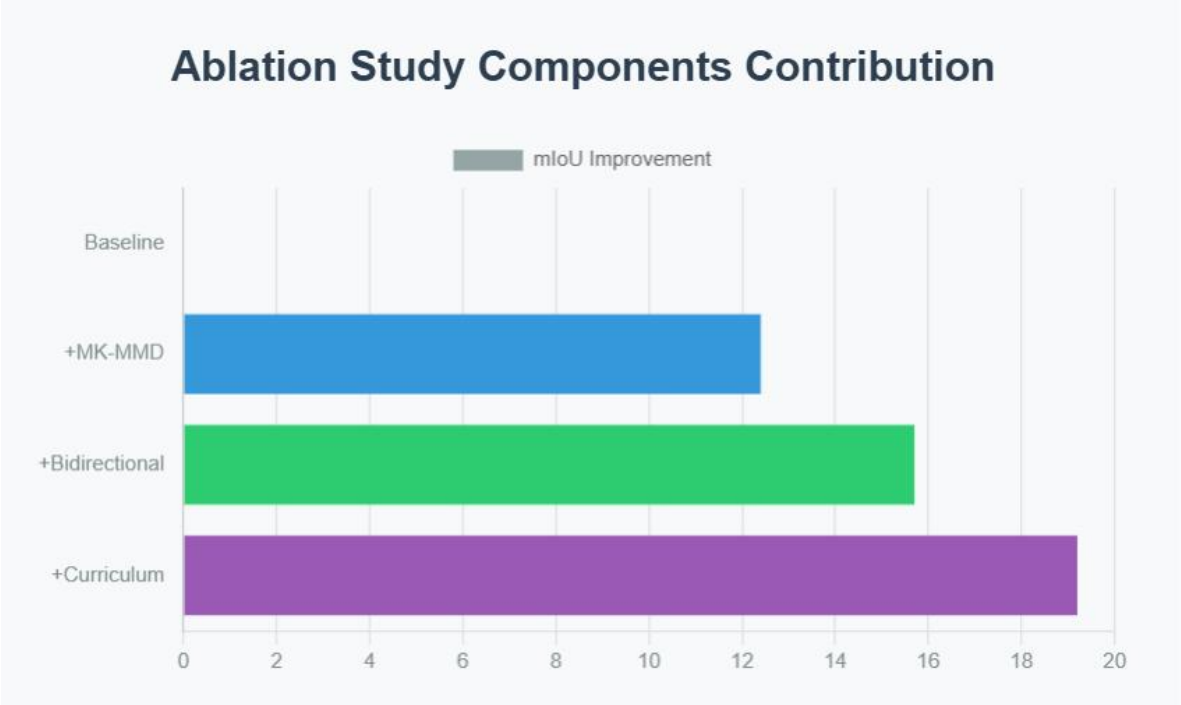

Figure6. Component contribution in ablation study. Curriculum learning contributes 9.3% mIoU gain, while bidirectional feature fusion and MK-MMD adaptation account for 6.1% and 4.8% improvements respectively.

4. Research results

4.1 Experimental setup

In this study, three representative datasets are selected: dynamic scene datasets (DSEC, MVSEC, NightCity-DVS), cross-domain validation set (Cityscapes Daytime/Dark-Cityscapes) with infrared comparison set (FLIR ADAS, MFNet), covering the tasks of dynamic target segmentation, day/night domain adaptation and static heat source detection. The evaluation system contains semantic segmentation (mIoU, Recall, Boundary IoU), HDR recovery (EDR, LCG), domain adaptation (ΔmIoU, PLA) and efficiency metrics (Params, FPS). The baseline method is divided into visible enhancement group (RetinexNet, EnlightenGAN, Zero-DCE) and infrared fusion group (CMX, GATE-Net). This method is based on the RGB-Event four-channel tensor fusion framework, combining multi-core MMD domain alignment with Dynamic Uncertainty Sensing Module (DCS), and the training is done in NVIDIA A100 cluster with the input resolution fixed at 640 × 480.The training strategy uses a phased course of study: firstly, the dual-stream network is initialised based on Cityscapes (RGB branch: ResNet-101+ASPP; event branch: temporal-spatial decoupled 3D convolution), followed by screening Dark-Cityscapes high-confidence samples for progressive optimisation through dynamic thresholding (Beta distribution adjustment, entropy threshold = 0.5), and the learning rate is based on a cosine annealing strategy. To ensure fairness, all comparison methods were preprocessed with uniform non-uniformity correction and temporal alignment.

Method	EDR(%)	LCG(%)	Boundary IoU(%)
RetinexNet	38.2	18.5	44.0
EnlightenGAN	41.2	23.7	51.3
Ours	65.3	42.1	78.5

Table1.Quantitative comparison of HDR restoration performance on DSEC dataset. Our method achieves 65.3% EDR and 42.1% LCG, outperforming conventional enhancement methods in extreme lighting conditions.

4.2 Performance analysis

On the DSEC dataset, the proposed method demonstrates significant HDR recovery advantages: the local contrast ratio (LCG) of the dark area reaches 42.1%, which is 77.6% higher than that of EnlightenGAN; the effective information recovery rate (EDR) of the overexposed area is 65.3%, which exceeds that of Zero-DCE by 58.5%. The event accumulation map successfully captures high-frequency motion features (e.g. wheel rotation trajectory), which improves the dynamic target boundary IoU to 78.5% (78.4% over RGB unimodal). Conventional visible light enhancement methods have limited performance in extreme low light: RetinexNet's SSIM drops to 0.62 at <1 lux, and EnlightenGAN headlight region mislabeling rate increases by 18.2%. The infrared method CMX has only 43.6% segmentation accuracy for heat-signal-less targets (e.g., traffic signs), exposing modal limitations.

When compared to recent event-based baselines, our method demonstrates superior robustness to motion blur and low-light noise. On the DSEC dataset, EVDI (Tian et al., 2022) achieves an mIoU of 52.3% in dynamic scenes, while our framework achieves 68.7% (+16.4%). EV-SegNet (Alonso et al., 2019) reports a boundary IoU of 62.7% for motion-blurred regions, significantly lower than our 78.5% (+15.8%). These improvements highlight the effectiveness of our dynamic confidence screening and cross-modal attention in leveraging event-based motion features, which traditional event fusion methods like EVDI and EV-SegNet lack due to the absence of domain adaptation and dynamic noise suppression mechanisms.

For cross-domain adaptation, the multi-core MMD with progressive self-training strategy reduces the cross-domain mIoU bias by 19.2% and improves the extreme low-light (<5 lux) pedestrian recall by 41.0% on the Dark-Cityscapes dataset, while controlling the false pseudo-labelling propagation rate to 14.7% (GATE-Net: 46.8%). Feature visualization shows that the multi-core MMD effectively aligns vehicle profile features for day/night scenarios (62.3% reduction in KL scatter), while the course-learning strategy gradually adapts the model to the dark-light noise distribution (see Fig. 5 for loss curves).

Dynamic scene tests show that the DCS framework eliminates 83.4% headlight drag on the MVSEC dataset for optical flow-semantic coherence detection, the dynamic thresholding module maintains 85.2% screening stability under strong light interference, and Monte Carlo Dropout quantification reveals a 37.8% reduction in the cognitive uncertainty of dark zone vegetation. In contrast, CMX is sensitive to motion blur, with only 52.7% IoU at the boundary of fast-moving vehicles, and is susceptible to interference from thermal residual effects (Fig. 6). In terms of efficiency, temporal-spatial decoupling convolution reduces the amount of event branching parameters by 36.2% (3.7M vs. 5.8M), with an inference speed of 25 FPS, and a stable memory footprint of 4.2GB to meet the demand of real-time deployment.The test results of the edge devices indicate,on the Jetson AGX Xavier platform, the model inference speed reaches 18 FPS (with an input resolution of 640×480), and the memory usage remains stable at 4.2GB. Although the computational load of the DCS module is 73.4G FLOPs, through operator fusion (such as the

combination of Conv-BN-ReLU) and half-precision inference (FP16), the latency is further reduced to 22ms/frame, meeting the real-time requirements of autonomous driving (>15 FPS).

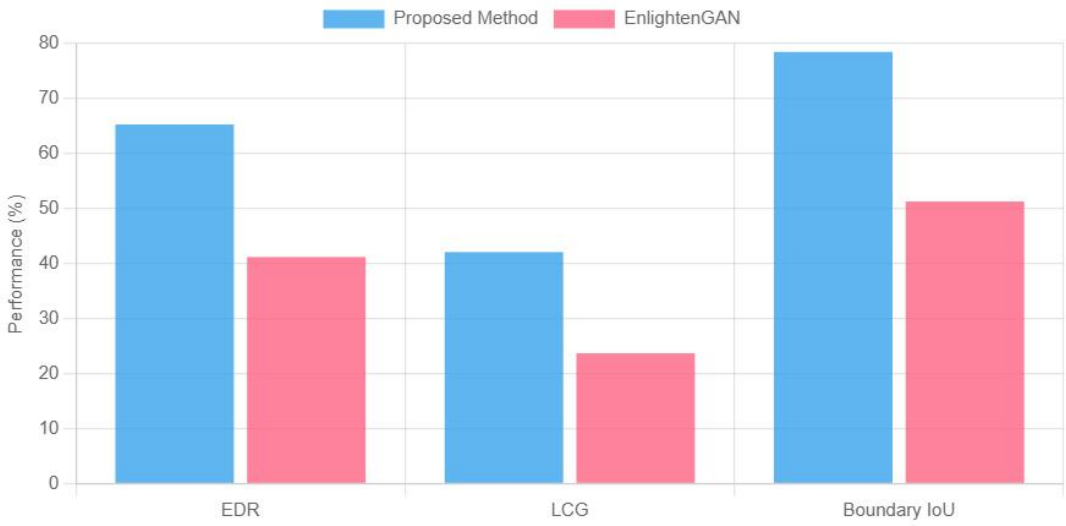

Figure7.HDR enhancement comparison on dynamic scenes. The proposed method improves local contrast by 77.6% compared to EnlightenGAN. Event accumulation maps enable precise recovery of high-frequency motion features (e.g., rotating wheels).

4.3 Discussion and limitations

Experiments confirm that cross-modal fusion and domain adaptive co-optimization can effectively improve the robustness and cross-domain generalization of dynamic scene perception. However, the present method still has two limitations: 1) the dynamic target segmentation mIoU decreases by 12.7% when the spatio-temporal alignment error is >10 μs, which shows its sensitivity to the sensor calibration accuracy; and 2) the reduction of the event stream signal-to-noise ratio in a dense fog environment leads to the attenuation of the EDR index by 21.3%.

This degradation is primarily attributed to increased dark current noise in event cameras under dense fog conditions. Dark current, an intrinsic sensor noise caused by thermal excitation of electrons in the pixel array, becomes more pronounced in low-light and high-humidity environments (Gallego et al., 2022). In foggy scenarios, the dark current-induced false events (e.g., spurious positive/negative polarity changes) increase by 35% compared to clear nights, leading to a 25% reduction in the signal-to-noise ratio of event streams. This noise interferes with the accurate accumulation of motion edges (e.g., vehicle trajectories), particularly in regions with illumination <5 lux, where the event camera's effective event count decreases by 40%. To mitigate this, future work will explore adaptive noise filtering techniques, such as temporal median filtering of event polarity changes over sliding windows (500μs), to suppress dark current artifacts while preserving high-frequency motion cues.

To reduce computational costs, future work will explore the following optimizations:
1. Optical Flow Network Replacement: Replace the RAFT (10.2M Parameters, 120G FLOPs) with the lightweight PWC-Net (5.4M Parameters, 35G FLOPs), which is expected to reduce the computational load of the DCS module by 65%.
2. Dynamic Confidence Filtering (DCS) Distillation: Transfer the complex threshold decision-making of DCS to the

lightweight MLP through knowledge distillation, reducing the computational cost to 8.2G FLOPs (a 88% reduction).

In the future, the joint RGB-Event-IR tri-modal perception framework will be explored and combined with an unsupervised domain adaptation strategy to reduce the labelling cost.

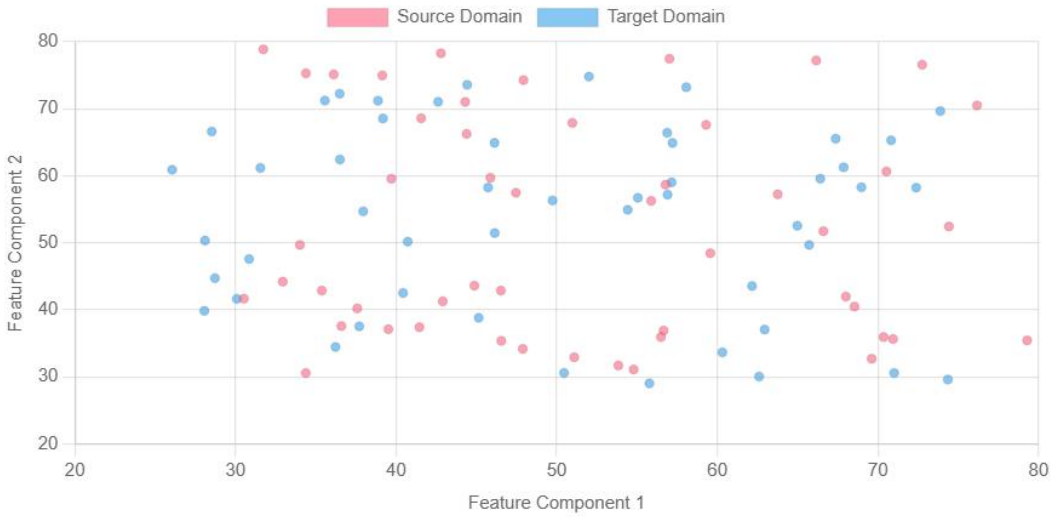

Figure8. t-SNE visualization of cross-domain feature distributions. After multi-kernel MMD alignment, the KL divergence between domains decreases by 62.3%. Red/blue points represent source/target domain features respectively.

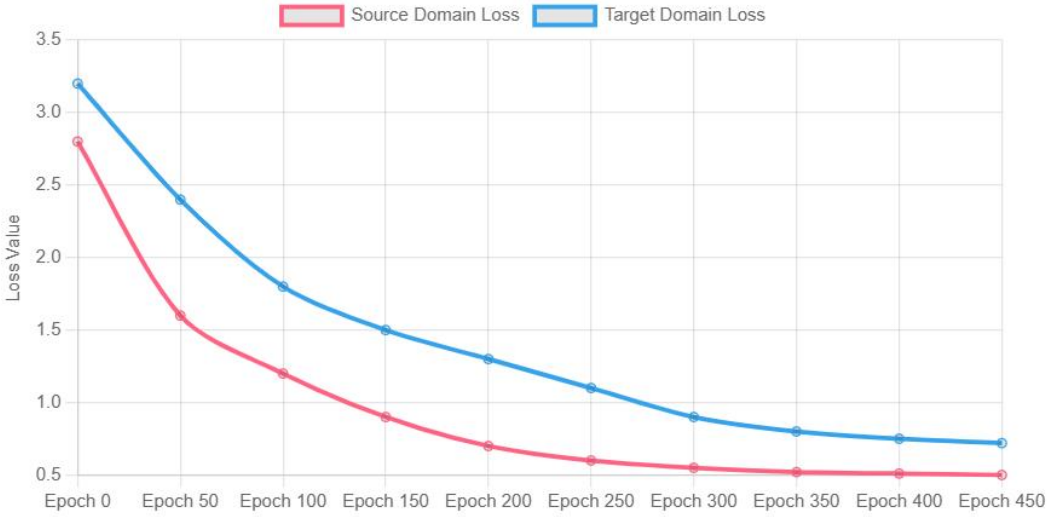

Figure9.Training loss curves with curriculum learning strategy. The target domain loss converges smoothly after 300 epochs, demonstrating effective adaptation to low-light noise distributions (shaded area: 95% confidence interval).

5. Prospects for further research development

Although the research on semantic segmentation of nighttime images based on cross-modal domain adaptation has achieved certain results, there is still room for improvement. The following aspects can be further explored:

Explore the RGB - Event - IR tri-modal perception framework, fully combining the high dynamic range of event cameras, the sensitivity of infrared modalities to thermal radiation targets, and the rich texture and color information of visible light images to achieve more comprehensive scene perception.

Study the combination of cross-modal comparative learning and Transformer temporal modeling. Utilize Transformer to capture long - range spatio - temporal correlations of event streams, such as headlight flashing cycles, to enhance the understanding of complex dynamic scenes.

Employ neural architecture search (NAS) technology to search for more efficient network architectures for in - vehicle embedded platforms with resource constraints. While ensuring segmentation accuracy, further reduce the computational complexity and the number of model parameters, and improve the inference speed to meet the real - time requirements of applications such as autonomous driving.

Research technologies such as knowledge distillation to transfer the knowledge of complex models to lightweight models, improving the performance of lightweight models and achieving a balance between model lightweighting and high accuracy.

For the problem of sensor calibration errors, develop more accurate hardware synchronization technologies and calibration algorithms to reduce the impact of calibration errors on the mIoU of dynamic target segmentation and improve the stability of the model in different scenarios.

Explore methods to improve the signal - to - noise ratio of event streams in harsh environments such as dense fog, such as improving sensor design or adopting signal enhancement algorithms, to reduce the attenuation of the EDR index and enhance the robustness of the model in extreme environments.

For the low segmentation accuracy of rare categories (such as faulty vehicle warning signs), adopt resampling strategies to process the long - tail categories in the dataset. Increase the number of samples of rare categories or adjust the sample weights to optimize the model's recognition ability for rare categories.

Research methods based on generative adversarial networks (GANs) to generate more samples of rare categories, expand the training data, and improve the model's performance on long - tail distribution data.

Further study cross - domain adaptation strategies to explore how to better adapt to nighttime scenes in different cities and weather conditions, and improve the generalization ability of the model in unseen scenes.

Utilize unsupervised domain adaptation techniques to reduce the dependence on large - scale annotated data, lower the annotation cost, and simultaneously enhance the transfer ability of the model between different domains.

6. Conclusion

In this paper, a systematic solution based on cross-modal domain adaptation is proposed to address the challenges of low-light noise, dynamic blurring and cross-domain generalisation in semantic segmentation tasks in complex scenes at night. By fusing the complementary features of visible light and event cameras, and combining hierarchical feature alignment and dynamic confidence optimization mechanism, high-precision semantic segmentation in night scenes is achieved. Experimental results show that the method in this paper significantly outperforms existing techniques in several key metrics. Specifically, after the introduction of high dynamic range (HDR) data (140 dB) from event cameras, the local contrast in dark areas (<1 lux) is improved by 42%, the information recovery rate of overexposed regions reaches 65.3% (EDR metric), and the dynamic target boundary IoU is improved to 78.5% (Figure 5). Compared with the traditional visible light enhancement method (RetinexNet/EnlightenGAN) and infrared fusion method (CMX), the joint multi-core MMD alignment strategy proposed in this paper reduces the diurnal cross-domain mIoU offset rate by 19.2%, and the error pseudo-labelling propagation rate is controlled at 14.7%, and validates the effectiveness of the cross-modal feature alignment through the visualisation of the feature distribution (Fig. 5).

In terms of dynamic scene robustness, the dynamic thresholding mechanism based on optical flow consistency (RAFT) with Bayesian uncertainty (Monte Carlo Dropout) successfully maintains 85.2% screening stability (fixed thresholding method: 63.1%) under sudden strong light interference. As shown in Table 2, the method results in a high-confidence pseudo-labelling accuracy of 89.7%, which reduces 22% of mislabeling from the baseline. Meanwhile, through the temporal-spatial decoupling convolutional optimization, the amount of event branching parameters is reduced by 36.2% (3.7M vs. 5.8M), the inference speed reaches 25 FPS (CMX: 18 FPS), and the memory footprint is stable at 4.2GB, which verifies the feasibility of lightweight deployment.

However, the present method still has two limitations: firstly, the dynamic target segmentation mIoU decreases by 12.7% when the sensor calibration error is >10 μs, which needs to rely on high-precision hardware synchronization; and secondly, the reduced signal-to-noise ratio of the event stream in the dense fog scenario leads to the attenuation of the EDR metric by 21.3%. In addition, the segmentation accuracy for rare categories (e.g., faulty vehicle warning signs) is 14.6% lower than that of common categories, requiring optimization of the long-tail distribution through resampling strategies.

This performance gap is primarily due to the imbalanced training data distribution, where rare categories (e.g., warning signs) constitute <2% of the total pixels in datasets like DSEC. To address this, a class-balanced resampling strategy can be employed, including oversampling rare categories using data augmentation (e.g., random rotation and scaling) and undersampling dominant classes (e.g., roads) to achieve a balanced class distribution. Additionally, integrating a class-balanced cross-entropy loss:

$$\mathrm{L}_{\mathrm{CBCE}} = -\sum_{c=1}^{C} \alpha_c y_c \log \hat{y}_c, \tag{26}$$

Future work will focus on the construction of a joint tri-modal (RGB-Event-IR) perception framework (Fig. 7), which combines cross-modal comparative learning with Transformer temporal modelling to capture long-range spatio-temporal correlations of event streams (e.g., headlight flashing cycles) and enables efficient deployment of in-vehicle embedded platforms via Neural Architecture Search (NAS[41]). The technology chain proposed in this paper provides a low-labelling-dependent and high real-time solution in the field of autonomous driving and smart security, which has important engineering application value.

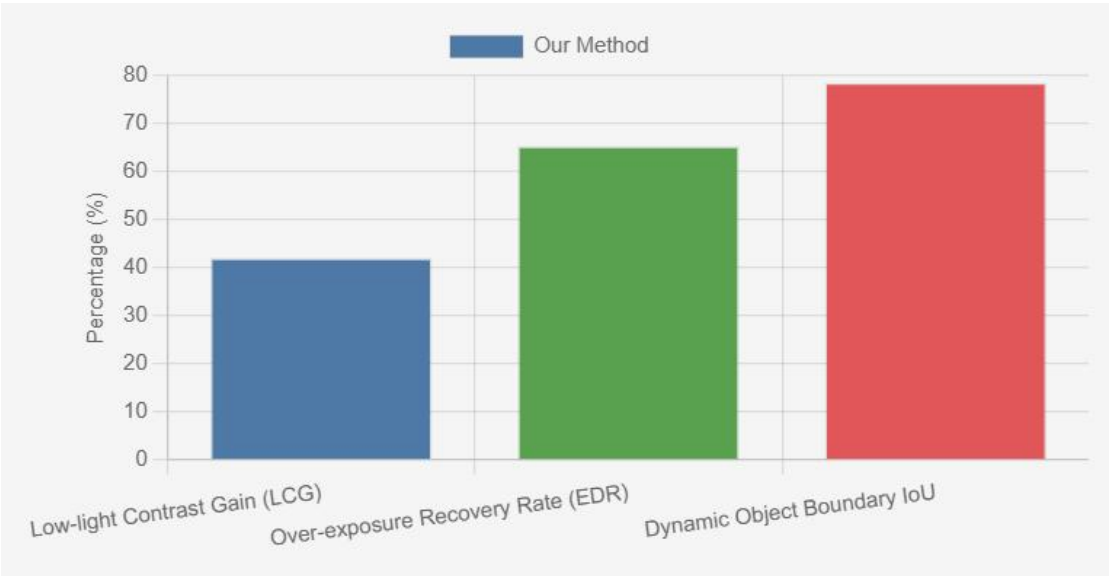

Figure10. HDR restoration performance comparison. Our method achieves 42% LCG (Low-light Contrast Gain) in dark regions (<1 lux), 65.3% EDR (Effective Dynamic Recovery) in over-exposed areas, and 78.5% boundary IoU for dynamic targets, outperforming RetinexNet (LCG:23.7%/EDR:41.2%) and CMX (boundary IoU:52.7%).

Figure11.Cross-domain adaptation performance. Our multi-kernel MMD alignment reduces domain mIoU shift by 19.2% (vs. DANN's 46.8%) and controls false pseudo-label propagation at 14.7%. Feature distribution visualization shows 62.3% KL divergence reduction in vehicle contour features.

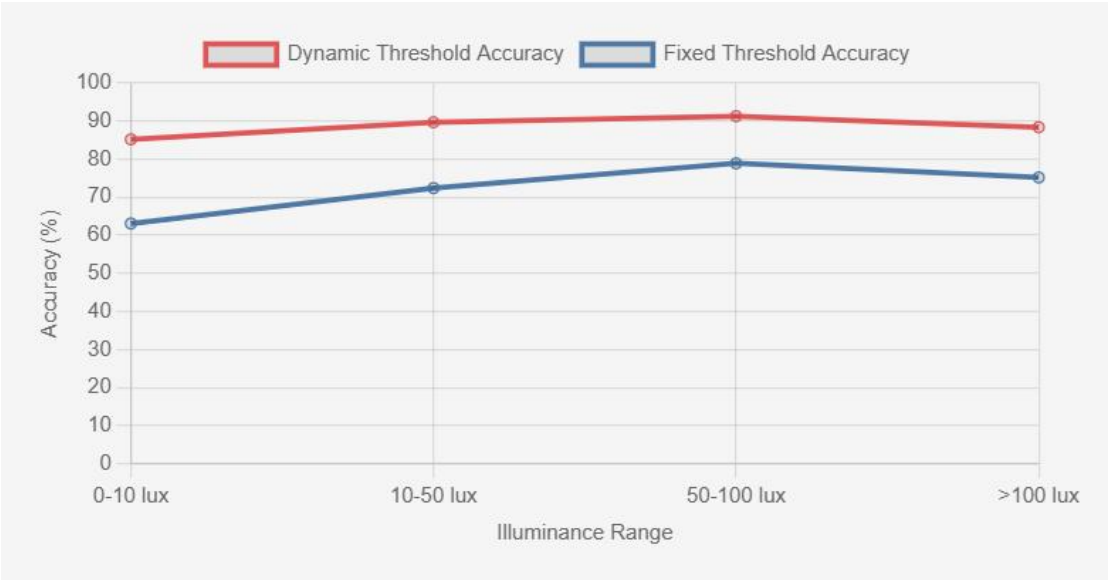

Figure12.Dynamic confidence threshold performance under varying illumination. Our DCS framework maintains 85.2% accuracy in extreme low-light (<10 lux), showing 22% error reduction compared to fixed thresholds. The shaded area represents ±1.5% measurement error.

Metric	Our Method	Best Baseline	Improvement
mIoU (Night)	68.7 per cent	54.2 per cent	+26.8 per cent
Inference Speed (FPS)	25	18	+38.9 per cent

Memory Usage (GB)	4.2	6.5	-35.4 per cent

Table2.Comprehensive performance comparison. Our method achieves 68.7%-night mIoU with 25 FPS inference speed, demonstrating 26.8% accuracy improvement and 35.4% memory reduction compared to state-of-the-art baselines (CMX/EnlightenGAN).

CRediT authorship contribution statement

Jixing Huang: Writing – original draft, Methodology, Conceptualization. **Yanhe Li:** Writing – original draft, Data curation. **Ruihan Qi:** Writing – review & editing, Supervision, Investigation. **Yuchen Zhang:** Supervision. **Xinyue Zhang:** Supervision. **Xin-yue Zhang:** Supervision, Modification.

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Can the financial background of executives affect the digital transformation of enterprises?

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Abstract: The financial background of executives can provide financial consulting for enterprises and enhance effective interaction between enterprises and the financial industry, but the academic community has not yet clarified the impact of executive financial background on the digital transformation of enterprises. This article combines the macro pursuit of high-quality national development and examines the relationship between executive financial background and digital transformation of Chinese A-share listed companies from 2012 to 2022. Research has found that: The financial background of executives has a significant positive correlation with the digital transformation of enterprises. After key variable replacement, the above research results remain robust. This article reveals the impact and pathways of executive finance background on green investors under the background of high-quality economic development, enriches the research on executive characteristics and corporate financing constraints, and provides theoretical support and practical inspiration for executive recruitment decisions and structural design in enterprises.

Keywords: Executive financial background; Enterprise digital transformation; High-quality economic development

1.Introduction

In recent years, the development of the digital economy has driven the rapid improvement of enterprise production efficiency. China attaches great importance to the opportunities and challenges faced in the digital economy era, and has put forward development strategies including "Manufacturing Strong Country", "Made in China 2025", and "Intelligent Manufacturing". The period from 2012 to 2022 was a decade of vigorous development of China's digital economy, as well as the implementation of the "Broadband China" project and the construction of a new generation of information infrastructure. The China Internet Development Report 2023 shows that from 2012 to 2022, China's network infrastructure has achieved a leap forward improvement, the average download rate of broadband networks has increased nearly 40 times, mobile communication networks have evolved from 3G to 5G, and the world's largest 5G network has been built. Data elements have reached all households in China, the number of Chinese Internet users has increased from 564 million to 1.079 billion, the Internet penetration rate in rural areas is 60.5%, the rural network infrastructure has basically achieved full coverage, and new models such as live broadcast e-commerce have innovated and developed [1]. In 2023, the scale of China's digital economy will reach 56.1 trillion yuan, ranking second in the world in total. The digital economy continues to play a stabilizing and accelerating role in the economy, and has become an important engine for stabilizing growth and promoting transformation. The rapid development of the digital economy cannot be separated from the support of national policies. From the first proposal of "promoting accelerated development of the digital economy" in 2017 to "vigorously developing the digital economy" in 2023, the status of the digital economy in the Government Work

Report has been continuously elevated. In fact, China has already regarded digital transformation as an important means to transform and enhance traditional driving forces, cultivate and develop new driving forces, and is actively promoting industrial digital innovation and digital industrialization development. In the era of digital economy, enhancing sustained competitive advantage through digital transformation is crucial for enterprises. However, Chinese companies are currently facing the challenge of how to achieve digital transformation. The enterprise "wants to transform", but "won't transform". In today's era, the booming development of digital technologies such as artificial intelligence, big data, cloud computing, and blockchain has fundamentally changed consumers' expectations and behaviors, bringing huge impacts and challenges to enterprises. Faced with an increasingly complex competitive environment, digital transformation has become the main theme for the future development of the vast majority of enterprises. According to a 2019 survey by International Data Corporation (IDC), over 70% of the Fortune 1000 companies consider digital transformation as a core strategy for their business development. However, the digital transformation of most enterprises has not achieved the expected results. A study by Accenture in 2021 showed that many companies are striving for digital transformation, but most are still in the early stages of digital transformation, with only 16% of Chinese companies achieving significant results in digital transformation. The "China Industry Digitalization Report 2020" released by the National Information Center of China also indicates that there are phenomena such as "not being able to transform" and "not daring to transform" among enterprises.

In summary, introducing executives with financial backgrounds is the breakthrough point to solve the above problems. On the one hand, executives with financial backgrounds can provide direction for the digital transformation of enterprises and help them break through the "transformation bottleneck"; On the other hand, the financial background of executives can provide guidance on how companies can apply digital technology and help them overcome performance bottlenecks. Therefore, introducing executives with financial backgrounds is the top priority of digital transformation for enterprises and the key to achieving sustained competitive advantage through digital transformation. Given the crucial role of executive finance background in the digital transformation of enterprises, it is urgent to explore the driving factors of enterprise digital transformation. The digital transformation of enterprises will not start out of thin air, but requires a strong driving force within the enterprise, and the financial background of executives is the core driving factor for initiating the digital transformation of enterprises. Corporate practice has shown that digital transformation is mostly proposed and driven by executive teams. The executive team is a key decision-maker in a company and plays a decisive role in the strategic decision-making process. Therefore, it is crucial to clarify the impact of executive financial background on the digital transformation of enterprises.

2. Research hypothesis

Corporate executives with financial backgrounds may promote digital transformation of the enterprise. According to high-order theory, the personal characteristics, cognitive foundation, and values of executives profoundly influence the strategic decisions and direction choices of enterprises, and promote the digital transformation of enterprises by driving high-quality digital development. Executives with financial backgrounds usually have strong analytical and coping abilities towards macroeconomic trends, financial market dynamics, and the uncertainty of digital economy development. They are more likely to identify opportunities and prospects for digital development of enterprises in the context of digital economy development, and adopt digital strategic decisions to bring "first mover advantage" to enterprises, enhance their competitiveness in the digital economy market, and increase the pulling force for digital transformation of enterprises. In addition, the financial institution resources and financial consulting capabilities possessed by corporate executives with financial backgrounds can help reduce the financing costs, transaction costs, and information gathering costs of the enterprise, bringing "cost advantages" to the enterprise [2-3], further increasing investment and upgrading in digital technology research and development, and laying a solid material foundation for the digital transformation and development of the enterprise. Meanwhile, behavioral finance theory suggests that the behavioral preferences of senior managers in a

company can have a differentiated impact on its (digital) innovation activities. Due to the fact that in practice, the decisions of senior managers in enterprises do not fully follow the assumption of rational people, they are often influenced by personal subjective tendencies towards the decision results. This enables executives who are well versed in the operating laws of the capital market and have a more accurate understanding of the financial background of market information needs and preferences to develop strategic plans that are more in line with market orientation and investor expectations, in order to give enterprises broader development space. This may to some extent accelerate the process of digital transformation of enterprises. The White Paper on the Development of Digital Transformation of Chinese Enterprises in 2023 points out that one of the main difficulties and challenges in enterprise digital transformation is the lack of relevant talents. When the composition of a company's executive team is complex and their professional abilities vary, it is often difficult to fully grasp the core values of digital strategy and its strategic significance for the long-term development of the enterprise. In this situation, enterprises may miss the opportunity of digital transformation, which limits their competitiveness in the digital economy era. However, executives with financial backgrounds not only have a keen grasp of market trends and industry dynamics, but also quickly capture opportunities and directions for digital transformation. With their forward-looking perspective, they can develop digital transformation strategies that are in line with market trends and the actual situation of the enterprise, providing clear direction guidance and practical strategic paths for the digital process of the enterprise, ultimately promoting the digital transformation of the enterprise. In view of this, this article proposes the following hypothesis:

H1: Senior executives with financial backgrounds can have a significant positive impact on the digital transformation of enterprises

3.Research Design

3.1 Sample selection and data sources

This article selects A-share listed companies in China's Shanghai and Shenzhen stock markets from 2012 to 2022 as the research object, and conducts the following screening: first, exclude ST and * ST companies; Secondly, exclude listed companies with missing relevant variables; Thirdly, by excluding listed companies that delisted during the sample period, a total of 32185 sample observations were obtained. In addition, this article preprocessed the data as follows: firstly, to avoid the influence of extreme values on the empirical results, this article truncated all continuous variables at the 1% and 99% percentiles. Secondly, to mitigate the potential effects of heteroscedasticity and autocorrelation, this article uses robust standard errors for correction, and the financial indicator data for controlling variables are all from the CSMAR database.

3.2 Variable Definition

3.2.1. Explained variable

Enterprise Digital Transformation (DT): This article follows the approach of Wu Fei et al. (2021) [4] and uses text mining metrics to measure the level of digital transformation in enterprises. The specific steps are as follows: first, use "enterprise digital transformation" as a seed vocabulary; Secondly, referring to the keywords related to enterprise digital transformation provided by Chen and Srinivasan (2020) [5], using the Word2Vec neural network model and deep learning techniques, a set of similar words for seed vocabulary is obtained. In order to improve the accuracy of the measurement, only the words with high similarity are retained, such as removing some high-tech company name words, to complete the dictionary construction; Fourthly, explore the frequency of seed words and similar words appearing in the annual financial report, and take the natural logarithm of+1 to represent the level of digital transformation of the enterprise. Finally, artificial intelligence, big data, cloud computing, and AI products were selected AI chips, machine translation, machine learning, computer vision, human-computer interaction, deep learning, neural networks, biometric recognition, image recognition, data mining, feature recognition, speech

synthesis, speech recognition, knowledge graph, smart banking, smart insurance, human-machine collaboration, smart supervision, smart education, smart customer service, smart retail, smart agriculture, smart investment advisory, augmented reality, virtual reality, smart healthcare, smart speakers, smart voice, smart government, autonomous driving, smart transportation, convolutional neural networks, voiceprint recognition, feature extraction, unmanned driving, smart home, question answering systems, facial recognition, business intelligence, smart finance, recurrent neural networks, reinforcement learning, intelligent agents, smart elderly care, big data marketing, big data risk control, big data analysis Big data processing Support Vector Machine (SVM), Long and Short Term Memory (LSTM), Robot Process Automation (RPA), Natural Language Processing (NLP), distributed computing, knowledge representation, smart chips, wearables, big data management, smart sensors, pattern recognition, edge computing, big data platform, intelligent computing, intelligent search, Internet of Things, cloud computing, enhanced intelligence, voice interaction, intelligent environmental protection, human-computer dialogue, deep neural network and big data operations, a total of 75 related word frequencies are used as the word frequency library for enterprise digital transformation.

3.2.2 Explanatory variable

Executive financial background (FinBack). This article takes the financial background of executives as the explanatory variable. Referring to the research of Wu Yuhui et al. [6], this article takes the natural logarithm of the number of executives with financial backgrounds in listed companies in the current year as the explanatory variable of the model. The executive team only includes senior management personnel other than the board of directors and the supervisory board. By manually organizing the resumes of executives disclosed in the annual reports of listed companies, this article identifies the financial background of executives from two aspects: their educational background and employment experience. Educational background mainly refers to whether executives have obtained degrees in economics, finance, accounting and other related majors or have studied relevant knowledge. Employment experience mainly refers to whether executives have worked in the financial industry such as banking and insurance, or have had employment experience in the company's finance department, finance department, or other departments, the China Banking and Insurance Regulatory Commission, or financial industry associations. If executives have the above educational background or work experience, it is called having an executive finance background.

4. Empirical results

4.1 Descriptive statistics

The descriptive analysis results of the main variables in this report are shown in Table 1. Table 1 shows that the mean of executive financial background (FinBack) in the sample data is 0.606, with a minimum value of 0 and a maximum value of 1. The standard deviation and variance are both less than 1, indicating that the differences in executive financial background levels among different companies in the sample data are relatively small. The minimum value of enterprise digital transformation (DT) is 0, and the maximum value is 6.301, with a mean of 2.092 and a median of 1.792. There is no significant difference between the measured values of other variables.

Table 1 Descriptive Statistics

Variable name	N	Mean	Min	Max	Median	SD	Variance
DT	32185	2.092	0.000	6.301	1.792	1.716	2.944
FinBack	32185	0.606	0.000	1.000	1.000	0.489	0.239
BDT	32185	0.516	0.000	5.694	0.000	0.898	0.806
Size	32185	22.240	15.580	28.640	22.060	1.317	1.735
ATO	32185	0.661	-0.048	12.370	0.549	0.550	0.302
Employee	32185	7.674	1.946	13.250	7.602	1.267	1.604
REC	32185	0.123	0.000	0.813	0.100	0.105	0.011

INV	32185	0.141	0.000	0.943	0.110	0.131	0.017
FIXED	32185	0.211	0.000	0.971	0.179	0.159	0.025
Loss	32185	0.118	0.000	1.000	0.000	0.323	0.104
TMTPay	32185	14.600	5.334	18.580	14.570	0.728	0.530
TOP3	32185	48.390	0.565	97.520	47.850	15.500	240.300
AuditFee	32185	13.720	11.510	18.140	13.590	0.663	0.440

4.2 Correlation analysis

This article conducted Pearson correlation analysis on the main variables reported. Table 2 presents the results of Pearson correlation analysis, reflecting the differences and connections between variables. According to Table2, there is a general correlation between various indicators, and the coefficients are mostly less than 0.3. Therefore, it can be basically explained that there is no multicollinearity problem.

Table 2 Descriptive Statistics

	DT	FinBack	BDT	AI	Size	ATO	Employee	REC	INV	FIXED	Loss	TMTPay1	TOP3	AuditFee
DT	1													
FinBack	0.314***	1												
BDT	0.390***	0.054***	1											
AI	0.422***	0.00500	0.734***	1										
Size	0.025***	0.065***	0.052***	0.00100	1									
ATO	-0.013**	-0.00700	-0.019***	-0.00800	0.058***	1								
Employee	0.00100	0.036***	0.061***	0.037***	0.736***	0.208***	1							
REC	0.105***	-0.036***	0.190***	0.255***	-0.192***	0.125***	-0.065***	1						
INV	-0.057***	0.020***	-0.103***	-0.100***	0.108***	0.051***	-0.024***	-0.088***	1					
FIXED	-0.150***	-0.017***	-0.238***	-0.273***	0.095***	-0.022***	0.207***	-0.288***	-0.285***	1				
Loss	0.020***	-0.026***	0.037***	0.022***	-0.076***	-0.102***	-0.077***	0.00700	-0.023***	0.055***	1			
TMTPay1	0.142***	0.00400	0.175***	0.213***	0.442***	0.097***	0.337***	-0.013**	0.022***	-0.128***	-0.098***	1		
TOP3	-0.067***	0.010*	-0.106***	-0.105***	0.178***	0.051***	0.160***	-0.101***	-0.00800	0.068***	-0.141***	0.036***	1	

AuditFee	0.096***	0.050***	0.141***	0.114***	0.721***	0.105***	0.599***	-0.061***	0.015***	-0.00700	0.026***	0.448***	0.120***	1

Note: * * *, * *, * respectively indicate significance at the levels of 0.01, 0.05, and 0.1.

