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Impact of CT Complexation and Adsorption on Antimicrobial Activity: Biochemical Mechanism and Statistical Analysis

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KEYWORDS

Antibiotic synergy;
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Sulfamerazine;
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Antimicrobial mechanism;
Density functional theory

ABSTRACT

To address the antibiotic resistance crisis, this study developed a novel antibiotic synergy strategy by constructing charge-transfer complexes of ofloxacin/sulfamerazine with three natural organic acids. Experiments demonstrated that the complexes significantly enhanced antibacterial activity against Escherichia coli and Staphylococcus aureus (increased inhibition zones, decreased MIC). Mechanistic studies revealed that the complexation achieved synergistic enhancement by optimizing antibiotic charge states, improving surface morphology, and enhancing membrane permeability, providing new insights for antimicrobial agent development.

INTRODUCTION

The global spread of antibiotic resistance (AMR) poses a severe threat to public health, compelling researchers to explore synergistic strategies beyond traditional antibiotic development [1]. In this context, the formation of antibiotic complexes through charge-transfer (CT) interactions with other molecules has garnered attention in recent years as a potential approach for enhancing antibacterial efficacy. Early research primarily focused on the fundamental scientific aspects of CT complexes, including their synthesis, spectroscopic properties, and interactions with biological macromolecules such as DNA and serum albumin [2, 3]. For instance, Mansour et al. investigated the DNA/bovine serum albumin binding and cytotoxicity of ternary metal complexes based on sulfamethazine and bromazepam drugs [4]. The Chohan team systematically synthesized sulfonamide-derived compounds and their transition metal complexes, evaluating their antibacterial, antifungal, and cytotoxic activities [5, 6]. These studies preliminarily confirmed that the biological activities of antibiotic-like compounds could be modulated through molecular design and metal coordination modification.

However, existing research has predominantly focused on combining antibiotics with synthetic receptors (e.g., quinones, metal centers) or utilizing them to construct metal complexes. In contrast, there has been insufficient exploration of the CT interactions between antibiotics and environmentally prevalent, biocompatible small organic acids serving as natural electron acceptors, and their practical impact on antibacterial activity. Meanwhile, although studies such as Pandya et al.'s work on the visible light-driven photocatalysis, quantum chemical calculations, and DNA binding studies of nickel complexes of sulfadiazine [7], and Sabt et al.'s DFT calculations and molecular dynamic simulations of quinoline-based derivatives [8] demonstrate the powerful capability of computational chemistry in elucidating mechanisms of

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action, these theoretical tools have seldom been applied to systematically reveal how the formation of antibiotic-small organic molecule CT complexes alters the physicochemical properties of the parent drug at the electronic level and subsequently influences its entire interaction process with bacterial cells.

To this end, we employed a combined approach of spectroscopy and density functional theory (DFT) calculations to confirm the formation and characteristics of CT interactions at the molecular level. Subsequently, we quantitatively evaluated the changes in antibacterial activity of the CT complexes against Gram-negative (Escherichia coli) and Gram-positive (Staphylococcus aureus) bacteria using the agar well diffusion method and broth microdilution method, supported by rigorous statistical analysis. Finally, we innovatively correlated theoretically obtained electronic structure parameters (such as HOMO-LUMO gap, charge distribution), the pKa properties of the antibiotics, and the ζ -potential of bacterial surfaces with experimentally measured antibacterial activity data. This allowed us to construct a coherent molecular mechanism model linking electronic structure changes to cell surface adsorption and ultimately to biological effects. This study not only provides a new perspective for understanding the environmental behavior of antibiotics but also aims to establish a solid theoretical and experimental foundation for the development of antibiotic synergy strategies based on the CT principle.

Following the comprehensive spectroscopic and computational characterization of the CT complexes formed between antibiotic donors (OFL, SMR) and organic acid acceptors (COA, CNA, SAA), this section aims to evaluate the practical biological implications of these interactions. Specifically, we investigated the impact of CT complexation and potential adsorption effects on the antibacterial efficacy against two model strains: the Gram-negative bacterium *Escherichia coli* (ATCC25922) and the Gram-positive bacterium *Staphylococcus aureus* (ATCC29213). A dual-method approach (agar well diffusion and broth microdilution) was employed to quantify antibacterial activity, supported by statistical analysis. Furthermore, the molecular mechanisms underlying the observed activity changes are rationalized based on the pKa properties of the antibiotics, their charge states, and the ζ -potential-related adsorption behavior, providing a biochemically grounded interpretation of the CT-enhanced antibacterial effects.

1.Materials and Methods

1.1Materials

This work aims to address this knowledge gap. We selected clinic ally common ofloxacin (OFL) and sulfamerazine (SMR) as model electron donors, along with environmentally relevant natural small organic acids (coumaric acid COA, cinnamic acid CNA, salicylic acid SAA) as electron acceptors, to construct novel CT complexes. Moving beyond the traditional characterization of CT complexes。

1.2 Agar Well Diffusion Assay

The agar well diffusion method was used for a preliminary qualitative and semi-quantitative assessment of antibacterial activity. Briefly, sterilized agar medium (2.35 g/100 mL LB agar) was poured into Petri dishes and allowed to solidify. Bacterial suspensions (adjusted to ~10^8 CFU/mL from logarithmic-phase cultures) were evenly spread on the agar surface. Wells (6 mm diameter) were punched into the agar, and 50 µL of each test solution (individual compounds and CT complexes at a fixed concentration of 64 µg/mL) was added to respective wells. Plates were incubated at 37 ° C for 18–24 h. The diameter of the inhibition zone (including the well diameter) was measured in triplicate, and the average ± standard deviation was calculated.

1.3.Statistical Analysis

All experiments were performed in triplicate (n=3). Data are presented as mean ± standard deviation. Statistical significance was determined using one-way analysis of variance (ANOVA) followed by Tukey's post-hoc test for multiple comparisons. A p-value of less than 0.05 was considered statistically significant. Analyses were performed using GraphPad Prism software (Version 9.0).

2.Results and Discussion

2.1.Enhanced Antibacterial Activity of CT Complexes

The antibacterial activity data, summarized in Table 1.1 (MIC values) and Table 1.2 (Inhibition zone diameters), unequivocally demonstrate that CT complexation

significantly enhances the antibacterial potency of both OFL and SMR against both bacterial strains.

MIC Analysis: The CT complexes consistently exhibited lower MIC values compared to their parent antibiotic donors. For instance, the MIC of OFL against *S. aureus* decreased from 40 µg/mL to 19.2, 15.0, and 14.1 µg/mL for the OFL-COA, OFL-CNA, and OFL-SAA complexes, respectively. A similar trend was observed for SMR complexes and against *E. coli.* Notably, the SMR-SAA complex showed the lowest MIC (12.6 µg/mL) against *E. coli.*

Inhibition Zone Analysis: Corroborating the MIC results, the agar well diffusion assay showed that the CT complexes produced larger inhibition zones than the individual components. For example, the inhibition zone for OFL-COA against *E. coli* was 9.44 ± 0.42 mm, significantly larger than that for OFL alone (8.44 ± 0.40 mm). The complex with the largest average zone was OFL-SAA against S. aureus (12.00 ± 0.38 mm).