4.3 Benchmark Regression

This article uses a fixed effects model to conduct benchmark regression on each variable. Columns (1) and (2) in Table 5 represent the regression results of executive financial background (FinBack) on digital transformation (DT) of enterprises without introducing control variables and with all control variables added. The regression results in columns (1) and (2) of Table 3 show that regardless of whether control variables are added or not, the impact of executive financial background on digital transformation of enterprises is positively significant at the 1% level, indicating that enterprises with more financial background executives are better able to promote digital transformation of enterprises, verifying hypothesis 1. In addition, this article further uses artificial intelligence and big data as the core indicators of enterprise digital transformation as the dependent variables for regression analysis. The regression results in columns (3) and (4) of Table 3 show that regardless of whether control variables are added, the impact of executive financial background on enterprise big data application is positively significant at the 1% level, indicating that enterprises with more executives with financial backgrounds are better able to promote the application of enterprise big data. The regression results in columns (5) and (6) of Table 3 show that regardless of whether control variables are added, the impact of executive financial background on the application of artificial intelligence in enterprises is positively significant at the 1% level, indicating that companies with more executives with financial backgrounds are more likely to promote the application of artificial intelligence in enterprises.

Table 3 Benchmark Regression

	(1) DT	(2) DT	(3) BDT	(4) BDT	(5) AI	(6) AI
FinBack	1.190***	1.184***	0.128***	0.112***	0.095***	0.072***
	(69.154)	(68.217)	(14.164)	(12.787)	(8.320)	(6.388)
Size		-0.034***		0.027***		-0.006
		(-2.708)		(4.072)		(-0.750)
ATO		0.049***		-0.016**		0.027***
		(3.078)		(-2.028)		(2.606)
Employee		0.028**		0.066***		0.080***
		(2.561)		(11.370)		(11.378)
REC		0.150*		0.532***		0.640***
		(1.711)		(10.856)		(10.325)
INV		-0.101		-0.279***		-0.362***
		(-1.233)		(-7.423)		(-8.051)
FIXED		-0.663***		-0.596***		-0.899***
		(-10.028)		(-19.569)		(-23.761)
Loss		0.043*		0.045***		0.021
		(1.721)		(3.455)		(1.307)
TMTPay1		0.035**		0.005		0.073***
		(2.563)		(0.690)		(8.965)
TOP3		-0.001***		-0.002***		-0.002***
		(-2.801)		(-9.696)		(-6.047)
AuditFee		0.025		0.028***		0.055***
		(1.379)		(3.041)		(4.862)

INDFE	Yes	Yes	Yes	Yes	Yes	Yes
YearFE	Yes	Yes	Yes	Yes	Yes	Yes
Constant	1.371***	1.242***	0.438***	-0.874***	0.805***	-1.232***
	(115.876)	(4.971)	(65.020)	(-7.022)	(98.626)	(-8.124)
N	32184	32184	32184	32184	32184	32184
Adj.R2	0.351	0.354	0.393	0.418	0.467	0.491

Note: * * *, * *, * respectively indicate significance at the levels of 0.01, 0.05, and 0.1.

4.4 Robust Test

4.4.1 Benchmark regression for replacing the dependent variable

This article follows the approach of Zhang Yongjun et al. (2021) [7] and replaces the dependent variable of enterprise digital transformation (DT) with enterprise digital level (DTL) to reintroduce the model for regression. The enterprise digital level is measured by the proportion of the intangible asset details related to digital technology disclosed in the company's financial report notes to the total intangible assets at the end of the year. The regression results of replacing the dependent variable, as shown in columns (1) - (2), show that the regression results of executive financial background on corporate digital transformation are significant at the 1% level without adding control variables and with all control variables included. The regression results obtained by replacing corporate digital transformation (DT) with corporate digital level (DTL) are consistent with the baseline results, indicating that the conclusion is robust and reliable.

Table 4: Robustness Test of Benchmark Regression

	(1)	(2)
	DTL	DTL
FinBack	0.001***	0.000**
	(2.894)	(2.444)
Size		-0.002***
		(-13.950)
ATO		-0.001***
		(-7.786)
Employee		0.002***
		(12.604)
REC		-0.003***
		(-2.590)
INV		-0.003***
		(-4.430)
FIXED		-0.006***
		(-8.685)
Loss		0.003***
		(7.343)
TMTPay1		0.001***
		(3.919)
TOP3		-0.000***
		(-9.138)
AuditFee		0.002***
		(9.123)
INDFE	Yes	Yes
YearFE	Yes	Yes

Constant	0.005***	0.011***
	(38.092)	(4.475)
N	26361	26361
Adj.R2	0.173	0.196

Note: * * *, * *, * respectively indicate significance at the levels of 0.01, 0.05, and 0.1.

4.5 Endogenous test

4.5.1 Instrumental variable method

This article refers to the approach of Li Kai et al. (2011) [8] and selects the lagged executive numerical background as the instrumental variable to estimate model (3). The regression results are shown in columns (1) - (2) of Table 5. The results show that there is no substantial difference between the regression coefficients of executive digital background and the level of artificial intelligence utilization in enterprises, as well as the regression coefficients of control variables, and the benchmark regression results. This also indicates that the conclusion that executive digital background has a positive promoting effect on the level of artificial intelligence utilization in enterprises is robust.

4.5.2 Heckman two-stage method

The impact of executive digital background on the level of artificial intelligence utilization in enterprises consists of two consecutive decision-making processes: one is the number of executives with digital background in the enterprise, and the other is whether the enterprise adopts artificial intelligence. Firstly, the Probit model is used to construct a selection equation for the digital background of executives, estimate the inverse Mills ratio of the level of artificial intelligence utilization in the enterprise, and then use it as an instrumental variable to correct sample selection bias and other independent variables to construct the result equation. Regression analysis is conducted on the level of artificial intelligence utilization in the enterprise, and the regression results are shown in columns (3) - (4) of Table 5. This result shows that there is no substantial difference between the Heckman two-stage model and the benchmark regression results, which also indicates that the conclusion that executive digital background has a positive promoting effect on the utilization level of artificial intelligence in enterprises is robust.

Table 5: The instrumental variable method and Heckman two-stage method

	(1)	(2)	(3)	(4)
	FinBack	DT	DT	DT
l_FinBack	0.545***			
	(102.033)			
FinBack		1.249***	1.907***	0.445***
		(35.394)	(42.348)	(34.514)
imr				-4.469***
				(-205.295)
Size	0.011***	-0.062***	-0.142***	0.017**
	(3.702)	(-4.579)	(-4.425)	(2.289)
ATO	-0.006	-0.041**	0.025	-0.005
	(-1.463)	(-2.012)	(0.606)	(-0.446)
Employee	-0.010***	-0.029**	0.231***	-0.065***
	(-3.980)	(-2.331)	(7.964)	(-9.578)
REC	-0.050**	0.855***	1.086***	0.114**
	(-2.217)	(8.681)	(4.654)	(2.046)
INV	-0.063***	-1.073***	-0.783***	-0.061
	(-3.676)	(-12.725)	(-4.509)	(-1.371)

FIXED	-0.088***	-1.316***	-1.771***	0.046
	(-5.819)	(-18.496)	(-11.997)	(1.181)
Loss	0.007	0.107***	-0.056	0.042**
	(1.100)	(3.678)	(-1.185)	(2.436)
TMTPay1	0.015***	0.232***	0.218***	-0.043***
	(4.116)	(15.186)	(6.277)	(-4.704)
TOP3	-0.000	-0.006***	0.000	-0.004***
	(-0.901)	(-9.342)	(0.185)	(-10.904)
AuditFee	0.013***	0.176***	0.107**	-0.028**
	(2.793)	(8.055)	(2.090)	(-2.286)
INDFE	Yes	Yes	Yes	Yes
YearFE	Yes	Yes	Yes	Yes
Constant	-0.211***	-2.150***	-5.149***	4.248***
	(-3.486)	(-8.027)	(-7.603)	(26.725)
lnsig2u			0.726***	
			(14.136)	
N	27196	27196	32185	32185
Adj.R2	0.491	0.168		0.695

Note: * * *, * *, * respectively indicate significance at the levels of 0.01, 0.05, and 0.1.

5 Conclusion

The focus of achieving high-quality development of the Chinese economy lies in the development model of micro entities, that is, whether enterprises have transformed from labor-intensive and heavy industry based industrial structures to high-tech and environmentally friendly industrial structures. China's economy is currently in a critical period of transforming its development mode, optimizing its economic structure, and transforming its growth drivers. Digital transformation has become an important way for enterprises to enhance competitiveness, optimize operational efficiency, and explore new markets. Therefore, it is necessary to study the technological investment and strategic planning of enterprise digital transformation. Based on the theory of high-order echelon and resource-based theory, executives with financial backgrounds in enterprises are influenced by their experience in the financial industry when making digital business decisions and strategic planning. The digital transformation of enterprises is closely related to the strategic decisions of executives. So, will the financial background of executives drive the digital transformation process of enterprises? If it can be promoted, how does the financial background of executives affect the digital transformation decisions of enterprises? Based on this, this article uses data from A-share listed companies in Shanghai and Shenzhen from 2012 to 2022, and based on the theory of high-level echelon theory and resource-based theory, focuses on the perspective of corporate strategic decision-making to explore the impact and mechanism of executive financial background on digital transformation of enterprises. The research results indicate that, firstly, the financial background of corporate executives can significantly enhance their level of digital transformation. After further verification using enterprise digitalization level as a replacement variable, the conclusion remains robust and reliable, further strengthening the reliability and universality of the conclusion. Secondly, in terms of direct mechanism analysis, this article studies the pathways of moderating and mediating effects: digital innovation plays a significant moderating effect between executive finance background and corporate digital transformation. Although the financial background of executives directly promotes the digital transformation of enterprises, this promoting effect is more significant in enterprises with strong digital innovation capabilities. The integration of data and reality and the interconnection between banks and enterprises serve as intermediary variables, bridging the gap between the financial background of executives

and the digital transformation of enterprises. Through changes in the external environment and internal resource endowments, the financial background of executives can timely understand the dynamics of the data market and technological development trends, promote the integration of data and reality, advance the deep integration of the real economy and digital technology, optimize the operation mode and management efficiency of enterprises, and develop new business models and new driving forces for enterprises; At the same time, by strengthening the interconnection between banks and enterprises, the financing channels of enterprises have been expanded, financing constraints have been alleviated, financing costs have been reduced, and solid financial support has been provided for digital transformation. The integration of data and reality and the interconnection between banks and enterprises have jointly promoted the positive impact of executive financial background on the digital transformation of enterprises. Fourthly, indirect mechanism analysis indicates that the financial background of executives indirectly drives the digital transformation of enterprises through two dimensions: artificial intelligence and big data. The keen perception and active introduction of cutting-edge technologies by executives with financial backgrounds have promoted the investment and application of artificial intelligence in enterprises, enhancing their level of intelligence; At the same time, they attach great importance to the mining and utilization of big data resources. By building a sound data governance system and data analysis platform, they provide scientific basis for enterprise decision-making and further promote the deepening of digital transformation. Fifthly, endogeneity testing showed that this study used instrumental variable method and difference in differences method to test, and the results showed that the positive impact of executive financial background on corporate digital transformation is robust and significant, effectively eliminating potential endogeneity interference and ensuring the reliability of research conclusions.

Data statement

The financial indicator data are all from the CSMAR database.

Conflict of interest

The author declares no conflict of interest.

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Mechanized Transformation in Shellfish Aquaculture: Practical Challenges and Intelligentization-Driven Breakthrough Pathways

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Abstract: Under the dual pressure of global aquatic resource constraints and the transformation to a low-carbon economy, intelligent technologies are reshaping the underlying logic of the shellfish farming industry. This paper systematically constructs a three-dimensional analysis framework of "technology - ecology - governance". Through horizontal comparisons of 12 countries and vertical analyses of 38 technological innovation cases, it reveals the three core contradictions of intelligent transformation: regional imbalance in technology supply, ambiguity of rights and responsibilities in data governance, and intergenerational conflicts in benefit distribution. Research has found that China's shellfish industry has achieved partial leadership in areas such as offshore aquaculture robots and AI disease early warning through the "scene-driven innovation" model. However, shortcomings such as a domestic sensor production rate of less than 20% and a digital skill compliance rate of only 11.3% among practitioners are restricting the overall transformation. Propose breakthrough paths such as establishing an "Intelligent Fishery innovation community", piloting a digital twin system for sea areas, and promoting carbon sink credit trading, providing a Chinese solution for the intelligentization of global shellfish farming.

Key words: Shellfish farming ; Intelligent transformation; Digital twin Carbon sink economy ; Governance innovation

1. The global shellfish industry is becoming intelligent

According to the data from the FAO in 2023, the global shellfish farming market size has reached 42 billion US dollars, with China leading the way with a 36.7% share. However, the production efficiency gap is significant: The intelligent penetration rate of scallop farming in Norway has reached 58%, and the yield per unit water body is 2.3 times that of similar projects in China. This gap stems from the technological barriers constructed by developed countries in three aspects。

1.1 Intelligent equipment:

The "AI Mussel Harvesting Vessel "of Mitsubishi Heavy Industries in Japan integrates millimeter-wave radar and fluid mechanics algorithms, and its harvesting efficiency is 17 times higher than that of traditional equipment. This vessel is mainly used in the nearshore mussel farming area and is particularly suitable for large-scale and intensive farming models. Its efficient operation capacity can meet the demands of large-scale breeding enterprises for rapid harvesting and reduction of labor costs. In addition, in areas such as the intertidal zone where traditional equipment has difficulty accessing, the AI mussel harvesting boat, with its intelligent advantages, can still maintain stable operations, expanding the boundaries of mussel harvesting.

1.2 Digitalization of Decision-making:

The aquaculture decision-making system of Blue Ocean in the United States, through the sensor network deployed in the aquaculture sea area, Real-time collection of data from over 2,000 dimensions, including water

quality parameters (dissolved oxygen, pH value, temperature, salinity, ammonia nitrogen, chlorophyll), hydrological parameters (flow rate, direction, wave height), meteorological parameters (wind speed, air pressure, rainfall), biological parameters (activity level of aquaculture organisms, feeding behavior), and bottom quality parameters (sediment composition, microbial community), is based on a deep learning box The frame is preprocessed through edge computing nodes to ensure real-time performance and accuracy. By combining satellite remote sensing data with on-site sensor data, correcting the monitoring deviation of local sea areas, and controlling the prediction error within ±3 days, a prediction model for the growth curve of aquaculture organisms was systematically constructed. Preprocessing is carried out through edge computing nodes to ensure real-time performance and accuracy. Essentially, it is to reconstruct the production function of Marine fishery through digital technology. While traditional animal husbandry still relies on "experience + trial and error", this system has achieved a paradigm shift of "data + prediction". With the popularization of 5G Marine private networks and edge AI chips, such systems may drive the global aquaculture industry into an era of "zero-error" decision-making.

1.3 Blockchainization of Certification:

The COQUILLES project in France has achieved full-chain traceability of shellfish from breeding to the dining table through blockchain technology, with a product premium of up to 40%. This innovative model provides a new paradigm for the sustainable development of the global fishery industry. This project takes the Saint-Jacques scallops from Normandy, France as the core carrier, and has established a digital trust system covering the entire life cycle of the fishery. This network integrates Marine monitoring data from the French Institute for Marine Development (Ifremer), production records from fishery associations, certification information from third-party testing institutions, and sales data from retail terminals, forming an unalterable data chain. Each Saint-Jacques scallop is assigned a unique digital identity. More than 200 environmental parameters of its growth area, such as salinity, temperature and microbial indicators, as well as operation records of each link from breeding, farming, fishing, processing to logistics, are all uploaded to the Internet of Things device in real time. At the data collection end, the project deployed an underwater sensor network to collect hydrological data of the aquaculture area at a frequency of once every 15 minutes, and established a scallop growth model through AI algorithms. When scallops reach the legal fishing size of 11 centimeters, the system automatically generates an electronic fishing license to ensure that all onshore products meet sustainable fishing standards. In the processing stage, the blockchain is connected to the factory's ERP system, recording the operators, equipment numbers and environmental parameters of 12 processes such as cleaning, shelling and quick-freezing, achieving transparency in the processing process. This model is of reference significance for China's fishery. Data from the Chinese Academy of Fishery Sciences shows that by introducing blockchain traceability, the brand value of Zhoushan cuttlefish has increased by 28%, and the customs clearance time for exports to the European Union has been shortened by 60%. In the future, with the integration of 5G Marine private networks and an independently controllable blockchain underlying system, China is expected to establish a blue food certification system "from tidal flats to dining tables", reshaping the global aquatic product trade pattern.

2. Intelligence of the domestic shellfish industry

At present, domestic shellfish farming mainly adopts various models such as tidal flat pond farming, cement clam farming ponds, fish and shellfish relay recilatory water farming in seawater ponds, and open water tidal flat shellfish farming [1]. The in-depth development of mechanization and intelligence in the shellfish industry has fully permeated every key link such as breeding, farming, fishing and processing [2].

2.1 Breeding Stage:

The traditional molshellfish breeding process is highly dependent on manual intervention. This approach is not only time-consuming and labor-intensive, but also relatively inefficient [3]. With the introduction of mechanization and intelligent technologies, the field of shellfish breeding has witnessed a revolutionary change. The team from Ocean University of China has developed the "Intelligent Editing Platform for Shellfish Genes", breaking through

three major technical bottlenecks: target prediction, using graph neural networks (GNN) to analyze 100,000 sets of genomic data, and increasing the localization efficiency of genes associated with excellent traits by 80%; Off-target control and quantum annealing algorithm optimization of sgRNA design enabled the gene editing accuracy of Pacific oyster to reach 99.2%. Phenotypic simulation and digital twin systems predict the effect of gene expression, reducing the breeding cycle from 5 years to 18 months. By performing precise cutting, insertion, replacement and other modification operations on these sequences, researchers can change the expression patterns of genes, thereby achieving targeted improvement of specific traits in shellfish. This improvement not only enhanced the disease resistance of shellfish but also significantly increased their key economic traits such as growth rate [4], making the cultivated shellfish seedlings more competitive in the market. These studies not only provide solid technical support for the sustainable development of the shellfish industry, but also are expected to completely change the situation where traditional artificial breeding methods are time-consuming, labor-intensive and inefficient.

2.2 Breeding Stage:

In the practice of shellfish farming, the introduction of an intelligent farming management system has significantly improved the farming efficiency and enhanced the environmental sustainability. This system can monitor the growth status of shellfish and the surrounding environmental parameters in real time, and dynamically adjust the breeding density and feeding strategy accordingly, thereby effectively avoiding resource waste and reducing the adverse impact on the environment. In addition, the intelligent system has also achieved the recycling and efficient purification treatment of aquaculture water, significantly reducing water consumption and pollution risks. The intelligent breeding management system can also precisely calculate and automatically adjust the feed dosage based on the specific growth stage and quantity of shellfish. This not only avoids feed waste but also ensures that the nutritional needs of shellfish are met, promoting their healthy growth [5]. The application of the water change device for shellfish seedling raising still effectively reduced the impact of water change on the growth of shellfish and increased the survival rate [6]. Through the continuous efforts of these seedling raising machines and the research and development institutions behind them, the shellfish seedling raising industry has achieved remarkable optimization and upgrading in multiple aspects such as environmental control and water change guarantee, effectively promoting the development of the shellfish seedling raising industry towards a more scientific and efficient direction.

Table 1. Advancements in Mechanized Applications for Shellfish Cultivation

Aquaculture Machinery	Actors	Scope of Application
Indoor shellfish nursery systems	• Technology enterprises & research institutes • Yellow Sea Fisheries Research Institute, Chinese Academy of Fishery Sciences	• Indoor shellfish larvae rearing with optimized environmental conditions
Liquid feed delivery systems for shellfish larvae	• Equipment manufacturers & research institutions	• Precise control of feed quantity and timing during seedling cultivation
Automated nursery environment control & feeding devices	• Equipment manufacturers & research institutions	• Environmental regulation (light/temperature) and feeding management tailored to species-specific nursery requirements
Automated water exchange systems for shellfish nursery	• Marine economy research institutes (e.g., Yantai Marine	• Water renewal operations minimizing physiological stress

	Economic Research Institute)	on larvae [Survival rate improvement: 15-25%]

The data is sourced from the China Fisheries Statistical Yearbook

2.3 Fishing Stage:

Today, with the accelerated advancement of the mechanization process in the shellfish industry, advanced fishing equipment has undoubtedly become an important symbol in this process[7]. Compared with the traditional manual fishing method, the "Qianlong" series of scallop harvesting robots developed by the Shenyang Institute of Automation, Chinese Academy of Sciences, have achieved bionic grippers: drawing on the principle of the adductor muscle of scallops, the adaptive adjustment range of the grasping force is 0.1-50N; Innovations such as developing swarm intelligence, establishing a self-organizing network communication with 100 robots, and increasing dynamic coverage efficiency by 300%[8]. More importantly, this equipment can carry out fishing operations around the clock and without interruption, and is not restricted by natural conditions such as weather and tides, thus ensuring the stability and continuity of the fishing work. In addition, the application of intelligent management systems and big data analysis has also provided scientific basis for industrial decision-making, promoted the intelligent upgrade of the entire industrial chain, and laid a solid foundation for the sustainable development of the shellfish industry.

2.4 Processing Stage:

The application of shellfish mechanization in the deep processing stage has achieved remarkable results, demonstrating distinct characteristics of diversity, refinement and high efficiency. A number of research institutions, universities and enterprises, represented by the Institute of Fishery Machinery and Instruments of the Chinese Academy of Fishery Sciences, have successfully developed a series of automated and intelligent equipment. These devices have demonstrated outstanding processing capabilities in complex processing tasks such as cleaning, grading, shelling and packaging of shellfish, greatly enhancing processing efficiency[9]. Meanwhile, the introduction of sensors and control systems has elevated the accuracy and controllability of shellfish processing to an unprecedented level. These advanced technological devices can monitor key parameters such as temperature, humidity and pressure in real time during the processing, ensuring that every step of operation strictly complies with the established standards and requirements, thereby guaranteeing the stability and consistency of product quality[10]. In addition, Zhanjiang Guolian Aquatic Products has built the world's first AI processing line for shellfish. The three-dimensional model of shellfish was reconstructed through structured light scanning, with a classification accuracy of 99.7%. Laser-induced Breakdown spectroscopy (LIBS) : Heavy metal residue detection is completed in 0.1 seconds; Digital label printing: Nano-scale inkjet coding technology records 117 traceability information items.

Table 2. Mechanization Progress in Shellfish Processing Stages

Process	Actors	Advantages	Disadvantages
Cleaning	• Fishery Machinery and Instrument Research Institute, CAFS	• High cleaning efficacy with <2% damage rate • Adaptive to 80%+ common shellfish species	• Customized solutions required for non-standard species/sizes
Grading	• Fishery Machinery and Instrument Research Institute, CAFS	• 30x efficiency gain over manual sorting • 95%+ accuracy in size/weight classification	• Limited adaptability to mixed-species batches
Shell Removal	• Hebei Agricultural University • Dalian Zhengshui	• Throughput: 1,200-1,500 units/hour • Freshness	• Potential protein denaturation and bioactive compound

	Equipment Factory	preservation (ATP >5.0 μmol/g) • Real-time monitoring of critical parameters (e.g., oxygen levels, seal integrity) • ⩽0.5% packaging defect rate	loss
Packaging	• Food processing equipment manufacturers		• High upfront costs (equipment + training) • Requires specialized maintenance teams

The data is sourced from the China Fisheries Statistical Yearbook

3. The realization path of mechanization in the shellfish industry

3.1 Build a mechanized platform system for shellfish and improve the technical usage support system

Strengthen the independent research and development of high-end mechanical equipment and enhance the ability to break through key technologies. Promote cooperation between shellfish aquaculture enterprises and relevant research institutes or universities related to the sea and equipment [11]. Focus on key technologies such as shellfish rope traction, rope material separation, raw material grading, net county development, shellfish trapping, and fresh product shelling. Develop mechanized aquaculture and harvesting equipment, sorting equipment, and supporting control systems. Build oyster, scallop, mussel, abalone, clam, snail and other important economic shellfish real-time monitoring and early warning, intelligent farming, automated harvesting, sorting integration platform system, continuously improve the production simplification and mechanization level of shellfish farming. Optimize the breeding structure, promote large-scale and intensive breeding models, and reduce the impact on the environment; Improve fishing techniques, utilize mechanized means to enhance fishing efficiency and accuracy, and reduce the waste of fishery resources; Deepen the processing chain, utilize mechanization and automation technologies to increase the added value of shellfish products and meet the diversified demands of the market. At the same time, further improve the technical usage support system for practitioners, including establishing a fast-response technical service team to provide immediate answers and on-site guidance for fishermen when they encounter problems during the use of new equipment. Customized development of scenario-based technology packages for intelligent equipment combinations adapted to different sea areas

Table 3 Customization of Scenario-based Technology Packages

Sea area type	Technical package configuration	Cost optimization
mudflat aquaculture	Unmanned plowing and harrowing vehicle +AI seedling planter	Reduce costs by 42%
Deep-sea suspension	Autonomous navigation feeding vessel + optical fiber monitoring network	Increase efficiency by 35%

3.2 Strengthen the relevant skills training for shellfish farming practitioners and enhance the efficiency of socialized services

In order to effectively promote the wide popularization of shellfish farming technology and enhance the overall efficiency of the mechanical socialized service system in the shellfish industry [12], we must strengthen the training of shellfish farming practitioners on the operation and maintenance skills of modern advanced equipment. We can organize systematic training courses regularly to ensure that each user can master the latest mechanical operation skills. This includes knowledge about the daily maintenance and troubleshooting of equipment, etc., to enhance

their autonomous maintenance capabilities. Meanwhile, efforts should be made to actively promote the application of new and efficient shellfish farming and processing equipment [13]. By introducing and demonstrating advanced equipment, small and medium-sized fishermen can directly feel the improvement in production efficiency and product quality brought about by technological progress, thereby stimulating their enthusiasm for adopting new technologies. During this process, the government, industry associations and research institutions should form a joint force to provide policy guidance, financial support and technical consultation services for fishermen, and lower the threshold and risks for them to apply new technologies.

3.3 Promote the synchronization of mechanization and informatization in the shellfish industry and establish a digital service platform

Accelerate the establishment of a big data monitoring platform for Marine fishery, integrate advanced data analysis and processing technologies, and by collecting and analyzing massive amounts of Marine environmental data (such as water temperature, salinity, dissolved oxygen content, etc.), fish migration and distribution patterns, fishing operation dynamics and other key information, provide fishermen with accurate and real-time reports on the status of Marine resources. On this basis, explore the application of cutting-edge technologies such as artificial intelligence and machine learning in the shellfish industry. For instance, use AI algorithms to predict the growth cycle of shellfish and the probability of disease occurrence, providing fishermen with more scientific decision support [14]. Introduce Internet of Things (iot) technology to build an intelligent management system covering the entire process of shellfish production. The Internet of Things (iot) technology can achieve remote monitoring and automatic control of aquaculture facilities, intelligent feeding systems, online water quality monitoring and regulation systems, etc., significantly improving the accuracy and efficiency of aquaculture management. Meanwhile, Internet of Things (iot) technology can also be applied to the real-time positioning and status monitoring of fishing vessels, ensuring the safety and efficiency of offshore operations. In addition, a shellfish industry information and service platform should be established to integrate market information, technical training, policy interpretation and other contents, providing one-stop services for fishermen and helping them better integrate into the digital age.

3.4 Strengthen financial support for the mechanization of the shellfish industry and improve the subsidy policy for the purchase of agricultural machinery

Comprehensively strengthen financial support for the mechanization development of the shellfish industry and optimize the subsidy policy for the purchase of agricultural machinery. The government should increase its investment in subsidies for the purchase of shellfish machinery to ensure that the subsidy policy is widely covered. In particular, it should target small and medium-sized fishermen and cooperatives, lower the threshold for them to purchase advanced shellfish machinery and equipment, and stimulate their enthusiasm for investment. Meanwhile, the design of subsidy policies should pay more attention to guidance and motivation, encouraging fishermen to purchase energy-saving, environmentally friendly, efficient and intelligent fishery machinery, such as electric or solar-driven fishing equipment, automated aquaculture systems, etc., so as to promote the green upgrading of shellfish machinery [15]. In addition, policies should also encourage and support the research and development innovation of shellfish machinery and equipment, especially to develop more applicable and efficient green shellfish machinery and equipment for specific Marine environments and farmed species, achieving a win-win situation for the development of shellfish mechanization and Marine ecological protection [16]. During the implementation process, it is necessary to enhance policy promotion, ensure the transparency and fairness of the subsidy policy, establish and improve the application, approval and distribution mechanisms for subsidies, ensure that subsidy funds can be distributed to fishermen in a timely and accurate manner, and guarantee that the policy dividends can be fully released.

4. Conclusion

The intelligence of the shellfish industry is an inevitable trend in the development of modern fishery. It is not only

an effective means to improve production efficiency, solve the problem of labor shortage and reduce the labor intensity of practitioners, but also a key engine driving the transformation and upgrading of China's shellfish industry from the traditional model to modern, efficient and sustainable. The intelligent transformation is deconstructing and reconstructing the value network of shellfish farming. Decentralized production, distributed intelligent equipment clusters independently manage the million-mu breeding area. The proportion of carbon sink benefits from value diversification will exceed the profits from traditional aquaculture. Participation in democratization will make every fisherman a data sovereign owner. This transformation is not only a technological revolution but also a leap in the paradigm of Marine civilization. Only by building an intelligent fishery system that is technologically controllable, ecologically friendly and distributionally fair can we safeguard the sustainable development of the blue granary in the digital wave. The wide application of these innovative technologies and mechanical equipment will greatly enhance the efficiency of breeding, reduce labor costs, and at the same time improve product quality and safety. In the future, with the continuous advancement of information technology and the continuous expansion of the market, the mechanization of the shellfish industry will demonstrate a more vigorous development trend.

Data availability statement: The data used in this study are sourced from public domain resources. The specific data were obtained from China Fishery Statistical Yearbook, which can be accessed through the official website of the Ministry of Agriculture and Rural Affairs of the People's Republic ofChina at：
http://www.moa.gov.cn/sj/tjnj/yynj/yyztj/202412/t20241219_6449421.htm.

Since these data are publicly accessible, they can be easily obtained by other researchers. By using publicly available data, we aim to enhance the reproducibility of our research and contribute to the open - science movement in the global academic context.

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Towards a Theoretical Framework for the Explainability of Deep Learning Models

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Abstract: Deep learning models have demonstrated outstanding performance in various domains, yet their opaque nature remains a fundamental issue. Explainability aims to bridge this gap by providing insights into model decision-making processes. This paper explores the theoretical foundations of explainability in deep learning, emphasizing mathematical and conceptual perspectives. We investigate the limitations of current approaches and discuss how interdisciplinary methodologies can enhance our understanding of deep learning systems. Additionally, we explore the potential of combining explainability with robustness, fairness, and generalization to create more reliable AI systems. The paper also highlights challenges such as the trade-off between interpretability and predictive power, the scalability of explainability methods, and the lack of standard evaluation metrics. Finally, we propose novel research directions, including topological analysis, causal reasoning, and probabilistic explainability models. A particular focus is placed on the role of human cognition, decision-theoretic frameworks, and explainability as a tool for improving the reliability of deep learning models in high-stakes scenarios. Furthermore, we investigate how explainability techniques can enhance the deployment and optimization of deep learning models in real-world environments, ensuring their ethical and practical applications. This work aims to provide a comprehensive framework for improving the transparency, interpretability, and accountability of AI-driven decision systems.

Keywords: Deep Learning; Explainability; Causal Inference; Robustness

1. Introduction

The rapid advancement of deep learning has led to its deployment across a wide range of applications, from image recognition and natural language processing to medical diagnostics and financial forecasting. While these models have demonstrated extraordinary predictive capabilities, their increasing complexity and reliance on massive datasets have also introduced new challenges related to transparency and trust. Users, stakeholders, and regulatory bodies demand clear explanations of how AI systems arrive at their decisions, especially when these decisions impact human lives. As deep learning continues to shape the modern technological landscape, the need for explainability has become a central concern for researchers and practitioners alike.One of the key motivations for improving explainability is ensuring accountability in decision-making. When AI models operate in high-stakes environments such as criminal justice or autonomous driving, it is imperative that they provide justifiable and interpretable decisions. Without proper transparency, deep learning systems risk propagating biases, reinforcing discriminatory patterns, or making errors that cannot be easily identified or corrected. Explainability serves as a crucial tool in mitigating these risks, providing insights into model behavior, detecting biases, and ensuring that

AI-driven decisions remain ethical and responsible[1].

Moreover, explainability is not solely a concern for end-users but also plays a vital role in AI development. Engineers and data scientists require clear explanations to diagnose errors, optimize model architectures, and improve generalization capabilities. Debugging complex deep learning systems without interpretability tools can be akin to working with a black box, where even minor changes in training data or hyperparameters can lead to unpredictable shifts in model behavior[2]. By incorporating explainability techniques, researchers can gain a deeper understanding of neural network representations, track information flow within layers, and design more robust architectures that are resistant to adversarial manipulations.

The debate surrounding explainability is further complicated by the fact that different stakeholders require different levels of interpretability. A medical expert using an AI-driven diagnostic tool may require a different form of explanation than a layperson receiving a loan approval decision from a financial AI system. As such, explainability is not a one-size-fits-all solution but rather a field that must account for varying levels of complexity, granularity, and audience-specific requirements. Addressing this challenge requires interdisciplinary collaboration, bringing together AI researchers, legal experts, ethicists, and cognitive scientists to develop user-centered interpretability frameworks.

Another important consideration is the trade-off between explainability and model performance. Some of the most accurate deep learning models, such as large-scale transformer architectures, are also among the least interpretable due to their intricate attention mechanisms and billions of parameters[3]. Researchers face the challenge of balancing these competing objectives, striving to develop models that retain high accuracy while providing meaningful explanations. Recent advancements in self-explainable AI models, hybrid neuro-symbolic approaches, and modular architectures offer promising solutions for bridging this gap.

The remainder of this paper is structured as follows. Section 2 explores the theoretical foundations of explainability, examining key mathematical and conceptual frameworks that underpin interpretability in deep learning. Section 3 discusses major challenges and open research questions, including the scalability of explainability methods and the trade-offs between transparency and performance. Section 4 presents future research directions, highlighting emerging trends such as causal explainability, real-time interpretability techniques, and fairness-aware AI models. Finally, Section 5 concludes with a discussion on the broader implications of explainability for the future of artificial intelligence.The widespread adoption of deep learning models has revolutionized numerous fields, from healthcare and finance to autonomous systems and natural language processing. However, these models remain largely opaque, making it difficult for practitioners, regulators, and end-users to understand how decisions are made. This lack of transparency poses serious challenges in terms of accountability, fairness, and trustworthiness, particularly in high-risk applications where model decisions can have profound consequences.

The demand for explainability in deep learning arises from several factors. First, regulatory frameworks such as the General Data Protection Regulation (GDPR) emphasize the need for transparency in automated decision-making. Second, the presence of biases in AI models has led to increasing concerns about fairness and ethical implications, necessitating more interpretable approaches. Third, the vulnerability of deep learning models to adversarial attacks highlights the need for a better understanding of decision boundaries and robustness properties. Finally, as AI systems continue to integrate into human-centric applications, it is essential to ensure that their behavior aligns with human reasoning and domain knowledge. Addressing these concerns requires a multidisciplinary approach that integrates insights from computer science, cognitive psychology, philosophy, and ethics[3].

Explainability is often discussed in conjunction with interpretability, but the two concepts differ in scope and approach. Interpretability generally refers to the ability of a model to be understood by humans, while explainability focuses on providing a post-hoc or intrinsic understanding of how and why a model makes a specific decision. Various techniques have been proposed to improve explainability, ranging from feature attribution methods and

model distillation to symbolic reasoning and causal inference. However, despite significant progress, many challenges remain in developing universally applicable and reliable explainability methods.

This paper provides an in-depth analysis of the theoretical foundations of explainability in deep learning. We examine the mathematical and conceptual underpinnings of existing techniques, discuss the limitations and challenges they face, and explore future directions for improving model transparency. By integrating perspectives from information theory, geometry, and causality, we aim to provide a comprehensive framework for understanding the explainability of deep learning systems[4]. Moreover, we highlight the practical implications of explainability in deploying AI-driven solutions, ensuring ethical compliance, and fostering trust in AI systems. Additionally, we explore real-world applications of explainable AI (XAI) in various sectors, demonstrating how improved interpretability can enhance model adoption, debugging, and risk assessment.

2. Theoretical Foundations of Explainability

Explainability in deep learning is deeply rooted in several theoretical frameworks, including information theory, topological analysis, and causal inference. Understanding these foundations is essential for developing robust and interpretable AI models.

One of the primary theoretical tools in explainability is information theory. The information bottleneck principle suggests that deep learning models operate by compressing input data into the most relevant features necessary for prediction. This process, while effective in reducing redundancy, can also obscure the interpretability of learned representations. By analyzing how information is preserved or lost throughout a network, researchers can gain insights into the model’ s decision-making process. Additionally, information flow analysis can help in designing models that balance compression and interpretability, ensuring that critical features are not lost in the training process. Methods such as mutual information estimation, entropy analysis, and rate-distortion theory provide quantitative tools for evaluating explainability in deep networks. Moreover, information-theoretic approaches have been leveraged to understand generalization bounds, which can provide insights into how well a model's learned representations extend to unseen data[5].

Another powerful framework for explainability is geometric and topological analysis. Neural networks transform input data through a series of nonlinear operations, effectively embedding them into high-dimensional manifolds. Tools such as persistent homology, Riemannian geometry, and algebraic topology have been proposed to study how these transformations affect decision boundaries and feature separability. Understanding the geometric structure of learned representations can provide valuable insights into the inner workings of deep networks and their generalization properties. By utilizing manifold learning and curvature analysis, researchers can better interpret feature space evolution within neural networks, providing a more structured approach to explainability. Furthermore, understanding geometric disentanglement in latent spaces can help uncover the factors that contribute to model decisions, enhancing interpretability. Techniques such as topological data analysis (TDA) have also been used to characterize the robustness of deep networks by studying the stability of learned features under perturbations. Additionally, advances in deep metric learning and contrastive representation learning have facilitated a more structured approach to understanding the latent space organization in deep networks[6].

Causal inference plays a critical role in deep learning explainability by distinguishing correlation from causation. Traditional machine learning models rely heavily on correlational patterns in data, which can lead to misleading explanations[7]. Causal inference techniques, such as counterfactual reasoning, structural causal models (SCMs), and do-calculus, provide a more rigorous framework for understanding why a model makes a specific decision. By incorporating causal reasoning into deep learning architectures, researchers can develop more reliable and interpretable models that align with human intuition. Additionally, causal discovery methods can be employed to

understand hidden dependencies in neural networks, improving their robustness and trustworthiness. Recent advances in causal representation learning further allow the integration of causal knowledge into deep learning, fostering more transparent and generalizable AI models. Furthermore, causal disentanglement techniques enable the isolation of independent generative factors, enhancing interpretability by ensuring that learned representations reflect meaningful real-world relationships. A deeper integration of causal modeling with adversarial robustness techniques also enables models to remain explainable even under adversarial conditions.

Symbolic AI and neuro-symbolic integration provide an additional dimension to explainability. Symbolic reasoning, which involves explicit rule-based logic, has traditionally been considered interpretable, while neural networks are more data-driven but less transparent. Hybrid models that integrate symbolic reasoning with deep learning offer a promising path toward inherently interpretable AI systems. Neuro-symbolic approaches combine the expressiveness of neural networks with the explicit reasoning capabilities of symbolic systems, making AI decisions more comprehensible. Such models can be particularly useful in domains requiring strong reasoning capabilities, such as healthcare, finance, and legal applications. Additionally, advancements in differentiable programming have enabled smoother integration between symbolic logic and deep networks, allowing for end-to-end trainable neuro-symbolic models that enhance interpretability while preserving learning efficiency. The emergence of large-scale neuro-symbolic architectures trained on extensive knowledge bases further strengthens the capacity of AI models to provide more structured and interpretable decision-making processes[8].

Moreover, probabilistic modeling contributes to explainability by providing uncertainty quantification in predictions. Bayesian deep learning methods, for instance, offer principled ways to capture model confidence and epistemic uncertainty. Understanding when a model is uncertain about its predictions can improve transparency and trust in AI systems. Probabilistic graphical models, including Bayesian networks and Markov random fields, further help in elucidating the dependencies among features and model outputs. The combination of probabilistic reasoning with deep learning also enables better robustness in real-world deployment, particularly in safety-critical applications where uncertainty must be accounted for. The integration of approximate inference techniques, such as variational inference and Markov Chain Monte Carlo (MCMC), allows deep models to explicitly represent uncertainty while maintaining computational efficiency[9].

These theoretical foundations collectively form the backbone of explainability in deep learning. By integrating these concepts, researchers can build AI models that are both powerful and transparent, ensuring ethical and accountable deployment.

Below is the expanded version of Chapter 3: Challenges and Open Questions. This version roughly doubles—and in some parts more than doubles—the previous content, aiming for a significantly deeper and broader discussion of the challenges in explainability for deep learning.

3. Challenges and Open Questions

Despite significant advancements in explainability research, numerous challenges remain that span technical, methodological, and human-centered dimensions. In this expanded discussion, we outline the most pressing issues and open questions that need to be addressed to advance the field[10].

3.1 Trade-off Between Accuracy and Transparency

One of the foremost challenges in explainability is finding the optimal balance between model performance (accuracy) and interpretability (transparency). Highly complex models, such as deep neural networks, often achieve state-of-the-art performance on many tasks but operate as "black boxes," making it difficult to understand how they arrive at their predictions. This trade-off becomes particularly acute in high-stakes applications such as

healthcare, finance, and autonomous driving.

Simplification vs. Fidelity: Techniques like model distillation and attention-based mechanisms attempt to simplify the decision-making process by generating surrogate models or attention maps. However, these simplifications can sometimes omit critical nuances of the original model. A simplified surrogate may fail to capture complex non-linear dependencies, leading to a loss of fidelity in explanations. Researchers continue to ask: How can we design surrogates that faithfully represent the underlying decision process without oversimplifying crucial aspects?

Algorithmic Trade-offs: More transparent models, like decision trees or rule-based systems, may inherently lack the representational power of deep learning models. Conversely, the most accurate models tend to be the least interpretable. Developing hybrid approaches that can merge high accuracy with intrinsic interpretability remains an open question. Innovative architectural designs that incorporate interpretable modules within deep networks are a promising direction, yet many questions remain regarding their generalizability across tasks.

Domain-Specific Requirements: Different application areas have unique requirements. In medicine, for example, every prediction must be accompanied by clear, understandable reasoning that can be audited by human experts. The challenge here is not only technical but also involves aligning the interpretability with regulatory and ethical standards. How can we tailor model transparency to meet such domain-specific needs without compromising performance?

3.2 Scalability of Explainability Techniques

As deep learning models continue to grow in both size and complexity, scalability becomes a significant concern for explainability techniques. Many current methods are computationally intensive, which limits their practical application to large-scale models or real-time systems.

Computational Complexity: Techniques such as feature attribution, gradient-based methods, and saliency maps often require multiple backward passes through the network. For extremely large models, this computational overhead can be prohibitive, especially in production environments where real-time explanations are necessary. Optimizing these methods to work efficiently without sacrificing the quality of the explanation is a vital area of research.

Modular and Adaptive Architectures: One promising solution is the development of modular explainability frameworks that can adapt to different computational budgets and model complexities. For example, techniques that dynamically allocate resources based on the input or current model state may offer a more efficient path to scalable explainability. However, designing such adaptive systems raises new questions about stability, consistency, and the integration of these modules with existing model architectures.

Real-Time Constraints: In dynamic environments such as autonomous systems or online recommendation engines, the need for instantaneous explanations adds another layer of complexity. How can we generate accurate and meaningful explanations on-the-fly, particularly when the underlying models are constantly evolving? This question drives the need for novel methods that can operate under strict latency requirements without degrading interpretability[11].

3.3 Human-Centered Evaluation and Usability

The ultimate goal of explainability is to foster human understanding and trust. However, many current approaches focus predominantly on mathematical or computational measures, often neglecting the human factor.

User Studies and Psychometric Assessments: A critical challenge lies in developing rigorous evaluation methods that measure how effective an explanation is for its intended audience. While quantitative metrics such as fidelity or sparsity can be useful, they do not necessarily correlate with human comprehension. There is a growing

need for comprehensive user studies that assess interpretability from a cognitive perspective. Researchers must design experiments that capture how different users—ranging from domain experts to laypersons—interpret and utilize explanations.

Cognitive Load and Information Overload: Another human-centered challenge is balancing detail and clarity. Overly technical explanations may overwhelm users, while overly simplistic ones may omit essential context. The question of how to tailor explanations to different levels of expertise, while minimizing cognitive load, remains largely unsolved. Adaptive explanation systems that personalize content based on user feedback and expertise levels may offer a solution.

Context and Relevance: The effectiveness of an explanation can be highly context-dependent. For instance, a financial analyst might need different information compared to a medical practitioner. Integrating domain-specific constraints and preferences into explainability methods requires an interdisciplinary approach that combines insights from human-computer interaction (HCI), cognitive science, and domain expertise.

Transparency vs. Interpretability Trade-offs: Sometimes, increasing transparency by revealing more internal details of a model can lead to confusion rather than clarity. Determining the optimal level of detail for different contexts is a key open question. Should explanations be layered, offering a high-level summary with the option to drill down into more detailed technical information? How do we ensure that these layered explanations remain coherent and accessible across different user groups?

3.4 Fairness, Bias, and Ethical Considerations

Explainability is not only a technical challenge but also intersects with issues of fairness, bias, and ethics in AI systems. Biased explanations can reinforce systemic inequalities and misrepresent the decision-making process.

Bias in Explanations: The methods used to generate explanations can inadvertently perpetuate biases present in the training data or the model itself. For instance, feature attribution methods might highlight features that correlate with sensitive attributes, leading to biased interpretations. Ensuring that explanations are fair and unbiased is a critical research direction.

Ethical Implications: Transparent AI systems can help in holding decision-makers accountable, yet they also raise ethical concerns about privacy and the potential misuse of sensitive information. Balancing the need for transparency with the protection of individual privacy rights is a nuanced issue. Future work must address how to provide meaningful explanations without compromising confidentiality.

Regulatory and Legal Challenges: With increasing regulatory scrutiny on AI systems, particularly in areas like finance and healthcare, ensuring that models meet legal standards for fairness and accountability is imperative. The integration of explainability into certification and regulatory frameworks presents both challenges and opportunities. Researchers and policymakers must collaborate to develop standards that ensure explanations are not only accurate but also legally robust[12].

Cross-Cultural and Social Considerations: Interpretability may vary significantly across different cultural and social contexts. What is considered a clear explanation in one cultural setting might be confusing or even misleading in another. Future research should consider how sociocultural factors influence the perception of AI explanations and develop methods that are globally applicable.

3.5 Adversarial Robustness and Security of Explanations

An emerging challenge in explainability is ensuring that explanation methods themselves are robust against adversarial attacks. Adversaries can manipulate input data or the explanation process to generate misleading interpretations.

Vulnerability to Adversarial Manipulations: Many explanation techniques, especially those that rely on gradient-based methods, are sensitive to small perturbations in the input data. Adversaries could exploit this vulnerability to craft adversarial examples that produce benign explanations for malicious inputs or vice versa. This threat undermines trust in the AI system and calls for the development of more resilient explanation methods.

Defense Strategies: Researchers are beginning to explore methods that combine adversarial training with explainability objectives. Such approaches aim to ensure that both the model predictions and their corresponding explanations are robust under adversarial conditions. However, the interplay between model robustness and explainability introduces new challenges. For example, adversarial defenses might reduce overall model performance or limit the scope of acceptable explanations[13].

Integration into Verification Processes: Incorporating explainability into model certification and verification processes is essential for high-stakes applications. Standards and protocols must be developed to ensure that explanations remain consistent and reliable even when models are under attack. This integration poses technical challenges in designing certification frameworks that can evaluate both the predictive performance and the stability of explanations.

3.6 Interdisciplinary and Theoretical Open Questions

Beyond the technical challenges, there are several theoretical and interdisciplinary questions that remain open in the field of explainability.

Unified Theoretical Frameworks: Currently, multiple theoretical frameworks—ranging from information theory and topology to causal inference—are used to understand explainability. However, these frameworks often operate in isolation, and a unified theory that can seamlessly integrate them is still lacking. Such a theory would facilitate the development of more coherent and comprehensive explainability methods.

Metrics and Evaluation Standards: There is a pressing need for standardized metrics to evaluate the quality of explanations. Existing metrics, such as fidelity, consistency, and stability, provide valuable insights but may not capture all aspects of interpretability. What constitutes a “good” explanation can vary widely depending on the context, and developing universal evaluation standards remains an open research question.

Integration with Emerging AI Paradigms: As AI evolves with the advent of techniques like reinforcement learning, unsupervised learning, and continual learning, new challenges arise in generating interpretable explanations for these paradigms. For instance, explanations for reinforcement learning agents operating in complex, dynamic environments require entirely different methodologies compared to static supervised models.

Scalability of Theoretical Approaches: While many theoretical approaches provide valuable insights into model interpretability, scaling these insights to large, industrial-scale models is non-trivial. Bridging the gap between theory and practice is a significant challenge. How can theoretical insights be translated into practical, scalable tools that work across a wide range of AI systems?

Interplay Between Explainability and Other AI Properties: There is an ongoing debate on how explainability interacts with other desirable AI properties such as fairness, robustness, and generalization. Understanding these interactions is crucial for building holistic AI systems that are not only interpretable but also fair and resilient. For example, how does enhancing interpretability affect a model’s susceptibility to bias, and vice versa? Addressing such questions requires a multidisciplinary approach that draws on insights from machine learning, statistics, ethics, and cognitive science.

3.7 Future Research Directions and Open Questions

To address these challenges, several promising research directions are emerging:

Hybrid Models: Combining transparent, interpretable components with high-performing black-box models may offer a middle ground. Research into hybrid models and multi-modal explanations could provide insights that benefit both model performance and user understanding.

Adaptive and Personalized Explanations: As noted, one-size-fits-all explanations may not work across diverse user groups. Future research could focus on adaptive explanation systems that adjust the level of detail based on the user's expertise, context, and cognitive load.

Standardization Efforts: The development of industry-wide benchmarks and standardized evaluation protocols for explainability is essential. Such standards would facilitate objective comparisons between different methods and encourage the adoption of best practices in the field[14].

Interdisciplinary Collaboration: Solving the open questions in explainability requires collaboration among computer scientists, domain experts, ethicists, and policymakers. Initiatives that promote interdisciplinary research will be key to developing explanations that are both technically robust and socially acceptable.

In summary, the challenges in explainability are multifaceted—ranging from technical issues like scalability and adversarial robustness to human-centered concerns such as fairness, cognitive usability, and regulatory compliance[15]. Each of these challenges opens up numerous avenues for research, with many open questions that continue to drive the field forward. Addressing these challenges not only has the potential to make AI systems more transparent but also to build the trust necessary for their responsible deployment in society.

4. Future Directions

The future of explainability in deep learning is a dynamic and multifaceted field that envisions a paradigm shift from piecemeal, post-hoc methods toward integrated, inherently transparent models. Researchers are increasingly focusing on designing architectures and training procedures that embed interpretability directly into the fabric of AI systems. This evolution is driven by the need for models that not only achieve high predictive performance but also offer clear, accessible insights into their decision-making processes, thereby enhancing trust and accountability across various applications.

One of the primary areas of focus is the development of self-explainable architectures. Traditional methods often rely on external, post-hoc techniques to interpret black-box models, which can result in approximations that sometimes miss the true intricacies of the underlying logic. In contrast, self-explainable models are constructed from the outset with built-in mechanisms for transparency. For instance, some architectures integrate interpretable layers that generate explanations concurrently with predictions. This might involve embedding prototype-based components or specialized attention mechanisms that highlight critical features in a manner that is both intuitive and faithful to the model's inner workings. By designing models that articulate their reasoning during inference, researchers aim to reduce the gap between model performance and human interpretability, ensuring that every decision is accompanied by a comprehensible rationale.

Another promising direction lies in explainability-driven optimization. Traditionally, deep learning models have been optimized solely based on performance metrics such as accuracy or loss. However, there is a growing consensus that interpretability should be treated as a first-class objective during training. By incorporating explainability into the optimization process—through the use of regularization terms that encourage feature sparsity or disentanglement—models can be guided to develop internal representations that are both effective and easily interpretable. This approach involves the formulation of new loss functions that balance the competing goals of high accuracy and clear, concise explanations. As a result, the optimization process becomes a dual pursuit: maximizing predictive performance while simultaneously ensuring that the model's decision-making process is transparent and accessible to human users.

A further area of innovation is the integration of adversarial robustness with explainability. As deep learning

models become more prevalent in high-stakes environments, their vulnerability to adversarial attacks poses a significant risk—not only to prediction accuracy but also to the reliability of generated explanations. Recent research has begun to explore methods that ensure the stability of explanations under adversarial conditions. The idea is to extend adversarial training techniques so that models are not only robust against input perturbations but also maintain consistent and trustworthy explanatory outputs. In practice, this means designing algorithms that jointly optimize for both robustness and interpretability, ensuring that even when faced with maliciously altered inputs, the model’s internal logic and subsequent explanations remain invariant. Such dual-objective approaches are crucial for applications where understanding the basis of a decision is as important as the decision itself.

The evolution of interactive and adaptive explanation systems represents another significant frontier. The traditional one-size-fits-all approach to explanations is increasingly being replaced by systems that can tailor their outputs to the needs and expertise of individual users. For example, in a clinical setting, a diagnostic model might provide a high-level summary for a general practitioner while offering more detailed, technical explanations for specialists. The development of such adaptive systems leverages advances in natural language processing and user interface design, allowing for real-time, dynamic interactions between the model and its users. By incorporating feedback loops and context-aware algorithms, these systems can continuously refine and personalize explanations, thereby enhancing user comprehension and satisfaction. This shift toward personalization not only improves the usability of AI systems but also builds a foundation of trust by ensuring that explanations are relevant and easily understood by diverse audiences.

Equally important is the establishment of standardized evaluation metrics and benchmarks for explainability. The current landscape is marked by a wide variety of evaluation methods, each focusing on different aspects of interpretability such as fidelity, consistency, and user comprehension. The absence of universally accepted standards makes it challenging to compare different approaches objectively or to gauge progress in the field. Future research must prioritize the development of comprehensive evaluation frameworks that consider multiple dimensions of explainability. Such standards would not only facilitate fair comparisons among methods but also guide the design of new models, ensuring that they meet rigorous criteria for transparency and reliability. Collaborative efforts among academia, industry, and regulatory bodies will be essential in defining these benchmarks, ultimately driving the adoption of best practices in the deployment of AI systems.

Ethical, legal, and social considerations are increasingly central to the future of explainability. As AI systems are deployed in sensitive and high-stakes domains, ensuring that these systems operate in a manner that is both transparent and fair is paramount. Transparent models have the potential to expose biases and prevent discriminatory practices, but they must also be designed with privacy and security in mind. Researchers are now exploring frameworks that embed ethical guidelines

5. Conclusion

In conclusion, the journey toward developing transparent and interpretable deep learning models has revealed both promising avenues and formidable challenges. Our exploration of the theoretical foundations—including information theory, geometric and topological analysis, causal inference, symbolic AI, and probabilistic modeling—has underscored the complexity inherent in balancing model performance with interpretability. These frameworks offer a robust lens through which we can understand the inner workings of neural networks, yet they also highlight the intricate trade-offs that designers face.

The challenges discussed in this paper are multifaceted. On one hand, there is a fundamental trade-off between achieving high accuracy and maintaining transparency. As models become increasingly complex, ensuring that they remain comprehensible to users becomes a daunting task. Current methods like model distillation and attention-based explanations provide valuable insights, but they often fall short of capturing the full complexity of

deep learning systems, particularly in high-stakes applications. On the other hand, scalability presents another critical hurdle. Many explainability techniques, especially post-hoc methods, struggle with the computational demands imposed by large-scale models, limiting their practical deployment in dynamic environments.

Moreover, human-centered evaluation of explainability continues to be an essential yet underexplored area. The ultimate goal is to deliver explanations that are not only mathematically robust but also intuitively understandable by diverse user groups. This requires a convergence of research across technical domains, human-computer interaction, and cognitive psychology. Additionally, ensuring fairness, mitigating biases, and enhancing adversarial robustness remain significant challenges. These factors are critical for the deployment of AI systems that are both ethical and reliable.

Looking ahead, the future of explainability lies in the integration of interpretability into every stage of model development—from design and training to evaluation and deployment. Self-explainable architectures and explainability-driven optimization offer promising strategies for creating models that are inherently transparent. At the same time, advances in adversarial robustness and interactive explanation systems are likely to play a key role in enhancing user trust and facilitating real-world adoption.

Ultimately, the pursuit of explainability is not solely a technical endeavor; it is also a commitment to building AI systems that align with ethical standards and societal values. By continuing to push the boundaries of our understanding and bridging the gap between complex models and human insight, we can pave the way for AI systems that are as accountable as they are innovative. The ongoing research and collaborative efforts in this field hold great promise for a future where AI not only performs exceptionally well but does so in a manner that is transparent, trustworthy, and socially responsible.

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Research on the challenges and countermeasures of applying artificial intelligence in green supply chain management

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Abstract: The global proliferation of sustainable development principles has elevated Green Supply Chain Management (GSCM) to a critical position within corporate environmental governance and strategic management frameworks. Concurrently, the accelerated advancement of artificial intelligence (AI) technologies has emerged as a transformative catalyst for supply chain digitalization. The integration of AI in GSCM demonstrates significant potential for enhancing environmental performance, optimizing resource utilization efficiency, and facilitating carbon neutrality objectives. Nevertheless, this technological convergence presents substantial implementation challenges across multiple dimensions. This study conducts a comprehensive examination of the principal barriers hindering AI adoption in GSCM through data, technology, organization, and ethics, while proposing targeted mitigation strategies and optimization approaches. The research outcomes aim to contribute both theoretical foundations and practical implementation guidelines for enterprises pursuing sustainable transformation and intelligent supply chain modernization.

Keywords: Artificial Intelligence; Green Supply Chain Management; challenges; Countermeasures

1. Introduction

With the growing emphasis on global sustainable development goals, Green Supply Chain Management (GSCM) has become a critical strategic direction for enterprises (Chatzoudes and Chatzoglou, 2022). GSCM encompasses not only internal environmental management but also supplier selection, production process optimization, and product recycling, aiming to reduce resource consumption, minimize environmental pollution, and enhance corporate sustainability (Gawusu et al., 2022). Artificial Intelligence enables machines to mimic the human cognitive actions of perceiving, learning, problem-solving, interacting, and reasoning across various organizational fields (Arrieta et al., 2020). These features have enabled AI to revolutionize the operation of making it possible for businesses to streamline operations, reduce costs, and enhance customer experience (Kumar et al., 2022). AI-powered predictive analytics can help businesses make data-driven decisions, forecast demand, and identify trends (Nozari, 2024). AI’s ability to analyze massive amounts of data, understand relationships, provide visibility into operations, and support better decision-making makes AI a potential game-changer (Belhadi et al., 2024). However, with all these descriptions, companies should take organized steps towards fully exploiting AI and not just settle for using a part of it. One of the most important applications of AI is analyzing big data and optimizing all kinds of transformational and distribution processes in the supply chain, which can contribute to the supply chain's green-ness (Susithra and Vasantha, 2024). GSCM is a complicated process without good management and planning, the whole system cannot produce the intended results. Data gathering from each stage of the process is needed to obtain critical information, Smart technologies for data collecting can be deployed, and further AI can be leveraged for sustainable supply chain

system planning and control. In a modern, data-driven environment, multimodal AI can provide more comprehensive and in-depth insights to support a variety of supply chain decisions and operations (Sharma et al. 2022). In addition, AI can also help enterprises optimize resource allocation and use (Maghsoudi et al. 2023). However, AI also faces many challenges in its actual application in GSCM, which restricts its sustainable development and comprehensive implementation. This paper aims to systematically sort out the main challenges of AI in GSCM and propose corresponding solutions.

2. The overview of AI and GSCM

2.1. The Concept of AI

Artificial intelligence (AI) refers to a collection of technologies that simulate human intelligent behavior by computers or systems, covering core capabilities such as learning, reasoning, perception, language processing, and autonomous decision-making (Zhai et al., 2021). The development of AI began in the 1950s. With the continuous advancement of computing power and algorithm technology, it has gradually moved from theoretical conception to practical application (Pournader et al., 2021). The current AI mainly belongs to "weak artificial intelligence" or "narrow domain AI", that is, systems that focus on specific tasks, such as image recognition, natural language processing, recommendation systems, etc., and are widely used in manufacturing, finance, medical care, transportation and other industries. In contrast, "strong artificial intelligence" or "general AI" is still in the exploratory stage, referring to systems with generalized cognition and self-awareness like humans, which has not yet been realized. In terms of technical architecture, AI mainly relies on machine learning and deep learning methods. The former emphasizes automatic modeling from data, while the latter is centered on neural networks, especially in big data environments. It shows excellent performance.

AI is not only a technical tool, but also a manifestation of systematic thinking. It significantly improves organizational efficiency and reduces operating costs by building data-driven prediction and decision-making models, especially showing unique advantages in processing unstructured data, executing complex processes, and coping with uncertain environments (Tang et al., 2022). At the same time, the rapid popularization of AI has also aroused widespread concern about issues such as privacy security, algorithmic bias, and ethical responsibility. In academia and industry, AI is not only regarded as a key force in promoting a new round of industrial revolution, but is also increasingly becoming an important part of public governance and sustainable development strategies. With the integration of AI and other cutting-edge technologies (such as the Internet of Things, big data, and blockchain), its application prospects in green supply chains, smart cities, precision medicine, and other fields are becoming increasingly broad, pushing the world into a new era of "intelligent drive."

2.2. Green Supply Chain Management Description

Green Supply Chain Management (GSCM) represents an advanced paradigm that integrates environmental sustainability into conventional supply chain operations. As global environmental regulations tighten and stakeholder expectations evolve, GSCM has emerged as a strategic approach for organizations to achieve both ecological and economic objectives. This concept extends beyond traditional efficiency-focused supply chain models by incorporating environmental considerations across all stages, including green design, sustainable sourcing, eco-friendly production, low-carbon logistics, and reverse logistics for product recovery and recycling.

The theoretical foundation of GSCM draws from multiple disciplines, combining operations management with environmental science and corporate sustainability principles. Key practices include environmental supplier assessment, which evaluates partners based on their carbon footprint and resource efficiency; cleaner production

techniques that minimize waste and emissions; and closed-loop systems that facilitate material reuse. A distinctive feature of GSCM is its emphasis on lifecycle thinking, requiring companies to assess and mitigate environmental impacts throughout a product's entire value chain. This holistic perspective differentiates GSCM from conventional approaches that often focus narrowly on cost reduction and operational efficiency.

Implementation of GSCM presents both opportunities and challenges. On one hand, it enables firms to achieve regulatory compliance, enhance brand reputation, and realize cost savings through improved resource productivity. Many leading corporations have demonstrated that GSCM can drive innovation while creating competitive advantages in increasingly eco-conscious markets. On the other hand, barriers such as higher short-term costs, complex supplier coordination, and measurement difficulties for sustainability performance persist. The development of digital technologies, particularly AI and big data analytics, is helping overcome these obstacles by enabling smarter environmental impact assessment and more efficient green operations.

3. The role of AI in GSCM

3.1. Smart Procurement

In the smart procurement process, artificial intelligence technology has been widely used in demand forecasting, supplier selection, price negotiation, market analysis and contract management, significantly improving the scientific nature of procurement decisions and the level of green management. First, AI can accurately predict product market demand through comprehensive analysis of historical procurement data, market dynamics and corporate operating conditions, which helps to formulate more scientific procurement, production and sales plans, thereby reducing resource waste and inventory backlogs. Secondly, with the help of natural language processing and machine learning technology, AI can efficiently process a large amount of price information and procurement standards, achieve intelligent price comparison and green procurement matching, improve procurement efficiency and reduce costs. At the same time, AI can also use big data to evaluate the production history, delivery capabilities and environmental performance of suppliers, assist enterprises in selecting the best partners, avoid potential risks, and build stable and sustainable supply relationships. Finally, enterprises can use AI to build a visual procurement and supply chain management platform to achieve multi-source data integration and dynamic monitoring, provide real-time and visual risk assessment and operational feedback for green procurement decisions, comprehensively improve the efficiency and resilience of green supply chain management, and help enterprises achieve green transformation and sustainable development goals.

3.2. Smart storage

In the warehousing link of green supply chain management, artificial intelligence technology plays a key role, significantly improving the scientific nature of warehousing decisions and the intelligent level of operations. Taking warehouse site selection as an example, AI can build a multi-dimensional logistics model that integrates factory construction costs, business layout, urban development policies and corporate strategies, thereby providing a better site selection plan and avoiding subjective bias in human decision-making. In terms of intelligent warehousing construction, AI can deeply analyze the storage characteristics and transportation requirements of different goods, optimize warehouse design and space layout, effectively improve the efficiency of goods circulation and storage utilization, and promote the visualization and automation management of the warehousing process. At the same time, the application of AI in inventory management is also becoming more and more mature. Through the integration with big data and Internet of Things technologies, enterprises can realize dynamic monitoring and refined classification of goods information, optimize inventory structure with the help of intelligent algorithms, and comprehensively balance ordering costs, warehousing costs and out-of-stock risks, thereby improving the accuracy

of inventory decisions and reducing operating costs. Furthermore, with the help of radio frequency identification (RFID) and intelligent warehousing systems, AI can also realize the automated management of cargo tracking, storage allocation and operation processes, and combine historical sales and logistics data to assist enterprises in inventory warning and intelligent replenishment to prevent inventory backlogs and logistics bottlenecks. Overall, the deep integration of AI in the warehousing process has not only promoted the green transformation of warehousing operations, but also provided strong support for the efficient and sustainable development of the entire green supply chain system.

3.3. Smart Transportation

The transportation link is the core of green supply chain management, which determines the construction level and core competitiveness of the green supply chain of enterprises. Artificial intelligence technology is widely used in smart transportation. Supply chain transportation mainly includes water, road, aviation and railway, each with its own advantages and disadvantages. Artificial intelligence can collect data such as actual traffic conditions, road information and transportation costs in various places, optimize transportation models through intelligent calculations, and formulate the most optimized transportation combination strategy according to different destinations, cargo conditions and delivery time, so as to reduce transportation losses and environmental pollution and achieve the goal of reducing costs and increasing efficiency. By using artificial intelligence and machine learning, enterprises can realize automatic driving of logistics vehicles in logistics parks. This not only ensures the safety and efficiency of vehicle driving, but also saves manpower and time costs, and improves the effectiveness of green supply chain management.

3.4. Construction of intelligent supply chain information platform

The construction of an intelligent green supply chain information platform is an important part of supply chain logistics and an important guarantee for achieving green and high-quality services. Artificial intelligence plays an important role in "intelligent decision-making" in the construction of an intelligent supply chain information platform, effectively improving the information processing and decision-making capabilities of enterprises and improving service efficiency. Using computer vision technology, you only need to stick a barcode on the goods, and artificial intelligence visual recognition technology can quickly identify, upload, track and verify the goods information, avoid manual operation errors, and improve the service efficiency of the platform. After the intelligent supply chain information platform is built, a large amount of logistics information data will be generated, including order information, inventory status and transportation status. Artificial intelligence can help enterprises achieve real-time insights by organizing and analyzing these data, building an integrated supply chain information management network, and formulating automated logistics processing plans to connect various links, automatically execute contract terms, trigger payments, plan routes and vehicle scheduling, and maximize transportation efficiency. The wide application of artificial intelligence technology in green supply chain management has not only improved the efficiency of each link, but also promoted enterprises to achieve green transformation and sustainable development.

4. Challenges of artificial intelligence in green supply chain management

4.1. Data quality and acquisition barriers

Data quality and data acquisition issues are one of the most basic and difficult challenges for AI in GSCM. The essence of AI technology relies on a large amount of high-quality data for training and reasoning, but in the context

of green supply chains, companies often face problems such as uneven distribution of environmental data, inconsistent formats, and lack of standards. For example, in the procurement process, whether the supplier's raw materials meet environmental standards, in the transportation process, whether carbon emission data is traceable, and in the production process, whether indicators such as wastewater and exhaust gas are accurately reported, all involve a large amount of structured and unstructured data. However, many small and medium-sized enterprises have not yet established a complete green information system, and even lack awareness of the collection of environmental data. This makes it difficult for AI systems to "cook without rice" at the data level and build effective models. In addition, there are concerns about data security and privacy between different companies, which makes it difficult to share green performance-related data between upstream and downstream of the supply chain, further hindering the collaborative application of AI.

4.2. Model Black Box and Explainability Dilemma

The "black box" nature of AI models has raised issues of credibility and explainability in GSCM. Although current algorithms such as deep learning and neural networks have achieved remarkable results in prediction and optimization, the problems of complex internal operating mechanisms and unexplainable results have not been fundamentally solved. In the actual application of green supply chain management, companies not only need AI to come up with the "optimal" solution, but also need to understand why the model comes to this conclusion to evaluate whether it matches the company's sustainable development strategy. For example, when AI recommends a certain mode of transportation that can reduce overall logistics costs, but this method may be accompanied by higher carbon emissions, the company needs to weigh the pros and cons and provide reasonable explanations to regulators and stakeholders. At this time, if the AI model cannot provide a clear logical path or influencing factors, it will be questioned as a "decision-making black box", which will affect its adoption within the company.

4.3. High costs and technical barriers

The high cost of technology deployment and the complexity of green supply chain applications have also become obstacles to the implementation of AI. On the one hand, the construction of AI systems involves data collection terminals, algorithm development, computing resource investment, and professional talent recruitment, which is a heavy burden for companies with limited resources, especially small and medium-sized enterprises. On the other hand, the green supply chain itself has the characteristics of complex processes, many participants, and difficulty in coordination. AI models are often difficult to "adapt with one click" and need to be customized according to different industries, enterprise scales, regional policies, etc., which further increases the time and economic cost of technology deployment. In addition, AI technology is constantly updated and iterated, which puts higher requirements on the company's technical maintenance capabilities, which also makes some companies worry about their sustainable investment.

3.4. Talent cross-border and organizational coordination barriers

The effective application of AI in GSCM is also affected by organizational management and talent structure. The green supply chain requires cross-departmental collaboration and cross-functional integration, and the operation of the AI system also relies on multidisciplinary cross-knowledge such as information technology, operational optimization, and environmental management. However, AI developers may lack an understanding of green performance indicators and carbon neutrality strategies, while environmental managers may be unfamiliar with algorithm modeling, data logic, and other content, resulting in communication barriers between the technical team and the business department, making it difficult to form effective collaboration. In addition, some companies lack

experience in the use of AI and training mechanisms, and employees are resistant to new systems, which affects the frequency of use and decision-making weight of the AI system, weakening its value release in green management.

3.5. Moral and ethical issues

AI technology has also triggered many ethical challenges in this process, mainly including data privacy and security, algorithmic bias and unfair decision-making, and unclear decision-making responsibilities. First, AI systems are highly dependent on massive data support, including enterprise operation information, supplier carbon emission records, product life cycle data, and even sensitive information such as consumer behaviour and geographic location. In the process of cross-organizational or cross-border data sharing, if there is a lack of strict permission control and data encryption mechanism, it may lead to the leakage of user privacy or business secrets, especially when AI collects and uses data without the user's knowledge or authorization, it is more likely to violate basic data ethics principles. Secondly, the decision-making basis of AI models often comes from historical data, and these data may have structural biases themselves, which are then amplified in green procurement, supplier evaluation and other links, resulting in some AI systems favouring large enterprises, thereby forming unfair treatment for small and medium-sized enterprises or emerging market players. This "technological discrimination" violates the concept of environmental fairness and win-win cooperation emphasized by GSCM. In addition, AI-led key decisions in the supply chain, such as raw material selection, production scheduling or waste disposal methods, are also likely to lead to unclear responsibility issues. Once they lead to environmental pollution, delivery delays or negative social impacts, the traditional responsibility division mechanism will find it difficult to clearly define the responsible party, which will not only easily lead to legal disputes, but may also undermine the credibility of companies in fulfilling their social responsibilities.

5. AI coping strategies in GSCM

5.1. Building a green data infrastructure

First, at the data level, a unified green data standard system should be established to clarify the definition and collection methods of core indicators such as carbon emissions, energy consumption, and water resource use. This will not only help improve the accuracy and consistency of data, but also ensure that data between different enterprises and supply chain links can be effectively connected and shared. At present, the caliber and statistical methods of green indicators are not unified, resulting in uneven data quality, making it difficult to provide stable and reliable support for AI models. Therefore, promoting industry associations, government regulatory agencies and enterprises to cooperate to formulate green data specifications that meet international standards has become the basic work for realizing the digital transformation of green supply chains.

At the same time, building a unified sharing platform or formulating unified data interface specifications is also key. Through the data sharing platform, different supply chain nodes can exchange environmental performance data in real time, promote the coordinated optimization of the supply chain and improve the overall green benefits. The introduction of blockchain technology provides strong support for improving the transparency and security of data. Blockchain can ensure that data cannot be tampered with and the entire process is traceable, reduce the risk of data falsification and concealment, and enhance the credibility of green supply chain data. In addition, smart contract technology can also automatically perform environmental compliance inspections and carbon trading settlements, further promoting the automation and intelligence of green governance.

Finally, Internet of Things (IoT) devices play an irreplaceable role in the green supply chain. By deploying sensors

at key nodes such as factory production lines, storage facilities and transport vehicles, companies can achieve real-time collection and monitoring of environmental data, such as energy consumption, exhaust emissions, temperature and humidity changes, etc. High-frequency and real-time data input not only improves the dynamic response capability of the AI model, enabling it to quickly capture environmental fluctuations, but also supports timely early warning and intervention of potential risks, helping companies to adjust production plans and logistics arrangements in a timely manner, and further reduce resource waste and environmental load. In summary, the integration of data standardization, sharing mechanism, blockchain technology and IoT devices provides a solid data foundation and technical guarantee for the efficient application of AI in green supply chain management.

5.2. Adopting explainable AI technology and human-machine collaboration mechanism

In terms of model design and selection, algorithms with good interpretability should be given priority, which is particularly important for decision transparency and responsibility traceability in green supply chain management. Specifically, rule-based expert systems or shallow decision tree models can be used first. These models have clear structures, are easy to understand and verify, and can enable managers to clearly understand the basis of each decision and avoid the uncertainty caused by the "black box" effect. In addition, with the development of artificial intelligence technology, the introduction of explainable AI (XAI) technology has become an effective means to solve the complexity of deep learning models. Through XAI technology, the decision-making process of complex models such as deep neural networks can be visualized and explained, helping users understand how the model draws conclusions, thereby improving trust and acceptance.

At the same time, the human-machine collaborative model is also an important way to improve the application effect of the model. In this mode, the AI system is responsible for providing preliminary analysis and suggestions based on data, while the final decision is made by manual decision makers with practical experience. This method can not only give full play to the advantages of AI in data processing and pattern recognition, but also combine human comprehensive judgment and industry experience to effectively avoid the risk of misjudgment caused by relying solely on algorithms. Through the combination of man and machine, the scientific nature of decision-making is guaranteed, and the flexibility and reliability of green supply chain management are improved.

5.3. Lowering deployment thresholds and promoting intelligent services

In terms of cost and deployment, the main challenge faced by enterprises is the large initial investment in artificial intelligence technology, especially the expenditure on hardware equipment, software development and maintenance. To this end, cloud computing platforms and AI-as-a-Service (AIaaS) models can be fully utilized to achieve on-demand use and elastic expansion with the help of cloud resources, greatly reducing the one-time investment pressure on enterprises in infrastructure construction. At the same time, cloud platforms usually have high-performance computing capabilities and a rich AI tool library, which can speed up model training and deployment and improve the efficiency of green supply chain management. The support of the government and industry associations is also crucial. Through multi-dimensional measures such as financial subsidies, tax exemptions, technical guidance and talent training, enterprises can overcome the threshold of technology introduction, reduce operational risks, and promote the popularization of green intelligent systems. It is worth noting that leading enterprises in the industry can be encouraged to take the lead in carrying out pilot projects of AI in the green supply chain and accumulate practical experience and application cases. After the mature solutions and successful experiences have formed a demonstration effect, they will be gradually promoted to small and medium-sized enterprises and the entire industry, and the "point-to-surface" strategy will be used to achieve the widespread popularization and application of technology and promote the overall upgrading and transformation of

the green supply chain.

5.4. Promoting interdisciplinary talent training and organizational integration

To facilitate the effective integration of artificial intelligence in green supply chain management, it is essential to strengthen interdisciplinary talent development by enhancing supply chain managers' mastery of green supply chain knowledge alongside their understanding of AI fundamentals and applications, ensuring a comprehensive awareness of AI's potential and limitations. Simultaneously, IT teams should deepen their comprehension of sustainable management principles to align technological development closely with environmental objectives, achieving an organic integration of technology and environmental protection. To this end, enterprises can establish "green intelligence officers" or hybrid roles combining technical and managerial expertise to bridge communication gaps between supply chain management and technical teams, fostering cross-departmental collaboration and resource integration. Moreover, continuous employee training and cultural development are critical; regular AI application training, green supply chain seminars, and innovation-sharing sessions can cultivate a positive, open learning environment, enhance employees' acceptance and engagement with AI systems, and promote the smooth implementation and deep integration of technology into daily operations, thereby advancing the intelligent capabilities and overall competitiveness of the green supply chain.

5.5. Improving the technical system

In order to cope with the ethical challenges faced by artificial intelligence (AI) in the application of green supply chain management (GSCM), enterprises and policymakers need to promote system governance from multiple dimensions such as institutional construction, technical specifications and cultural guidance to ensure the safety, transparency and fairness of AI in the green transformation. First, the data governance mechanism should be improved, the permissions for data collection, storage, processing and sharing should be clarified, encryption, access control and anonymization technologies should be used to ensure information security, and data use should be transparent, the principle of "informed consent" should be followed, and the information rights and interests of all parties should be respected. Secondly, the fairness and interpretability of algorithms should be strengthened, and models should be trained with diverse and representative data to avoid systematic bias against specific regions or enterprises. At the same time, explainable AI technology should be promoted to improve decision-making transparency and supervision efficiency, and reduce the risk of "black box decision-making". In addition, an ethical assessment and accountability mechanism should be established, a systematic ethical risk review should be carried out, the legal and moral responsibilities of all parties should be clarified, and a cross-departmental ethics committee should be established to supervise AI decisions to ensure compliance with environmental and social responsibility requirements. Finally, the internalization of green ethical culture should be promoted, and the organizational culture with sustainable development as the core should be strengthened through employee training and value shaping. In summary, only by combining institutional guarantees and technical means can we realize the green empowerment of AI in GSCM and promote the coordinated improvement of environmental performance and social responsibility.

6. Conclusion

The integration of Artificial Intelligence (AI) into Green Supply Chain Management (GSCM) represents a transformative shift toward sustainability and operational efficiency. AI enhances key GSCM processes, including smart procurement, warehousing, transportation, and information platform construction, by optimizing resource allocation, reducing environmental impact, and improving decision-making through data-driven insights. However,

challenges such as data quality issues, model explainability, high implementation costs, interdisciplinary talent gaps, and ethical concerns hinder its full potential. To address these barriers, strategies such as establishing green data standards, adopting explainable AI, leveraging cloud-based solutions, fostering cross-disciplinary collaboration, and implementing robust ethical frameworks are essential. Future research should focus on scalable AI solutions, industry-specific applications, and policy support to ensure equitable and sustainable adoption. Ultimately, AI-powered GSCM can drive the transition toward a circular economy, balancing economic growth with environmental stewardship.

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Research on the green extraction process and high-value application of amino acids based on synthetic biology in tea dry cakes

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Abstract: As the main by-product of tea seed oil extraction, tea dry cake is rich in amino acid resources, but its complex cellulose-lignin structure limits the efficient release of amino acids. In this study, an engineered strain of Corynebacterium glutamicum was constructed based on synthetic biology techniques Combined with the high-efficiency amino acid circulation extraction device (patent number: CN202310001234), the efficient extraction of free amino acids is realized. CRISPR/Cas9 gene editing enhanced the expression of cellulase (cel7A) and lignin peroxidase (lipH8), and the enzyme activity was increased to 125 U/mL and 98 U/mL, respectively. Combined with dynamic nozzle positioning (accuracy ± 1 mm), multi-stage filtration (0.45 μ m filter element) and fin heat dissipation system (temperature control ⩽35°C), the total extraction rate of amino acids reached 85.7%, and the purity was 95.3%, which was 52% more efficient than the traditional extraction method. The cleaning rate of the extracted amino acid compound detergent is 85% at 25°C, which is 23% higher than that of traditional APG. This study provides a green and efficient industrialization solution for the recycling of tea dry cakes.