Compound	*E. coli* (ATCC25922)	*S.aureus* (ATCC29213)
COA	44.3	32.0
CNA	16.61	27.4
SAA	>64*	48.0
OFL	26.0	19.1
SMR	36.0	30.0
OFL-COA	24.0	19.2
OFL-CNA	15.1	15.0
OFL-SAA	15.2	14.1
SMR-COA	15.4	14.2
SMR-CNA	14.0	14.8
SMR-SAA	12.6	14.0

***Incomplete inhibition at highest tested concentration.**

Table.1.1. Minimum Inhibitory Concentration (MIC, µg/mL) of antibiotics and their CT complexes.

Compound	*E. coli* (ATCC25922)	*S. aureus* (ATCC29213)
COA	6.44 ± 0.38	7.44 ± 0.83
CNA	7.44 ± 0.22	6.44 ± 0.24
SAA	7.44 ± 0.32	7.44 ± 0.32
OFL	8.44 ± 0.40	7.44 ± 0.34
SMR	8.44 ± 0.23	8.44 ± 0.28
OFL-COA	9.44 ± 0.42	9.44 ± 0.32
OFL-CNA	10.44 ± 0.31	10.00 ± 0.22
OFL-SAA	11.00 ± 0.41	12.00 ± 0.38
SMR-COA	10.44 ± 0.33	10.44 ± 0.23
SMR-CNA	9.44 ± 0.24	10.20 ± 0.24
SMR-SAA	9.66 ± 0.25	8.93 ± 0.28

Table.1.2. Inhibition zone diameters (mm, mean ± SD, n=3) for antibiotics and CT complexes (64 µg/mL).

2.2.Molecular Mechanism: Synergy of CT Complexation and Adsorption

The enhanced antibacterial activity can be attributed to a synergistic mechanism involving improved cellular penetration via CT-induced charge modulation and increased local concentration via adsorption, as elucidated by our spectroscopic, microscopic, and computational data.

2.3.pKa-Driven Charge State Optimization and Membrane Interaction

The pKa values of OFL (carboxyl ~6.0, piperazinyl amine ~8.3) and SMR (sulfonamide ~7.4) dictate their charge states at physiological pH (~7.4). OFL exists as a zwitterion, while SMR is partially deprotonated. The organic acid acceptors (COA, CNA pKa~4.2; SAA pKa~2.9) are predominantly anionic ($-COO^-$). CT complexation, confirmed by UV-Vis redshifts and FTIR hydrogen bonding signatures (N-H···O, O-H···O), facilitates a favorable charge reorganization. This interaction can effectively reduce the net negative charge or create localized positive patches on the antibiotic molecule. Since bacterial membranes (particularly of E. coli, ζ -potential ≈ -25 mV) are negatively charged, this CT-mediated charge optimization reduces electrostatic repulsion, thereby enhancing the initial adsorption and association of the antibiotic complex with the bacterial cell envelope.

24.Adsorption Enhancement via Altered Physicochemical Properties:

The SEM analysis revealed that the CT complexes possess distinct and often more adsorption-favorable morphologies compared to the individual components. For instance, the COA-SMR complex formed large, rough clusters with surface pores, and the SAA-SMR complex displayed a

columnar structure with elongated pores. These structural features significantly increase the effective surface area and porosity, promoting physical adsorption onto the bacterial surface. This adsorption effect acts as a "reservoir," maintaining a high localized concentration of the active antibiotic at the cell surface, which is reflected in the lower MIC values. The correlation between larger inhibition zones (indicative of better diffusion and potency) and these morphologies supports this claim.

2.5.Facilitated Intracellular Delivery and Target Engagement:

DFT calculations provide crucial insights at the electronic level. The reduced HOMO-LUMO gap (Egap) observed for the OFL-based complexes (e.g., 3.59 eV for COA-OFL vs. ~4.1-4.5 eV for SMR-based complexes) indicates higher chemical reactivity and polarizability. This favors stronger interactions with biological membranes. The HOMO was localized on the donor's aromatic ring, while the LUMO was on the acceptor or shared, confirming the CT character. This electronic redistribution likely improves lipophilicity or creates a more amphiphilic character, easing passage through the lipid bilayer of the cell membrane, especially critical for penetrating the thick peptidoglycan layer of S. aureus. Once inside, the complex may dissociate or interact as a whole with its target (e.g., DNA gyrase for OFL, dihydropteroate synthase for SMR), with the initial CT interaction having served as a “Trojan horse” delivery mechanism.

Conclusion

In summary, the antibacterial activity studies confirm that charge-transfer complexation between OFL/SMR and small organic acids (COA, CNA, SAA) leads to a statistically significant enhancement in antibacterial potency against both E. coli and S. aureus. This enhancement is not merely additive but synergistic, arising from a coherent molecular mechanism: (i) CT interaction optimizes the antibiotic's charge state for reduced electrostatic repulsion with bacterial cells, (ii) the resulting complex exhibits a morphology conducive to surface adsorption, increasing local drug concentration, and (iii) electronic structure modifications (smaller Egap) potentially facilitate membrane penetration and intracellular delivery. These findings highlight the potential of strategically designing CT complexes as a viable approach to rejuvenate or enhance the efficacy of existing antibiotics

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Research on Tourism Economic Development in Hainan Free Trade Port: Policy Innovation and Path Optimization

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KEYWORDS

Hainan free trade port;

Eourism economy;

Policy innovation;

International tourism consumption center;

Comparative study

ABSTRACT

This study focuses on the tourism economic development under the background of the Hainan Free Trade Port. Through a systematic review of its current development status, analysis of its policy system, and horizontal comparison with similar domestic and international tourist destinations, it delves into Hainan's unique advantages, shortcomings, and challenges in this process. The study finds that Hainan, leveraging its dual strategic positioning as a "Free Trade Port" and an "International Tourism Consumption Center," has conducted numerous cutting-edge policy explorations in areas such as tourism opening-up and internationalization of consumption, resulting in a significant "policy synergy effect." However, its tourism product structure, service quality, and international competitiveness still need improvement. Based on this, this paper proposes targeted optimization schemes for the high-quality and sustainable development of Hainan's tourism economy from the dimensions of policy support, product innovation, service quality, and talent development.

INTRODUCTION

Since the central government entrusted Hainan with the significant historical mission of building a free trade pilot zone and a free trade port with Chinese characteristics in 2018, this tropical island has ushered in a golden opportunity in its development history. Among these opportunities, the clearly defined strategic positioning as an "international tourism consumption center" has propelled tourism to the core stage of Hainan's economic development. Recently, the formal implementation of the "Hainan Free Trade Port Tourism Regulations" has further consolidated the strategic position of the tourism industry through legislation and provided a solid legal guarantee for its development. Against this backdrop, in-depth research into the development path of Hainan Free Trade Port's tourism economy is not only crucial for the high-quality development of the regional economy but also has significant pioneering and demonstrative significance for China's tourism industry's exploration under a higher level of openness. This article, based on Hainan's provincial conditions and the latest policy developments, aims to outline the current landscape and future direction of Hainan Free Trade Port's tourism economic development through comparative analysis

1.The Current State of Hainan's Tourism Economy: Opportunities and Challenges Coexist

1.1.Tourism Economy Scale and Growth Drivers

In recent years, Hainan's tourism economy has shown strong growth momentum, one of the core driving forces of which is the unique offshore duty-free policy. We have observed that with the continuous release of policy dividends, duty-free shopping has become a "golden signboard" to attract tourists. For example, during the recent National Day and Mid-Autumn Festival holidays, the sales amount of duty-free shopping in Hainan exceeded 944 million yuan, an increase of 13.6% year-on-year, and the number of shoppers exceeded 120,000. This set of impressive data directly

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confirms the strong traction of the policy on tourism consumption [1] .

Meanwhile, Hainan's tourist source structure is showing a welcome international trend. Benefiting from the visa-free policy for citizens of 86 countries, Hainan's inbound tourism market continues to heat up. Related data shows that during the National Day holiday in 2025, Haikou entered the top ten most popular domestic cities for foreign tourists for the first time, which is undoubtedly a positive signal, indicating that Hainan's international attractiveness is steadily increasing.

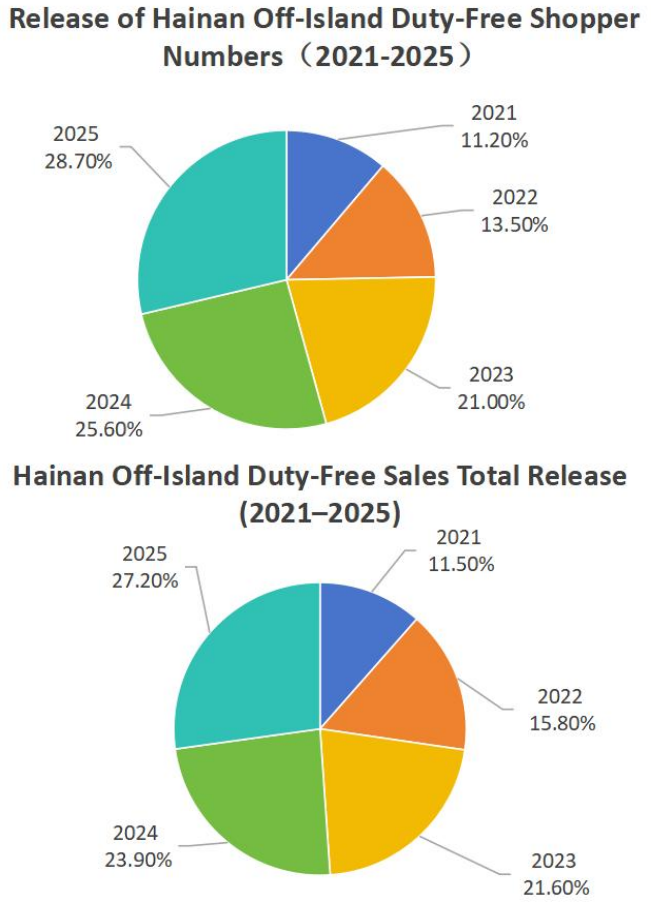

Fig.1. Growth Trends in Hainan's Offshore Duty-Free Sales and Tourist Numbers (2021-2025)

Chart description: This chart intuitively reflects the strong driving effect of the offshore duty-free policy on Hainan's tourism economy. Data shows that duty-free sales and the number of shoppers have shown a continuous and rapid growth trend, especially after 2023, the growth rate has accelerated, highlighting the policy dividend release effect [2] .

Data source: Compiled from publicly available data released by the Hainan Provincial Department of Tourism, Culture, Radio, Television and Sports and Haikou Customs over the years.

1.2.Diverse Business Formats and Structural Characteristics

After years of development, Hainan has gradually broken away from its past development model that relied solely on coastal tourism, and has initially formed an industrial pattern in which coastal resorts are the leading sector, with duty-free shopping, medical and health care, and convention and exhibition businesses developing in synergy. Taking Sanya, a major tourist city, as an example, its Haitang District, Jiyang District, and Tianya District have all been selected as among the top 100 districts in China in terms of tourism competitiveness. The average number of tourists received and the total tourism revenue have all achieved double-digit growth, leading the national average growth rate and becoming an important engine for driving Hainan's tourism economic growth.

Specifically, each region has developed its own differentiated development path based on its own resources: Haitang District has gathered high-end projects such as Atlantis and Sanya International Duty-Free City, becoming a luxury resort and shopping paradise; Tianya District focuses on developing new and trendy industries such as cruise ships, yachts, and low-altitude flights; and Jiyang District explores the integration model of "agriculture + tourism", presenting a diversified panoramic view of Hainan tourism.

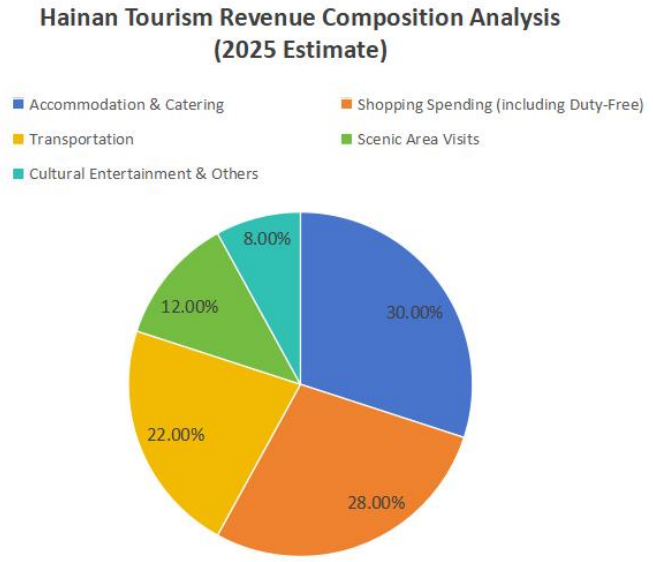

Fig.2. Analysis of Hainan Tourism Revenue Composition Chart (2025 Forecast)

Chart Description: This chart shows the revenue structure of Hainan's tourism economy. Although traditional basic

consumption of "eating, accommodation and transportation" still accounts for the majority, "shopping" consumption with duty-free shopping on the island as the core has become the second largest source of income, while the proportion of in-depth experience consumption such as "culture, entertainment and leisure" is still relatively small, clearly revealing the advantages and disadvantages of Hainan's tourism economy in terms of consumption structure [3] .

Data source: Based on historical data and development trend forecasts from Hainan Provincial Bureau of Statistics and Hainan Provincial Department of Tourism, Culture, Radio, Television and Sports.