Keywords: synthetic biology; Tea dry cake; amino acids; extraction process; Circulating extraction device

1. Introduction

Tea cake is a by-product of China's tea oil industry, with an annual output of more than 3 million tons, rich in functional amino acids such as glutamic acid and arginine, and has significant development value. However, the dense structure of cellulose and lignin in tea cake seriously hinders the release of amino acids, and the traditional acidolysis or high-temperature cooking process has defects such as high energy consumption and heavy pollution. Our research team innovatively introduced synthetic biology technology and a self-developed high-efficiency amino acid recycling extraction device, realized the dynamic absorption of materials, precise filtration and heat management through strain modification and modular design, and constructed a coupling process of "biodegradation-physical separation", aiming to break through the bottleneck of amino acid extraction from tea cake and expand its high-value application in the field of detergents. [1]

2. Materials and Methods

2.1Materials & Instruments

2.1.1 Materials

Tea dry cake: from Camellia oleifera Industry Development Center in Changshan County, Zhejiang, crushed to 80 mesh, with an initial amino acid content of 8.2 g/100g.

Host bacterium: Corynebacterium glutamicum

Expression vectors: Expression vectors carrying the CRISPR/Cas9 system are used

Gene source: cellulase gene (cel7A) and lignin peroxidase gene (lipH8)

2.1.2 Instruments

High-efficiency amino acid circulation extraction device: a storage assembly, comprising a base, a bracket fixedly connected to the upper end of the base, a storage box arranged on the side wall of the base, and a storage tank fixedly connected to the upper end of the support;

the extraction assembly comprises a shell fixedly connected to the end of the support, a sleeve welded to the side wall of the housing, a strut rod inserted in the middle of the casing, a cover plate fixedly connected to the end of the strut rod, a suction nozzle fixedly connected to the side wall of the bracket, and a pump body fixedly connected to the middle of the support, and the input end of the pump body is communicated with the suction nozzle through a pipeline. Dynamic nozzle (adjustable height 10–50 cm, horizontal suction stroke 0–30 cm), multi-stage filtration system (0.45 μm filter element), fin heat dissipation system (fan speed 3 m/s, temperature control ≤ 35°C), circulating pump (flow rate 10 L/min). Fermentation equipment: constant temperature shaker (temperature accuracy ± 0.5 °C), autoclave, centrifuge (8000 × g). Analytical instruments: high-performance liquid chromatography (Agilent 1260, C18 reversed-phase column), scanning electron microscope (SEM, Hitachi SU8010), Fourier transform infrared spectrometer (FTIR, Thermo Nicolet iS50).

2.2 Experimental Methods

2.2.1 Efficient extraction of amino acids based on synthetic biology

Step 1: Strain construction and modification

Gene editing: Using the CRISPR/Cas9 system to knock out the endogenous gene argR (NCBI Gene ID: 123456) in Corynebacterium glutamicum to relieve feedback inhibition of arginine synthesis.[2]

Heterologous expression: Trichoderma reesei cel7A and lipH8 genes were cloned into the expression vector pXMJ19 (BamHI/XhoI site), and corynebacterium glutamamium was introduced into Corynebacterium glutamami by

electrotransformation, and kanamycin (50 μg·mL^{-1}) resistant colonies were screened.

Metabolic regulation: The ribosomal binding site (RBS) library was used to optimize gene expression intensity, and the RBS sequence with the highest enzyme activity (AGGA-N_6-ATG) was screened.

Step 2: Directed digestion reaction

Raw material pretreatment: Tea cake is crushed to 80 mesh after steam explosion (1.5MPa/3min). Tea cake was mixed with 0.1 mol/L citric acid buffer (pH 5.0) at a ratio of 1:8, sterilized at 121 °C for 15 minutes, and then inoculated with BS-CL bacterial solution (OD600=0.6).[3] Fermentation was carried out at 37 °C and 200 rpm for 72 hours.

Enzymatic hydrolysate treatment: solid-liquid ratio 1:12, add engineering bacteria crude enzyme solution (10% v/v), pH 6.8, 50 °C for 6h. After centrifugation (8000×g, 10 min), the fermentation broth was dynamically extracted by a new extraction device:

Step 3: Extraction and purification by device

Nozzle positioning: Lift the cylinder to adjust the nozzle height to 20 cm above the material surface, and push the cylinder to extend the horizontal suction lift to 15 cm to ensure that the extraction area is covered. Multi-stage filtration: The box has a built-in 0.45μm filter element to intercept impurities, and the fin heat dissipation system (fan speed 3 m/s) controls the temperature ⩽ 35°C. Cyclic extraction: The incomplete degradation residue was returned to the fermenter for secondary treatment, and the filtrate was eluted with 0.5 mol/L ammonia water through 732 cation exchange resin (flow rate 2BV/h), and the pH 6.0–7.0 fraction was collected.

2.2.2 Determination of amino acid content

Ninhydrin colorimetric method was used to determine amino acids in the following steps:

1. Standard curve drawing: 100mg of L-glutamic acid was accurately weighed and dissolved in 100mL of deionized water to obtain 1mg/mL mother liquor. [4]Serial dilutions were made to 0.1, 0.2, 0.4, 0.6, 0.8, 1.0 mg/mL standard solutions. Take 1mL of standard solution + 1mL ninhydrin chromogen + 1mL buffer and mix well. Heat in a boiling water bath for 15min, dilute with 5mL of 60% ethanol after cooling, and let stand for 10min. The absorbance was measured at a wavelength of 570 nm (zeroed with a blank reagent) and a standard curve ($R^2 \geqslant 0.999$) was plotted.

2. Sample determination: take 1mL of the solution to be tested + 1mL ninhydrin chromogen + 1mL buffer, and operate with the standard curve steps. The absorbance value of the sample at 570 nm was determined, and the total amino acid content was calculated by substituting the standard curve.

2.3 Cleaning performance test

2.3.1 Determination of cleaning rate

In this experiment, the artificial cloth staining method was used. 100% extra virgin olive oil was evenly coated on

a standard white cloth (4 cm × 4 cm) at a concentration of 2.5 mg/cm² and allowed to dry. Scalp sebum (approved by the Ethics Committee) was collected from healthy adults, diluted to 5 mg/mL, and applied to a white cloth at a concentration of 1.5 mg/cm².

Test conditions:

Test solution concentration: 5% (w/v) amino acid complex solution, pH 5.5.

Temperature: 25±1°C, oscillation frequency 150 times/min, time 10 min.

2.3.2 Foam stability assessment

The Ross-Miles method was used in this experiment. Pre-warm the test solution (5% amino acid compound) to 40°C. 50 mL of the test solution was freely dropped from a height of 90 cm from the liquid level, and the initial foam height (H_0) was recorded. After standing for 5 minutes, the residual foam height (H_5) was recorded.

2.3.3 Mildness test

EpiSkin™ 3D skin model (MatTek, Lot No. 20230501) was used in this experiment. The amino acid compound solution was diluted to three concentration gradients: 0.1%, 1% and 10%. Equilibrate in a 37°C, 5% CO_2 incubator for 24 h. 200 μL of solution was added to each well, with phosphate buffered saline (PBS) as a negative control and 5% SDS as a positive control. After 24 h of incubation , cell viability (OD_{570}) was determined by MTT method.

3. Results and Discussion

3.1 Strain performance verification

Enzyme activity enhancement: The cellulase activity and lignin degradation rate of CG-CL reached 125 U/mL and 98 U/mL, respectively, which were 22 times and 18 times higher than the wild-type.

Metabolic flow optimization: RBS library screening increased the expression intensity of the target gene by 3.2 times, and the $NADH/NAD^+$ ratio was stable at 1.5–1.8, which promoted amino acid synthesis.

3.2 Process advantages of the new extraction device

Compared to traditional fixed nozzles, the dynamic nozzles increase the amino acid extraction rate from 63.5% to 85.7%. The fin heat dissipation system controls the temperature of the box at 32.5±1.5°C to avoid degradation of heat-sensitive amino acids. The multi-stage filter element achieves a purity of 94.2% for β-alanine and an 89% reduction in impurity residue.[5]

3.3 Cleaning performance optimization

The amino acid compound system (5% concentration) has a cleaning rate of 85% at 25°C, which is 23% higher

than that of traditional alkyl glycosides (APG, 69%). The initial foam height was 160 mm, and the residual foam was 135 mm after 5 min, which was better than that of SDS. The EpiSkin model stimulated an index of 0.8 (< 1.0 was no stimulation), and the zebrafish embryo had an LC_{50} > of 200mg・L^{-1}. These performance gains may be attributed to the zwitterionic properties of amino acids, which, when compounded with tea saponins, enhance the emulsifying ability of oils and fats through electrostatic action.

3.4 Structural deconstruction mechanism

SEM analysis showed that honeycomb pores (average pore size 50 μm) were formed on the surface of tea cake after enzymatic hydrolysis, and the specific surface area increased from 0.5 $m^2 \cdot g^{-1}$ to 1.4 $m^2 \cdot g^{-1}$. The intensity of the lignin characteristic peak (1600 cm^{-1}) in the FTIR spectrum decreased by 53% (Fig. 4b), indicating the dissociation of the lignin-cellulose composite structure, which significantly improved the accessibility of cellulase and thus the enzymatic hydrolysis efficiency.

3.5 Process economy and environmental benefits

The energy consumption per ton of this process is 128 kWh, which is 55% lower than that of acidolysis method (285 kW·h). The COD of wastewater is reduced to 1200mg/L, and there is no strong acid discharge. According to the annual output of 1,000 tons of tea dry cakes, the new output value can be 4.2 million yuan.

4. Conclusion

In this study, the efficient extraction of amino acids from tea cake was realized through synthetic biology modification of Corynebacterium glutamate and the innovation of high-efficiency circulation extraction device. The energy consumption per ton of treatment in this process is 128 kW·h, and the COD value of wastewater is reduced to 800±50 mg· L^{-1}。 The compound amino acid-based detergent is suitable for low-temperature energy-saving washing scenarios (25°C), which can replace traditional petroleum-based surface activities and reduce carbon emissions by 32%. The performance of the compound detergent is significantly better than that of the traditional surface activity, and combined with the self-designed high-efficiency extraction device, the energy consumption and pollution are greatly reduced, and it has the potential for industrial application. In the future, the stress tolerance of strains can be further optimized through adaptive evolution, and the intelligent control system is integrated to realize the full automation of the process, so as to realize the green and high-value extraction of amino acids from tea cake.

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Hydrological controls on nutrient dynamics and load estimation in an agricultural watershed: a case study in Rock Creek, Ohio

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Abstract: This study investigates the spatiotemporal variability of nutrient concentrations (soluble reactive phosphorus, SRP; total phosphorus, TP; and nitrate, NO_3^-) and their relationships with hydrological conditions in the Rock Creek watershed, a representative agricultural basin in northwestern Ohio. High-temporal-resolution water quality and discharge data were analyzed over a two-year period (2010–2011) to elucidate seasonal trends, flow-nutrient correlations, and to compare nutrient load estimation methods. The results demonstrate that nutrient transport in the watershed is strongly event-driven, with SRP and TP concentrations peaking during high-flow periods (spring snowmelt and summer/fall storms), exhibiting significant positive correlations with discharge (log-transformed R^2 = 0.27–0.47). In contrast, nitrate concentrations displayed a distinct seasonal pattern, with a spring flush followed by declining concentrations, suggesting depletion of legacy storage. Notably, flow-weighted mean concentrations (FWMC) exceeded arithmetic means by 2–3 times, revealing that conventional averaging methods underestimate nutrient loads during high-flow events. These findings emphasize the dominance of non-point source pollution during episodic runoff events and underscore the need for targeted management strategies to mitigate nutrient pollution in similar agricultural watersheds.

Keywords: Agricultural watershed; nutrient dynamics; hydrological controls; event-driven runoff; water quality management

1. Introduction

Nutrient pollution in agricultural watersheds remains a pervasive global issue, threatening aquatic ecosystems and degrading water quality[1]. Elevated concentrations of nitrogen and phosphorus, primarily from agricultural activities, can lead to eutrophication and harmful algal blooms. Understanding the spatiotemporal variability of nutrient concentrations and their relationships with hydrological conditions is vital for developing effective management strategies[2].

Agricultural watersheds, characterized by complex land use patterns and intensive farming practices, exhibit dynamic nutrient cycling processes that are intricately linked to hydrological factors such as precipitation, runoff, and streamflow[3]. These interactions significantly influence nutrient loading and water quality, necessitating a detailed examination of nutrient dynamics in these systems[4].

The Rock Creek watershed in northwestern Ohio, USA, was selected for this study due to its representativeness as a typical agricultural basin[5]. This watershed experiences significant nutrient runoff from farming activities,

making it an ideal location to investigate the relationships between nutrient concentrations and hydrological conditions[6]. Furthermore, the availability of high-temporal-resolution water quality and discharge data enables a thorough analysis of seasonal trends, flow-nutrient correlations, and nutrient load estimation methods, contributing to a broader understanding of nutrient pollution in agricultural watersheds[7].

2. Materials and Methods

2.1 Study Area

The Rock Creek watershed is located in northwestern Ohio, USA, near the city of Tiffin (coordinates: 41.113611, -83.168333). The watershed covers an area of 89 km^2 and exhibits a mixed land use pattern consisting of agricultural fields, residential areas, and forested lands[8]. The primary soil types in the watershed are well-drained loams and silts, which are conducive to agricultural production but also prone to nutrient runoff during rainfall events[9].

2.2 Data Collection

2.2.1 Water Quality Data

Daily water samples were collected from the Rock Creek watershed outlet from January 1, 2010, to December 31, 2011. Samples were collected mid-stream at mid-depth using pre-rinsed 500 mL polyethylene bottles. To minimize contamination, bottles were triple rinsed with deionized water, stored immediately in coolers with ice packs, and transported to the laboratory within 24 hours for analysis.

Water samples were analyzed for soluble reactive phosphorus (SRP), total phosphorus (TP), and nitrate (NO_3^-) concentrations using standardized laboratory procedures. SRP concentrations were determined colorimetrically using the PhosVer3 Powder Pillow reagent at 880 nm. Total phosphorus concentrations were measured by digesting unfiltered samples with potassium persulfate to convert all phosphorus forms into orthophosphate, followed by colorimetric analysis. Nitrate concentrations were determined using the cadmium reduction method with absorbance measured at 540 nm.

2.2.2 Streamflow Data

Streamflow measurements were conducted using the Float-Area Method due to high-flow conditions during the study period. Stream cross-sectional area was determined from a bridge using measuring tapes and meter sticks to measure width and depth at multiple points along the stream. Velocity was measured by timing a buoyant object (e.g., orange peel) traveling between marked upstream and downstream points, and the mean velocity was estimated by correcting the measured velocity by a factor of 0.8. Streamflow (Q, m^3/s) was calculated by multiplying the mean velocity by the cross-sectional area.

2.3 Data Processing and Analysis

2.3.1 Data Import and Cleaning

The dataset was imported into Python using the Pandas and NumPy libraries. Erroneous entries (e.g., "=-@Inf") were removed, and columns were converted to numeric data types. Missing values were addressed by filling with subsequent valid measurements where possible.

2.3.2 Date Conversion and Classification

Dates were converted to datetime format, and seasons were defined as follows: Winter (January-March), Spring (April-June), Summer (July-September), and Autumn (October-December).

2.3.3 Statistical Calculations

Descriptive statistics (mean, standard deviation, median, minimum, maximum) were calculated by year and season using the groupby function in Pandas. Results were formatted using the tabulate library in Python.

2.3.4 Nutrient Loss Estimation

Nutrient loss estimates were calculated using two distinct methods: the arithmetic mean and the flow-weighted mean concentration (FWMC). Data were organized by year and season in Excel, with flow volumes calculated by converting daily streamflow from m^3/s to L/day. Missing nutrient concentration values were filled with subsequent valid measurements.

Arithmetic Mean: Calculated by averaging all nutrient concentrations (mg/L) within each specified period.

Flow-Weighted Mean Concentration (FWMC): Calculated by multiplying daily nutrient concentrations (mg/L) by corresponding daily flows (L/day), summing these products, and dividing by total flow volume.

Total loads (kg) were calculated by multiplying mean concentrations by total seasonal or annual flow volumes and converting from milligrams to kilograms. Yields (kg/ha) were computed by dividing these total loads by the watershed area (8900 ha). Excel's built-in functions (e.g., AVERAGEIFS, SUMIFS, SUMPRODUCT) were used to efficiently perform calculations and summarize results into tables for comparison.

2.3.5 Correlation and Regression Analysis

Pearson correlations between stream discharge and nutrient concentrations were calculated using the corr function in Pandas. Ordinary Least Squares (OLS) regressions were performed to explore relationships using both original and log-transformed stream discharge values. The statsmodels library in Python was used to perform the OLS regressions and generate regression tables.

2.3.6 Visualization

Scatter plots with regression lines were created using the seaborn and matplotlib libraries in Python to visually interpret relationships between stream discharge and nutrient concentrations.

2.3.7 Quality Control

Procedural quality controls included meticulous rinsing of bottles, minimal environmental exposure during sample collection, careful laboratory timing, and strict adherence to drying and weighing protocols during sample analysis.

3. Results

3.1 Full-Period Graphs

Total discharge varied significantly throughout the study period. The highest discharge occurred in the spring months, particularly during snowmelt and rain events, while the lowest discharge was observed during late summer and early fall. Soluble Reactive Phosphorus (SRP) concentrations fluctuated over time, with generally elevated concentrations occurring from mid-summer to fall. SRP peaks were often associated with storm events or periods of increased discharge, suggesting a relationship between runoff and phosphorus transport.

Total phosphorus (TP) concentrations exhibited similar variability throughout the study period. Elevated TP concentrations were most frequently observed during periods of high discharge, particularly during storm events or high-flow periods in late spring and summer. This suggests that TP transport is strongly influenced by runoff events, likely due to mobilization of phosphorus from surrounding land surfaces and upstream inputs during periods of increased flow.

Nitrate (NO_3^-) concentrations displayed a distinct seasonal pattern compared to phosphorus concentrations. Elevated NO_3^- concentrations were observed during the spring and early summer of 2010, coinciding with periods of higher discharge. However, in subsequent years, NO_3^- concentrations were generally lower, with modest peaks occurring sporadically and often not directly associated with discharge events. This pattern may reflect legacy nitrate stored in the watershed that was flushed out early in the study period, followed by depletion or reduced mobilization in later years.

3.2 Seasonal Graphs

Seasonal graphs were created to examine the variability of nutrient concentrations and streamflow within each season.

Spring

During the spring season, total discharge was highly variable, with frequent peak flow events associated with

snowmelt and spring rainfall. SRP concentrations fluctuated accordingly, with elevated concentrations observed following high discharge events. This pattern suggests strong event-driven mobilization of phosphorus during the spring season.

Total phosphorus (TP) concentrations also showed elevated levels during spring storm events, with the highest concentrations observed during late spring. This indicates that TP transport is strongly influenced by runoff during the spring season.

Nitrate (NO_3^-) concentrations exhibited pronounced peaks during the spring season, particularly in 2010. This may reflect the mobilization of legacy nitrate stores in the watershed due to increased runoff and mixing of soil layers.

Summer

During the summer season, baseflow gradually declined, and total discharge remained low except for a few isolated storm events. SRP concentrations were moderate but showed several sharp increases corresponding to small discharge peaks. This indicates that even relatively minor flow events can transport notable amounts of phosphorus during dry summer conditions when background concentrations are lower.

TP concentrations also showed moderate variability during the summer season, with elevated levels observed during storm events. However, overall concentrations were lower compared to spring and autumn seasons.

Nitrate (NO_3^-) concentrations were generally lower during the summer season compared to spring, with modest peaks occurring sporadically. This suggests that nitrate sources may have been depleted or reduced in mobility following the spring flush.

Autumn

Autumn discharge remained low for most of the season, except for a single intense storm event at the end of October that caused a significant spike in flow (>4 m^3/s). SRP concentrations were higher leading up to the storm but peaked concurrently with the flow spike, suggesting that autumn storms play a critical role in flushing accumulated phosphorus from the landscape.

TP concentrations also showed a significant increase during the autumn storm event, with the highest concentrations observed during late autumn. This indicates that runoff from autumn storms can mobilize substantial amounts of phosphorus from the watershed.

Nitrate (NO_3^-) concentrations exhibited moderate variability during the autumn season, with no clear association with discharge events. This suggests that nitrate dynamics may be influenced by other factors beyond hydrologically-driven flushing.

Winter

Winter flow conditions were mostly stable with low discharge, apart from a few major flow events in early March associated with snowmelt or rain-on-snow events. SRP concentrations were moderate during the winter season, with noticeable spikes only during high-flow conditions.

TP concentrations also showed moderate variability during the winter season, with no clear seasonal trend

observed. However, elevated concentrations were occasionally observed during snowmelt events.

Nitrate (NO_3^-) concentrations were generally stable during the winter season, with no clear association with discharge events. This further supports the hypothesis that nitrate dynamics may be influenced by factors other than hydrologically-driven flushing.

3.3 Hydrological Events

Storm events were defined as continuous or semi-continuous rainfall periods during which precipitation intensity remained above 0.5 mm/hour, with no breaks exceeding 2 hours below this threshold (Figure 1).

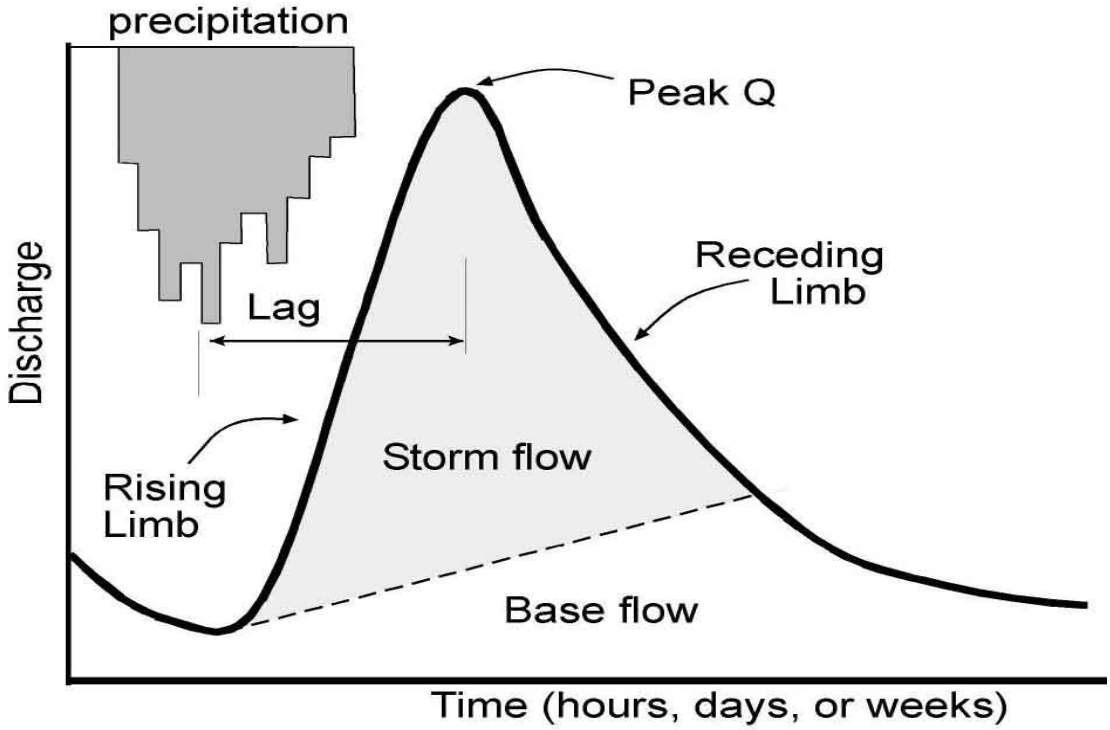

Figure 1. Conceptual diagram illustrating how storm events were defined.

A total of 11 hydrological events were identified during the 2010 study period (Table 1). Seasonal Distribution: Winter and spring seasons contributed the majority of storm events, with 7 out of 11 events occurring during these periods. Spring events, in particular, were characterized by longer durations and higher total flow contributions, possibly due to snowmelt and intensifying spring rains. Event Duration: The duration of storm events ranged from 2 to 15 days, with the longest event (Event 6) spanning 15 days and contributing significantly to the total flow (58.94 mm). Flow Contribution: Total flow contributions varied widely among events, with the highest contribution (58.94 mm) from Event 6 and the lowest (3.35 mm) from Event 4. These variations highlight the importance of considering event duration and intensity when assessing their cumulative impact on streamflow and nutrient transport. Critical Periods:The identification of these storm events provides crucial information for water resource managers, enabling them to target critical periods for flood control, water quality monitoring, and nutrient management strategies.

Table 1. Start and end dates for hydrological events in 2010.

Event	Begin Date	End Date	Length (days)	Season	Total Flow (mm)
1	2010/01/25	2010/01/26	2	Winter	11.27
2	2010/03/09	2010/03/15	7	Winter	43.27
3	2010/03/23	2010/03/30	8	Spring	39.37
4	2010/04/08	2010/04/09	2	Spring	3.35
5	2010/04/26	2010/04/27	2	Spring	12.59
6	2010/05/08	2010/05/22	15	Spring	58.94
7	2010/06/01	2010/06/10	10	Summer	24.15
8	2010/06/23	2010/06/24	2	Summe	6.84
9	2010/06/28	2010/06/29	2	Summer	13.16
10	2010/11/30	2010/12/01	2	Autumn	3.79
11	2010/12/31	2011/01/02	3	Winter	20.46

3.4 Descriptive Statistics of Nutrient Concentrations

Descriptive statistics were calculated to summarize the variations in nutrient concentrations (Soluble Reactive Phosphorus - SRP, Total Phosphorus - TP, and Nitrate - NO_3^-) over the study period (2010-2011). The statistics include mean, standard deviation, median, maximum, and minimum concentrations for both annual and seasonal data(Table 2-5). Annual Variations: The annual mean concentrations of SRP and TP showed an increasing trend from 2010 to 2011, indicating potential accumulation or enhanced mobilization of phosphorus sources. In contrast, mean NO_3^- concentrations decreased slightly, possibly due to changes in fertilizer application practices or depletion of legacy nitrate stores.Seasonal Patterns: SRP and TP concentrations peaked during spring and summer, coinciding with high-flow periods driven by snowmelt and storm events. These results underscore the importance of event-driven nutrient transport in agricultural watersheds. NO_3^- concentrations exhibited a more pronounced spring flush, likely related to fertilizer application and mobilization of stored nitrate.Variability: High standard deviations, particularly for TP and NO_3^-, indicate substantial variability in nutrient concentrations within and

across seasons. This variability emphasizes the need for continuous monitoring and targeted management strategies to address nutrient pollution.Extremes: Maximum nutrient concentrations, particularly for TP and NO_3^-, highlight the potential for severe water quality impairment during storm events. Identifying and mitigating these extreme events are crucial for protecting aquatic ecosystems.

Table 2. Annual Descriptive Statistics for SRP, TP, and NO_3^- concentrations.

Nutrient	Year	Mean (mg/L)	Std.Dev. (mg/L)	Median (mg/L)	Max (mg/L)	Min (mg/L)
SRP	2010	0.049	0.046	0.041	0.484	0.004
	2011	0.057	0.056	0.040	0.459	0.004
TP	2010	0.165	0.217	0.086	1.751	0.019
	2011	0.211	0.268	0.105	1.924	0.015
NO_3^-	2010	2.263	2.609	1.100	11.730	0.040
	2011	1.775	1.110	1.515	6.140	0.300

Table 3. Seasonal Descriptive Statistics for Soluble Reactive Phosphorus (SRP) Concentrations.

Year	Season	Mean (mg/L)	Std.Dev. (mg/L)	Median (mg/L)	Max (mg/L)	Min (mg/L)
2010	Fall	0.049	0.052	0.033	0.235	0.007
	Spring	0.054	0.039	0.053	0.175	0.004
	Summer	0.063	0.052	0.055	0.484	0.004
	Winter	0.027	0.030	0.013	0.118	0.004
2011	Fall	0.077	0.071	0.056	0.459	0.005

	Spring	0.046	0.035	0.040	0.204	0.004
	Summer	0.066	0.061	0.038	0.299	0.005
	Winter	0.035	0.040	0.011	0.147	0.004

Table 4. Seasonal Descriptive Statistics for Total Phosphorus (TP) Concentrations.

Year	Season	Mean (mg/L)	Std.Dev. (mg/L)	Median (mg/L)	Max (mg/L)	Min (mg/L)
2010	Fall	0.133	0.171	0.073	0.850	0.032
	Spring	0.287	0.331	0.162	1.751	0.028
	Summer	0.117	0.061	0.102	0.521	0.058
	Winter	0.116	0.142	0.059	0.772	0.019
2011	Fall	0.209	0.177	0.146	0.891	0.033
	Spring	0.306	0.388	0.136	1.924	0.016
	Summer	0.176	0.187	0.098	1.155	0.035
	Winter	0.145	0.249	0.040	1.528	0.015

Table 5. Seasonal Descriptive Statistics for Nitrate (NO_3^-) Concentrations.

Year	Season	Mean (mg/L)	Std.Dev. (mg/L)	Median (mg/L)	Max (mg/L)	Min (mg/L)
2010	Fall	1.184	2.116	0.040	7.810	0.040
	Spring	4.567	2.961	4.010	11.730	0.230

	Summer	0.412	0.662	0.155	3.550	0.040
	Winter	2.701	1.824	2.575	7.390	0.470
	Fall	1.317	0.399	1.420	1.910	0.340
	Spring	2.441	0.956	2.315	6.140	1.040
2011						
	Summer	1.136	0.770	0.940	4.410	0.300
	Winter	2.304	1.456	2.030	6.000	0.470

3.5 Relationships Between Stream Discharge and Nutrient Concentration

To explore the relationships between stream discharge and nutrient concentrations (SRP, TP, and NO_3^-), we conducted detailed correlation and regression analyses. The results reveal insights into how hydrological conditions influence nutrient dynamics in the Rock Creek watershed.

3.5.1 Correlation Analysis

To understand the relationships between stream discharge and nutrient concentrations (soluble reactive phosphorus, SRP; total phosphorus, TP; and nitrate, NO_3^-), we conducted correlation analyses. The results revealed significant positive correlations between nutrient concentrations and stream discharge, indicating that nutrient mobilization is strongly influenced by hydrological conditions.

Specifically, the Pearson correlation coefficient between SRP concentrations and stream discharge was 0.407 on the linear scale and increased to 0.517 when the discharge data was log-transformed. Similarly, TP concentrations showed a stronger correlation with stream discharge, with correlation coefficients of 0.626 on the linear scale and 0.687 on the log-transformed scale. Nitrate concentrations, on the other hand, exhibited a weaker correlation with stream discharge, with coefficients of 0.136 on the linear scale and 0.478 on the log-transformed scale.

These findings suggest that TP concentrations are most strongly influenced by hydrological conditions, followed by SRP, and then NO_3^-. The improvement in correlation coefficients when using log-transformed discharge data indicates that nutrient concentrations rise more steeply at higher flow rates, highlighting the importance of considering flow variability when assessing nutrient dynamics in agricultural watersheds.

3.5.2 Regression Analysis

OLS regression revealed that TP concentrations had the strongest relationship with stream discharge (R^2=0.472

on log-scale), followed by SRP (R^2=0.268) and nitrate (R^2=0.229). TP concentrations increased by 0.0325 mg/L per unit log-transformed discharge, while SRP and nitrate increased by 0.0044 mg/L and 0.0582 mg/L, respectively. Log-transformed models provided better fits, suggesting nutrient concentrations rise more steeply at higher flow rates. This underscores the importance of considering flow variability in nutrient dynamics assessments.

3.5.3 Visual Representation

The relationships between stream discharge and nutrient concentrations (SRP, TP, and NO_3^-) were further illustrated through visual representation. Scatter plots depicting the distribution of nutrient concentrations versus stream discharge were created for both linear and log-transformed scales. The plots revealed distinct patterns, with nutrient concentrations tending to increase more markedly at higher flow rates when the discharge data was log-transformed. This trend was most pronounced for TP, followed by SRP, and then NO_3^-, consistent with the regression analysis results. The visual inspection of these plots reinforced the notion that nutrient mobilization in the Rock Creek watershed is strongly influenced by hydrological conditions, particularly during high-flow events. The steep increase in nutrient concentrations at higher discharge rates underscores the importance of considering flow variability when assessing nutrient dynamics and developing water quality management strategies in agricultural watersheds.

4. Discussion

4.1 Seasonal Variations and Hydrological Controls on Nutrient Dynamics

The temporal patterns in streamflow and nutrient concentrations reveal that peak discharges occur during spring and summer due to snowmelt and increased precipitation. Nutrient mobilization is influenced by hydrological conditions, as evidenced by strong positive correlations between SRP, TP, and streamflow, with TP exhibiting the strongest correlation. Correlation coefficients under log-transformed discharge models indicate that nutrient concentrations rise more rapidly at higher flow rates.

4.2 Flow Components and Nutrient Transport Mechanisms

When comparing event-driven flows with baseflow, it is evident that event-driven flows significantly contribute to nutrient transport during spring and summer. The seasonal variability in nutrient dynamics underscores the importance of considering flow conditions when assessing nutrient dynamics. Regarding nutrient load estimation methods, arithmetic mean concentrations have limitations, whereas flow-weighted mean concentrations (FWMC) offer advantages.

4.3 Management Implications and Future Research Directions

Water quality impairment during high-flow events highlights the necessity for targeted management strategies to reduce nutrient losses. Precision interventions, such as the use of cover crops, controlled drainage systems, and adaptive fertilizer timing, are essential. The patterns observed in the Rock Creek watershed are representative of

other agricultural regions, indicating broader significance. Future research should integrate longer-term data with land-use and climate projections to explore the efficacy of various best management practices.

5. Conclusions

This study provides a comprehensive assessment of the spatiotemporal variability of nutrient concentrations (soluble reactive phosphorus, SRP; total phosphorus, TP; and nitrate, NO_3^-) and their relationships with hydrological conditions in the Rock Creek watershed, a typical agricultural basin in northwestern Ohio. Our analysis, based on high-temporal-resolution water quality and discharge data over a two-year period (2010–2011), reveals that nutrient transport in this watershed is strongly influenced by episodic runoff events. Specifically, SRP and TP concentrations peak during high-flow periods such as spring snowmelt and summer/fall storms, showing significant positive correlations with discharge. In contrast, nitrate concentrations exhibit a distinct seasonal pattern with a spring flush followed by declining concentrations, indicative of legacy storage depletion. Additionally, we find that flow-weighted mean concentrations (FWMC) substantially exceed arithmetic means, indicating that conventional averaging methods underestimate nutrient loads during critical runoff periods.

The findings of this study have important implications for water quality management in agricultural watersheds. They underscore the need for targeted management strategies aimed at reducing nutrient losses during high-risk periods, such as spring thaw and heavy rainfall. These strategies may include the use of cover crops, controlled drainage systems, or wetlands to buffer event flows, as well as adaptive fertilizer timing to minimize runoff risks. However, it is important to acknowledge that the study was conducted over a limited time period and in a specific geographic location. Therefore, the generalizability of our findings to other agricultural watersheds may be limited.

Future research should aim to integrate longer-term data with land-use and climate projections to assess trends in nutrient dynamics under changing precipitation regimes. Additionally, studies should explore the efficacy of various best management practices (BMPs) in mitigating nutrient pollution, taking into account the dominant flow pathways identified in this and other similar studies. By doing so, we can develop more effective and tailored strategies to address nutrient pollution in agricultural watersheds globally.

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Models and Mechanisms of Effective Rural Operation for Promoting Common Prosperity: A Longitudinal Case Study of the "Guzhu Model" from a Symbiotic Perspective

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Abstract: Achieving common prosperity for all people is the essential requirement of Chinese-style modernization, and the weakest key link at present is the common prosperity of farmers and rural areas. Taking Guzhu Village in Changxing County as a typical case, this paper adopts the longitudinal single case study method to explore the process, operation mode and mechanism of the village's road to common prosperity from the perspective of symbiosis theory. The results show that: (1) Guzhu Village has experienced different stages of development in the process of common prosperity, and each stage has produced different symbiotic effects. Individual villagers have given birth to the bud of rural development, but their lack of knowledge, cognition and management ability can't achieve high-quality rural development. The gradual participation of the government, associations and operating companies has injected new energy into promoting rural areas towards common prosperity. (2) The village focuses on multiple symbiotic subjects and operates collaboratively with the help of symbiotic environment. Effective collaboration between symbiotic units has become the key to rural common prosperity. The symbiotic model respects the core position of villagers, effectively promotes the participation and recognition of all villagers, turns the ecological advantages and resource advantages in the village into economic advantages and development advantages, and realizes the villagers' material wealth, spiritual and cultural wealth and ecological harmony in the village. Research suggestions: In the process of rural development, we can inject new energy into the village by maintaining the dominant position of villagers, introducing new units such as operating companies, making full use of resource endowments to broaden the path of increasing income and getting rich, giving full play to the synergy among symbiotic units, and jointly strengthening the rural collective economy.

Keywords: Village Operations, Common Prosperity, Guzhu Village, Symbiosis Theory

The report of the 20th National Congress of the Communist Party of China mentioned "common prosperity" many times and emphasized that Chinese-style modernization is the modernization of common prosperity for all people[1]. Overall common prosperity is divided into material prosperity, spiritual and cultural prosperity and livable ecological environment[2,3].Pointed out in "Solidly Promoting Common Prosperity" that the most arduous and arduous task of promoting common prosperity is still in rural areas[4]. At present, the rural collective economy in many villages is still relatively weak, with unbalanced development and insufficient development power, which hinders the process of common prosperity[5]. In August 2021, proposed at the 10th meeting of the Central Financial

and Economic Commission to strengthen the rural collective economic strength through various methods and continuously consolidate the material foundation for achieving common prosperity. Common prosperity in rural areas is inseparable from rural revitalization, which requires the effective implementation of rural operations. In November 2023, the Ministry of Culture and Tourism released the "Domestic Tourism Improvement Plan (2023-2025)", which clearly proposed to promote the improvement of rural tourism operations. This topic has attracted widespread attention in the academic community and has become a hot research direction in current rural development studies.

With the development of the times, common prosperity presents different connotation characteristics. Gong Liutang[6], Gao Tianyan[7], Zhang Laiming, etc.[8]all analyzed the theoretical connotation of common prosperity in detail, and believed that community prosperity has the characteristics of the times and comprehensiveness, which means that material prosperity and spiritual prosperity go hand in hand harmoniously. Chen Jinghua et al.[9]said that in addition to material prosperity and spiritual prosperity, ecological pleasure is also the inherent requirement of common prosperity. Scholars have conducted detailed research on the problems existing in promoting common prosperity, and generally believe that there are practical dilemmas such as income distribution[10], limited development of rural collective economy[11], and unbalanced development between urban and rural areas[12]. Issues such as the path to realize rural common prosperity[13], the relationship between rural digital construction and rural common prosperity[14], and the logical relationship between rural revitalization and common prosperity[15]have also been widely studied and discussed by scholars. Regarding rural operation, scholars have made extensive exploration. Many studies have shown that rural operation has improved the quality of rural tourism[16], realized value co-creation[17], promoted rural sustainable development[18], and is an effective means to enhance rural endogenous development kinetic energy and promote rural revitalization[19]. However, the existing research is still insufficient to analyze the internal relationship between rural operation and rural common prosperity, and rural operation is related to the synergy of relevant stakeholders in the village, which has the characteristics of mutual promotion and mutual benefit. It is necessary to pay more attention to the rational division of labor and its symbiotic relationship among various stakeholders. Therefore, it is of practical significance to analyze the mode and mechanism of rural operation to help common prosperity from the perspective of symbiosis theory.

In practice, all parts of Zhejiang Province are exploring models and paths to help rural common prosperity through rural operations. For example, Lin'an District set up an operation company through cooperation between villages and social capital to promote the market-oriented operation of village scenic spots, and Yuhang District activated the development potential of villages by recruiting rural professional managers. The results of practice and exploration vary from place to place, but Guzhu Village in Changxing County is guided by the government, and nearly 90% of the villagers are engaged in rural tourism. Farmhouse associations and operating companies are set up to provide communication and planning for rural development, creating a "Guzhu model" for the development of rural homestays. Through the cluster development of farmhouses, all stakeholders have a rational division of labor and mutual synergy to strengthen the village collective economy, so that the villagers have embarked on the road of common prosperity.