1.3.Spatial layout and Coordinated Regional Development

From a spatial perspective, Hainan's tourism economy presents a clear pattern of "comprehensive tourism in the north, resort tourism in the south, and east-west corridors." This layout is both a rational response to its resource endowment and a reflection of the guiding role of strategic planning.

However, we must be soberly aware that the problem of unbalanced regional development still exists. Tourism resources and development enthusiasm are highly concentrated in the southeast coastal areas, while the potential of the central and western regions has not yet been fully released. It is gratifying that with the advancement of major infrastructure projects such as the island ring road and the tropical rainforest national park road, this situation of "hot in the east and cold in the west" is expected to be broken, creating new possibilities for the balanced development of tourism across Hainan [4-5] .

2.SWOT Analysis of Hainan Free Trade Port Tourism Policy

2.1.Advantages

Hainan Province is located at the southernmost tip of China and is the only tropical island province. It has a unique geographical location and a pleasant climate. Hainan's tourism industry started early and has accumulated rich industry experience. It attracts a large number of tourists every year and has formed a relatively complete tourism ecosystem. Hainan Province's geographical advantage of being surrounded by the sea on all sides provides excellent conditions for the development of water sports. Diving, surfing and other water sports have therefore become popular features among tourists. With the in-depth advancement of the construction of the free trade port and the continuous improvement of the duty-free shopping policy, the offshore duty-free has become a very attractive feature of Hainan in the domestic tourism market, and its irreplaceable nature continues to stand out [6] .

Against the backdrop of the construction of the Hainan Free Trade Port, a series of supporting policies and measures introduced by the national and local governments have provided solid institutional support for the high-quality development of the tourism industry. For example, preferential policies in areas such as financial support, tax breaks, and land supply have created a favorable policy environment for investment and project implementation in Hainan's tourism industry. The continued implementation of these policies has not only effectively guided more social capital towards the development and construction of high-quality tourism projects in Hainan, but also promoted collaborative innovation and coordinated development among upstream and downstream enterprises in the tourism industry chain, significantly enhancing the overall competitiveness and brand influence of Hainan's tourism industry in domestic and international markets.

2.2.Disadvantages

The tourism industry in Hainan is affected by the geographical environment and has obvious seasonal characteristics and a relatively simple tourism product structure. In the existing product system, there is still a lack of in-depth experience projects and differentiated design projects, which to some extent affects its attractiveness to tourists who pursue diversified experiences. Although Hainan has rich natural landscapes and unique cultural resources, the existing tourism products are still too concentrated on the traditional seaside sightseeing model, and the in-depth exploration of cultural connotations and the full release of characteristic experience value are still insufficient. For example, although water sports such as diving and surfing have market potential, due to the need to improve the development level and the lack of a cluster of characteristic brands with widespread recognition, it is difficult to fully meet the growing diversified and quality

needs of tourists. In addition, the planning and development of festival tourism products are relatively weak, and the local cultural resources have not been fully utilized for effective integration and innovation, resulting in a relatively obvious phenomenon of tourism product homogenization [7] . This relatively simple product structure may not only limit the length of stay and consumption intention of tourists, but also put Hainan under certain pressure in the differentiated competition of the international tourism market.

In terms of marketing, Hainan Province faces challenges such as insufficient marketing precision, weak brand promotion, and unclear domestic and international market positioning, which hinder the growth of tourism revenue. Firstly, Hainan's ability to accurately target markets using big data technology is inadequate, affecting the efficiency of marketing resource allocation. Secondly, brand promotion efforts are insufficient, particularly in enhancing international brand awareness and influence, failing to effectively cultivate an attractive cultural tourism brand image. Finally, Hainan's positioning in domestic and international markets is unclear; it has neither fully tapped into the needs of high-end domestic consumers nor developed differentiated marketing strategies for the international market, which to some extent affects the effectiveness of customer acquisition. These marketing shortcomings not only restrict the expansion of Hainan's tourism market but also hinder the release of its international tourism revenue potential.

2.3.Opportunities

Against the backdrop of the new development pattern of "dual circulation" and the in-depth advancement of the construction of Hainan Free Trade Port, Hainan's tourism industry has ushered in multiple development opportunities. First, the strengthening of the domestic circulation has provided Hainan with a continuously growing source of tourists. The trend of upgrading domestic residents' consumption is obvious, and the demand for high-quality, diversified, and experiential tourism is increasingly strong. As a popular domestic tourist destination, Hainan's unique resources such as coastal resorts, tropical rainforests, and duty-free shopping are highly compatible with this demand upgrading direction. Second, the window of opportunity for international circulation is opening. The policy dividends of Hainan Free Trade Port, such as more open air rights policies, visa-free policies, and optimized offshore duty-free policies, have significantly enhanced its international attractiveness and created favorable conditions for developing the international high-end tourist market and deepening cooperation with international tourism organizations and enterprises. The recovery trend of the global tourism market has also provided Hainan with an opportunity to attract international tourists. Third, the accelerated process of regional economic integration, especially the deepening of cooperation with Southeast Asian countries, has provided potential opportunities for Hainan to develop cruise tourism, cross-border tourism, and build a regional tourism hub. Finally, the continuous focus of national strategies has provided strong support for the development of Hainan's tourism industry [8] . The convergence of a series of national strategies, including the "dual-ring" development strategy, the construction of an international tourism consumption center, and the development of a free trade port, has endowed Hainan with unique advantages in policy innovation, industrial openness, and resource aggregation, opening up vast space for the transformation, upgrading, and international development of the tourism industry. These opportunities collectively constitute a favorable external environment for Hainan's tourism economy to achieve high-quality development under the new "dual-ring" development pattern.

2.4.Threats

Against the backdrop of the new "dual circulation" development pattern and the construction of the Hainan Free Trade Port, Hainan Province's tourism industry has achieved remarkable results, but it still faces challenges. How to effectively utilize policy advantages, while adhering to the principles of rational resource utilization and green innovation, to improve the industrial structure and promote high-quality development is one of the key challenges related to the success of the Hainan Free Trade Port construction.

3.Strategies for Building a Health Tourism Model in Hainan under the Background of the Hainan Free Trade Port

3.1.Rational Use of Resources

xHainan Free Trade Port boasts a superior ecological environment and abundant medicinal plant and animal resources, which are conducive to the management and improvement of various chronic diseases. This supports the development of health-related industries such as health care products and agriculture. Furthermore, during the construction of the Free Trade Port, various transportation facilities, such as the island ring road and transportation hubs, have been gradually improved, providing the necessary infrastructure for tourism development. In addition, the Free Trade Port's significant policy advantages facilitate the aggregation of information, capital, and other resources to local industries, providing strong support for the development of health tourism models. In terms of resource utilization, Hainan possesses 1944 kilometers of coastal natural ecological resources, allowing for the design of marine-themed health tourism activities. It can also leverage Hainan's rich tropical rainforest resources to develop health tourism projects such as forest oxygen bar therapy, creating a unique Hainan health tourism model based on local ecological and natural resources. In this process, advanced medical industry resources can be introduced to build a number of ecological health and wellness bases in Hainan, providing one-stop services such as ecological health management and medical services. For example, in June 2024, Boao Lecheng launched the "Healthy Island, Happy City" medical tourism brand. This brand combines physical and mental healing with local coastal environmental resources to create a coastal healing health tourism product. It integrates local medical and tourism resources, allowing tourists to not only play in the surrounding scenic spots but also enjoy high-end health and wellness services, forming a health tourism model with Hainan characteristics. However, in the process of utilizing natural and ecological resources, we should adhere to the concepts of green, low-carbon, and environmental protection, strengthen tourists' environmental awareness education, advocate green tourism and civilized tourism, and realize the green development of Hainan's health tourism model in all aspects [9] .