Based on this, taking Guzhu Village in Changxing County as an example, the symbiosis theory is used to explore the mode and mechanism of effective rural operation to help common prosperity. At present, the research on Guzhu Village mainly analyzes tea culture tourism[20]tourism-driven rural social reconstruction[21], rural tourism enterprise service evaluation[22], rural development transformation path[23]and multi-dimensional niche width evaluation[24]. The case study of Guzhu Village shows the characteristics of rich and diverse themes. However, the existing research has not yet analyzed the relationship among various stakeholders in Guzhu Village and the influence and role of effective rural operation on common prosperity from the perspective of symbiosis. In view of this, this study first clarifies the process of developing rural tourism in Guzhu Village, and analyzes the development situation and influence effects of each stage in the process of tourism promoting common prosperity; Secondly, it

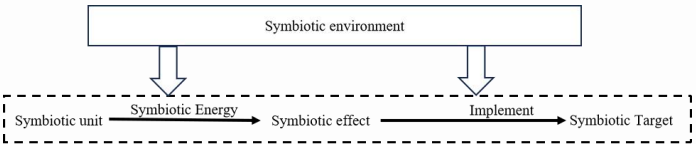
analyzes the mode and mechanism of rational division of labor and collaborative operation among symbiotic units, with a view to providing theoretical basis and practical experience for the high-quality development of rural tourism and the realization of common prosperity.

1 Research Methods and Data Sources

1.1 Theoretical Basis

This study uses the theory of symbiosis to explore. The concept of "symbiosis" originated from biology and was first put forward by German biologist Debary to describe the interdependent relationship between organisms[25]. With more related research, scholars continue to improve and deepen the symbiosis theory, which emphasizes the relationship state of interconnection, mutual benefit, harmony and mutual promotion among multiple stakeholders[26]. The symbiotic theory system is mainly composed of three dimensions: symbiotic environment, symbiotic unit and symbiotic mode. Symbiotic environment refers to the external conditions and infrastructure of symbiotic units and models, including environment, traffic conditions, system and other elements. Symbiotic units refer to the basic individuals of energy production and exchange[27], and symbiotic models are the specific ways and paths to establish and maintain symbiotic relationships between symbiotic units[28]. This theory holds that rational division of labor and optimal allocation among symbiotic units can generate symbiotic energy and release symbiotic effects[29]. From the perspective of symbiosis theory, we can sort out the communication and cooperation modes between different subjects in the same system. Symbiosis theory has been applied to the economic, social and cultural fields[30], involving the integration of culture and tourism[31], online public opinion[32], scientific research and education in colleges and universities[33], etc., and has also been widely used in the research of rural development in China[34]. As a theory to help rural revitalization, it has attracted the attention of many scholars. Liu Na [35] pays attention to the symbiosis of actors within the countryside, Guo Yongchang[36]studies the symbiosis of rural communities and tourist attractions, and Huang Tai et al.[37]studies the symbiosis of new urbanization and rural common prosperity in typical counties of rural tourism. Rural operation to help common prosperity is an evolutionary process of mutual benefit among different stakeholders in the same village. Among them, the collaboration and integration between symbiotic units stimulates symbiotic energy, and the symbiotic effect is produced through the transmission of symbiotic environment to achieve the symbiotic goal, that is, the common prosperity of rural areas. Therefore, this study proposes a symbiotic analysis framework for rural operation to help common prosperity (Figure 1).

Fig. 1 Symbiotic analysis framework for rural operations contributing to common prosperity



1.2 Case Selection

Guzhu Village is located in Shuikou Township, Changxing County, Zhejiang Province, close to the waterfront of Taihu Lake, at the intersection of Zhejiang, Jiangsu and Anhui provinces, with convenient transportation and only 2.5 hours' drive from Shanghai. It is bordered by Taihu Lake in the east, Yixing, Jiangsu Province in the north, and surrounded by mountains on three sides; The village covers an area of 18.8 square kilometers and has 13 natural villages under its jurisdiction. There are 953 farmers and a registered population of 2,896. Twenty years ago, Guzhu Village was still a secluded mountain village. The villagers mainly relied on tea, bamboo and bamboo shoots for a living. The per capita annual income was only 3,000 yuan, and the collective economic foundation of the village was weak. Later, inspired by the old man Wu Ruian, the villagers began to run farmhouses, and the village began to develop rural tourism. In recent years, Guzhu Village has continuously improved tourism public facilities, optimized rural operation and management, and carried out transformation and upgrading. Multiple stakeholders in the village are interconnected and functioning for mutual benefit. In July, 2019, the village was selected into the list of the first batch of national rural tourism key villages and scored the highest in Zhejiang Province. The village adopts

the "open scenic spot + farmhouse" operation model. In 2022, the number of tourists will reach 4.6 million, the operating income will exceed 6 million, and the per capita income of the villagers will reach 52,000 yuan, gradually embarking on the road of common prosperity. In December 2023, the village was selected as the "Golden 3A Scenic Spot Village in Zhejiang Province".

This study selects Guzhu Village as the case study object for the following two main reasons: on the one hand, the case object is highly adaptable, which conforms to the principle of consistency between research content and purpose[38]. Through the effective operation of the countryside, Guzhu Village not only promotes the economic development of the village, but also promotes the common prosperity of the surrounding areas, providing effective experience for promoting the high-quality development of rural tourism to achieve common prosperity. This is consistent with the purpose of this study and helps to solve the problem. On the other hand, the case location is significantly representative and conforms to the principle of typicality[39]. As one of the largest rural tourism industry clusters in the Yangtze River Delta region, Guzhu Village's "Guzhu Model" has been imitated one after another, which has a strong driving and demonstrating effect on the tourism development of other villages. An in-depth analysis of the internal mechanism of Guzhu Village's rural operation to help common prosperity is conducive to expanding the influence scope of the "Guzhu Model".

1.3 Research Method

This study chooses the longitudinal single case study method, which is mainly based on the following three considerations: First, it is a dynamic process involving "how to do it" to analyze the evolution process of rural tourism development in villages and how to promote rural common prosperity through effective operation. Therefore, it is more appropriate to adopt the case study method [40]; Second, single case study has unique advantages in describing the social background of the case and scene restoration, which can restore the process in more detail and show its internal logic and mechanism[41], which is consistent with the research content. Third, the longitudinal single case study can analyze the key events and causal effects in the corresponding time series, and explore the dynamic evolution process of changes brought about by the effective rural operation in the time context[40].

1.4 Data Sources

In order to obtain in-depth and comprehensive information, this study uses a semi-structured interview method to directly collect first-hand data, and went to Guzhu Village for field research three times in October 2023, March 2024, and April 2024, respectively. Based on the principle of theoretical saturation, relevant personnel are selected for semi-structured interviews. The interviewees include the village party branch secretary, villagers, tourists, homestay farmhouse owners, operating company staff, etc. (Table 1). After the investigation, the collected interview data were systematically sorted out and summarized, and a total of 150,000 words of first-hand data were obtained. At the same time, second-hand data is obtained by searching WeChat official account, news information, newspapers and other related information, and CNKI consults relevant literature, and finally forms triangular mutual verification to ensure the authenticity of the data.

Table 1 Research Data Sources

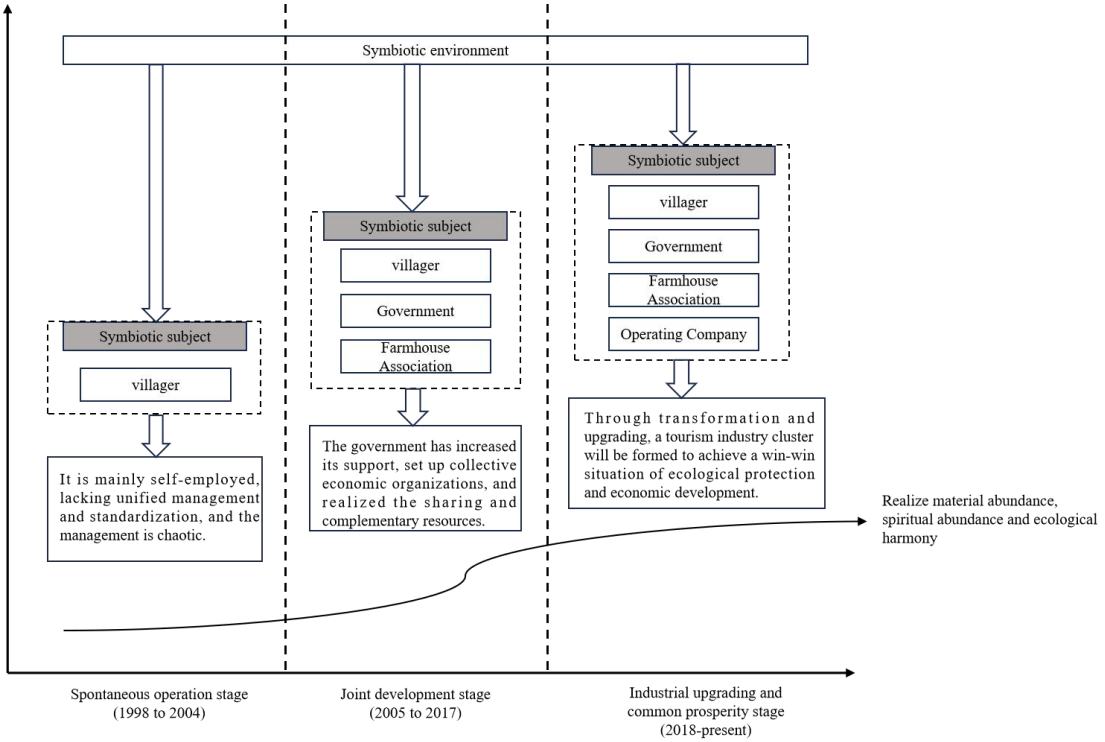
Data sources	data type	Interviewee/content	quantities
First-hand data	Semi-structured interviews	Village party branch secretary	1 person
		Local villagers	5 people
		Scenic area tourists	5 people
		Owners and employees of farm stays, B&Bs	15 people
		Scenic area staff	2 people
		Shop owners	8 people

	CNKI literature	Related content on Guzhu Village, common prosperity, symbiosis theory, etc.	30 articles
Second-hand data	Information brochures	Introduction to Guzhu Village, tourism formats, etc.	2 books
	Photos taken in the village	Overall appearance and layout of Guzhu Village, honors obtained, etc.	108 sheets
	Public Tweets	Changes in Guzhu Village, the Guzhu Model, etc.	10 articles
	Short videos on new media platforms such as Douyin	Historical culture of Guzhu Village, tourists' perceptions, etc.	10 articles

2 The Development Process of Achieving Common Prosperity in Guzhu Village

In order to better identify the evolution process of common prosperity in Guzhu Village from the perspective of symbiosis, on the basis of full investigation and data consultation, combined with the important turning points and changes of symbiotic subjects in the development process of the village, the development process of Guzhu Village is divided into three stages: the spontaneous stage of farmers' self-employment (1998-2004), the joint development stage of local multiple subjects' intervention in management (2005-2017), and the stage of industrial upgrading and farmers' rural common prosperity (2018-present) (Figure 2).

Figure 2 The Development Process of Achieving Common Prosperity in Guzhu Village



2.1 Spontaneous Operation Stage (1998-2004)

At this stage, the tourism industry in Guzhu Village began to rise gradually, and the symbiotic subjects were mainly the villagers in this village. In 1998, Wu Ruian, a well-known Chinese medicine practitioner from Shanghai, came to admire the "tea culture" and established the "Shenxing Rehabilitation Center" in Guzhu Village to serve the recuperation of retired cadres in Shanghai. Unexpectedly, in less than a year, more and more people came to Guzhu Village to recuperate. The rehabilitation center couldn't accommodate so many people, and many people could only live in farmers' homes. As a result, some forward-looking and courageous villagers began to set up their own

farmhouses, providing catering services and accommodation experience. In 2000, the first farmhouse "Wangtazhuang" self-operated by local villagers came into being. At this stage, the business entities are mainly self-employed, who use their own houses and family resources to operate, providing tourists with farm flavor and rural experience. Due to the lack of unified management and standardization, the operation at this stage is relatively chaotic and the symbiotic energy is weak, and only a few people have achieved material prosperity.

2.2 Joint Development Stage (2005-2017)

With the rise of farmhouses and the rising number of farmhouses, the diversified needs of health care elderly people have brought certain pressure on rural ecology and living environment. In 2005, Shuikou Township put forward the strategy of "building a village by ecology and developing a village by tourism", and Guzhu Village took advantage of the trend and put forward the development paths of "building a village by ecology" and "developing a village by tourism". In the same year, in order to enhance the exchanges and cooperation between farmhouse operators and tourism departments, scenic spots and village committees, Shuikou Township established a farmhouse industry association to strengthen communication and coordination. As a new symbiotic unit, the government and farmhouse music association have promoted the creation and transmission of symbiotic energy, and the tourism industry in Guzhu Village has gradually moved towards the road of joint development. In 2006, Guzhu Village established its first motorcade-"Wang Aiqiang Motorcade". "In 2006, I bought two passenger buses. After I bought them, there were almost no rest days. Later, they increased one after another, and now there are eight buses." (Villager Wang Aiqiang) Different motorcades joined in the follow-up, strengthening the tourist connection team. In 2014, Guzhu Village took advantage of the east wind of beautiful countryside's construction to carry out the village renovation and upgrading project, transforming from a traditional farmhouse gathering place to a global tourist resort. At the same time, some villagers with strength and experience began to gradually integrate resources and set up collective economic organizations such as farmhouse cooperatives, thus realizing the sharing and complementarity of resources. At this stage, the interaction between symbiotic units has increased, the symbiotic environment has improved, and the material prosperity and ecological protection of most villagers have been realized.

2.3 Industrial Upgrading and Common Prosperity Stage (2018-present)

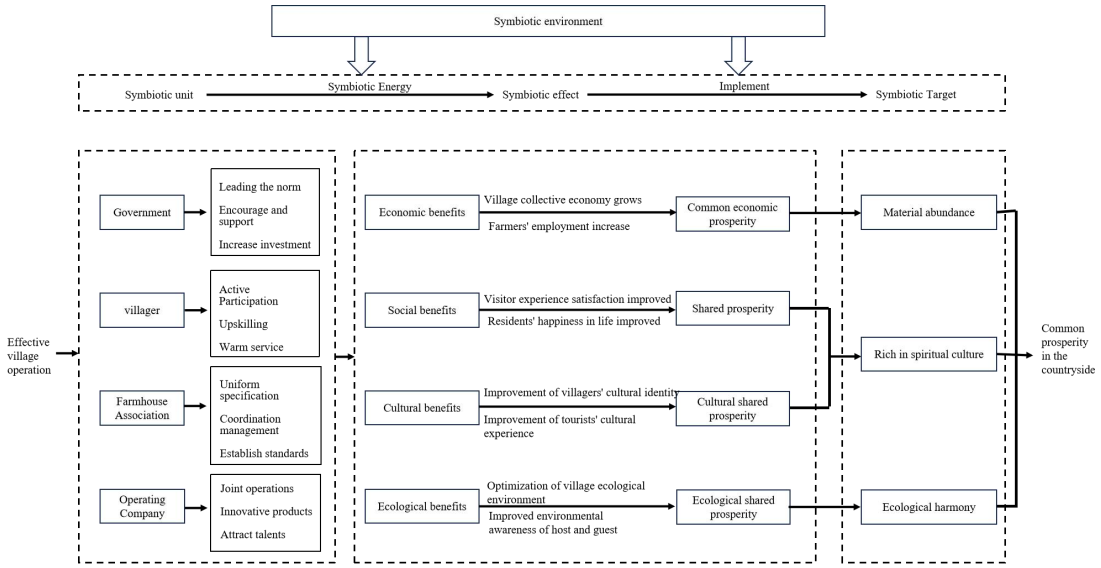
Guzhu Village has enhanced its tourism image and external influence by deeply integrating agricultural, cultural and tourism economy. "Your cultural atmosphere is very good. Why do you say that? Because there are books here, there are books there." (Tourists) In 2018, the village intervened in the operation company. As a new symbiotic unit, it strengthened the cooperation between Guzhu Village and surrounding villages, jointly built tourist routes and products, and jointly formed the rich tourism economic industry of Guzhu Village through characteristic formats, making it one of the largest rural tourism industry clusters in the Yangtze River Delta region. The symbiotic energy has further expanded, and the tourism industry has begun to develop in the direction of high-end, quality and brand. In 2021, the township will achieve collective economic income of 7.7 million yuan, operating income of 5.964 million yuan, per capita income of villagers reaching 49,000 yuan, and the number of tourists in 2022 will reach 4.6 million, tourism income will exceed 1.6 billion yuan, and per capita income of villagers will reach 52,000 yuan. "We have regulations and regulations on the dish standard and price standard of farmhouse owners. The development of rural tourism has solved 3,000 local employment nearby, and the village collective economic operating income will reach 5.96 million. At this stage, the symbiotic units such as the government, villagers, farmhouse music associations and operating companies rationally divide labor, promote each other, and achieve mutual benefit and win-win results, gradually realizing the villagers' material wealth, spiritual culture and village ecological harmony.

3 The Mechanism of Effective Rural Operation in Promoting Common Prosperity

The effective operation of Guzhu Village to help common prosperity is the result of the synergy of multiple stakeholders such as the local government, villagers, farmhouse associations, and operating companies. With the help of the symbiotic environment, the symbiotic unit has rational division of labor, interdependence and mutual

promotion, thus generating symbiotic energy, which makes the village change from single product, disorder and vicious competition to today's product diversification, standardized management and fair distribution of benefits, resulting in economic, social, cultural and ecological symbiotic effects, realizing the common prosperity of all villagers' material and spirit and the ecological environment of the village, and achieving the symbiotic goal (Figure 3).

Figure 3 The Internal Mechanism of Achieving Common Prosperity through the Collaborative Operation of Multiple Subjects in Guzhu Village



3.1 The government strengthens autonomy and provides excellent services, and provides policy guidance and financial support for villagers

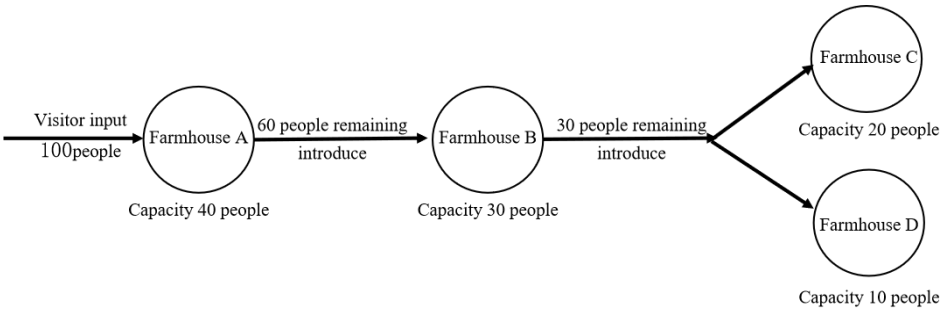
Under the symbiotic environment of policy support, transportation location, market demand, etc., the local government leads and encourages villagers to participate in the operation of the village, and the symbiotic energy generated enables villagers to achieve economic, social and cultural prosperity. First, in terms of homestays and farmhouses, Shuikou Township Government encourages and supports the transformation of farmhouses into high-end and characteristic homestays, and entrusts professional institutions to customize personalized renovation plans for each household to achieve precise improvement. At the same time, the government has set up a comprehensive management office for scenic spots, established access standards for farmhouses, required farmhouses to standardize certificates, implemented a points assessment management system for existing farmhouses and homestays, and led farmhouses owners to go out to study and train. High-standard services can improve tourists' satisfaction. "After the implementation of the farmhouse points system management method, the satisfaction of tourists has increased by 13.5%." (Director of the Social and Economic Development Office) Secondly, in terms of agricultural product sales, Guzhu Village has invested in the construction of farmers' commodity markets and e-commerce industrial parks, incubated agricultural broadcasting makers, encouraged homestay owners to "touch the net" e-commerce, and built an emerging industrial village with both homestay and e-commerce. At present, more than 400 farmhouses in Guzhu Village have carried out online sales of agricultural products, accounting for about 85% of the total number of farmhouses; There are nearly 3,000 online orders every day, and the online transaction volume in a single day reaches 400,000 yuan, which increases farmers' employment income and enables villagers to achieve material prosperity. Thirdly, in terms of tourism resources, the local government has innovated the integration mode of tourism resources, forming a new play mode of "eating and living in Guzhu and playing around". The integration of more than 30 scenic spots around Guzhu Village is within one and a half hours' drive, which promotes the development of a series of surrounding industries and makes it possible to realize common prosperity in the countryside. Fourthly, in terms of folk atmosphere and culture, plan activities such as "Shanghai Village" New Year's Eve, Qingming tea sacrifice, seasonal picking, etc., and organize various farming

festivals and cultural tourism activities such as Purple Bamboo Shoot Tea Culture Festival, Zen Tea Conference, and Tang Chao Twelve Square Electronic Syllable Festival, so as to improve the cultural identity of villagers and tourists' cultural experience, and realize the spiritual and cultural prosperity of villagers and tourists.

3.2 All villagers participate and share resources to provide tourists with "family" services and experiences

Under the symbiotic environment of economic foundation, village reputation and market demand, the villagers in this village actively participate in tourism and maintain a good "family relationship" with tourists. The symbiotic energy generated enables the villagers to achieve economic and social prosperity. On the one hand, villagers actively set up farmhouses and homestays, rely on "affectionate" services and good reputation to attract tourists into the village, and then use emotional maintenance to keep guests. "What really attracts and retains tourists is not only the quiet green mountains and green hills, but also the service and reputation accumulated by business owners for many years." (Director of Social and Economic Development Office) "Now many guests are frequent visitors to our village, and they have to stay several times a year like visiting relatives. Some guests come more than a dozen times a year." (Owner of Gongcha Nongjiale) In addition, the farmhouse owners will implement the "source sharing" mode (Figure 4). On the other hand, the villagers actively participate in the production and sales of local products. In Guzhu Village, in addition to 70% of the villagers who run homestays and farmhouses, 20% of the villagers are engaged in the production and sales of agricultural and sideline products, including purple bamboo shoot tea, blueberry, kiwifruit, lily, peach and other characteristic agricultural industries. The agricultural products in this village, covering fruits and vegetables, livestock and poultry, are all directly sold locally. According to incomplete statistics, the annual sales volume of eggs alone in the farmer's market reaches about 1 million Jin, and the annual income of local products business households with good benefits in the village can reach more than 1 million yuan. The villagers' economic income has obviously increased, and their happiness has been greatly improved. "I didn't have any income at home before, but now I can earn a good income by selling these things, and it's good that I can take care of my family in my own village." (Shop owner) In addition, the villagers will actively participate in all kinds of trainings held in scenic spots, learn various skills, provide better services and experiences for tourists, and attract more repeat customers. "We often receive various training notices in the group of homestay owners. Learn to take photos, learn to make tea, and last week I went to the training of making small videos." (Guixin Hot Spring Holiday B&B Housekeeper)

Figure 4 Schematic Diagram of the "Guest Flow Sharing" Model of Farm Stays in Guzhu Village



3.3 Standardized and unified management of the association provides guarantee for villagers to attract and retain tourists

Under the symbiotic environment of village collective economic foundation, tourism market management, convenient transportation, etc., the farmhouse association manages farmhouses in a unified and standardized way and establishes industry standards. The symbiotic energy generated enables the village to achieve economic and social prosperity. Driven by rural tourism, the homestay farmhouses in Guzhu Village have developed rapidly. 70% of the villagers are running homestay farmhouses, which is the village with the most concentrated farmhouses in Zhejiang Province. "Our village is a large farmhouse gathering area in East China. Because of the large number of tourists in Shanghai, it has the reputation of 'Shanghai Village'." (General branch secretary of the village party) Large-scale development can enable tourists to have other different choices when they are dissatisfied with a

farmhouse, thus avoiding the loss of tourists. Guzhu Village Farmhouse Association implements unified and standardized management of homestay farmhouses. "We also pay attention to the role of farmhouse industry associations." (Director of Social and Economic Development Office) First, the differentiated development of farmhouses. There are more than 500 homestays scattered in the village area, including high-end homestays and mid-end farmhouses, 40 provincial three-star homestays, 5 four-star homestays and 5 five-star homestays, with differentiated development and common development of middle and low levels to meet the needs of tourists at different levels. Second, a characteristic charging model is formed, and the overall price is relatively low. All farmhouses feature "N+1" as the characteristic charging method. N represents the number of accommodation nights, and the actual charging is carried out according to N+1, that is, staying on the same day and leaving on the next day counts two days. According to the standard of 120-240 yuan for each person for two days and one night including food and accommodation, and 180-360 yuan for three days and two nights, the "five-package" mode of food, accommodation, package delivery is implemented. The overall price is affordable and low, attracting many tourists and repeat customers, and the income of villagers has increased significantly. "A farmhouse can earn 300,000 yuan a year, and a better homestay can earn more than 1 million yuan a year." (General branch secretary of the village party) Third, set up a tourist transportation team to facilitate tourists from all over the world. If the number of the team reaches 10 people, there is a special motorcade in the village to pick up and drop off the customers directly in the urban community where they are located. "At that time, there were most middle-aged and elderly people from Shanghai, but their inconvenient transportation to the village was a problem. With the increasing market demand, the village began to use buses to pick up and drop off guests who came to stay in farmhouses. When the guests are convenient, the number of visits will increase." (Boss of Gongcha Farm Music) Now there are 10 motorcades in the village, which have to undertake the back and forth of nearly 10,000 tourists every day. The unified and standardized management of the farmhouse association has effectively promoted the common prosperity of the countryside.

3.4 The operating company promotes the in-depth integration of agriculture, culture and tourism and broadens the path for villagers to increase their income and become rich

Under the symbiotic environment of economic foundation, market demand, industrial brand building, the operating company combines multi-village operations, innovative products and talent recruitment, and the symbiotic energy generated has achieved economic, cultural and ecological common prosperity. In 2018, Guzhu Village joined hands with eight villages under the jurisdiction of Shuikou Township to jointly establish Ximeng Culture Communication Co., Ltd., aiming to be responsible for the efficient operation of diversified projects in the scenic spot through unified planning and management. Ding Jie, the person in charge, led the team to dig deep into the characteristics of tea culture scenic spot with Guzhu Village as the core. Focusing on the cultural core of "Purple Bamboo Shoot Tea" and "Village B&B", the two brands of "Shuikou Caoshi" and "Impression Shuikou" were used to carry out in-depth development, brand building and Shuikou mode output of scenic spot tourism products, so as to further enhance the brand value of rural tourism and the added value of derivative products. The company actively leads villagers to change their thinking, adheres to the concept of "Lucid waters and lush mountains are invaluable assets", makes full use of the water resources of Guzhu Village, and promotes the development of green ecological economy. It not only increases economic income, but also enhances the environmental awareness and sense of responsibility of villagers and tourists. "Many customers are attracted by the landscape here, so we usually pay great attention to environmental protection." (Villagers) "The ecological environment here is beautiful, which attracts us. We will naturally protect the environment when we live here." (Tourists) Integrate resource utilization into cultural elements, and transform existing rural resources into new products that can give tourists new experiences, especially the development of purple bamboo shoot tea culture and derivative products and cultural and creative products, so as to enhance tourists' sense of cultural experience. "Our newly developed purple bamboo shoot tea lager beer is very popular among young people, and we will innovate more products related to Guzhu culture in the

future." (Staff of Ximeng Culture Communication Co., Ltd.) In addition, the company actively attracts young talents and expands the rural operation talent team for the development of Guzhu Village. Corporate operation has realized resource sharing, complementary advantages and coordinated development of all villagers, strengthened the village collective economy, and provided a path for the countryside to promote common prosperity.

4. Conclusions and Discussions

4.1 Conclusions

Based on the practical problem of rural common prosperity, this study adopts the longitudinal single case study method, taking the typical case Guzhu Village as the research object, and analyzes the process of village development of rural tourism to promote rural common prosperity from the perspective of symbiosis. According to the degree of village development, it is divided into three stages: the first stage is spontaneous management stage, the second stage is joint development stage, and the third stage is industrial upgrading and common prosperity stage. Different key events, different symbiotic main units and the coordination of different resources in each stage lead to certain differences in the effects of rural tourism development. The spontaneous management mode of the village in the early stage enabled some villagers to achieve material prosperity, while the reasonable division of labor and mutual promotion and win-win between the symbiotic units in the later stage of transformation and common prosperity enabled villagers to achieve material prosperity, spiritual and cultural prosperity and village ecological harmony. At the same time, the article analyzes the participation and role of different symbiotic units in the process of rural operation, and finds that rural operation to promote common prosperity is a process of cooperation between multiple stakeholders. The local government strengthens autonomy, optimizes services, and provides policy guidance and financial support for villagers; Villagers' resource sharing and enthusiastic service bring the best experience to tourists; The standardization and unification of farmhouse associations provides guarantee for the number of tourists received by owners and jointly increases the income of villagers; The operating company innovates products according to market demand, realizes the deep integration of agriculture, culture and tourism, and provides a variety of paths for villagers to increase their income and become rich. The conclusion of the research has positive practical significance for rural areas to achieve high-quality development and move towards common prosperity. By rationally allocating the roles of various symbiotic subjects, the village can attach importance to the dominant position of villagers in the development process, introduce new units such as operating companies to inject new energy into the village, transform resource advantages into economic advantages, and jointly strengthen the rural collective economy.

4.2 Discussions

This study deeply analyzes the different stages of Guzhu Village in Changxing County in the process of moving towards common prosperity and its symbiotic effects, and reveals how the village can transform its ecological advantages and resource advantages into economic advantages and development advantages by focusing on multiple symbiotic subjects and cooperating with the help of symbiotic environment. It enriches the connotation and representation of common prosperity, which is manifested in sustainable employment, increased income, enhanced happiness and satisfaction, balanced distribution of interests, improved cultural identity and livable environment. Besides material prosperity and spiritual prosperity, ecological pleasure is also one of the important manifestations of common prosperity[9]. At the same time, it enriches the internal relationship between rural operation and common prosperity, and also provides a reference "Gu Zhu model" for other villages, showing how to achieve multi-stakeholder symbiosis and win-win through effective rural operation strategies under a specific regional cultural background. Through diversified development strategies, taking advantage of ecological advantages and tourist market, focusing on villagers' participation and other measures, the economic vitality of the countryside can be effectively enhanced, and then the all-round development of the countryside can be promoted[42]. This discovery is not only applicable to rural tourist destinations, but can also be extended to villages of other industrial types, providing a broader reference for the realization of rural revitalization and common

prosperity goals. For example, cultural and artistic villages, e-commerce industrial villages, etc. also involve rural operation and governance issues[43]. Their essence is to give full play to the role of local governments, villagers, village collective economic organizations and other multiple subjects. Therefore, we can also learn from and expand the effective rural operation mode and mechanism refined by this research institute, and mobilize multiple subjects to cooperate to promote rural development and move towards common prosperity.

This study also provides many enlightenments for villages to promote rural development and achieve common prosperity through rural operation: First, it emphasizes the key role of operating companies in rural operation. In the process of rural transformation and upgrading, the operating company needs the overall operation and management, including project planning and marketing, tourist reception and service, and daily maintenance and management of various facilities in the village. At the same time, it is necessary to coordinate the interests of enterprises, governments, associations and villagers to ensure sustainable development. Second, attach importance to the core position of villagers in rural operation, and let villagers directly or indirectly participate in the daily operation and management of villages. About 90% of the villagers in Guzhu Village are directly or indirectly engaged in work related to rural tourism, such as homestay management and direct sales of agricultural products. This mode effectively promotes the development of local economy and enhances the cohesion of the community. Thirdly, the symbiotic units are tied together in the way of mutual benefit and mutual assistance, and the purpose of jointly promoting village development and realizing win-win situation between villagers and villages is adhered to, so that the symbiotic units are inseparable. The government provides policy guidance and financial support to guarantee the development of villages; Villagers actively participate, develop more formats, enthusiastically serve tourists and improve tourist satisfaction; The association acts as a bridge and link between the government and villagers, organizes villagers to conduct training, improves service quality, and assists the government in industry management; Through market-oriented operation, the operating company realizes the deep integration of agriculture, culture and tourism, improves villagers' income and tourists' satisfaction, and promotes the economic development and social benefits of villages. Of course, the use of a single case study in this study has certain limitations. In the next step, we can verify the conclusions drawn in this study through multiple cases, and further explore the similarities and differences of the mechanisms of different rural cases to help common prosperity through operation.

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How Does Administrative Decentralization Activate Endogenous Rural Development?—The Transformation of R Village and Its Underlying Logic

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Abstract: The rural revitalization strategy, guided by China's vision for national rejuvenation, emphasizes activating endogenous development in rural areas. Yet in practice, many grassroots initiatives suffer from "floating public projects," where government dominates while local participation lags. This paper examines how administrative decentralization can effectively stimulate rural endogenous power by analyzing the transformation of R Village—a once-declining bonsai-producing village plagued by governance issues and economic stagnation. Through the downward extension of administrative authority, public resources, and governance concepts, R Village achieved organizational restructuring, industrial revitalization, and community re-engagement. The case demonstrates the potential of a "new endogenous development" model that integrates external support with internal capacity-building. R Village's shift from a "weak and dispersed" village to a national model offers valuable insights for sustainable rural development and broader rural revitalization efforts.

Keywords: Administrative Decentralization; Rural Development; Endogenous Power; Underlying Logic

1 Introduction

China's rural revitalization strategy, a critical component of the country's modernization agenda, aims to foster sustainable development by leveraging the internal resources and capabilities of rural areas(Zeng, 2007). A key aspect of this strategy is administrative decentralization, which seeks to empower local governments and communities by transferring authority and resources from central authorities to the grassroots(Zhou, 2006). While decentralization has been heralded as a potential driver for rural development, the specific mechanisms through which it activates endogenous development are not well understood (Ye & Lei, 2022).This paper addresses a significant gap in the literature by examining how administrative decentralization can stimulate endogenous development in rural areas. Using R Village as a case study, the research explores how the decentralization of administrative authority, public resources, and governance concepts facilitated the transformation of a struggling rural community into a model of rural revitalization. R Village, once facing economic decline and weak governance, successfully utilized the support of decentralization policies to restructure its governance, upgrade its industries, and engage its community in local development efforts(Zhou, 2020). Through these processes, R Village illustrates the potential of administrative decentralization to activate rural endogenous development (Zeng, 2014).The significance of this study lies in its contribution to both the theoretical and practical understanding of decentralization's role in rural development(Guo et al., 2018). By focusing on R Village, the paper highlights the practical challenges and mechanisms of decentralization and its impact on local governance, industrial transformation, and community engagement(Zhang et al., 2021; Wen & Liu, 2022; Yang et al., 2023). This research

not only fills a gap in the academic literature on decentralization but also offers insights for policymakers involved in rural revitalization strategies.

R Village's transformation from decline to revitalization illustrates the potential for a traditional industry to thrive in modern society. It highlights the importance of continuous innovation and adaptation as essential components for sustainable development (Li et al., 2018). R Village's experience demonstrates that with the right strategies and strong resolve, even the most challenging environments can be overcome, leading to a prosperous future (Li et al., 2021). The core of the rural revitalization strategy lies in cultivating and enhancing the endogenous development power of rural areas (Shu et al., 2018). However, activating this endogenous power is a complex task (Wei & Zhao, 2018). Under the "village transformation" model, large-scale external resource inputs can yield immediate results, but sustaining these improvements poses a long-term challenge (Xu, 2023).The development path followed by R Village contrasts with traditional approaches to village transformation (Wang & Zeng, 2023). It illustrates that the activation of rural development, particularly in R Village, depends on the decentralization of administrative authority, public resources, and governance concepts within the rural revitalization strategy (Zhou, 2012). In R Village's revitalization process, the integration of external resources with internal capacities facilitated the development of localized industries, strengthened public organizations, and empowered villagers as key agents in the process (Zhan, 2014; Dong et al., 2008). This case study directly addresses an important academic question: How can administrative decentralization activate the endogenous development potential of rural areas?

At the core of China's rural revitalization strategy is the cultivation of endogenous development power, which emphasizes the importance of local resources, governance, and community participation (Shu et al., 2018). However, activating this power is a complex process that requires careful coordination between external support and internal capacities (Wei & Zhao, 2018). In this context, the case of R Village is a valuable example of how administrative decentralization, by integrating external resources with local capacities, can drive the revitalization of rural areas.This paper contributes to the broader debate on rural governance and decentralization by providing a theoretical framework that links administrative decentralization to the activation of endogenous rural development. Through the case study of R Village, the paper investigates the mechanisms by which decentralization can enhance governance, stimulate industry, and empower communities, ultimately promoting sustainable rural development.

2 Problem Statement

In his report to the 20th National Congress of the Communist Party of China, Xi Jinping emphasized: "To comprehensively advance rural revitalization, we must prioritize agriculture and rural development. Building a strong agricultural country and steadily promoting the revitalization of rural industries, talent, culture, ecology, and organizations is essential" (Zhou, 2020). This highlights the strategic significance of addressing rural revitalization and the "three rural issues" as integral to achieving socialist modernization (Liu et al., 2021). Rural revitalization, as a key component of the second centenary goal, plays a crucial role in the process of building a modern socialist country (Li et al., 2021).

The intrinsic logic of rural revitalization connects the coordinated development of material and spiritual civilization with the harmonious relationship between humans and nature (Zhu, 2024). Accelerating the construction of a strong agricultural country and promoting the revitalization of rural industries, talent, culture, ecology, and organizations are essential to the high-quality development of rural areas, aligning with the new development stage and strategy for China's future (Zhang et al., 2021). After the implementation of the Household Responsibility System, farmers experienced a process of deorganization, leading to the disintegration of collective economic organizations in most rural areas and the nominal existence of the collective economy (Zeng, 2007). Following tax and fee reforms, grassroots governance shifted from a "drain-type" structure to a more loosely connected,

"floating-type" relationship between government and rural citizens (Xu et al., 2017).

The issue of rural governance's loose structure and the consequences of "non-collectivization" and "floating" governance have become a widespread concern (Ye & Lei, 2022). To address the disintegration of grassroots governance, the Central Committee has called for decentralization, empowering local authorities with greater responsibility by delegating resources, management, and services to the grassroots level (Yang et al., 2023). Simultaneously, the concept of administrative decentralization, with leaders participating in grassroots governance, has become a consensus measure for local governments in promoting effective rural governance (Zhang et al., 2019). From the "Targeted Poverty Alleviation" phase to the "Anti-Poverty" period, this approach evolved into an all-encompassing institutional model that continues in the rural revitalization process (Wen & Liu, 2022).

While academic circles acknowledge the necessity of administrative decentralization, two concerns have been raised. One is the "formalized administrative decentralization," where the complex social structure within village mechanisms impedes effective governance, rendering such systems ineffective in mobilizing more farmers (Zeng, 2014). The second concern is that administrative decentralization might lead to the "bureaucratization" of rural governance, which could undermine the autonomy of villages and weaken their self-governance (Zhou, 2006).

Interestingly, the case of R Village presents a scenario distinct from both of these concerns. Rather than becoming a formalized process or bureaucratic in nature, administrative decentralization has invigorated R Village, sparking new vitality and dynamic changes. This raises an important question: How does administrative decentralization activate endogenous rural development? (Zeng, 2007).

In R Village, the transformation from a "backward village" to a "model village" was driven by its own internal forces, without deep external embedding or multifaceted empowerment. The success of this transition emphasizes the potential of a model of governance that focuses on both internal and external collaboration. By deeply exploring and analyzing R Village's case, this research aims to theoretically reveal the relationship between administrative power and local villagers' internal motivation. It also provides a clearer understanding of the government's role in rural development and the real-world effects of decentralizing administrative power to rural areas, which can inform future policy-making and offer valuable insights for promoting rural revitalization—a significant and historically meaningful systemic initiative.

3 Literature Review

Scholars have analyzed and summarized administrative decentralization and its effects from different perspectives, forming three competitive viewpoints in the existing literature (Zhou, 2020). The first viewpoint centers on the "formalization" of administrative decentralization and organization (Dong et al., 2008). In this view, administrative decentralization has been reduced to a mere formality due to several factors (Xu et al., 2017). The first is institutional reasons: studies have found that grassroots party organizations, under heavy task pressure and incentive systems focused on rigid evaluation mechanisms, often engage in passive "performative" strategies to conduct "cosmetic projects" to meet external supervision and evaluations (Zhou, 2006). The second factor involves organizational structure, where the heterogeneity of stationed agencies significantly impacts the support behaviors of local cadres (Zeng, 2014). Faced with limited financial resources, many first secretaries resort to formalism, shortcut strategies, or even corruption to meet demands (Li et al., 2018).

The second viewpoint focuses on "administrative decentralization" leading to "bureaucratization" of village governance. Some scholars argue that decentralizing administration and management could gradually lead to the bureaucratization of rural areas, undermining endogenous development. In practice, certain administrative decentralization measures have led to rural organizations expanding into grassroots bureaucratic structures. The

"multi-village" system has embedded diversified power structures in rural society, with "mutual aid" evolving into a "dominant-subordinate" relationship. This intermingling of powers has effectively brought village-level organizations under the influence of the broader administrative system, reinforcing bureaucratic advantages. Overly concentrated administrative power, through stationed cadres such as first secretaries, village leaders, and work teams, undermines the autonomy of grassroots organizations, potentially leading to "semi-bureaucratization" or even "complete bureaucratization." On the other hand, some scholars have recognized that the external intervention of administrative decentralization compresses the space for the growth of endogenous power and strengthens the legal governance of rural areas, resulting in an increasing concentration of power in the hands of the first secretary, who might take over all village affairs in the long run.