The cultures of the Li and Miao ethnic groups in Hainan, as well as the Qiong culture and the culture of Lady Xian, are highly distinctive regional features. These high-quality cultural resources can be utilized to integrate into health tourism through experiential tours and performances, adding tourism projects with Hainan cultural characteristics to tourism products and creating local health and cultural tourism products.

3.2.Improve Industrial Iayout

To address Hainan's past reliance on a single industrial structure and excessive dependence on tourism, the development of a health tourism model should be leveraged to actively connect tourism with other industries, allowing tourism to drive the development of other sectors and enhance the overall effectiveness of health tourism development. In this context, the industrial layout should be actively improved, and the integration of health tourism with medical, elderly care, and sports industries should be promoted to build a complete industrial chain and cluster. This will leverage the synergistic effect of industrial development, enhance the overall effectiveness of the health tourism model, and better promote local economic development. Currently, the Hainan Free Trade Port possesses core policies of "zero tariffs, low tax rates, simplified tax system, and five freedoms and conveniences, and one safe and orderly flow." In terms of industrial layout, we should make full use of the above-mentioned policy advantages, attract international advanced medical equipment, medicines and traditional Chinese medicine technology to Hainan, improve the level of medical care, support the integration of medical care and tourism industries, improve the quality of health tourism products, actively introduce intelligent and information technology, create intelligent and convenient elderly care service facilities, build a number of health towns, health communities and health resorts, provide high-quality health and elderly care services for sub-healthy people and elderly tourists, thereby promoting the integrated development of tourism industry and elderly care industry, while actively promoting the integration of medical services and elderly care services to achieve the sharing and optimization of medical and elderly care resources, improve the quality and professionalism of elderly services, and create more high-quality health tourism products. In addition, Hainan's natural resources and climate conditions can also promote

sports tourism, build and develop water sports, mountain sports, outdoor expansion and other sports tourism projects, combine tourism and sports industry by building sports venues, sports bases and hosting international sports events, form a strong sports tourism brand, develop a variety of health tourism products, and improve the market competitiveness of Hainan's health tourism [10] . Ultimately, the goal is to develop Hainan's health tourism industry towards high-end, intelligent, and green development, cultivate a number of internationally competitive health tourism enterprises, achieve industrial clusters, and improve the overall development efficiency of Hainan.

3.3.Strengthen the Development of Tourism Products

In developing specific tourism products, consideration can be given to focusing on the six key elements of food, accommodation, transportation, sightseeing, shopping, and entertainment, designing rich and diverse health tourism projects to provide tourists with a comprehensive and high-quality health tourism experience. In the development of tourism products, the abundant local tropical fruits, seafood, and other specialty ingredients should be fully utilized to develop healthy and nourishing cuisine, introducing international healthy eating concepts to create high-quality catering solutions. Dedicated healthy dining areas should be set up in scenic spots, hotels, and other tourist venues to provide tourists with a high-quality and convenient healthy dining experience. By holding healthy food festivals, cooking competitions, and other activities, tourists can be attracted while enriching the depth and breadth of tourism products. Regarding accommodation, leveraging the local natural environment advantages, clusters of health and wellness hotels and resorts should be developed, introducing intelligent and green health and wellness accommodations to further optimize the quality of tourism products. In terms of transportation, more health walking trails and cycling paths should be built to provide convenience for citizens and tourists to exercise and relax, and facilities such as health stations should be built along the coastal highways of Hainan Island to further enhance the tourist travel experience. In terms of scenic tourism, local culture and natural resources can be fully utilized to create health-themed scenic areas and related activities, and to organize health tourism festivals to enrich tourists' experiences. Regarding shopping, local characteristics should be leveraged to develop health-themed tourism products, such as organic foods, and dedicated shopping areas should be set up in various tourist and shopping venues. The duty-free shopping policy of the Hainan Free Trade Port should also be actively utilized to improve supporting duty-free shopping facilities, accelerate the improvement of shopping services, and optimize the shopping environment to better meet tourists' shopping needs. In terms of entertainment, diverse health-themed recreational activities should be designed, such as beach yoga. By developing in a coordinated manner across the six aspects of food, accommodation, transportation, sightseeing, shopping, and entertainment, the quality of tourism products can be further optimized to provide tourists with more healthy tourism experiences.

Conclusion and Outlook

In conclusion, the establishment of the Hainan Free Trade Port has provided significant support for the development of Hainan's tourism industry in multiple aspects, including policy, transportation, and healthcare. Looking back, by implementing the aforementioned optimization strategies, the possibility of Hainan's tourism industry achieving leapfrog development in terms of scale, quality, and efficiency will be significantly enhanced. Based on the new development pattern of " digital economy and green tourism , " Hainan should fully unleash its potential as an international tourism island. Strengthening tourism talent cultivation and improving the service standardization system will effectively improve the quality of tourism services, increase tourist satisfaction and repeat visit rates, thereby promoting the transformation of Hainan's cultural and tourism industry towards high-quality development and accelerating the construction of the Hainan Free Trade Port.

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Breaking Through Dilemmas and Innovating: An Analysis of the Current Situation and Development Paths of Track and Field Teaching in Middle Schools

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KEYWORDS

Middle school track and field;

Physical education Teaching;

Teaching innovation;

Lifelongsports;

Health first;

ABSTRACT

As a fundamental component of school physical education, track and field plays an irreplaceable role in enhancing students' physical fitness and fostering their willpower. This study focuses on track and field teaching in middle schools, employing research methods such as literature review, questionnaire survey, and interviews. It systematically analyzes the practical dilemmas faced by current middle school track and field teaching in aspects like teaching philosophy, resource allocation, and student participation. Combined with the policy orientation of educational reform and the background of technological development, the study examines the challenges and opportunities in its development process. Finally, targeted development strategies are proposed from the dimensions of concept renewal, content innovation, teacher team construction, and resource optimization. The aim is to provide practical references for promoting the high-quality development of middle school track and field teaching and implementing the educational concept of "Health First".

INTRODUCTION

1.1.Research Background and Significance

Known as the "mother of sports", track and field serves as the foundation for various sports. Its basic movement forms, including walking, running, jumping, and throwing, are closely related to students' daily activities and occupy a core position in the middle school physical education system. With the issuance of policy documents such as the "Opinions on Deepening the Integration of Sports and Education to Promote the Healthy Development of Adolescents", school physical education has been elevated to a more important strategic height. As a core part of school physical education, the quality of track and field teaching is directly related to the realization of the goal of improving adolescents' physical health.

Current physical health monitoring data of middle school students shows that some students have a downward trend in core physical fitness indicators such as endurance and strength, which is related to the weakening of track and field teaching. Against this backdrop, conducting a systematic study on the current situation of middle school track and field teaching, accurately identifying its development bottlenecks, and exploring innovative paths can not only provide theoretical support for improving the quality of middle school track and field teaching, but also have important practical significance for cultivating middle school students' good sports habits, laying a solid foundation for lifelong sports, and promoting the reform of school physical education.

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1.2.Research Status at Home and Abroad

From the perspective of foreign research, developed countries in Europe and America have integrated track and field into the youth physical education system at an early stage. Relevant studies mainly focus on the correlation between track and field teaching and youth health promotion, and the construction of personalized teaching models. For example, American scholars have found through long-term follow-up studies that regular basic track and field training can effectively reduce the obesity rate of adolescents and improve their cardiopulmonary function. Germany implements a "modular teaching" approach in middle school track and field teaching, designing teaching content based on students' interests and physical differences, which has significantly improved students' participation. These studies provide valuable references for middle school track and field teaching in China, but due to differences in educational systems and cultural backgrounds, their achievements need to be localized in combination with China's actual situation.

In terms of domestic research, studies on middle school track and field teaching have gradually increased in recent years, mainly focusing on the investigation of teaching status and problem analysis. Some scholars, through surveys in middle schools in different regions, have pointed out that current track and field teaching has problems such as boring content, single methods, and insufficient resources. There are also studies focusing on the innovation of teaching methods, proposing to integrate gamified teaching and situational teaching into track and field classes. However, existing studies still have shortcomings: first, the systematic analysis of teaching dilemmas is not in-depth enough, mostly staying at the description of surface phenomena; second, innovative strategy research combining technological means and policy backgrounds is relatively scarce, which is difficult to meet the actual needs of current educational reform. Based on this, this study constructs a more comprehensive research framework with the logical main line of "dilemma-opportunity-strategy" to make up for the shortcomings of existing research.

1.3.Research Methods and Innovations

This study comprehensively adopts multiple research methods to ensure the scientificity and effectiveness of the research: first, the literature review method, which systematically sorts out policy documents and academic achievements related to middle school track and field teaching and school physical education reform at home and abroad, laying a theoretical foundation for the research; second, the questionnaire survey method, which selects 800 students and 50 physical education teachers from 10 middle schools in different regions as survey objects, designs questionnaires on issues such as track and field teaching participation and teaching content satisfaction, and collects 762 valid student questionnaires and 48 valid teacher questionnaires to provide data support for the analysis of the current situation; third, the interview method, which selects 10 senior middle school physical education teachers and 5 physical education experts for in-depth interviews to obtain qualitative data on teaching dilemmas and development suggestions.

The innovations of this study are mainly reflected in two aspects: first, the systematic research perspective, which places middle school track and field teaching under the multiple backgrounds of educational reform, technological development, and the upgrading of social health needs, comprehensively analyzes the challenges and opportunities it faces, and avoids the limitations of single-dimensional research; second, the practicality of strategy proposal, which combines the results of questionnaire surveys and interviews to put forward specific and implementable innovative strategies for different problems, rather than making general remarks, thereby enhancing the practical guiding value of the research.

2.Challenges and Opportunities Faced by Middle School Track and Field Teaching

2.1.Challenge Analysis

2.1.1.Competitive Impact from Emerging Sports

With the diversified development of sports culture, emerging sports such as basketball, football, badminton, street dance, and skateboarding have quickly gained the favor of middle school students due to their high entertainment and social nature. Questionnaire surveys show that only 23% of students list track and field as their "most interesting sports project", while the proportions of students choosing basketball and football are 38% and 25% respectively. The

impact of emerging projects has caused track and field teaching to face an "attractiveness crisis". Some schools even reduce track and field teaching hours to cater to students' interests and allocate more resources to popular projects, further weakening the fundamental position of track and field. Compared with emerging projects, some traditional track and field contents (such as long-distance running and long jump) have strong competitiveness but relatively insufficient entertainment, making it difficult to gain an advantage in the competition with emerging projects.

2.1.2.Difficulties in Meeting Students' Personalized Needs

Middle school students have significant individual differences in physical fitness, interests, and sports foundations. Questionnaire surveys show that 45% of students believe that "the teaching content does not conform to their own interests", and 38% of students report that "the teaching difficulty is too high or too low". Traditional track and field teaching mostly adopts a one-size-fits-all model, requiring all students to meet unified standards, which is difficult to take into account the needs of different students. For example, students with good physical fitness feel bored with basic training, while students with weak physical fitness feel frustrated because they cannot complete the training tasks. At the same time, some students have the need for sports specialty development, such as hoping to improve their scores in the high school entrance examination for physical education through track and field training, or having the potential to become professional athletes. However, there is a lack of targeted training programs in current teaching, resulting in the inability to effectively meet personalized needs.

2.1.3.Safety Risks and Teaching Concerns

Track and field events such as running, jumping, and throwing have high requirements for physical explosive power and coordination. Improper teaching guidance or inadequate protective measures can easily lead to sports injuries. In interviews, 65% of teachers stated that "worrying about students' sports injuries" is the main concern in teaching. To avoid safety risks, some schools have adopted an overcautious approach, such as reducing high-risk teaching contents like long-distance running and hurdles, lowering training intensity, and even simplifying track and field classes into "free activities". This overly conservative teaching attitude not only affects the quality of track and field teaching but also violates the original intention of physical education to cultivate students' tenacious quality. In addition, the unclear responsibility identification mechanism after sports injuries further intensifies the teaching concerns of schools and teachers.

2.2.Opportunity Discussion

2.2.1.Strong Support from Educational Reform Policies

In recent years, the national government has intensively issued a series of policy documents supporting the development of school physical education, bringing policy dividends to middle school track and field teaching. The "Opinions on Deepening the Reform of School Physical Education in the New Era to Promote the Comprehensive Development of Students" clearly proposes to "strengthen the teaching of basic sports projects such as track and field", requiring track and field to be the core content of middle school physical education and ensuring sufficient teaching hours. At the same time, the reform of the high school entrance examination for physical education continues to advance. In most regions, track and field events (such as 1000m/800m running, standing long jump, and solid ball throwing) are included as mandatory items, and their score proportion is constantly increasing. This has to a certain extent enhanced the attention of schools, students, and parents to track and field teaching. The guiding role of policies provides a strong guarantee for consolidating the position and improving the quality of track and field teaching.