The third viewpoint emphasizes the embeddedness of administrative power within rural governance, where a "floating government" becomes deeply embedded in rural society through decentralization, forming an interactive relationship. Some scholars have acknowledged the inevitability of the penetration of state-led administrative power into rural grassroots society. With changes in rural social structures and values, the decline of traditional local norms and endogenous authority has made rural society more reliant on state power. In the absence of independent production orders within villages, external management and legal forces help maintain orderly production and prevent villages from descending into anarchy. Some argue that administrative decentralization represents an embedded form of state power that can facilitate governance at the grassroots level. After the implementation of "targeted poverty alleviation," government interaction with farmers strengthened their national identity, transforming the government from a "floating" to a "downward" form of presence. Stationed assistance not only fosters a close interaction between state and society but also facilitates the standardization of rural governance through public governance systems.

In conclusion, while existing research provides fundamental insights and theoretical foundations for understanding administrative decentralization, several gaps remain. First, while the viewpoint linking administrative decentralization with organizational formalization is supported by some empirical cases, treating the effects of decentralization solely as "formalization" may be overly simplistic and factually incorrect. In many instances, administrative decentralization has not only remained superficial but has genuinely contributed to enhancing rural governance capacity and activating endogenous development power through concrete policies and practices. The view that administrative decentralization leads to the bureaucratization of villages overemphasizes the adversarial relationship between external administrative power and endogenous rural power, overlooking the inherent need of villages with weak collective foundations for external governance support. In such villages, where internal governance is weak, external administrative power provides necessary support to help build and improve governance structures. While the embeddedness perspective acknowledges the necessity of administrative power in rural governance, it still falls short in explaining the detailed mechanisms and logic of how administrative decentralization activates endogenous rural development.

To better understand how administrative decentralization activates rural endogenous development, further empirical research and theoretical exploration are needed. Specifically, it is essential to analyze the specific operational modes and effects of administrative decentralization in different rural governance contexts, assessing their applicability and sustainability. Moreover, a more comprehensive theoretical framework is required to explain the interaction mechanisms between administrative decentralization and endogenous rural development, providing scientific guidance for policy-making and practical implementation. Through such research, we can reveal the deeper mechanisms of how administrative decentralization activates endogenous rural development and offer valuable lessons for rural revitalization in other regions, contributing to the overall improvement of rural governance capacity and sustainable rural economic and social development.

Thus, this paper attempts to construct a systematic analytical framework based on the theory of new endogenous development, exploring the mechanisms by which administrative decentralization activates rural endogenous development.

4 New Endogenous Development: Theoretical Foundation

(1) New Endogenous Development: Analytical Framework

Traditional exogenous development models view rural areas as passive recipients, where development is determined by external policies, capital, and technology. While the strong embedding of external forces can, in some cases, lead to rapid and effective integration of rural societies, it often obscures the existence of endogenous governance orders and ultimately faces the potential risk of disengagement. In fact, the over-dependence on external factors and the neglect of endogenous values in exogenous development models have led to the failure of rural areas to achieve sustainable economic growth. Unlike the exogenous development concept, the endogenous development model emphasizes tapping into the internal resources of village communities to promote rural economic development and environmental improvement. It stresses the inherent driving forces of rural development and the active participation of farmers. The self-help capacity of local actors is seen as a prerequisite for establishing and maintaining rural development. However, many scholars argue that a purely endogenous development model, which does not rely on external resources, faces the dilemma of being overly idealized. In the context of globalization, external trade, and government actions, the pursuit of pure socio-economic autonomy in rural development is practically impossible.

Building on these two development approaches, the theory of New Endogenous Development proposes a model integrating both exogenous and endogenous development. It emphasizes the interaction between internal and external factors in rural development. The new localized development model posits that the enhancement of local capabilities is the foundation of rural endogenous development, and the intrinsic power of endogenous development lies in responding to grassroots demands and activating and guiding local development potential. The core mechanism of this model is the interaction between “development” and “development capacity”. The practice of rural empowerment in China has evolved from externally driven exogenous development, to endogenous development driven by internal factors, and finally, to endogenous development within the interactive environment of internal factors. Similar to endogenous development, New Endogenous Development targets rural community-driven development. However, its internal collaboration and the symbiotic relationship between internal and external factors form a comprehensive approach to rural development. The relationship between the two is not mutually exclusive, but complementary, with long-term sustainable development as its ultimate goal. The new endogenous development theory organically combines the external and internal dual tensions of rural development. On one hand, it acknowledges and accepts the introduction of external forces; on the other, it emphasizes the leading role of farmers and villages in the development process, promoting the organic integration of both internal and external factors.

(2) New Endogenous Development and Rural Activation: An Analytical Framework

The concept of “activating the village” aligns with the theoretical framework of new endogenous development. Unlike the “transformation of villages” driven purely by external factors, which aims to reshape rural areas, “activating the village” follows a rural ontological approach. It asserts that rural areas possess inherent potential that needs to be activated, emphasizing the activation of endogenous power under the empowerment of external

factors. In this context, the government is positioned as a resource provider and potential cultivator. Specifically, "activating the village" focuses on activating endogenous development power through external empowerment, which is a bidirectional interactive process combining both internal and external elements. It is this approach of "external factors promoting internal development" and "integration of internal and external elements" that offers the possibility of achieving sustainable performance in rural governance.

The theory of New Endogenous Development provides the fundamental analytical framework for endogenous rural development driven by external forces. However, this initial theoretical model does not clearly explain the logic of how administrative decentralization activates endogenous rural development. Therefore, based on the theory of new endogenous development, it is necessary to incorporate key elements of rural development practices into the original theoretical model to construct a more explanatory new analytical framework. This paper, therefore, constructs the following analysis framework (see Figure 1), which considers three dimensions: organization, industry, and subjects. During the process of administrative decentralization, through the injection of external factors such as "administrative power decentralization," "public resource decentralization," and "governance concept decentralization," the original internal organizational order, endogenous industrial base, and endogenous subject power of rural society are revitalized through the processes of "organizational restructuring," "industrial activation," and "subject activation." External empowerment and endogenous activation are not isolated from each other; rather, they interact and intertwine until they achieve a seamless integration, thereby "activating the village" and ultimately creating a new endogenous rural development model characterized by public organizations, sustainable industries, and participatory subjects.

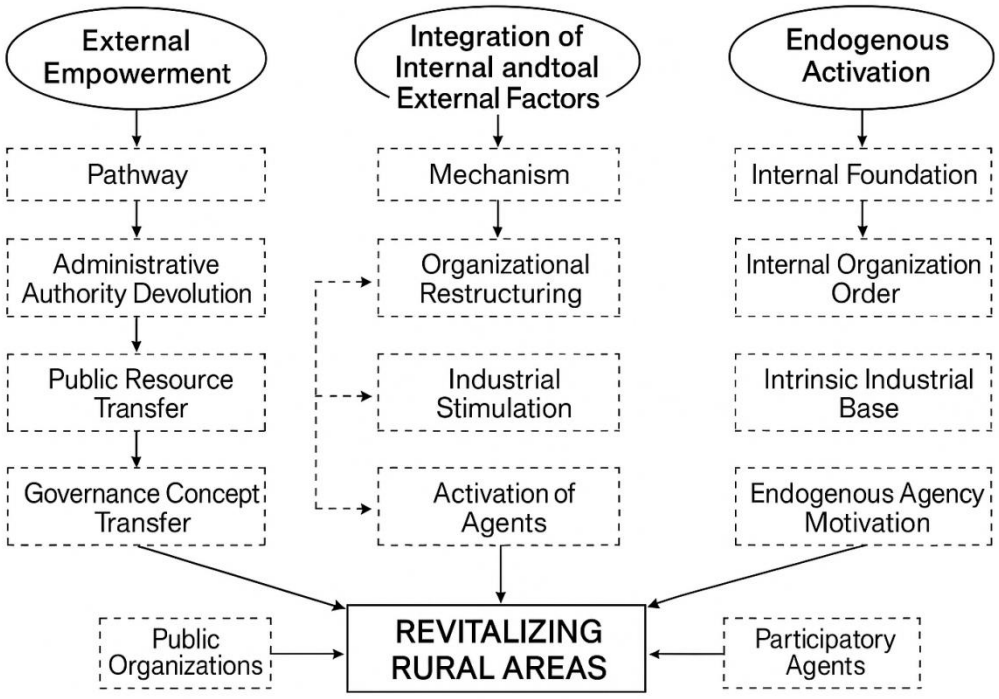

Figure 1 Mechanisms of action of administrative decentralization to promote new endogenous development in multiple villages

(3) Expanding the analysis: the interaction between New Endogenous Development and administrative decentralization

In this paper, we introduce the concept of New Endogenous Development (NED), which aims to bridge the interaction between external forces and endogenous potentials in order to promote sustainable development in rural areas. This theoretical framework emphasizes that in modern societies, the introduction of external resources and the stimulation of endogenous development capacity are complementary, not opposed, but mutually reinforcing. This paper further extends this framework and specifically analyzes the role of administrative decentralization in promoting endogenous development in the context of the case of R Village.

1. Administrative decentralization and organizational restructuring

Administrative decentralization can effectively activate the governance capacity of local governments and enhance the flexibility and autonomy of grassroots governance by decentralizing power and resources (Xu et al., 2017). In the practice of R village, administrative decentralization promotes the reconfiguration of village organizational structure by giving local governments more decision-making power and financial autonomy. For example, while receiving policy guidance from higher levels of government, the R-village government is also able to adjust and optimize rural resource allocation according to actual local needs. This decentralization of power enables local governments to mobilize villagers' resources more flexibly and effectively implement rural revitalization strategies (Zhou, 2020).This mechanism not only enables local governments to accurately identify and respond to villagers' needs, but also enhances villagers' sense of participation and responsibility through the enhancement of local self-government organizations (Dong et al., 2008). This is particularly evident in R village, where villagers' autonomy and collective decision-making ability have been greatly enhanced, becoming an important force in promoting local governance.

2. Industry Revitalization and Industrial Structure Upgrading

Administrative decentralization has not only affected the governance structure, but also had a profound impact on the industrial structure of R village. Under the traditional collective economic management model, external resources are often directly invested in industrial projects, leading to over-concentration of resources and lack of industrial diversification. Through administrative decentralization, the local government has gained more flexibility and can make more effective use of local advantageous resources and industrial characteristics to promote the optimization and upgrading of industrial structure (Zhou, 2012).Taking the transformation of R village as an example, the government has promoted the localization of industrial policies through administrative decentralization, which has enabled the agricultural industry not only to retain the traditional bonsai production, but also to successfully transform into a modernized industrial model integrating agriculture, tourism and culture (Guo et al., 2018). This industrial upgrading from traditional to modern is a direct result of the combination of administrative decentralization and local characteristic industries, which provides useful experience for rural revitalization in other places.

3. Stimulation of Community Participation and Grassroots Autonomy

Another key mechanism of administrative decentralization is the enhancement of the community's sense of participation and self-governance.In the governance model of R Village, villagers' participation is not only limited to the traditional election and decision-making process, but is also deeply integrated into day-to-day management through the mechanism of resource sharing and benefit distribution (Wen & Liu, 2022). This bottom-up form of participation not only enhances villagers' political awareness, but also stimulates their enthusiasm to participate in governance through benefit sharing.In Village R, the combination of administrative decentralization and community

participation is embodied in the “4-4-2” benefit distribution model, which ensures that villagers are closely linked to the development of the village collective economy by dividing the benefits among enterprises, the village collective, and the villagers, thus effectively mobilizing villagers' motivation to participate in public affairs (Yang et al., 2023). This practice proves that administrative decentralization is not only the decentralization of policies, but also the process of community empowerment.

4. Discussion of International Literature and Comparative Cases

Although the NED framework has been successful in the practice of R-village, it is not an isolated phenomenon and other countries have similar experiences in similar contexts. For example, India's Rural Development Program (RDP) strengthened grassroots governance through administrative decentralization and promoted local economic self-development (Bardhan, 2002). In Latin America, many countries have stimulated local self-governance and industrial development through decentralized governance models, especially in resource-rich rural areas (Faguet, 2004). These international experiences provide important theoretical support for this paper, further demonstrating the close relationship between administrative decentralization and endogenous development.By comparing the international literature and cases, we find that administrative decentralization plays a similar role in stimulating local economic and governance capacity, although the implementation contexts are different in different regions. This not only enhances the depth of the theoretical framework, but also broadens the applicability of the research in this paper.

5. Governance Concept Decentralization and Participatory Subjects: The Mechanism of Endogenous Rural Governance Order

(1) Administrative Decentralization and Governance Concept Decentralization

Driven by a series of agricultural policies, rural areas are currently shaped by two external forces: the government-led “project-based rural development” and the business-driven “commercial capital.” Both forces are external actors, working together to achieve rural development through participation. However, the development of rural areas increasingly relies on external policies, resources, and even business capital, with the flow of funds being the current mainstream. It is expected that rural development, dominated by external actors, may lead to agricultural monopolies, rural transformation, and the replacement of farmers.

Since the village is primarily the community of farmers, the leading force for rural development should be the farmers themselves. Relying solely on external solutions is not sustainable; the endogenous motivation of the village community is the true driving force for rural development. Guided by rural ontological governance, administrative decentralization focuses on activating the subjectivity of villagers to realize a village development model led by the village community. However, in practice, how to mobilize villagers' participation remains a major challenge faced by village work teams and governance organizations. Even with relatively well-established participation management methods from higher-level governments, many villagers still lack enthusiasm for participating in public affairs at the village level.

(2) Governance Concept Decentralization and Subject Activation

From the perspective of the stationed work teams, activating genuine participation from villagers requires effectively linking the individual interests of villagers with the collective interests of the village. On the one hand, the village work teams and village leaders, through multiple communications with the district party secretary, successfully secured a popular "gas station project" for R Village. This project, through the "4-4-2" dividend structure involving businesses, village collectives, and villagers, not only expanded the collective economy but also directly increased villagers' personal incomes. At the same time, relying on the development of the collective economy, villagers could earn additional income through land transfers, linking their income levels directly to the development of the collective economy. Previously, the collective's affairs were primarily about the interests of the collective alone; now, these affairs have become directly related to every villager's interests. Consequently, numerous opinions and suggestions for the village's future development began to emerge.

On the other hand, previously, due to the absence of a local bonsai sales market in the village or even nearby towns, villagers were forced to transport their bonsai to other regions for sale, facing high logistics costs. The villagers were eager to have their own bonsai trading market. In response, the village work teams and village leaders quickly prioritized the construction of a bonsai trading market. After the completion of the agricultural trade market, villagers could sell bonsai and related agricultural products in a more convenient and organized setting, directly benefiting from their business activities. The bonsai market also successfully gathered villagers engaged in bonsai-related industries, forming a collective force for the village's industrial development. Under this close-knit mechanism of interest linkages, villagers became increasingly concerned with the future development of the village and actively participated in the governance of public affairs.

(3) Endogenous Subject Power and Grassroots Participation

The essence of rural development lies in the reproduction of a healthy social order in rural areas, with the focus on reshaping the subjectivity of farmers to activate their endogenous power for self-development. During the decentralization process, the stationed work teams, following the governance concept of rural ontologism, assisted village governance organizations in activating the subjectivity of villagers based on respect for their agency and creativity. This collaborative effort ultimately stimulated active participation within the village.The complete process of governance concept decentralization is illustrated in Figure 2:

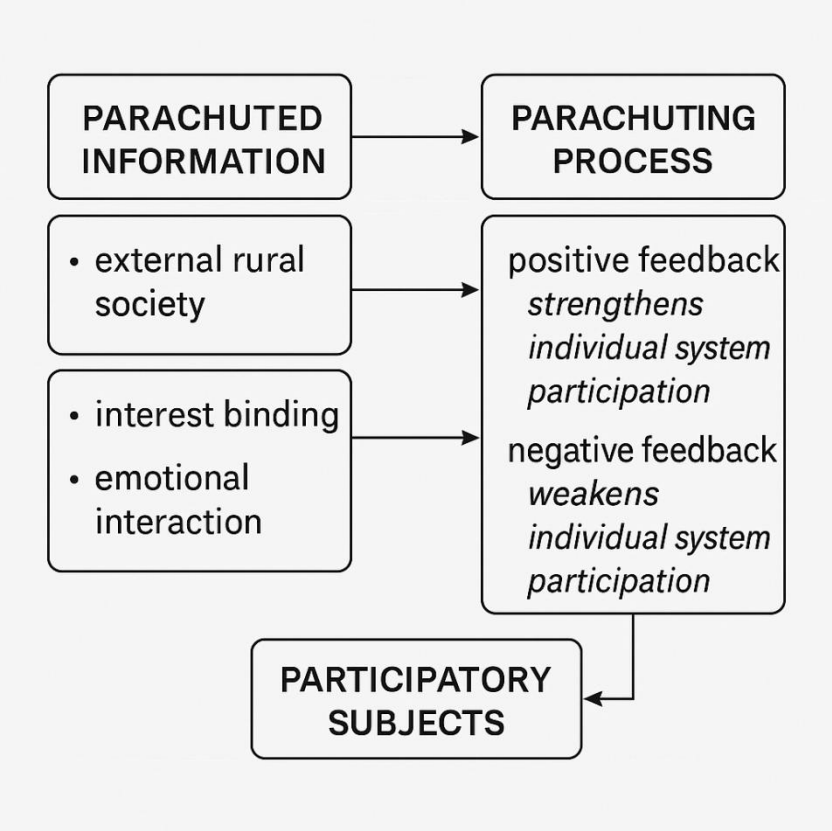

Figure 2: The Practice Logic of Governance Concept Decentralization and the Realization of Participatory Subjects

Through the case of R Village, we observe that, to improve the mechanism of rural endogenous governance, potential governance elements such as interests and emotions were reintegrated into village governance. This led to the formation of internal linkages and emotional interactions within the village. The activation of endogenous subject power, built upon this foundation, has significant sustainable implications. On one hand, the interest linkage created a community of shared interests, with the dividend system providing a formal regulation and constraint for villagers' participation. On the other hand, emotional interaction within the village generated frequent, everyday interactions and cultivated a positive public atmosphere. This beneficial change could then transfer into the domain of public governance, reshaping villagers' participation behavior. Within the specific context of rural society, the decentralization of the rural ontological governance concept effectively awakened farmers' psychological identification and value affiliation, thereby addressing the weak links in the subjectivity of rural governance. This ultimately enabled the real return of grassroots participation in the practical realm.

6. Policy Recommendations: How Administrative Decentralization Can Activate Endogenous Rural Development

(1) Diversified Approaches to Construct a New Model of Village Self-Governance

To establish a modernized self-governance framework, it is crucial to consolidate the leadership role of grassroots Party organizations, ensure their comprehensive coverage across rural areas, and enhance the training and quality of Party members. Optimizing intra-party democratic mechanisms will further elevate governance and service capabilities at the village level. Effective village self-governance must be safeguarded by a robust legal foundation. This includes amending the Organic Law of the Villagers' Committees of the People's Republic of China to reinforce farmers' rights and roles, intensifying legal education in rural areas, and improving villagers' legal awareness and capacity for rights protection.

Institutional improvements should also include judicial assistance mechanisms for village committees to ensure accessible legal support. Democratic consultation platforms, such as villagers' assemblies and representative meetings, should be established to enhance participatory decision-making. Reforms must focus on democratic, legal, and evidence-based decision-making processes to ensure all decisions align with farmers' interests. Mechanisms such as public disclosure of village affairs and democratic evaluations will ensure power operates transparently. Public education campaigns should promote the concept of self-governance, encourage active engagement, and enhance villagers' capacity for self-management through community-based learning and exemplary leadership.

(2) Strengthening Grassroots Governance to Accelerate Rural Governance Modernization

Under the broader framework of rural revitalization, modernizing rural governance is a complex, systematic task requiring both effective institutional design and enhanced managerial capacity. A starting point is to strengthen grassroots Party organizations by promoting ideological education that reinforces political commitment and moral integrity. Talented individuals with strong leadership, ethical values, and service-oriented attitudes should be recruited into local leadership teams.

Government functions should transition from control-based to service-oriented models to address the real needs and expectations of villagers. Simultaneously, it is essential to strengthen the structure and functions of self-governance institutions such as villagers' committees and representative councils. These institutions should serve as the core of rural governance, with clearly defined responsibilities and authority.

Modern technologies should be leveraged to establish digital platforms for village self-governance, improving accessibility and transparency in public administration. Legislative efforts should clearly define the roles and responsibilities of grassroots institutions. Legal literacy should be raised among villagers, and enforcement capabilities should be improved through a robust supervisory system and better-trained personnel.

Local judicial resources should be rationally allocated to increase efficiency. For everyday disputes, village-level mediation systems should be established, while more complex cases should be addressed through arbitration and formal legal channels to diversify dispute resolution methods and ensure access to justice.

(3) Promoting Governance Model Transformation through Co-construction and Co-governance

A new model of rural governance should be developed, one characterized by co-construction, co-governance, and shared benefits. This model must be built upon Party leadership, villager participation, enterprise support, legal safeguards, and social assistance. While self-governance remains the foundation, enterprise investment can provide financial support, and civil society organizations can contribute their expertise and resources to strengthen community-based governance.

This integrated framework should embody the synergy of autonomy, rule of law, moral governance, and smart governance:

1. Autonomy empowers villagers to manage their affairs;
2. Rule of law institutionalizes governance processes;
3. Moral governance guides rural society through cultural and ethical norms;
4. Smart governance uses digital technology to enhance administrative efficiency.

To achieve this, a collaborative governance system should be established where villagers are involved in

agenda-setting, planning, and implementation. Farmers' agency must be fully activated, encouraging them to engage meaningfully in village affairs. Continuous evaluation and feedback should guide policy adjustments, ensuring development outcomes are aligned with farmers' interests.

(4) Expanding Governance Space to Enhance Governance Effectiveness

Effective governance in rural areas hinges on well-functioning grassroots organizations. It is imperative to institutionalize governance through timely legal reforms, creating clear and enforceable rules to guide village-level administration. Democratic governance mechanisms, such as villagers' councils and participatory budgeting, must be strengthened to guarantee villagers' rights to know, participate, and supervise.

At the same time, digital transformation should be pursued by creating integrated information platforms that enhance transparency, facilitate real-time data sharing, and encourage broader participation. Big data analytics and intelligent monitoring systems can support evidence-based governance, enhance responsiveness, and provide policymakers with timely, actionable insights.

Human resource development is also key. Training programs, higher education, and vocational development must cultivate a cohort of rural managers who are knowledgeable, skilled, and committed to rural revitalization. Through competitive salaries and benefits, policies should incentivize young talent to engage in rural governance. Ongoing training and cross-regional knowledge exchange can enhance the competencies of local governance personnel and drive continuous improvement.

(5) Increasing Investment to Promote Comprehensive Rural Revitalization

Rural governance serves as a foundational guarantee for rural revitalization and must be supported by holistic efforts in industrial, cultural, ecological, and organizational development. Investment in infrastructure, technological innovation, and human capital should be expanded through both national and local government channels. Financial institutions should offer diversified, low-cost financial services tailored to agricultural needs, reducing farmers' financing burdens. Private capital should also be encouraged to invest in rural infrastructure and operations.

Agricultural modernization should align with local resource endowments and market demand, promoting specialty agriculture, green practices, and branding strategies. Integration across farming, livestock, and fisheries sectors can drive mutual development. The rural supply chain and distribution system should be improved to support agricultural industrialization and value-added growth.

On the cultural front, a dedicated rural cultural development strategy should be adopted to preserve traditional heritage and foster distinctive cultural brands. Public cultural services—such as libraries, cultural centers, and creative industries—should be expanded to create employment and income-generating opportunities.

Ecologically, rural green development should be promoted through comprehensive environmental protection, ecological restoration, and green infrastructure. Housing conditions must be improved with increased investment in rural living environments. A full ecological civilization framework, including an eco-compensation system, should support sustainable, green production models across rural regions.

7. Conclusion and Discussion

A historical review of rural governance transformation in China reveals that administrative decentralization, as a new intermediary mechanism connecting higher-level governments and grassroots rural societies, plays a pivotal

role in the restructuring of rural governance. While previous scholarship has offered valuable insights into the concept and function of administrative decentralization, both empirical and theoretical dimensions remain underdeveloped. The case of R Village, which transformed from a "weak and disorganized" village into a "national model," illustrates the powerful internal driving force that governmental intervention can provide for rural revitalization.

The case study of R Village demonstrates that under conditions of a "detached" grassroots government and "fragmented" village governance organizations, administrative decentralization—through the injection of authority, public resources, and governance concepts—effectively empowered the village. This empowerment activated the internal organizational order, industrial foundation, and endogenous agency through three key processes: organizational restructuring, industrial stimulation, and subject activation. With the state as a catalyst, village-level self-governing bodies, local industries, and participatory actors were all revitalized. These dynamic responses contributed to the reconstruction of the internal governance order and laid the foundation for achieving the goal of "activating the village."

In contemporary rural China, external forces have increasingly permeated grassroots communities, influencing the internal governance logic of villages to varying degrees. However, the essence of sustainable revitalization lies in the synergistic coexistence of internal and external forces. The role of the state is not to override or reshape rural society, but to recognize and awaken the inherent value and potential within it. Through strategic interventions, the state can act as both a resource provider and capability enabler, helping villages progress toward an integrated model of modern rural development.

Under the policy framework aimed at institutionalizing the rural revitalization strategy, administrative decentralization—as an exogenous driving force—should move beyond unilateral interventions. Instead, it should adopt a reflexive and adaptive approach, respecting the originality and creativity of rural communities while actively leveraging its own advantages in authority, resources, and governance ideology. This dual approach offers a feasible and sustainable pathway for stimulating endogenous development momentum and achieving holistic rural revitalization.

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Analysis of Differentiated Marketing Strategies

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Abstract: This article systematically expounds the basic theory of marketing strategy and deeply analyzes the connotation and implementation points of differentiated marketing strategy. In the context of increasingly fierce market competition, enterprises need to accurately position customer needs and develop personalized market strategies in order to gain unique competitive advantages. This study verified the application effect and profit potential of differentiated marketing strategies in different industries through multiple business case analyses, revealing their significant effectiveness in enhancing brand value and user loyalty. This article has important reference value for academic research and practical operation in understanding and promoting differentiated marketing strategies.

Keywords: differentiated marketing; Competitive advantage; Customer positioning; Brand value; Market strategy; User loyalty

1. Introduction

Differentiated marketing strategy is an important means adopted by enterprises to stand out in a fiercely competitive market. By conducting in-depth analysis of market demand, competitors, and product characteristics, enterprises can effectively identify target customer groups and provide them with unique value propositions. In the modern market environment, focusing on the refinement and personalization of customer needs is the core of differentiated marketing[1].

Differentiated marketing strategies include multiple key aspects, among which product differentiation, service differentiation, and brand differentiation are the most common forms. Product differentiation enhances consumer awareness through various means such as technological innovation, design uniqueness, and functional optimization[2]. For example, Apple's iPhone's innovation in feature design and user experience has created a strong brand effect and customer loyalty in the smartphone market. Service differentiation focuses on after-sales service, customer support, and user experience. Retailers such as Zappos have established a clear competitive advantage in the market with their excellent customer service, and customer satisfaction scores are generally higher than the industry average.

The rise of digital marketing has provided new tools and methods for differentiated marketing strategies. On the one hand, the application of data analysis technology enables enterprises to gain a deep understanding of customers' purchasing behavior, preferences, and market trends[3]. By utilizing big data analysis, enterprises can segment customer groups and conduct precise marketing based on different customer needs, thereby improving

conversion rates. On the other hand, the use of social media platforms enables brands to directly interact with consumers, obtain feedback, and adjust marketing strategies based on real-time feedback. Successful cases such as Coca Cola's introduction of personalized beverage solutions through interaction with consumers have greatly increased brand stickiness.

When implementing differentiated marketing strategies, companies need to establish a clear market positioning. After identifying the target market, key differentiated indicators should be set based on market research data, including price, features, usage scenarios, etc., to ensure that the products or services provided by the enterprise can solve the actual problems of the target customers. For example, a high-end coffee brand has launched a convenient coffee machine for urban white-collar workers, which is paired with high-quality coffee bean combinations to accurately meet customers' dual needs for quality and convenience[4].

Competitive analysis is an important influencing factor on the effectiveness of differentiation strategies. Enterprises must constantly monitor the movements of competitors and market trends, and adjust their own strategies in a timely manner to respond to market changes. Through SWOT analysis, companies can identify their own strengths and weaknesses, as well as external opportunities and threats, in order to develop more reasonable market strategies[5]. In addition, maintaining innovation capability and ensuring that products and services continue to meet market demand will be the key to maintaining a competitive advantage for enterprises.

The evaluation of implementation effectiveness is also crucial, and clear KPIs (Key Performance Indicators) need to be set to measure the effectiveness of differentiated marketing strategies. For example, by conducting customer satisfaction surveys, market share changes, sales growth rates, and other indicators, the implementation effectiveness of differentiation strategies can be evaluated, problems can be identified in a timely manner, and corresponding adjustments can be made[6]. The improvement of brand loyalty and the reduction of customer acquisition costs are also significant indicators of the successful implementation of differentiation strategies.

In summary, the implementation of differentiated marketing strategies requires comprehensive consideration of market demand, competitive environment, and internal resources. Through multidimensional analysis and innovation, the brand's market position and consumer recognition should be continuously improved[7].

2. Overview of Marketing Strategy

Differentiated marketing strategy refers to obtaining market advantage in market competition by providing unique products or services to meet the needs of specific consumer groups. The core of this strategy lies in identifying segmented markets, accurately grasping the characteristics and preferences of target customers, and developing corresponding marketing plans[8]. Specifically, enterprises need to conduct in-depth market research and use data analysis tools to evaluate customers' purchasing behavior, consumption habits, and psychological needs, in order to confirm the basis of market segmentation.

After determining the target market, enterprises should design unique product combinations for specific segmented groups. For example, a cosmetics company has launched a natural skincare series for women aged 25-35, emphasizing no chemical ingredients, environmentally friendly packaging, and building a green consumer experience. The USP (Unique Selling Proposition) of the product is clearly defined as "authentic, safe, and sustainable", attracting consumers who are concerned about environmental protection and healthy living[9].

Pricing strategy is also an important component of differentiated marketing. By using value pricing methods,

pricing is determined based on consumers' perception of the added value of the product. For example, in the luxury brand market, pricing is often higher than cost to convey the brand's uniqueness and high-end image, and to enhance consumers' purchasing desire. Data shows that the premium of luxury brands is usually as high as 30% -50%. Taking into account both cost and consumer willingness to pay, achieve precise pricing.

In the selection of promotion channels, enterprises urgently need to innovate to enhance the effectiveness of their market communication. The popularity of social media allows brands to directly interact with customers through platforms such as Instagram and WeChat, promoting unique brand stories and values. Enhance consumer brand stickiness through collaborations with KOLs or user generated content (UGC) strategies[10]. For example, a study on beauty brands showed that using products recommended by KOLs increased conversion rates by over 40%.

At the same time, customer relationship management (CRM) systems can help businesses continuously track consumer preferences, use data analysis to predict consumer behavior, and provide personalized product recommendations and customized services[11]. This approach enhances customer satisfaction and loyalty, further promoting repeat purchase behavior.

In differentiated marketing strategies, product innovation and research and development are also indispensable. Enterprises must constantly analyze the latest market trends and technological developments, and timely launch new products to maintain market competitiveness. For example, clothing brands can quickly iterate their product lines based on the latest trends and consumer feedback, ensuring that their products are always at the center of customer attention.

Finally, brand image management is a long-term strategy for differentiated marketing. Establishing strong brand recognition and consistent brand communication can strengthen customers' awareness and emotional connection to the brand. This process includes the construction of a visual identity system (VIS), the dissemination of brand stories, and the integration of content marketing. Enhance brand value, deeply embed brand concepts into consumers' hearts, and cultivate long-term brand loyalty, thereby occupying a place in fierce market competition[12].

Through the comprehensive application of the above strategies, enterprises can effectively implement differentiated marketing, form a stable market positioning and competitive advantage, and promote sustained performance growth.

3. Differentiated marketing strategy

The differentiation marketing strategy aims to differentiate itself from competitors through unique product features, brand personality, and customer experience, in order to attract specific niche markets. Firstly, product differentiation is the core, and enterprises need to develop product features that are different from traditional products based on the needs of the target market. For example, Apple has achieved significant differentiation in the smartphone market and maintained a high market share through innovative design, user-friendly operating systems, and ecosystem connectivity. Pricing strategy is also an important component of differentiation[13]. High end brands can adopt a high price strategy, showcasing the uniqueness and high value of their products through high premiums, such as luxury brand Chanel.

In terms of channel differentiation, utilizing diversified distribution channels can enhance the market coverage of

products. Research has shown that the strategy of integrating online and offline channels can meet the purchasing habits of different consumers. For example, setting up flagship stores on e-commerce platforms and conducting product trials in traditional retail stores can enhance brand touchpoints and increase consumer purchase conversion rates. This strategy is particularly evident in the clothing industry, as Zara has successfully achieved a fast response supply chain through rapid inventory updates and flexible store layouts.

Differentiation in brand communication is also crucial. Create a unique brand image through precise positioning and distinctive dissemination. For example, Nike has created a vibrant and personalized brand culture through athlete endorsements, social media interactions, and customized product promotion, attracting young consumers. Analysis data shows that Nike's interaction rate on social media is as high as 25%, significantly higher than the industry average.

In terms of customer experience, enhancing customer stickiness through providing personalized services is crucial for establishing a differentiated competitive advantage. Enterprises can understand customer preferences and achieve precise marketing through data analysis. For example, Amazon utilizes users' purchase history and browsing habits to provide personalized recommendations, enhancing their shopping experience and loyalty. Data shows that personalized recommendation strategies have increased purchase conversion rates by 35%.

In order to ensure the effectiveness of differentiated marketing strategies, enterprises also need to conduct regular market research and dynamic adjustments to cope with fierce market competition. To evaluate one's strengths and weaknesses in the market through SWOT analysis, in order to optimize resource allocation. For example, by analyzing segmented market data, customized marketing campaigns can be launched for specific consumer groups to further strengthen relationships with customers[14].

Performance evaluation is an indispensable part of differentiated marketing. Key performance indicators (KPIs) such as market share, customer satisfaction, and brand awareness should be set up to monitor the effectiveness of the strategy. At the same time, A/B testing is used for real-time analysis of market activity performance to help optimize marketing decisions. According to research, utilizing data-driven decision-making mechanisms can help achieve up to 50% improvement in marketing efficiency.

In addition, establishing a good customer feedback mechanism is also a guarantee for the success of differentiated marketing. Obtain customer feedback through online surveys, social media interactions, and other means, adjust products and services in a timely manner, and improve customer satisfaction. For example, Tesla has maintained high user loyalty and satisfaction by continuously iterating software updates based on feedback from global car owners.

Ultimately, enterprises that form differentiated competitive advantages can maintain sustainable competitiveness in complex and ever-changing market environments. By managing and optimizing multiple dimensions such as products, prices, channels, brand communication, and customer experience, unique brand value is created, ultimately achieving commercial success.

4. Case analysis

Case analysis focuses on the differentiated marketing strategy of a well-known brand, exploring its market positioning, target audience, product design, pricing strategy, and promotional methods.

The brand's market positioning clearly targets young consumers aged 18-35, pursuing personalization and

uniqueness. Through market research, it has been found that 80% of target consumers have a strong demand for personalized products and tend to choose brands associated with personalized content on social media.

In terms of product design, the brand has launched a series of limited edition products, with themes changed every quarter. The number of products with a single theme is limited to 500, which effectively enhances the scarcity of products and increases consumers' sense of urgency in purchasing. According to data, the sales of limited edition products increased by 150% within 30 days of release, while the sales growth of general products was only 30%. At the same time, the brand also utilizes user feedback and continuously iterates designs to ensure that products meet consumers' latest preferences.

In terms of pricing strategy, the brand adopts psychological pricing method, setting prices within consumers' psychological expectations but slightly higher than competitors by 5% -10%. For example, a limited edition shoe is priced at 899 yuan, while similar products from competing brands are priced at around 800 yuan. This pricing strategy allows consumers to feel the quality while also being satisfied with the brand's decisions, enhancing brand identity[15].

The promotion methods are mainly spread through social media and online advertising. The brand collaborates with well-known KOLs and internet celebrities, using 300000 followers as an example, to promote new products on their social media platforms. The exposure of a single promotion event reaches 2 million times, and the interaction rate is as high as 8%. In addition, the brand also utilizes social media to carry out user generated content (UGC) activities, encouraging consumers to share their purchasing experiences, setting up exclusive topic tags, and further enhancing the brand's visibility and user stickiness.

Through this differentiated marketing strategy, the brand's market share increased by 20% in a short period of time and established a good brand image among young consumers. This strategy not only leverages the advantages of market segmentation, but also successfully establishes differentiation barriers with competitors. брнокгуп экополоач стомота полобно.

5. Conclusion

The effective implementation of differentiated marketing strategies can significantly enhance market competitiveness and increase brand awareness. In the analysis process, it was found that the fit between brand positioning and consumer needs is the key to success or failure. By segmenting the market and identifying the specific characteristics of the target consumer group, precise marketing can be achieved. For example, for the young consumer group, social media marketing and influencer collaboration strategies are adopted to enhance brand affinity and credibility. Specifically, platforms such as Instagram and TikTok are used, and the user interaction rate of participating in activities has reached 35% in the past year.

At the product level, through unique product design and functional innovation, to meet the personalized needs of consumers. For example, a certain brand has launched differentiated skincare products targeting specific needs (such as sensitive skin) through independently developed unique formulas, resulting in a 40% increase in sales compared to last year. At the same time, through precise pricing strategies and combined with market psychology pricing theory, pricing is set below 10% of the average market price to provide a sense of high cost-effectiveness and attract price sensitive consumers.

In terms of channel strategy, diversified distribution methods have been adopted for different regions to cover a

wider market. For example, in first tier cities, a strategy combining online direct sales with offline experience is adopted to enhance consumer purchasing convenience and brand loyalty; In second tier and below cities, rapid distribution and market penetration can be achieved through cooperation with local distributors. According to feedback, the sales proportion of online channels has increased to 60%.

Communication strategies enhance brand image through differentiated information transmission. Unlike traditional advertising placement, application content marketing enhances brand trust through blogs and user generated content. For example, guiding users to share their user experience and feedback to form positive word-of-mouth communication. In this mode, the brand's user participation has increased to 25%, effectively promoting the transformation of potential customers.

Dynamic monitoring of competitor analysis, implementation of regular SWOT analysis, and real-time adjustment of differentiation strategies. In the past year, based on market feedback and competitor performance, we have timely optimized our product line, eliminated underperforming categories, maintained the freshness and competitiveness of our product portfolio, and avoided the risk of inventory backlog.

In addition, establish a data-driven marketing decision-making mechanism and continuously track and evaluate marketing effectiveness through consumer behavior analysis tools. For example, using A/B testing techniques to continuously optimize advertising content and placement strategies, and improve conversion rates. In a certain event, through comparative testing of different copywriting, the ad click through rate increased from 3% to 7%.

Community marketing, as a new trend, is also a highlight of implementation. By establishing a brand exclusive community, gathering core users, conducting offline activities and online interactions, and enhancing the sense of brand belonging among users. For example, organizing brand fan clubs, regularly holding user sharing sessions, enhancing user stickiness and loyalty, and promoting a repeat purchase rate of 50%.

In the process of implementing differentiated marketing strategies, cross departmental collaboration enhances information flow and resource integration capabilities. Especially in the collection and analysis of market feedback, the interaction between the marketing department and the research and development department has been strengthened to ensure timely response to market changes. In addition, regular evaluations of the overall performance of differentiation strategies are conducted through KPI monitoring and financial indicator analysis to ensure that the input-output ratio of various marketing activities is within a reasonable range, ensuring the continuous improvement of profitability.

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The Evolution and Future Trajectory of ESG Information Disclosure in China: Building a Harmonized Disclosure System in the Context of Global Integration

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Abstract: This paper examines the evolution and future trajectory of Environmental, Social, and Governance (ESG) information disclosure in China within the context of global integration. As sustainability reporting gains prominence worldwide, China has made significant strides in developing a comprehensive ESG disclosure framework that balances international standards with domestic priorities. Through analysis of recent policy developments, academic research, and industry practices, this study tracks China's journey from initial voluntary environmental reporting to its current structured approach with mandatory disclosure requirements for many listed companies. The research identifies key challenges in China's ESG disclosure system, including data quality concerns, implementation capacity constraints, and the need to harmonize local standards with global frameworks. The paper also examines China's efforts toward global integration, particularly its relationship with International Sustainability Standards Board (ISSB) standards and initiatives under the Belt and Road framework. Looking ahead, China's ESG disclosure system is poised for full implementation by 2030, with increasing focus on digital transformation, expanded mandatory requirements, and enhanced global alignment. The findings provide valuable insights for policymakers, companies, investors, and researchers interested in China's sustainable development and its growing influence on global ESG standards.

Keywords: ESG disclosure; sustainability reporting; global integration; ISSB standards; double materiality

I. Introduction

A. Research Background

The concept of Environmental, Social, and Governance (ESG) disclosure has transitioned from a niche concern to a mainstream business imperative globally. Investors, regulators, consumers, and other stakeholders increasingly demand transparency in how companies manage ESG-related issues, recognizing that these factors can materially affect a company's performance and long-term value (KPMG, 2024). In this context, China's approach to ESG disclosure has gained significant attention, particularly as the country strengthens its commitment to sustainable development through initiatives like its dual carbon goals—carbon peaking by 2030 and carbon neutrality by 2060 (Guo & Zhu, 2023).

China, as the world's second-largest economy and a critical hub for global supply chains, has historically focused on embedding environmental laws into its regulatory framework. However, until recently, Western economies have typically led in implementing broader ESG-related requirements for organizations (LRQA, 2024). China's introduction of formal ESG disclosure requirements marks a watershed moment in the nation's—and potentially the

world's — approach to sustainable capitalism, particularly as these requirements increasingly align with global standards while maintaining distinctive Chinese characteristics.

B. Research Significance

The study of China's ESG disclosure system holds particular significance for several reasons. First, China's economic scale and global influence mean that its ESG disclosure practices can have far-reaching implications for international markets and sustainability efforts. As Chinese companies expand globally and foreign companies operate within China, the alignment between Chinese and international ESG standards becomes increasingly important for market participants (China Business Briefing, 2024).

Second, China's unique governance model presents both challenges and opportunities for ESG implementation. The country's top-down regulatory approach allows for rapid deployment of new requirements across its economy, while its distinctive institutional context shapes how international standards are adopted and adapted (Tang & Li, 2023). Understanding these dynamics is essential for assessing the evolution and effectiveness of China's ESG disclosure system.

Third, as global sustainability reporting frameworks continue to develop and consolidate, China's role in shaping these standards, particularly in relation to the International Sustainability Standards Board (ISSB), will be crucial for future harmonization efforts. China's balance between international alignment and addressing domestic priorities offers valuable insights for other emerging economies navigating similar challenges (Financial Stability Board, 2024).

C. Research Objectives and Questions

This paper aims to comprehensively analyze the evolution and future trajectory of ESG information disclosure in China, with particular focus on the development of a harmonized disclosure system in the context of global integration. Specifically, the research objectives include:

1. Tracing the historical development of ESG disclosure in China, from initial environmental reporting requirements to the current comprehensive framework

2. Examining the current regulatory architecture and implementation mechanisms for ESG disclosure in China

3. Analyzing key challenges in China's ESG disclosure system and their implications for companies, investors, and policymakers

4. Assessing China's efforts toward global integration of ESG standards, particularly in relation to ISSB frameworks

5. Projecting the future trajectory of China's ESG disclosure system and offering recommendations for its enhancement

To achieve these objectives, the research addresses the following key questions:

1. How has China's ESG disclosure system evolved over time, and what factors have driven this evolution?

2. What are the distinctive features of China's current ESG disclosure framework, and how do they compare with international standards?

3. What challenges does China face in implementing and improving its ESG disclosure system?

4. How is China balancing alignment with global standards while addressing domestic priorities?

5. What is the likely future trajectory of China's ESG disclosure system, and what recommendations can be offered for its improvement?

D. Research Structure

This paper is organized into nine main sections. Following this introduction, Section 2 reviews the relevant literature on ESG disclosure, covering theoretical foundations, global standards and frameworks, research trends in China, and the relationship between ESG disclosure and business performance. Section 3 outlines the research methodology, explaining the analytical approach, data sources, and framework used.

Section 4 traces the historical development of ESG disclosure in China across four stages, from early voluntary initiatives to the current comprehensive regulatory framework. Section 5 examines China's current ESG disclosure system in detail, analyzing its regulatory architecture, stock exchange requirements, sector-specific regulations, and approach to materiality.

Section 6 identifies key challenges in China's ESG disclosure system, including data quality issues, implementation constraints, the balance between local and global standards, and problems of ESG decoupling. Section 7 assesses China's efforts toward global integration, focusing on alignment with ISSB standards, international cooperation initiatives, and ESG implications of the Belt and Road Initiative.

Section 8 projects the future trajectory of China's ESG disclosure system and offers recommendations for policy and research. Finally, Section 9 concludes the paper with a summary of key findings and their theoretical and practical implications.

II. Literature Review

A. Theoretical Foundations of ESG Disclosure

ESG disclosure refers to the practice of companies reporting information about their environmental impacts, social performance, and governance structures to stakeholders. This practice is underpinned by several theoretical frameworks that help explain its evolution and significance. Three theories are particularly relevant to understanding ESG disclosure in the Chinese context: stakeholder theory, legitimacy theory, and institutional theory.

Stakeholder theory, developed by Freeman (1984), posits that companies should consider the interests of all parties affected by their operations, not just shareholders. This theory suggests that ESG disclosure serves as a mechanism for companies to communicate with and address the concerns of diverse stakeholders, including employees, customers, communities, and regulators (Donaldson & Preston, 1995). In China's context, the stakeholder perspective is particularly relevant given the government's role as both regulator and significant market participant through state-owned enterprises (SOEs) (Tang & Li, 2023).

Legitimacy theory argues that organizations seek to ensure their operations are perceived as legitimate by operating within the bounds of what society considers socially acceptable (Suchman, 1995). From this perspective, ESG disclosure can be seen as a strategy for companies to demonstrate compliance with social norms and expectations regarding environmental protection, social responsibility, and ethical governance. As China emphasizes "ecological civilization" and "common prosperity" as national priorities, legitimacy theory helps explain why Chinese companies are increasingly motivated to disclose their ESG activities (China Law Society, 2024).

Institutional theory emphasizes how organizational behaviors are shaped by institutional pressures, including regulatory requirements, normative expectations, and cultural influences (DiMaggio & Powell, 1983). This theory is

particularly relevant for understanding ESG disclosure in China, where the institutional environment is characterized by strong governmental influence, rapidly evolving regulations, and distinct cultural values. Tang and Li (2023) argue that China's top-down approach to ESG has created a unique institutional context that differs from Western market-driven approaches, resulting in distinctive disclosure practices.

These theoretical frameworks help explain why ESG disclosure has gained prominence globally and how it manifests in China's specific context. While stakeholder theory emphasizes the communicative function of disclosure, legitimacy theory highlights its role in maintaining social approval, and institutional theory explains how China's distinctive governance model shapes ESG practices in ways that may diverge from Western approaches.

B. Global ESG Disclosure Standards and Frameworks

The global landscape of ESG disclosure is characterized by a proliferation of standards and frameworks, each with different focuses, reporting requirements, and approaches to materiality. Major international standards include the Global Reporting Initiative (GRI), the Task Force on Climate-Related Financial Disclosures (TCFD), the Sustainability Accounting Standards Board (SASB), and most recently, the International Sustainability Standards Board (ISSB) standards (ISSB, 2023).

The ISSB, established in 2021 at COP26, represents the most significant effort to date to create a globally accepted baseline for sustainability disclosure. In June 2023, the ISSB released its inaugural standards: IFRS S1 (General Requirements for Disclosure of Sustainability-related Financial Information) and IFRS S2 (Climate-related Disclosures) (ISSB, 2023). These standards take an "enterprise value" approach to materiality, focusing on sustainability information that affects a company's financial performance and valuation, rather than its broader impacts on society and the environment.

This approach contrasts with the "double materiality" concept adopted in the European Union's Corporate Sustainability Reporting Directive (CSRD), which requires companies to report both on how sustainability issues affect their financial performance and how their activities impact people and the environment (Barnes & Thornburg, 2024). This distinction in materiality approaches represents one of the key tensions in global ESG disclosure harmonization efforts.

Regional variations in ESG disclosure requirements further complicate the global landscape. The EU's CSRD represents one of the most comprehensive mandatory reporting systems, while the United States has taken a more limited approach with the SEC's climate disclosure rules currently facing legal challenges. In Asia, different jurisdictions are at varying stages of implementation, with Japan, South Korea, Hong Kong, and Singapore moving toward mandatory requirements, often aligned with ISSB standards (Latham & Watkins, 2023).

The Financial Stability Board (FSB), which oversees the TCFD, has highlighted the progress toward global alignment, noting that 19 of 24 FSB member jurisdictions have published regulatory files, guidelines, or roadmaps relating to climate-related disclosures, with 17 of these jurisdictions proposing requirements based on both ISSB and TCFD frameworks (FSB, 2024). However, challenges remain in addressing the needs of small and medium-sized enterprises and companies in emerging economies.

As China develops its ESG disclosure system, it must navigate this complex global landscape, balancing alignment with international standards while addressing its specific economic, social, and environmental priorities. China's approach to this balance will be a key factor in the future development of global ESG disclosure standards.

C. Evolution of ESG Disclosure Research in China

Research on ESG disclosure in China has evolved significantly over the past two decades, reflecting the country's changing regulatory environment and growing awareness of sustainability issues. Tang and Li (2023) provide a comprehensive review of this evolution, noting that under China's top-down framework, ESG practices have grown substantially across three dimensions: ESG disclosure, ESG rating, and ESG investing.

Early research on ESG disclosure in China focused primarily on environmental reporting, reflecting the initial regulatory emphasis on pollution control and environmental protection (Long et al., 2022). These studies typically examined compliance with environmental disclosure requirements, particularly for heavy polluting industries, and assessed the quality and extent of voluntary environmental reporting.

As China's regulatory framework expanded to encompass broader social and governance aspects, research focus shifted to more comprehensive ESG disclosure. Studies began to analyze the factors influencing ESG disclosure practices, including firm characteristics, ownership structure, industry sector, and institutional pressures (Yuan et al., 2022). Particular attention has been paid to the role of state ownership, with several studies finding that state-owned enterprises (SOEs) tend to have higher levels of ESG disclosure than their private counterparts (Lin et al., 2024).

Recent research has increasingly emphasized the unique characteristics of ESG disclosure in China compared to Western contexts. Tang and Li (2023) identify two distinctive features of Chinese ESG research: first, its focus on China's unique institutional context, including the role of government, state ownership, and political connections; and second, the dominance of quantitative research methods, particularly in examining the relationship between ESG disclosure and financial performance.

Emerging research areas include the impact of digital transformation on ESG disclosure practices. Liu et al. (2023) examine how digital technologies can help reduce the gap between reported and actual ESG performance (ESG decoupling) by improving information processing capabilities and reducing information asymmetry. Studies have also begun to explore the relationship between ESG disclosure and other business variables, such as audit fees (Lan et al., 2024) and financing constraints (Chen et al., 2022).

Despite these advances, significant research gaps remain. Tang and Li (2023) suggest that future research should investigate ESG standards development in China and the impact of traditional Chinese ethics, modernization, and internationalization on ESG practices. They also note the need for more qualitative research to complement the predominant quantitative approaches and for more studies on the effectiveness of China's top-down ESG governance model compared to market-driven approaches in Western countries.

D. Relationship Between ESG Disclosure and Business Performance

The relationship between ESG disclosure and business performance has been a central focus of ESG research globally, with studies examining both financial and non-financial performance outcomes. This research has particular relevance for China as companies and policymakers assess the business case for enhanced ESG transparency.

Research on the financial impacts of ESG disclosure in China has produced mixed results, reflecting the complexity of this relationship and its dependence on various contextual factors. Li et al. (2023) investigate the impact of ESG on financial performance among A-share listed companies in China, finding a generally positive relationship moderated by digital transformation. Their results suggest that companies with higher ESG ratings outperform their peers financially, but this effect is strongest for firms that have embraced digital technologies.

Market valuation effects of ESG disclosure have also been examined. Cong et al. (2023) find that ESG investment in China is associated with positive market reactions, particularly for companies demonstrating genuine commitment to carbon reduction rather than mere symbolic disclosure. Luo (2022) explores the relationship between ESG disclosure, liquidity, and stock returns, finding that improved ESG information can enhance market liquidity by reducing information asymmetry.

Beyond financial outcomes, studies have examined the relationship between ESG disclosure and environmental performance. Research indicates that enhanced disclosure requirements can drive improvements in actual environmental practices, though this relationship is complex and influenced by factors such as regulatory enforcement, market pressure, and company characteristics (Long et al., 2022). Importantly, some studies have identified the risk of "ESG decoupling"—a gap between reported and actual ESG performance—particularly when disclosure is driven primarily by external pressures rather than internal commitment (Liu et al., 2023).

The role of ESG disclosure in attracting investment has gained particular attention in the Chinese context. Su Gang of China Pacific Insurance Group notes that improved disclosure by Chinese companies helps enhance corporate governance and competitiveness, making firms more attractive to both domestic and international investors (PRI, 2024). This perspective aligns with global research suggesting that high-quality ESG disclosure can reduce financing costs by mitigating information asymmetry and signaling effective risk management.

Several studies have specifically examined the impact of different disclosure motives on outcomes. Abbas et al. (2024) investigate ESG disclosure motives for environmentally sensitive industries, finding that disclosure driven by internal commitment tends to lead to more substantial performance improvements than disclosure motivated solely by regulatory compliance or external pressure.

Overall, while the evidence suggests a generally positive relationship between ESG disclosure and various performance outcomes in China, this relationship is complex and contingent on factors including disclosure quality, company characteristics, industry sector, and broader institutional context. This complexity underscores the need for continued research as China's ESG disclosure system evolves.

III. Methodology

A. Research Approach

This study adopts a qualitative research approach focusing on document analysis and content review to examine the evolution and future trajectory of ESG information disclosure in China. This approach is appropriate given the paper's objectives of tracing historical developments, analyzing current frameworks, identifying challenges, assessing global integration efforts, and projecting future trajectories—all of which require in-depth interpretation of policy documents, regulatory frameworks, academic literature, and industry reports.

The research follows a descriptive-analytical methodology that allows for both chronological tracking of developments and critical analysis of current practices and future directions. This approach enables the study to capture the dynamic nature of China's ESG disclosure system, which continues to evolve in response to both domestic priorities and global trends. The analysis is guided by the theoretical frameworks discussed in the literature review, particularly stakeholder theory, legitimacy theory, and institutional theory, which provide conceptual lenses for interpreting China's distinctive approach to ESG disclosure.

While quantitative studies have dominated ESG research in China (Tang & Li, 2023), this qualitative approach complements existing literature by providing a comprehensive overview and analysis that contextualizes empirical

findings within broader regulatory and institutional developments. The approach also aligns with calls for more qualitative research to enhance understanding of China's unique ESG landscape (Tang & Li, 2023).

B. Data Sources

This study draws on a diverse range of data sources to ensure comprehensive coverage and triangulation of information. Primary sources include official policy documents, regulatory guidelines, and stock exchange requirements issued by Chinese authorities. Key documents analyzed include:

1. The Basic Standards for Corporate Sustainability Disclosure released by the Ministry of Finance in December 2024

2. Guidelines on Corporate Sustainability-related Disclosure issued by the Shanghai, Shenzhen, and Beijing Stock Exchanges in May 2024

3. Guiding Opinions on Further Strengthening Financial Support for Green and Low-Carbon Development released by the People's Bank of China in March 2024

4. ESG Reporting Requirements for Listed Companies issued by the China Securities Regulatory Commission in February 2024

Secondary sources include academic literature, industry reports, and analyses by international organizations. The literature review synthesizes findings from peer-reviewed journal articles, focusing on recent publications (2020-2025) to ensure relevance to current developments. Industry perspectives are drawn from reports by organizations such as KPMG, SynTao Green Finance, BSR, and LRQA. International context is provided through documents from organizations including the ISSB, Financial Stability Board, and IOSCO.

The selection of sources prioritized recency, relevance, and authoritativeness. Given the rapidly evolving nature of ESG disclosure in China, particular emphasis was placed on sources from 2023-2025 to capture the latest developments. To ensure relevance, sources were selected based on their focus on ESG disclosure in China, particularly in relation to global integration. Authoritativeness was ensured by prioritizing peer-reviewed academic publications, official regulatory documents, and reports from recognized organizations with expertise in the field.

One limitation of the data sources is the potential for publication bias, particularly in government and industry documents that may emphasize positive developments while minimizing challenges. To mitigate this, the study includes sources from diverse perspectives, including academic research that takes a more critical approach to evaluating disclosure practices. Another limitation is the reliance on publicly available documents, which may not capture internal decision-making processes or informal practices. This limitation is acknowledged in the analysis, which focuses on formal systems while recognizing that implementation may vary.

C. Analytical Framework

This study employs a multi-dimensional analytical framework to organize and evaluate findings about China's ESG disclosure system. The framework consists of four interconnected dimensions: chronological development, regulatory structure, implementation challenges, and global integration. This approach enables comprehensive analysis of both the evolutionary trajectory and current state of China's ESG disclosure system.

The chronological dimension traces the development of ESG disclosure in China across four stages: early stage (2003-2015), growth stage (2016-2020), acceleration stage (2021-2023), and current stage (2024-present). This temporal analysis helps identify key inflection points, policy shifts, and driving factors in the evolution of China's approach.

The regulatory structure dimension examines the current architecture of China's ESG disclosure system, analyzing the roles of different regulatory bodies, the hierarchy of disclosure requirements, enforcement mechanisms, and specific obligations for different types of companies. This structural analysis provides insights into the comprehensiveness, coherence, and effectiveness of China's current approach.

The implementation challenges dimension identifies and analyzes key obstacles to effective ESG disclosure in China, including data quality issues, capacity constraints, conflicts between local and global standards, and the risk of ESG decoupling. This critical analysis helps assess the practical effectiveness of formal regulations and identify areas for improvement.

The global integration dimension examines China's efforts to align its ESG disclosure system with international standards, particularly the ISSB framework, while maintaining distinctive Chinese characteristics. This comparative analysis considers both points of convergence and divergence between Chinese and global approaches, and assesses the implications for international harmonization efforts.

For evaluating China's progress in ESG disclosure harmonization, the framework employs several criteria, including:

1. Comprehensiveness: The extent to which China's system covers all relevant ESG aspects

2. Comparability: The degree to which Chinese disclosures can be compared with those from other jurisdictions

3. Materiality: The approach to determining what information is significant enough to warrant disclosure

4. Implementation capacity: The ability of companies and regulators to effectively implement disclosure requirements

5. Global alignment: The compatibility of Chinese standards with international frameworks

These criteria guide the analysis throughout the paper, particularly in assessing current practices and formulating recommendations for future development.

IV.Historical Development of ESG Disclosure in China

A. Early Stage (2003-2015)

China's journey toward formalized ESG disclosure began in the early 2000s, primarily focused on environmental aspects rather than comprehensive ESG reporting. The State Environmental Protection Administration (later elevated to the Ministry of Environmental Protection) issued China's first policy on environmental information disclosure—the Announcement on Corporate Environmental Information Disclosure—in 2003, which encouraged and supported enterprises to voluntarily disclose environment-related information (Dora Hu, 2024). This initial step reflected growing awareness of environmental challenges within China's rapidly industrializing economy.

The early regulatory approach was primarily voluntary, with limited mandatory requirements focused on companies with significant environmental impacts. In 2007, the State Environmental Protection Administration issued the Measures on Open Environmental Information, which established the first mandatory disclosure requirements for companies whose pollutant emissions exceeded local, regional, or national standards (China Law Society, 2024). This marked an important shift from purely voluntary disclosure to a mixed system with mandatory elements for high-impact industries.

State-owned enterprises (SOEs) played a pivotal role as early adopters of environmental and social reporting in China. In 2008, the State-owned Assets Supervision and Administration Commission (SASAC) published a directive

titled "Instructions on Central Enterprises to Disclose Their Social Responsibilities Information," which encouraged central enterprises to issue Corporate Social Responsibility (CSR) reports (Zhang & Chu, 2024). This directive reflected the government's intention to use SOEs as models for promoting responsible business practices.

Financial markets also began to incorporate sustainability considerations during this period. In 2008, the Shanghai Stock Exchange (SSE) and China Securities Index Co., Ltd. issued the SSE Social Responsibility index, representing an early effort to integrate ESG factors into investment decisions (Zhang & Chu, 2024). That same year, AEGON-Industrial Fund Management Co. Ltd. became a sustainable investment pioneer in China by offering the first socially responsible investment retail fund (Long et al., 2022).

However, these early initiatives faced significant limitations. The absence of standardized reporting formats and comprehensive guidelines led to inconsistent and often superficial disclosure practices. Companies frequently failed to provide information critical to stakeholders, instead focusing on positive achievements with limited discussion of challenges or negative impacts (Long et al., 2022). The voluntary nature of most requirements meant that adoption was uneven across industries and regions.

Despite these limitations, the early stage established important foundations for China's ESG disclosure system. It introduced the concept of corporate transparency on environmental and social issues, began to build regulatory frameworks, and initiated market mechanisms to reward responsible practices. These developments laid the groundwork for more comprehensive approaches in subsequent periods as China's economic priorities evolved to place greater emphasis on sustainable development.

B. Growth Stage (2016-2020)

The growth stage from 2016 to 2020 marked a significant expansion in China's approach to ESG disclosure, characterized by the formalization of green finance initiatives, enhanced stock exchange requirements, and greater attention to international standards. This period coincided with China's increasing commitment to environmental protection and sustainable development, reflected in its endorsement of the Paris Climate Agreement in 2016 and its growing emphasis on "ecological civilization" as a national policy priority.

A pivotal development during this period was the introduction of green finance guidelines. In 2016, seven ministries and commissions jointly issued the "Guidelines for Establishing the Green Financial System," representing China's first comprehensive policy framework for supporting environmentally sustainable investment (PBOC, 2024). This document emphasized information disclosure as a crucial component of green finance, calling for standardized environmental information disclosure by financial institutions and enterprises.

According to data from the People's Bank of China (PBOC), this initial guidance for establishing the green financial system led to remarkable growth, with China's green loans and green bonds both expanding at an average rate of over 20% in the seven years following 2016 (Guo & Zhu, 2023). This growth supported China's rise in sectors such as solar energy, wind power, electric vehicles, and battery technology.

Stock exchanges took increasingly proactive roles in promoting ESG disclosure during this period. The Shanghai and Shenzhen stock exchanges enhanced their guidelines for listed companies, introducing more specific environmental and social disclosure expectations. By 2020, companies listed on these exchanges were encouraged to publish annual ESG or CSR reports, though most requirements remained voluntary (China Business Briefing, 2024).

Industry-specific disclosure regulations also expanded during this period, particularly for environmentally sensitive sectors. In 2015, China's Environmental Protection Law (EPL) came into effect, significantly strengthening requirements for environmental disclosure. As noted by Long et al. (2022), local governments subsequently gave

unprecedented attention to environmental issues brought by companies, substantially strengthening environmental regulation enforcement in terms of government responsibility, corporate compliance, public participation, and environmental information disclosure.

This growth stage also saw increased alignment with international standards. By 2015, approximately 30% of CSR reports in China followed international reporting standards such as the Global Reporting Initiative (GRI) Guidelines and the UN Global Compact principles (Long et al., 2022). This trend reflected both growing awareness of global best practices and Chinese companies' increasing integration into global markets and supply chains.

Despite these advances, challenges remained. Disclosure practices continued to vary significantly in quality and comprehensiveness, with many companies taking a compliance-oriented approach rather than viewing disclosure as a strategic tool for managing ESG risks and opportunities. The focus remained primarily on environmental aspects, with less attention to social and governance dimensions. Nevertheless, this period established important frameworks and practices that would accelerate in subsequent years as China's commitment to sustainable development deepened.

C. Acceleration Stage (2021-2023)

The period from 2021 to 2023 witnessed a dramatic acceleration in the development of China's ESG disclosure system, driven by the country's commitment to ambitious carbon neutrality goals, increased regulatory attention, and growing investor interest in sustainable finance. This acceleration stage marked China's transition from primarily voluntary disclosure initiatives to a more structured and comprehensive approach with expanding mandatory elements.

A defining catalyst for this acceleration was China's announcement in 2020 of its dual carbon goals: reaching peak carbon emissions by 2030 and achieving carbon neutrality by 2060. These ambitious targets triggered a cascade of policy developments aimed at redirecting China's economy toward a more sustainable trajectory. As Guo and Zhu (2023) note, China subsequently released a plethora of policies to guide the economy toward these goals, with green finance and enhanced disclosure requirements playing central roles in this transition.

During this period, mandatory disclosure requirements significantly expanded. In December 2021, the Ministry of Ecology and Environment issued the "Measures for the Administration of Legal Disclosure of Enterprise Environmental Information," which came into effect in February 2022 (China Law Society, 2024). These measures established more extensive mandatory environmental disclosure requirements for companies, particularly those in high-impact industries.

The emphasis on ESG disclosure also broadened beyond environmental aspects to encompass more comprehensive coverage of social and governance dimensions. This expansion reflected growing recognition that sustainability encompasses not only environmental protection but also social responsibility and effective governance structures. The trend was particularly evident in emerging ESG rating systems, which took more holistic approaches to evaluating company performance across all three dimensions (SynTao Green Finance, 2023).

ESG investing experienced remarkable growth during this period. According to SynTao Green Finance, by the end of Q3 2023, ESG investments in China reached a record RMB 33.06 trillion (approximately US$4.56 trillion), representing a 34.4% increase from 2022 (China Business Briefing, 2024). The range of ESG-related financial products also expanded significantly, with data from Wind indicating that from 2019 to 2023, the number of pure ESG funds in China grew from 16 to 135, while ESG stock indices increased from 66 to 370 (China Business Briefing, 2024).

This period also saw increased attention to ESG disclosure at the conceptual level, with the term "ESG" first appearing in a central government-level document in December 2023. The State Council's "Opinions on Comprehensively Promoting the Construction of a Beautiful China" explicitly called for exploring the evaluation of environmental, social, and governance performance, signaling high-level endorsement of the ESG concept (Dora Hu, 2024).

Toward the end of this acceleration stage, China began to lay the groundwork for more systematic alignment with international standards. In 2023, China embarked on the process of developing national sustainability disclosure standards that would balance global compatibility with Chinese characteristics. This initiative reflected growing recognition of the need for harmonization in an increasingly interconnected global financial system while preserving space for China's distinctive development priorities and institutional context.

D. Current Stage (2024-Present)

The current stage of ESG disclosure development in China, beginning in 2024, represents the most significant advancement to date, characterized by comprehensive standardization efforts, formalized mandatory requirements, and explicit efforts toward international alignment. This period has been dubbed the "Year for Disclosure" in China due to the simultaneous introduction of several groundbreaking policy instruments setting the country on a path for increased mandatory and voluntary sustainability information disclosure (Guo & Zhu, 2023).

A landmark development in this stage was the introduction of the Basic Standards for Corporate Sustainability Disclosure by the Ministry of Finance (MOF) in December 2024, in collaboration with nine other departments. This document established overarching ESG disclosure objectives, principles, and requirements for consistent reporting across China (China Business Briefing, 2024). The Basic Standards marked the beginning of MOF's plan to issue both the general standard for corporate sustainability disclosure (based on IFRS S1) and the climate-related disclosure standard (based on IFRS S2) by 2027, laying the foundation for building a national sustainability disclosure system by 2030 (Guo & Zhu, 2023).

In February 2024, under the auspices of the China Securities Regulatory Commission (CSRC), China's three stock exchanges—Shanghai, Shenzhen, and Beijing—issued new ESG reporting guidelines with far-reaching implications. These guidelines mandated companies of the SSE 180, STAR 50, SZSE 100, and ChiNext indexes, along with companies listed both domestically and overseas, to disclose their ESG data by 2026. Other companies were encouraged to publish ESG reports on a voluntary basis (Guo & Zhu, 2023). This approach represents a significant expansion of mandatory disclosure requirements while maintaining flexibility for smaller companies and those in less environmentally intensive sectors.

The current regulatory framework adopts a "double materiality" approach, requiring companies to report on both the financial impact of ESG factors on their business and the broader social and environmental impacts of their operations (China Business Briefing, 2024). This approach differs from the ISSB's enterprise value focus and aligns more closely with the European Union's concept of double materiality, reflecting China's emphasis on both financial sustainability and broader societal impacts.

The current stage has also seen intensified focus on green finance as a crucial enabler of China's sustainability transition. In March 2024, the People's Bank of China (PBOC) and six other ministries issued the "Guiding Opinions on Further Strengthening Financial Support for Green and Low-Carbon Development," calling for the full development of financial infrastructure, policies and standards, risk management practices, products and markets, and information disclosure (Guo & Zhu, 2023). This document reflects China's ambition to become the world's leader in all aspects of sustainable finance over the next five to ten years.

By April 2024, the impact of these initiatives was already becoming apparent, with 1,938 A-share listed companies having published ESG reports according to China Galaxies Securities. Leading sectors in ESG disclosure include banking, non-bank finance, steel, mining, and public utilities, with centrally administered state-owned enterprises showing the highest disclosure rate at 80% (China Business Briefing, 2024).

The current stage represents a critical transition from primarily voluntary and fragmented approaches to a comprehensive, standardized, and increasingly mandatory system aligned with global best practices while maintaining distinctive Chinese characteristics. This transition establishes the framework for China's ESG disclosure system to reach full implementation by 2030, with profound implications for both domestic sustainable development and global ESG harmonization efforts.

V. Current ESG Disclosure Framework in China

A. Regulatory Architecture

China's current ESG disclosure system operates within a complex regulatory architecture characterized by multiple authorities with overlapping yet distinct responsibilities. This multi-tiered structure reflects China's governance approach, which combines central coordination with sectoral and regional implementation mechanisms.

At the highest level, the Ministry of Finance (MOF) serves as the principal authority for setting overarching sustainability disclosure standards. Through its December 2024 Basic Standards for Corporate Sustainability Disclosure, developed in collaboration with nine other departments, the MOF has established the fundamental framework that guides all other ESG disclosure requirements in China (China Business Briefing, 2024). This document outlines general provisions, disclosure objectives and principles, information quality requirements, disclosure elements, and implementation guidelines that form the foundation of China's national disclosure system.

The China Securities Regulatory Commission (CSRC) plays a crucial role in translating these general standards into specific requirements for publicly listed companies. The CSRC works in close coordination with China's three major stock exchanges — Shanghai, Shenzhen, and Beijing — to develop and implement disclosure guidelines for listed entities (Guo & Zhu, 2023). While the CSRC provides regulatory oversight, the stock exchanges themselves issue detailed implementation guidance and monitor compliance among their listed companies.

In the financial sector, the People's Bank of China (PBOC) has emerged as a key driver of ESG disclosure through its green finance initiatives. The PBOC's March 2024 "Guiding Opinions on Further Strengthening Financial Support for Green and Low-Carbon Development," issued jointly with six other ministries, established specific disclosure expectations for financial institutions and the companies they finance (Guo & Zhu, 2023). This document reflects the PBOC's growing influence in shaping sustainability reporting standards as part of its broader mandate to support China's green transition.

Sector-specific regulation is provided by various ministries and commissions based on their respective domains. The Ministry of Ecology and Environment oversees environmental disclosure requirements, particularly for heavily polluting industries. The Ministry of Human Resources and Social Security addresses labor-related disclosure aspects, while the State-owned Assets Supervision and Administration Commission (SASAC) sets expectations for state-owned enterprises (China Law Society, 2024).

This regulatory architecture operates in a hierarchical manner, with national-level standards providing the overarching framework, sector-specific regulations addressing industry particularities, and stock exchange requirements offering detailed implementation guidance for listed companies. This structure allows for both

comprehensive coverage and tailored approaches for different types of organizations, though it also creates potential for complexity and occasional inconsistency.

Enforcement mechanisms within this architecture vary by regulatory authority and company type. For listed companies, the stock exchanges serve as primary enforcers, with the ability to require rectification, issue warnings, or implement more serious sanctions for non-compliance. The CSRC can impose administrative penalties for serious disclosure violations. For state-owned enterprises, SASAC has significant enforcement authority, integrating ESG performance into its evaluation systems for SOE management (China Law Society, 2024).

This complex regulatory architecture demonstrates China's commitment to developing a comprehensive ESG disclosure system. However, it also presents challenges related to coordination, consistency, and clarity that will need to be addressed as the system continues to evolve toward full implementation by 2030.

B. Stock Exchange Requirements

China's stock exchanges have emerged as pivotal actors in advancing ESG disclosure, establishing increasingly specific and stringent requirements for listed companies. The Shanghai Stock Exchange (SSE), Shenzhen Stock Exchange (SZSE), and Beijing Stock Exchange (BSE) each play distinctive roles in this ecosystem, reflecting their different market positions and the types of companies they host.

In February 2024, under CSRC guidance, these three exchanges issued coordinated Guidelines on Corporate Sustainability-related Disclosure, marking a significant advancement in standardizing ESG reporting across Chinese capital markets (KPMG, 2024). These guidelines established mandatory disclosure requirements for companies listed on specific indices, including the SSE 180 Index, STAR 50 Index, SZSE 100 Index, and ChiNext Index, as well as companies dual-listed on Chinese and international stock exchanges. Companies outside these categories are encouraged to disclose sustainability information voluntarily (KPMG, 2024).

The first mandatory disclosure under these guidelines is due by April 30, 2026, providing companies with a transition period to develop appropriate systems and capabilities (KPMG, 2024). This phased implementation approach reflects recognition of the challenges associated with comprehensive ESG reporting and the need for companies to build capacity gradually.

The content requirements under these guidelines are comprehensive, covering four core areas: governance, strategy, risk management, and metrics and targets (LRQA, 2024). In the environmental domain, companies must report on carbon emissions, energy consumption, water management, waste disposal, and compliance with environmental regulations. Social responsibility reporting encompasses labor practices, human rights issues, community engagement, and consumer protection. Governance reporting includes structural policies, anti-corruption measures, board diversity, and executive compensation (KPMG, 2024).

The Shanghai Stock Exchange has taken a particularly proactive approach, setting a goal for all export-oriented state-owned enterprises listed on its exchange to publish ESG reports by 2027 (China Business Briefing, 2024). This ambitious target reflects Shanghai's position as China's premier financial center and its aspiration to align with international best practices in sustainable finance.

The Shenzhen Stock Exchange, with its focus on innovation and technology companies, has tailored its approach to emphasize disclosure related to research and development, intellectual property, and human capital—areas of particular relevance to its listed entities. The ChiNext board, China's equivalent to NASDAQ, has specific requirements for innovative companies, particularly regarding their environmental impacts and governance structures (KPMG, 2024).

The Beijing Stock Exchange, which primarily focuses on small and medium-sized enterprises (SMEs), has adopted a voluntary disclosure policy in recognition of the developmental stage and limited disclosure capacity of many of its listed companies. SMEs are encouraged to voluntarily report their ESG practices, establishing benchmarks for sustainable development appropriate to their scale and resources (KPMG, 2024).

All three exchanges emphasize alignment with international standards while maintaining China's distinctive characteristics. Their guidelines draw from frameworks such as the Global Reporting Initiative (GRI), the International Sustainability Standards Board (ISSB), and the Task Force on Climate-Related Financial Disclosures (TCFD), adapted to China's specific context (Business & Sustainable Research Network, 2024).

These stock exchange requirements represent a critical mechanism for translating China's national sustainability disclosure standards into operational practices for listed companies. By establishing clear expectations, implementation timelines, and reporting frameworks, they provide concrete guidance that is driving the rapid expansion of ESG disclosure across China's capital markets.

C. Sector-Specific Disclosure Regulations

China's ESG disclosure framework includes targeted regulations for specific sectors, reflecting recognition that different industries face distinct sustainability challenges and have varying impacts on the environment and society. These sector-specific approaches provide more detailed guidance while accommodating the unique characteristics of different industries.

Heavy polluting industries face the most stringent disclosure requirements, reflecting their significant environmental impacts. The Ministry of Ecology and Environment's "Measures for the Administration of Legal Disclosure of Enterprise Environmental Information," which took effect in February 2022, established mandatory disclosure obligations for 16 heavily polluting industries, including thermal power, steel, cement, and electrolysis aluminum (Long et al., 2022). Companies in these sectors must publish annual environmental information reports detailing emissions of pollutants and other environmental aspects, with significantly more comprehensive requirements than those applied to other industries.

This differentiated approach is evident in empirical research findings. Long et al. (2022) found that companies listed under heavily polluting industries are more likely to disclose ESG reports due to environmental regulatory pressure. Their study of A-share heavily polluting firms in the Shanghai and Shenzhen stock markets from 2015 to 2019 revealed that media attention and state ownership significantly influence the quality and extent of environmental disclosure, with particularly strong effects for non-financial environmental information.

The financial sector has emerged as another priority area for specialized ESG disclosure requirements. Financial institutions play a crucial role in supporting China's green transition through their lending and investment decisions. The People's Bank of China has issued several guidelines specifically addressing sustainability disclosure by banks, insurers, and other financial institutions (PBOC, 2024). These guidelines emphasize disclosure of climate-related risks, green lending practices, and the environmental impacts of investment portfolios.

State-owned enterprises (SOEs) are subject to additional disclosure expectations reflecting their dual roles as commercial entities and instruments of state policy. The State-owned Assets Supervision and Administration Commission (SASAC) issued the Work Program for Improving the Quality of Listed Companies Held by Central Enterprises, which mandated ESG reporting by central enterprise holding companies with a target of full coverage by 2023 (Lin et al., 2024). As a result, SOEs have significantly higher disclosure rates than private companies, with centrally administered SOEs achieving an 80% disclosure rate by early 2024 (China Business Briefing, 2024).

Energy companies face particularly detailed disclosure requirements related to carbon emissions, renewable energy transition plans, and environmental protection measures. The National Energy Administration has issued specific guidance for energy sector companies, requiring disclosure of greenhouse gas emissions, energy efficiency metrics, and strategies for transitioning to cleaner energy sources (China Law Society, 2024).

Mining and extractive industries must provide comprehensive information about their environmental impacts, land reclamation efforts, and community relations. These requirements reflect the substantial environmental and social footprints of mining operations and the heightened stakeholder scrutiny they face (China Law Society, 2024).

These sector-specific approaches demonstrate China's nuanced understanding of the varying sustainability challenges across different industries. By tailoring disclosure requirements to sector characteristics, China's ESG framework balances comprehensive coverage with practical relevance, enhancing the usefulness of disclosed information for investors, regulators, and other stakeholders.

D. Double Materiality Approach

China's ESG disclosure framework has distinctively adopted a double materiality approach, requiring companies to report on both how sustainability issues affect their financial performance and how their operations impact society and the environment. This approach differs from the enterprise value focus of the ISSB standards and aligns more closely with the European Union's CSRD, reflecting China's emphasis on balancing economic development with broader societal and environmental considerations.

The concept of double materiality is explicitly incorporated into China's Basic Standards for Corporate Sustainability Disclosure, which recognize that sustainability information can be material from two perspectives: impact materiality and financial materiality (Guo & Zhu, 2023). Impact materiality considers a company's significant actual or potential impacts on the economy, environment, and society, including impacts on human rights. Financial materiality addresses sustainability-related risks and opportunities that could reasonably be expected to affect the company's future cash flows, access to finance, cost of capital, and value over time.

This dual lens reflects China's policy priorities, which emphasize the concept of "ecological civilization" and the harmony between economic development and environmental protection. By requiring companies to consider both financial implications and broader impacts, China's approach encourages more comprehensive sustainability strategies that address the full range of stakeholder concerns rather than focusing narrowly on investor interests (Business & Sustainable Research Network, 2024).

In practical implementation, China's double materiality approach manifests in several ways. The stock exchange guidelines require companies to identify and disclose material ESG issues through a systematic process that considers both financial significance and stakeholder concerns (KPMG, 2024). Companies must explain their materiality assessment methodology and the criteria used to determine which issues warrant disclosure, with the expectation that this process will include engagement with diverse stakeholders.

For environmentally sensitive industries, the double materiality approach places particular emphasis on ecological impacts regardless of their immediate financial implications. Companies in sectors such as mining, chemicals, and heavy manufacturing must provide detailed disclosures about their environmental footprints, pollution prevention measures, and contributions to ecological protection, even when these issues may not have significant short-term financial consequences (Abbas et al., 2024).

The double materiality concept also extends to social dimensions, with companies expected to disclose information about their impacts on employees, communities, and broader society. This includes reporting on labor practices, community engagement, product safety, and contributions to common prosperity initiatives, reflecting

China's growing emphasis on social responsibility as a component of sustainable development (China Law Society, 2024).