2.2.2.Comprehensive Improvement of Social Health Awareness

With the in-depth implementation of the "Healthy China" strategy, the whole society has significantly increased its attention to the health of adolescents, and the concept of national fitness has gradually taken root in people's hearts. More and more parents have begun to recognize the importance of track and field in improving their children's physical fitness and cultivating their willpower, and their

support for track and field teaching is constantly increasing. Questionnaire surveys show that 72% of parents say they "are willing to encourage their children to participate in track and field training". At the same time, the extensive development of various mass track and field events (such as campus mini-marathon and fun track and field sports meet) has provided more platforms for middle school students to participate in track and field, creating a good social atmosphere and laying a solid social foundation for the development of middle school track and field teaching.

2.2.3.Teaching Innovation Space Brought by Technological Development

The rapid development of modern technology has provided new possibilities for the innovation of middle school track and field teaching. Sports monitoring equipment (such as heart rate bracelets and sports cameras) can collect students' sports data in real-time, helping teachers accurately grasp students' training intensity and movement standardization, and realize "data-driven teaching"; Virtual Reality (VR) technology can simulate track and field training environments in different scenarios, such as simulating long-distance running competition scenarios, to enhance the entertainment and immersion of teaching; Online teaching platforms provide support for after-class expansion, allowing students to watch movement demonstration videos and obtain personalized training plans through the platform. In interviews, 80% of young teachers said they "are willing to try to integrate technological means into track and field teaching", and the integration of technology and teaching has become a development trend of middle school track and field teaching.

3.1.Renew Teaching Concepts and Anchor Core Goals

3.1.1.Establish the Dual Orientation of "Health First" and "Lifelong Sports"

Abandon the traditional teaching concept centered on competitive achievements, take "Health First" as the primary goal of track and field teaching, and focus on improving students' basic physical fitness and health literacy through track and field training. At the same time, strengthen the penetration of the "Lifelong Sports" concept, shift the teaching focus from "skill teaching" to "habit cultivation", guide students to recognize the fundamental value of track and field, and enable them to master sports methods that benefit them for life. For example, in long-distance running teaching, instead of simply pursuing speed improvement, personalized endurance improvement plans are formulated to cultivate students' perseverance and sports interests, enabling them to form the habit of "being willing to run and being good at running".

3.1.2.Construct a Personalized and Diversified Goal System

Combine students' individual differences to construct a three-level teaching goal system of "basic goals + expanded goals + specialty goals". Basic goals are for all students, focusing on the mastery of core skills such as walking, running, jumping, and throwing, and the improvement of basic physical fitness; Expanded goals are for students with high interests, setting contents such as track and field culture cognition and event organization; Specialty goals are for students with sports potential, formulating special training plans to lay a foundation for the cultivation of sports specialties. For example, in response to the needs of the high school entrance examination for physical education, differentiated training goals are formulated for students with different physical fitness levels: students with poor physical fitness take "completing the specified distance and improving endurance" as the goal, while students with good physical fitness take "breaking their personal best" as the goal.

3.2.Innovate Teaching Content and Methods to Enhance Attractiveness

3.2.1.Optimize Teaching Content and Integrate Interesting and Life-related Elements

Carry out "interesting transformation" of traditional track and field teaching content, and integrate games, competitions, and life scenarios into teaching. For example, combine sprinting with the "relay treasure hunt" game, where students need to find designated items while completing the sprint task, enhancing the interest of teaching; combine long jump with the scenario of "jumping over

obstacles to save partners" to improve students' participation enthusiasm. At the same time, increase track and field content closely related to life, such as "emergency escape running" and "load carrying", so that students can recognize the practical value of track and field skills in life. In addition, introduce fun track and field events (such as obstacle relay and soft equipment throwing) to enrich the teaching content system and reduce the competitive pressure of traditional events.

3.2.2.Adopt Diversified Teaching Methods to Stimulate Active Participation

Break through the traditional model of "teacher demonstration + student imitation" and promote diversified teaching methods. First, the hierarchical teaching method, which divides students into basic groups, improvement groups, and specialty groups according to their physical fitness and skill levels, and implements differentiated teaching; second, the group cooperative learning method, which divides students into several groups to carry out inter-group track and field competitions, cultivating students' teamwork ability; third, the situational teaching method, which stimulates students' learning motivation by creating scenarios such as "sports meet venue" and "Olympic champion growth". For example, in throwing teaching, create a scenario of "delivering materials to disaster areas", allowing students to cultivate a sense of social responsibility while completing the throwing task.

3.3.Strengthen Teacher Team Construction and Improve Teaching Ability

3.3.1.Improve the Teacher Training System

Educational administrative departments and schools should increase investment in the training of track and field teachers, and construct a three-dimensional training system of "pre-service training + in-service training + academic exchange". Pre-service training focuses on strengthening the mastery of track and field professional skills and teaching methods; in-service training promotes the improvement of teachers' teaching ability through regularly organizing teaching seminars and excellent lesson observation activities; actively build academic exchange platforms, organize teachers to participate in domestic and foreign track and field teaching seminars, and learn advanced teaching concepts and methods. At the same time, encourage teachers to conduct interdisciplinary learning, improve their technological application capabilities, and master the use of sports monitoring equipment and VR teaching tools.

3.3.2.Establish Incentive Mechanisms to Encourage Teaching Innovation

Schools should establish a scientific incentive mechanism to stimulate teachers' enthusiasm for teaching innovation. Incorporate track and field teaching innovation achievements into the teacher performance evaluation system, and commend and reward teachers who have made outstanding achievements in teaching innovation and student cultivation; set up a special fund for track and field teaching research to support teachers in carrying out teaching reform research and innovative practices; establish a teacher teaching innovation sharing mechanism, encourage teachers to promote successful teaching experiences, and form a virtuous cycle of "innovation-sharing-improvement".

3.4.Optimize Resource Allocation and Improve Teaching Conditions

3.4.1.Increase Investment and Improve Venue and Equipment Construction

Educational administrative departments should increase financial investment in middle school physical education, focusing on supporting the upgrading and transformation of track and field venues and equipment. For schools with limited venue space, the methods of "three-dimensional design" and "multi-functional utilization" can be adopted to optimize the venue layout and improve venue utilization efficiency; replace old and outdated equipment, and equip track and field equipment with high safety performance suitable for middle school students, such as soft javelins and elastic long jump mats. At the same time, establish a regular maintenance mechanism for venues and equipment to ensure teaching safety. In addition, encourage schools to develop simple track and field equipment based on actual conditions, such as using waste tires to make obstacle equipment, reducing teaching costs.

3.4.2.Promote Resource Sharing and Realize Balanced Development

Break the resource barriers between schools and regions, and promote the sharing of track and field teaching resources. On the one hand, establish a regional middle school physical education resource sharing platform, coordinate the allocation of venue and equipment resources, so that schools with insufficient resources can use the venues of surrounding schools for teaching; on the other hand, strengthen cooperation between schools and social sports venues, and use the high-quality resources of social venues for track and field teaching and training. For example, schools can sign cooperation agreements with local sports centers to organize students to carry out special track and field training in the sports centers, making up for the lack of internal resources. At the same time, promote the flow of high-quality track and field teaching resources to rural schools through forms such as "urban-rural school pairing assistance" to narrow the urban-rural gap.