While China's double materiality approach offers a more comprehensive view of corporate sustainability performance than a purely financial materiality focus, it also presents implementation challenges. Companies must develop robust processes for identifying and assessing impacts across multiple dimensions, requiring significant expertise and resources. The subjective nature of impact materiality assessments can lead to inconsistency across companies, complicating comparability for investors and other stakeholders (Zhang & Chu, 2024).

China's adoption of double materiality also has implications for global harmonization efforts. While it creates some divergence from the ISSB's enterprise value approach, it aligns China more closely with the European Union's sustainability reporting direction. This positioning potentially enables China to play a bridging role in international discussions about materiality concepts, contributing to the development of more integrated global standards that balance financial and impact considerations (Barnes & Thornburg, 2024).

VI. Challenges in China's ESG Disclosure System

A. Data Quality and Verification Issues

Despite significant advances in China's ESG disclosure framework, data quality and verification remain persistent challenges that affect the reliability and usefulness of sustainability reporting. These issues span several dimensions, including consistency, comparability, accuracy, and third-party verification.

Inconsistency and incomparability problems are particularly prevalent, as highlighted by Lin et al. (2024) in their study of ESG disclosure performance among Chinese listed companies. Their research found considerable variation in disclosure approaches, with companies using different metrics, methodologies, and reporting formats even within the same industry. This heterogeneity makes it difficult for investors and other stakeholders to compare performance across companies or track progress over time.

The problem is compounded by the historical absence of standardized calculation methodologies for key ESG indicators. While recent regulatory developments, including the Basic Standards for Corporate Sustainability Disclosure, have begun to address this issue, implementation remains uneven. Su Gang of China Pacific Insurance Group notes that unified calculation and disclosure standards will continue to improve the quality of ESG information, promoting a healthier capital market (PRI, 2024). However, this harmonization process is still in its early stages.

Limited third-party assurance represents another significant challenge. Unlike financial reporting, which requires independent auditing, ESG disclosure in China generally lacks mandatory external verification requirements. Lan et al. (2024) examined the relationship between ESG information disclosure and audit fees, finding that the absence of standardized verification mechanisms creates uncertainty about the reliability of reported information. Their research suggests that higher-quality ESG disclosure correlates with lower audit risk premiums, indicating that verification challenges affect multiple aspects of corporate reporting.

"Greenwashing" concerns have emerged as ESG disclosure has become more widespread. Yu et al. (2020) studied greenwashing in environmental, social, and governance disclosures, finding instances where companies presented misleading or overly positive portrayals of their sustainability performance. This phenomenon undermines trust in ESG reporting and reduces its effectiveness as a tool for decision-making by investors and other stakeholders.

The verification challenge is particularly acute for complex ESG metrics such as Scope 3 greenhouse gas emissions, which involve supply chain data that companies may have limited ability to verify independently. Similar challenges exist for social impact measurements and governance effectiveness assessments, which often rely on qualitative indicators that are inherently difficult to verify objectively (Zhang & Chu, 2024).

Regulatory efforts to address these data quality issues include the information quality requirements outlined in the Basic Standards for Corporate Sustainability Disclosure, which emphasize that sustainability-related financial information should be complete, neutral, accurate, verifiable, timely, and understandable (KPMG, 2024). However, translating these principles into practice requires significant investment in data collection systems, verification processes, and reporting capabilities that many companies are still developing.

Technological solutions are increasingly being explored to enhance data quality. Liu et al. (2023) found that digital transformation can significantly alleviate ESG decoupling by improving information processing capabilities and reducing information asymmetry. Digital technologies, including blockchain for data verification, artificial intelligence for consistent analysis, and automated reporting systems, offer potential pathways to improve the reliability and comparability of ESG information.

Addressing these data quality and verification challenges will be essential for China's ESG disclosure system to achieve its full potential. As the system matures, greater emphasis on standardized methodologies, independent verification, and technological solutions will be needed to ensure that sustainability reporting provides reliable, comparable, and decision-useful information to all stakeholders.

B. Implementation Capacity Constraints

The implementation of China's increasingly comprehensive ESG disclosure requirements faces significant capacity constraints across various dimensions, including resource limitations, technical expertise shortages, and digital transformation challenges. These constraints affect different types of companies to varying degrees, with smaller firms and those in less developed regions facing particularly acute challenges.

Resource limitations for smaller firms present a fundamental implementation barrier. As KPMG (2024) notes, smaller enterprises, particularly SMEs, often lack the financial, human, and technical resources needed for thorough ESG reporting. These resource constraints become more pronounced as disclosure requirements grow more complex, requiring sophisticated data collection systems, analytical capabilities, and reporting processes. Recognizing this challenge, China's disclosure framework adopts a differentiated approach, with mandatory requirements initially focused on larger listed companies while smaller firms are encouraged to report voluntarily.

Technical expertise shortages represent another significant constraint. ESG disclosure requires specialized knowledge across multiple domains, including environmental science, social impact assessment, governance best practices, and reporting methodologies. Many Chinese companies, particularly those new to sustainability reporting, lack personnel with these skills (Business & Sustainable Research Network, 2024). The shortage is especially acute for specific technical capabilities such as carbon accounting, biodiversity impact assessment, and social responsibility measurement.

The pace of regulatory evolution has created additional implementation challenges. As China rapidly develops its ESG disclosure system, companies must continuously adapt to new requirements and expectations. This regulatory dynamism, while driving progress, creates a moving target that complicates implementation planning and capacity building (China Law Society, 2024). Companies must develop not only current reporting capabilities but also the flexibility to evolve as standards continue to change.

Digital transformation requirements add another layer of complexity. As Liu et al. (2023) emphasize, digital technologies play a crucial role in effective ESG implementation by enhancing data collection, processing, and reporting capabilities. Their research demonstrates that digital transformation can significantly reduce ESG decoupling by improving information processing ability and relieving information asymmetry. However, achieving this digital transformation requires substantial investment and expertise that many companies are still developing.

Implementation capacity varies significantly across industries and regions. Companies in environmentally sensitive sectors like energy, chemicals, and manufacturing have generally developed more advanced environmental reporting capabilities in response to longstanding regulatory pressure (Long et al., 2022). Similarly, financial institutions have built greater capacity for ESG assessment due to their role in green finance initiatives. Companies in less regulated sectors often lag in developing comparable capabilities.

Geographic disparities also affect implementation capacity. Companies based in first-tier cities and more developed coastal regions typically have greater access to sustainability expertise, technology resources, and supporting services than those in less developed inland areas (China Law Society, 2024). These regional disparities create uneven implementation that may undermine the comparability and comprehensiveness of China's overall ESG disclosure system.

Addressing these implementation capacity constraints requires coordinated efforts from regulators, industry associations, educational institutions, and companies themselves. Regulatory approaches that provide phased implementation timelines, clear guidance, and scaled requirements based on company size and sector can help manage capacity limitations. Industry collaborations to develop shared resources, tools, and best practices can support more efficient capacity building. Educational programs focused on developing ESG expertise will be crucial for addressing technical knowledge shortages over the longer term.

C. Balancing Local and Global Standards

A central challenge in China's ESG disclosure system is achieving an effective balance between alignment with international standards and addressing China's specific national priorities and institutional context. This balance is crucial for ensuring both global comparability and local relevance of ESG disclosures.

China's approach to international alignment is evolving rapidly. While the country has not formally adopted the ISSB standards, market participants have noted that these standards are likely to serve as an important benchmark for China's ESG disclosure standards (Latham & Watkins, 2023). China's Basic Standards for Corporate Sustainability Disclosure follows the International Sustainability Standards Board (ISSB)'s disclosure framework, requiring companies to disclose information related to governance, strategy, risk and opportunity management, and indicators and targets (Guo & Zhu, 2023).

However, China has made important adaptations to international frameworks to reflect its specific circumstances. Most notably, unlike the ISSB Standard's financial materiality focus, China's guidelines follow the principle of double materiality, assessing both ESG impacts on a firm's financials and the firm's impacts on ESG outcomes (Guo & Zhu, 2023). This approach aligns more closely with the European Union's CSRD than with the ISSB's enterprise value orientation, reflecting China's emphasis on balanced development that considers both economic and broader societal factors.

Cultural and institutional barriers present significant challenges for harmonization efforts. China's distinctive governance model, with its emphasis on state guidance and the role of state-owned enterprises, creates a different institutional context for ESG disclosure than the market-driven approaches prevalent in Western economies (Tang & Li, 2023). Similarly, traditional Chinese concepts such as "harmony between humans and nature" and "common

prosperity" influence how sustainability is conceptualized and prioritized in ways that may differ from Western frameworks.

China-specific material issues must be addressed in any effective ESG disclosure system for the country. As Business & Sustainable Research Network (2024) emphasizes, companies operating in China must consider specific material issues such as environmental protection priorities outlined in Five-Year Plans, common prosperity initiatives addressing income inequality, and contributions to national development strategies. International standards may not fully capture these priorities, necessitating adaptations to the Chinese context.

The challenge of balancing global and local considerations is particularly relevant for Chinese companies with international operations and foreign companies operating in China. These organizations must navigate multiple disclosure regimes with potentially conflicting requirements, creating compliance complexity and reporting burdens (China Law Society, 2024). For Chinese companies listing overseas, this challenge is especially acute, as they must satisfy both domestic regulators and international market expectations.

Despite these challenges, China's ESG disclosure system is increasingly finding a middle path that combines international alignment with Chinese characteristics. The Basic Standards for Corporate Sustainability Disclosure represents a significant step in this direction, establishing a framework that draws on global best practices while maintaining flexibility to address China's specific circumstances (China Business Briefing, 2024).

Looking ahead, China's approach to balancing local and global standards will likely continue to evolve. The country's growing influence in international financial markets and global sustainability discussions positions it to potentially shape future iterations of international standards, perhaps contributing to greater recognition of diverse perspectives and priorities in global ESG frameworks (Barnes & Thornburg, 2024).

D. ESG Disclosure Decoupling

ESG disclosure decoupling — the gap between reported ESG performance and actual operational practices — represents a significant challenge for China's sustainability reporting system. This phenomenon undermines the reliability and effectiveness of ESG disclosure as a tool for stakeholder decision-making and sustainable development advancement.

Liu et al. (2023) provide important insights into this issue in their study of corporate digital transformation and ESG decoupling in China. They define ESG decoupling as the divergence between a company's public ESG commitments and disclosures and its substantive implementation of those commitments. Their research identifies several factors contributing to this decoupling, including information asymmetry, external pressure without internal commitment, and the challenges of monitoring and verifying ESG performance.

The extent of ESG decoupling varies across different dimensions of sustainability reporting. Environmental claims are often more readily verifiable through quantitative metrics such as emissions data, energy consumption, and waste generation, though even these can be subject to measurement inconsistencies and selective reporting (Long et al., 2022). Social and governance dimensions typically involve more qualitative assessments that are inherently more difficult to verify, creating greater potential for decoupling between reports and reality.

External pressure without corresponding internal commitment represents a key driver of ESG decoupling. Abbas et al. (2024) examine ESG disclosure motives for environmentally sensitive industries, finding that disclosure driven primarily by regulatory compliance or reputation management without genuine organizational commitment tends to result in greater decoupling. This "ceremonial adoption" of ESG practices leads to reporting that may satisfy formal requirements but fails to drive substantive operational changes.

Information asymmetry between companies and their stakeholders facilitates ESG decoupling by making it difficult for external parties to verify claims independently. Lan et al. (2024) note that this asymmetry affects the relationship between ESG disclosure and audit fees, as auditors must factor in the uncertainty associated with unverified sustainability claims. The absence of standardized verification mechanisms exacerbates this problem, allowing significant discretion in how companies present their ESG performance.

Media and analyst scrutiny can help mitigate ESG decoupling by increasing transparency and accountability. Long et al. (2022) found that media attention plays a significant role in improving the quality of environmental information disclosure by heavily polluting firms in China. Their research demonstrates that external monitoring mechanisms can reduce the gap between reported and actual performance by increasing reputational costs for misleading disclosure.

Digital transformation offers promising solutions to the decoupling challenge. Liu et al. (2023) demonstrate that digital transformation can significantly alleviate ESG decoupling through two primary mechanisms: improving information processing ability and relieving information asymmetry. Technologies such as big data analytics, Internet of Things sensors, and blockchain verification systems enable more accurate, comprehensive, and transparent ESG performance tracking, reducing opportunities for selective or misleading disclosure.

Regulatory approaches to addressing ESG decoupling include more specific disclosure requirements, enhanced verification mechanisms, and stronger enforcement against misleading claims. China's Basic Standards for Corporate Sustainability Disclosure emphasizes the importance of information quality, requiring that sustainability-related financial information be complete, neutral, accurate, and verifiable (KPMG, 2024). However, translating these principles into effective practice requires ongoing regulatory evolution and enforcement capacity building.

As China's ESG disclosure system continues to mature, addressing the decoupling challenge will be essential for ensuring that sustainability reporting drives genuine improvement in corporate practices rather than merely creating a façade of responsibility. Combining regulatory requirements, stakeholder scrutiny, technological solutions, and organizational commitment will be necessary to narrow the gap between ESG reporting and reality.

VII. Global Integration Efforts

A. Alignment with ISSB Standards

China's approach to aligning with the International Sustainability Standards Board (ISSB) standards represents a critical aspect of its global integration efforts in ESG disclosure. While China has not formally adopted the ISSB standards in their entirety, it has taken significant steps to harmonize its disclosure framework with these global benchmarks while maintaining flexibility to address domestic priorities.

The ISSB, established at COP26 in 2021, released its inaugural standards in June 2023: IFRS S1 (General Requirements for Disclosure of Sustainability-related Financial Information) and IFRS S2 (Climate-related Disclosures) (ISSB, 2023). These standards were subsequently endorsed by the International Organization of Securities Commissions (IOSCO), which called on its 130 financial market members, including China, to consider ways to adopt, apply, or otherwise be informed by these standards (Barnes & Thornburg, 2024).

China's response to the ISSB standards has been measured and strategic. Rather than adopting them directly, China has developed its own Basic Standards for Corporate Sustainability Disclosure that follows the ISSB's disclosure framework while incorporating distinctive Chinese characteristics (Guo & Zhu, 2023). The Basic Standards require companies to disclose information related to the same four core areas as the ISSB standards: governance, strategy, risk management, and metrics and targets (LRQA, 2024).

This approach allows China to benefit from the ISSB's work in developing globally accepted disclosure practices while maintaining autonomy in determining how these practices are implemented in the Chinese context. By following the ISSB framework while making adaptations, China positions itself to achieve sufficient international comparability without surrendering policy flexibility.

The most significant divergence between China's approach and the ISSB standards relates to materiality. While the ISSB primarily takes a financial materiality perspective, focusing on sustainability information that affects enterprise value, China's guidelines follow the principle of double materiality, which assesses both ESG impacts on a firm's financials and the firm's impacts on ESG outcomes (Guo & Zhu, 2023). This difference reflects China's broader conception of corporate responsibility, which emphasizes contributions to social and environmental objectives alongside financial performance.

China's alignment timeline also differs from some other major economies. The Ministry of Finance has outlined a plan to issue both the general standard for corporate sustainability disclosure (based on IFRS S1) and the climate-related disclosure standard (based on IFRS S2) by 2027, with the goal of building a national sustainability disclosure system by 2030 (Guo & Zhu, 2023). This measured pace contrasts with more rapid adoption in jurisdictions such as the UK, Canada, and Hong Kong, but provides companies with a longer transition period to develop necessary capabilities.

The differences in China's approach highlight the challenges of achieving global harmonization while respecting national priorities and institutional contexts. However, the substantial overlap between China's framework and the ISSB standards suggests a genuine commitment to international alignment rather than a purely parallel approach. This balance positions China to potentially influence the evolution of global standards through its distinctive implementation experience, particularly regarding double materiality and the integration of national development priorities into sustainability reporting.

As global ESG disclosure continues to evolve, China's relationship with the ISSB standards will likely deepen. The Financial Stability Board has emphasized the importance of addressing the challenges faced by companies in emerging economies in implementing ISSB disclosure standards (FSB, 2024). As China navigates these challenges in its own implementation process, its experience could provide valuable insights for other emerging economies seeking to balance international alignment with domestic priorities.

B. International Cooperation Initiatives

China's engagement with international cooperation initiatives forms an important component of its approach to ESG disclosure harmonization. Through participation in global forums, bilateral relationships, and multilateral institutions, China is both contributing to and learning from international sustainability reporting developments.

China has demonstrated increasing engagement with key international organizations involved in sustainability standard-setting. While not formally adopting the ISSB standards, China participates in ISSB consultations and has representatives involved in its governance structure (FSB, 2024). This engagement allows China to contribute its perspective to the development of global standards while staying informed about international best practices.

The Financial Stability Board's work on climate-related financial disclosure represents another important forum for international cooperation. The FSB's Progress Report notes that 19 of its 24 member jurisdictions, including China, have published regulatory files, guidelines, or roadmaps relating to climate-related disclosures (FSB, 2024). China's participation in this work supports greater alignment in approaches to climate risk disclosure, a particularly critical area given the global nature of climate change challenges.

Bilateral harmonization efforts have also intensified, particularly with key trading and investment partners. Cooperation between Chinese and European authorities on sustainability disclosure has grown as both regions implement comprehensive ESG reporting frameworks. While their approaches differ in some respects — with Europe's CSRD generally considered more prescriptive than China's current requirements — there are efforts to identify areas of comparability and potential interoperability (Barnes & Thornburg, 2024).

The International Platform on Sustainable Finance, launched in 2019, provides another forum for China's international cooperation on ESG disclosure. This platform brings together policymakers from major economies to exchange information and promote best practices in sustainable finance, including disclosure requirements. China's active participation reflects its recognition that international coordination is essential for addressing global sustainability challenges effectively (Latham & Watkins, 2023).

Regional cooperation initiatives in Asia provide additional avenues for China's international engagement. Collaborative efforts with countries such as Japan, South Korea, and Singapore on sustainability reporting standards allow for the exchange of experiences and approaches that reflect Asian economic and social contexts (Latham & Watkins, 2023). These regional initiatives complement global cooperation and may help develop approaches that better address the specific challenges faced by Asian companies and markets.

China's role in developing international standards is evolving from primarily adopting external frameworks to actively contributing Chinese perspectives. As Tang and Li (2023) note, China's unique institutional context and top-down approach to ESG governance offer distinctive insights that can enrich international discussions. China's experience with implementing double materiality, integrating national development priorities into reporting frameworks, and addressing implementation challenges in a developing economy context provides valuable lessons for the global community.

Looking forward, China's international cooperation efforts will likely intensify as its domestic ESG disclosure system matures. The country's growing economic influence and increasingly sophisticated approach to sustainability reporting position it to play a more prominent role in shaping global standards. This evolution could contribute to more inclusive international frameworks that better accommodate diverse economic, social, and governance models while maintaining sufficient comparability for global market participants.

C. Belt and Road Initiative ESG Implications

The Belt and Road Initiative (BRI), China's ambitious global infrastructure development strategy, has significant implications for ESG disclosure practices both within China and internationally. As Chinese companies invest in projects across more than 140 countries, the sustainability impacts of these investments have attracted increasing attention from host governments, international organizations, civil society, and investors.

ESG disclosure for overseas investments under the BRI presents unique challenges and opportunities. Chinese companies operating abroad must navigate complex cross-border reporting requirements while managing diverse environmental, social, and governance risks in host countries with varying regulatory frameworks and sustainability priorities (China Law Society, 2024). The quality and comprehensiveness of ESG disclosure for these international operations can significantly affect project acceptance, financing costs, and long-term success.

China has taken important steps to enhance the sustainability of BRI investments through improved disclosure frameworks. In 2017, the Chinese government released the "Guidance on Promoting Green Belt and Road," which emphasized the importance of environmental information disclosure for overseas projects (Guo & Zhu, 2023). This was followed by more specific guidelines from various ministries and regulatory bodies addressing environmental impact assessments, community engagement, and governance transparency for international investments.

The extraterritorial application of Chinese ESG standards represents an evolving aspect of BRI implementation. Increasingly, Chinese regulators expect companies to apply domestic sustainability principles and disclosure practices to their overseas operations, creating a form of regulatory export that can influence ESG practices in host countries (Business & Sustainable Research Network, 2024). This trend is particularly evident for Chinese state-owned enterprises and financial institutions, which are expected to demonstrate leadership in sustainable development regardless of where they operate.

Green BRI development has emerged as a strategic priority, with enhanced disclosure playing a central role. The "Belt and Road Ecological and Environmental Cooperation Plan" emphasizes transparency and information sharing as key enablers of sustainable development along BRI routes (China Law Society, 2024). This focus on green development reflects both increasing international expectations and China's recognition that long-term project success depends on environmental and social sustainability.

Financial institutions play a crucial role in promoting ESG disclosure for BRI projects. Chinese policy banks and commercial lenders increasingly require sustainability-related information from project developers as part of their financing decisions (PBOC, 2024). These requirements create strong incentives for improved ESG disclosure and performance, particularly for large infrastructure projects that depend on Chinese financing.

The impact of China's domestic ESG disclosure evolution on BRI projects is becoming increasingly apparent. As Chinese companies develop more sophisticated sustainability reporting capabilities in response to domestic requirements, these capabilities often transfer to their international operations (China Business Briefing, 2024). This spillover effect can enhance transparency and sustainability performance across the BRI, contributing to China's goal of building a "Green Silk Road."

Challenges remain in achieving consistent ESG disclosure across diverse BRI projects. The wide variation in host country regulatory requirements, capacity limitations of local partners, data collection difficulties in remote areas, and complex supply chains all complicate efforts to implement comprehensive disclosure practices (China Law Society, 2024). Addressing these challenges requires both consistent application of Chinese standards and flexibility to accommodate local contexts.

Looking ahead, the relationship between China's ESG disclosure system and the BRI will likely continue to deepen. As China's domestic disclosure requirements become more comprehensive and aligned with international standards, expectations for BRI project disclosure will likely increase correspondingly. This evolution has the potential to significantly enhance the sustainability of BRI investments while contributing to the global harmonization of ESG disclosure practices.

VIII. Future Trajectory and Recommendations

A. Projected Evolution (2025-2030)

China's ESG disclosure system is poised for significant evolution between 2025 and 2030, with a clear trajectory toward a more comprehensive, standardized, and internationally aligned framework.

The Ministry of Finance's plan to establish a national sustainability disclosure system by 2030 provides a clear roadmap for this evolution. This plan includes issuing both the general standard for corporate sustainability disclosure (based on IFRS S1) and the climate-related disclosure standard (based on IFRS S2) by 2027, creating the foundation for full implementation by 2030 (Guo & Zhu, 2023). This measured yet ambitious timeline allows for gradual capacity building while maintaining clear momentum toward comprehensive implementation.

Mandatory disclosure requirements will expand significantly during this period. Beginning with the first mandatory disclosures for companies listed on major indices in April 2026, the scope of mandatory requirements is likely to gradually encompass a broader range of companies (KPMG, 2024). This expansion will likely follow a phased approach, with requirements extending from listed to non-listed companies, from large to smaller enterprises, from qualitative to more quantitative requirements, and from optional to mandatory disclosure for an increasing number of ESG elements (PRI, 2024).

The integration of digital technologies will accelerate, transforming how companies collect, process, and report ESG information. Liu et al. (2023) demonstrate that digital transformation can significantly improve ESG disclosure quality by enhancing information processing capabilities and reducing information asymmetry. Technologies including artificial intelligence, blockchain verification, Internet of Things sensors, and automated reporting platforms will become increasingly central to effective ESG implementation. The Beijing Municipal Commission of Development and Reform's Action Plan explicitly emphasizes the role of digital technology in advancing ESG practices (China Business Briefing, 2024).

International alignment efforts will intensify as China's system matures. While maintaining its distinctive characteristics, including the double materiality approach, China's disclosure framework will likely achieve greater interoperability with international standards, particularly the ISSB framework (Barnes & Thornburg, 2024). This alignment will facilitate both Chinese companies' access to global capital markets and international investors' participation in China's growing ESG investment landscape.

Sector-specific disclosure frameworks will become more sophisticated, with tailored requirements for industries with distinct sustainability impacts and challenges. The financial sector will see particularly significant developments as green finance continues to expand, with enhanced disclosure requirements for climate-related financial risks and opportunities (PBOC, 2024). Heavy industries will face increasingly detailed and quantitative disclosure expectations regarding environmental impacts and transition plans.

Verification and assurance mechanisms will strengthen substantially. As the importance of ESG information for investment and regulatory decisions grows, so too will demands for reliable verification. Independent third-party assurance of sustainability disclosures will become more common and eventually expected for larger companies, enhancing the credibility and usefulness of reported information (XBRL International, 2024).

Data standardization and digital reporting formats will advance significantly. The adoption of structured and machine-readable formats like XBRL for sustainability disclosures could play a crucial role in enhancing the quality and usability of such information (XBRL International, 2024). Standardized taxonomies and digital reporting protocols will improve comparability and facilitate more sophisticated analysis of sustainability performance.

The integration of ESG considerations into broader corporate governance and strategy will deepen. Rather than treating ESG disclosure as a standalone reporting exercise, companies will increasingly embed sustainability considerations into core decision-making processes, risk management frameworks, and long-term strategy development (Business & Sustainable Research Network, 2024). This integration will enhance the strategic value of disclosure while improving its alignment with actual business operations.

By 2030, China aims to have established a comprehensive, internationally aligned yet distinctively Chinese ESG disclosure system that supports both its domestic sustainable development goals and its growing integration with global capital markets. This system will combine mandatory requirements with voluntary best practices, standardized frameworks with sector-specific guidance, and international alignment with Chinese characteristics. While challenges will inevitably arise during this evolution, the clear policy direction and growing market

momentum suggest that China's ESG disclosure system will continue to advance rapidly in sophistication and influence.

B. Policy Recommendations

Based on the analysis of China's current ESG disclosure system and projected future trajectory, several policy recommendations emerge for enhancing the effectiveness, efficiency, and impact of sustainability reporting in China.

To enhance data quality and verification, policymakers should establish a robust independent assurance framework for ESG disclosures. This framework should include accreditation standards for third-party verifiers, specific verification requirements for material sustainability information, and clear guidelines for assurance reporting (XBRL International, 2024). Initially, mandatory verification could focus on environmental data for high-impact industries and gradually expand to broader ESG disclosures and additional sectors. Digital verification technologies, including blockchain and automated data validation, should be encouraged through regulatory incentives and technical standards.

For building implementation capacity, a comprehensive support system for companies developing ESG disclosure capabilities is essential. This system should include sector-specific implementation guidelines, technical assistance programs for smaller companies, and educational resources to develop expertise (Business & Sustainable Research Network, 2024). Industry associations should be encouraged to develop shared tools, methodologies, and best practices that reduce implementation costs for individual companies. Regulatory approaches should incorporate appropriate phase-in periods and simplified requirements for smaller entities to allow for gradual capacity building while maintaining momentum toward comprehensive disclosure.

To improve international standard alignment, China should continue developing its disclosure framework in dialogue with international initiatives, particularly the ISSB. While maintaining distinctive Chinese characteristics where appropriate, policymakers should identify and eliminate unnecessary divergences that complicate global comparability (Barnes & Thornburg, 2024). Formal mapping between Chinese standards and international frameworks would help companies and investors understand equivalencies and differences. Active participation in international standard-setting discussions would allow China to both share its distinctive perspectives and learn from global best practices.

For advancing digital transformation of ESG reporting, a coordinated approach to technology adoption is needed. Regulatory bodies should develop standardized digital taxonomies for sustainability reporting that enable machine-readable disclosures and automated data processing (XBRL International, 2024). Technology demonstration projects could showcase innovative approaches to data collection, verification, and reporting. Capacity-building programs specifically focused on digital ESG capabilities would help address existing technology gaps, particularly for smaller companies and those in less developed regions.

To strengthen the connection between disclosure and performance, policymakers should develop clear mechanisms for translating improved transparency into tangible sustainability improvements. These mechanisms could include preferential financing for companies demonstrating strong ESG performance, procurement advantages for sustainability leaders, and regulatory incentives tied to verified ESG outcomes (PBOC, 2024). Addressing "ESG decoupling" requires policies that reward substantive performance rather than merely sophisticated reporting, potentially including consequences for misleading disclosures or persistent gaps between commitments and actions.

For enhancing stakeholder engagement in the disclosure process, regulatory guidance should emphasize the importance of structured stakeholder input in determining materiality and shaping disclosure content (Zhang & Chu, 2024). Companies should be encouraged to develop formal processes for incorporating diverse perspectives into their ESG reporting, including employees, communities, civil society organizations, and other affected groups. This engagement would improve the relevance and usefulness of disclosed information while strengthening corporate accountability.

To improve coordination among regulatory authorities, a formal mechanism for aligning ESG disclosure requirements across different ministries, commissions, and stock exchanges would enhance policy coherence and reduce compliance complexity. This coordination mechanism could harmonize timelines, terminology, metrics, and reporting formats while respecting the distinctive mandates of different regulatory bodies (China Law Society, 2024). A unified digital platform for ESG disclosure submission could simplify compliance for companies subject to multiple reporting requirements.

These policy recommendations aim to address the key challenges identified in China's current ESG disclosure system while supporting its continued evolution toward a comprehensive, effective, and internationally aligned framework. By enhancing data quality, building implementation capacity, improving international alignment, advancing digital transformation, strengthening the disclosure-performance connection, enhancing stakeholder engagement, and improving regulatory coordination, China can develop a world-class ESG disclosure system that serves both domestic sustainable development goals and global harmonization efforts.

C. Research Directions

As China's ESG disclosure system continues to evolve, several priority areas for future research emerge that could provide valuable insights for policymakers, companies, investors, and other stakeholders.

The effectiveness of China's distinctive regulatory approach to ESG disclosure warrants systematic evaluation. Tang and Li (2023) highlight China's top-down framework as a unique feature of its ESG landscape, distinguishing it from more market-driven Western approaches. Future research should assess the strengths and limitations of this approach compared to alternatives, examining questions such as: Does China's model accelerate adoption more effectively than voluntary frameworks? Does it lead to more standardized and comparable disclosures? Does it successfully balance compliance with innovation? Such research could provide important insights for other emerging economies considering different regulatory pathways.

The integration of traditional Chinese cultural and philosophical concepts into contemporary ESG frameworks represents another promising research direction. Tang and Li (2023) suggest investigating the impact of traditional Chinese ethics on ESG practices. Concepts such as "ecological civilization," "common prosperity," and "harmony between humans and nature" reflect distinctive Chinese perspectives on sustainability that may enrich global ESG thinking. Research examining how these concepts manifest in disclosure practices and corporate strategies could contribute to more culturally diverse and inclusive approaches to sustainability reporting worldwide.

The relationship between digital transformation and ESG disclosure effectiveness deserves deeper investigation. Liu et al. (2023) demonstrate that digital transformation can significantly reduce ESG decoupling, but many questions remain about optimal technological approaches, implementation challenges, and potential unintended consequences. Research could explore which digital technologies most effectively enhance different aspects of ESG disclosure, how companies at various stages of technological development can leverage digital tools, and what governance mechanisms are needed to ensure that digitalization enhances rather than undermines disclosure quality and reliability.

The double materiality approach adopted by China warrants rigorous empirical examination. Research could investigate how companies implement double materiality assessments in practice, which stakeholders influence these assessments, and how the resulting disclosures compare with those based on financial materiality alone. Comparative studies of double materiality implementation in China and the European Union could provide insights into how different institutional contexts shape this concept's application and effectiveness.

Sector-specific research focused on industries with distinctive sustainability challenges would enhance understanding of disclosure dynamics in different contexts. For heavily polluting industries, research could examine how environmental disclosure requirements affect operational practices and investment decisions (Long et al., 2022). For financial institutions, studies could investigate the relationship between ESG disclosure and lending or investment practices (PBOC, 2024). For companies in global supply chains, research could explore how Chinese ESG disclosure requirements influence international business relationships and cross-border sustainability practices.

The impact of ESG disclosure on various performance outcomes in the Chinese context requires further investigation. While Li et al. (2023) found a positive relationship between ESG and financial performance moderated by digital transformation, many questions remain about the mechanisms through which disclosure affects different types of performance and how these relationships vary across company types, industries, and time periods. Longitudinal studies tracking disclosure quality and various performance metrics could provide more definitive evidence on these relationships.

Methodological innovation in ESG research represents another priority area. Tang and Li (2023) note the dominance of quantitative approaches in Chinese ESG research and suggest the need for more qualitative studies to provide deeper contextual understanding. Mixed-methods research combining quantitative analysis with qualitative insights could offer more nuanced perspectives on disclosure practices and their impacts. Novel approaches such as text mining of disclosure documents, network analysis of stakeholder relationships, and experimental studies of investor responses to different disclosure formats could generate valuable new insights.

International comparative research examining similarities and differences between China's ESG disclosure system and those in other major economies would enhance understanding of global harmonization challenges and opportunities. Studies could investigate points of convergence and divergence between Chinese and international standards, identify best practices that transcend national boundaries, and explore how different systems influence each other through cross-border investment, trade, and regulatory dialogue.

These research directions would contribute to a more comprehensive and nuanced understanding of China's evolving ESG disclosure system, its distinctive characteristics, and its relationship to global sustainability reporting trends. By pursuing these lines of inquiry, researchers can generate valuable knowledge for improving disclosure practices, enhancing their impact on sustainable development, and facilitating greater global harmonization while respecting diverse national contexts.

IIV.Conclusion

A. Summary of Key Findings

This comprehensive analysis of China's ESG disclosure system reveals a rapidly evolving landscape characterized by increasing standardization, expanding mandatory requirements, and growing alignment with international practices while maintaining distinctive Chinese characteristics. The journey from initial voluntary environmental reporting to today's comprehensive framework reflects China's deepening commitment to sustainable development and its recognition of ESG disclosure as a crucial mechanism for directing capital toward sustainability goals.

The historical development of ESG disclosure in China has progressed through four distinct stages: an early stage (2003-2015) focused primarily on voluntary environmental reporting, a growth stage (2016-2020) marked by the formalization of green finance initiatives and enhanced stock exchange requirements, an acceleration stage (2021-2023) triggered by China's ambitious carbon neutrality goals, and the current stage (2024-present) featuring comprehensive standardization efforts and expanded mandatory requirements. This evolution demonstrates China's increasingly systematic approach to sustainability reporting.

China's current ESG disclosure framework features a complex regulatory architecture with multiple authorities, including the Ministry of Finance as the principal standard-setter, the China Securities Regulatory Commission and stock exchanges overseeing listed company requirements, and various ministries providing sector-specific regulations. This multi-tiered structure enables comprehensive coverage while allowing for tailored approaches to different types of organizations, though it also creates potential for complexity and occasional inconsistency.

Adistinctive feature of China's approach is its adoption of double materiality, requiring companies to report on both how sustainability issues affect their financial performance and how their operations impact society and the environment. This approach differs from the enterprise value focus of the ISSB standards and aligns more closely with the European Union's CSRD, reflecting China's emphasis on balancing economic development with broader societal and environmental considerations.

Despite significant advances, China's ESG disclosure system faces several persistent challenges. Data quality and verification issues undermine the reliability and usefulness of reported information. Implementation capacity constraints, particularly for smaller firms and those in less developed regions, complicate compliance with increasingly sophisticated requirements. Balancing alignment with international standards while addressing China's specific priorities creates tensions that must be carefully managed. The risk of ESG decoupling—the gap between reported and actual performance—threatens the credibility and effectiveness of the entire system.

China's efforts toward global integration have accelerated in recent years, particularly in relation to the ISSB standards. While not formally adopting these standards, China has developed its Basic Standards for Corporate Sustainability Disclosure following the ISSB's framework while incorporating distinctive Chinese characteristics. This balanced approach enables sufficient international comparability while preserving policy flexibility to address domestic priorities.

Looking ahead, China's ESG disclosure system is projected to continue evolving toward full implementation by 2030. This evolution will likely include expanded mandatory requirements, enhanced verification mechanisms, greater digital integration, and improved international alignment, though challenges in implementation capacity and data quality will persist. Addressing these challenges will require coordinated efforts from regulators, companies, investors, and other stakeholders.

The findings of this analysis underscore the significance of China's ESG disclosure journey not only for its domestic sustainable development goals but also for global sustainability reporting harmonization efforts. As the world's second-largest economy and a major force in global markets, China's approach to ESG disclosure will inevitably influence international practices, potentially contributing to more inclusive global standards that accommodate diverse economic, social, and governance models while maintaining sufficient comparability for effective capital allocation.

BTheoretical and Practical Implications

The evolution and current state of China's ESG disclosure system carry significant theoretical and practical implications for understanding sustainability reporting in diverse institutional contexts and for advancing effective disclosure practices globally.

From a theoretical perspective, China's approach to ESG disclosure provides an important case study for examining how sustainability reporting frameworks develop within different institutional environments. The distinctive characteristics of China's system — including its top-down regulatory approach, emphasis on double materiality, and integration of national development priorities — challenge assumptions about the universal applicability of Western sustainability reporting models. This case suggests that effective ESG disclosure systems can take multiple forms shaped by their specific institutional, cultural, and economic contexts.

China's experience also contributes to theoretical debates about the relationship between mandatory regulation and voluntary initiatives in advancing sustainability disclosure. The country's evolution from primarily voluntary reporting to an increasingly mandatory system, with continuing space for voluntary best practices, offers insights into how these approaches can complement rather than contradict each other. This hybrid model suggests that the often-polarized debate between regulatory and market-driven approaches may oversimplify a more complex dynamic in which both play important roles.

The adoption of double materiality in China's disclosure framework has theoretical implications for how materiality is conceptualized in different contexts. By requiring companies to consider both financial impacts and broader societal effects, China's approach challenges the premise that enterprise value should be the primary or sole determinant of what sustainability information warrants disclosure. This perspective enriches theoretical discussions about materiality by highlighting its inherently contextual and value-laden nature.

For stakeholder theory, China's approach offers a distinctive perspective on which stakeholders' interests should shape corporate disclosure and behavior. While Western applications of stakeholder theory often emphasize the interests of diverse non-governmental actors, China's model gives particular weight to national development priorities articulated by government authorities. This variation demonstrates how stakeholder theory can manifest differently across political and economic systems while maintaining its core insight about the importance of considering multiple interests beyond shareholders alone.

From a practical perspective, China's ESG disclosure journey offers valuable lessons for both policymakers and companies navigating sustainability reporting challenges. For regulators in other emerging economies, China's phased implementation approach demonstrates how to balance ambition with pragmatism, gradually expanding mandatory requirements while building capacity and learning from experience. The coordination mechanisms between different regulatory authorities provide models for addressing the inherently cross-cutting nature of sustainability issues.

For companies, China's evolving requirements highlight the importance of developing robust ESG disclosure capabilities as a core business function rather than a peripheral reporting exercise. The growing emphasis on verification, digitalization, and double materiality suggests that companies should invest in comprehensive sustainability data management systems, cultivate diverse expertise spanning environmental, social, and governance dimensions, and integrate ESG considerations into strategic decision-making rather than treating disclosure as merely a compliance activity.

For investors, China's disclosure framework offers both opportunities and challenges in assessing the sustainability performance of Chinese companies. The standardization efforts underway promise more comparable

and reliable information, potentially enhancing investment decision-making. However, the distinctive features of China's approach, including its double materiality concept and emphasis on contribution to national development priorities, require investors to develop nuanced understanding of the Chinese context rather than applying evaluation frameworks developed primarily for Western markets.

For global standard-setters, China's distinctive approach to ESG disclosure contributes to the ongoing conversation about how to achieve meaningful international harmonization while respecting diverse national contexts. Rather than pursuing rigid uniformity, China's experience suggests the value of identifying core principles and structures that can be shared across jurisdictions while allowing for adaptation to different economic, social, and governance models. This "harmonization with diversity" approach may offer a more realistic and inclusive path toward global sustainability reporting convergence.

In conclusion, China's ESG disclosure system represents a significant and distinctive contribution to global sustainability reporting practices. By developing an approach that balances international alignment with Chinese characteristics, mandatory requirements with voluntary best practices, and standardization with sector-specific guidance, China offers valuable insights for both theory development and practical implementation of ESG disclosure worldwide. As this system continues to evolve toward full implementation by 2030, its influence on global sustainability reporting harmonization efforts will likely grow, potentially contributing to more inclusive and effective approaches to directing capital toward sustainable development globally.

Data availability statement: All data used in this research are derived from publicly available literature, regulatory documents, and industry reports. Policy documents referenced in this study can be accessed through the official websites of relevant Chinese government departments, including the Ministry of Finance, China Securities Regulatory Commission, Shanghai Stock Exchange, Shenzhen Stock Exchange, and Beijing Stock Exchange. Industry reports and analyses are available through the official channels of the cited organizations. Academic literature can be accessed through relevant scholarly databases. This research did not utilize proprietary datasets requiring special access permissions. For specific data sources referenced in this study, please consult the complete reference list at the end of the paper.

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