3.5.Enrich Activity Carriers and Stimulate Students' Interests

3.5.1.Carry Out Diversified Campus Track and Field Activities

Schools should enrich the forms of campus track and field activities and create a strong track and field sports atmosphere. In addition to the traditional spring and autumn sports meets, track and field culture festivals, fun track and field carnivals, and campus mini-marathons can be held regularly to encourage more students to participate in track and field; establish track and field clubs to absorb students interested in track and field and carry out systematic special training and exchange activities; invite professional track and field athletes to enter the campus to give lectures and demonstrations, stimulating students' sports enthusiasm. For example, through the activity of "Track and Field Stars Entering Campus", students can interact closely with athletes and feel the charm of track and field.

3.5.2.Establish Scientific Evaluation and Incentive Mechanisms

Change the traditional evaluation method centered on skill testing, and establish a diversified evaluation system of "process + result + progress". Process evaluation focuses on students' participation, performance, and progress in track and field classes; result evaluation combines physical fitness testing and skill assessment; progress evaluation focuses on students' individual improvement, and affirms and rewards students with significant progress. At the same time, adopt diversified incentive methods, such as issuing honorary certificates such as "Progress Star" and "Best Participation Award", and providing material rewards such as sports supplies and after-class expansion activities to stimulate students' participation enthusiasm.

4.Conclusions and Prospects

4.1.Research Conclusions

Through the systematic research on middle school track and field teaching, this study finds that under the background of policy support and the improvement of social health needs, current middle school track and field teaching is facing good development opportunities, but at the same time, it is also confronted with multiple challenges such as the impact of emerging sports, difficulties in meeting personalized needs, and safety risk concerns. From the perspective of teaching practice, the core dilemmas of middle school track and field teaching are concentrated in the backward teaching concepts, single content and methods, insufficient teacher capabilities, unbalanced resource allocation, and low student interest.

To address the above problems, this study proposes to construct innovative development strategies from five dimensions: first, renew teaching concepts, establish the orientation of "Health First" and "Lifelong Sports", and build a personalized goal system; second, innovate teaching content and methods, integrate interesting elements, and adopt diversified methods such as hierarchical teaching and situational teaching; third, strengthen teacher team construction, improve the training system, and establish innovation incentive mechanisms; fourth, optimize resource allocation, increase investment in venues and equipment, and promote resource sharing; fifth, enrich activity carriers, carry out diversified campus track and field activities, and establish scientific evaluation and incentive mechanisms. The implementation of these strategies is expected to provide effective support for breaking through the dilemmas of middle school track and field teaching and improving teaching quality.

4.2.Future Prospects

With the continuous deepening of educational reform and the continuous development of science and technology, middle school track and field teaching will face a broader development space. In the future, middle school track and field teaching should further strengthen the integration with technology, promote the development of "intelligent track and field teaching", and use big data, artificial intelligence and other technologies to realize the precision and personalization of teaching; strengthen the collaboration with families and society, construct a "school-family-society" trinity track and field education system, and form an educational synergy; pay attention to the track and field teaching needs of special groups of students, such as designing adaptive track and field teaching content for students with weak physical fitness or disabilities, and promoting educational equity.

At the same time, continuous attention and research should be paid to middle school track and field teaching, and teaching strategies should be continuously optimized in combination with the changes of the times and students' needs, so that track and field can truly become an important carrier for improving the physical health of middle school students and cultivating their comprehensive quality, and contribute to the implementation of the "Healthy China" strategy and the all-round development of adolescents.

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Digital Project Management in the Construction Industry: Bim, Ai And Pmis as Drivers of Sustainable Performance

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Digital project management;

Building information modeling (BIM);

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Systems (PMIS);

Data integration

ABSTRACT

Digital transformation is transforming construction project management by redefining how information is created, processed and shared. Although Building Information Modelling (BIM), Artificial Intelligence (AI) and Project Management Information Systems (PMIS) have each shown value in improving efficiency, their combined effect on sustainability has not been well theorized. This extended conceptual paper responds to this gap by examining how the three technologies interact through data integration, predictive analytics and structured coordination to enhance environmental, economic and social performance. The discussion synthesizes recent research, highlights impact mechanisms, and clarifies organizational conditions for achieving sustainability outcomes.

INTRODUCTION

The construction industry remains to be challenged by the perennial problems of disorganized coordination, waste of materials, delays in schedule and rising demands to meet sustainability standards. The digital project management technologies are often advertised as solutions that have the potential to enhance accuracy of decisions and minimize resource usage. Current research indicates that BIM facilitates design optimization[1], AI enhances risk prediction and automation[2], and PMIS promotes transparency and communication[3]. Nevertheless, the literature is disjointed, with little elaboration on how these technologies collectively contribute to sustainability in multi-stakeholder construction contexts. This paper thus formulates an integrated conceptual argument: that meaningful sustainability benefits do not result from individual tools but rather their combined socio-technical interaction[4]. It is aimed at explaining mechanisms, dependencies and enabling conditions.Over the past few years, climate targets, resource depletion, and social responsibility have created a pressure on the global construction sector to undergo dual transformation of both green and digital transformation. In this respect, the convergence of BIM, AI, and PMIS is not interpreted as a technological upgrade but as a sustainability-enabling architecture. The current literature mainly focuses on one technology, e.g., the use of BIM in energy-efficient design, the value of AI in schedule prediction or the role of PMIS in collaboration without a systematic description of how they interact with each other. This paper tries to build a cyclical framework of data-prediction-decision and considers technological integration as a dynamic process instead of a stack of tools. This paradigm places emphasis on the fact that sustainable performance can be attained not only through technologies themselves but also through the flow of data and closure of decision loops within and between organizations. This view is consistent with the theory of socio-technical systems in which technology is incorporated into organizational practices, transforming work processes, power relations, and distribution of knowledge, hence affecting the triple bottom line of environmental, economic, and social performance[5].

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1.BIM as a Foundation for Sustainable Decision-Making

BIM is a multidimensional digital model of the project components, which allows stakeholders to interact with common information that is constantly updated. BIM influences performance in terms of sustainability by enhancing design coordination, simulation at an early stage, clash detection and quantification of materials. BIM enhances quality of decisions and facilitates environmentally friendly procurement by minimizing design mistakes and facilitating lifecycle evaluation. Its data environment, which is structured, also becomes the foundation on which AI algorithms and PMIS workflows are based. However, the benefits of BIM sustainability rely on the richness of data, inter-organizational cooperation and stable modelling standards. In their absence, its ability to minimize waste, emissions and rework is compromised.In addition, BIM has a special potential in operationalizing the principles of circular economy in construction. Through creation of material databases and component libraries, BIM is able to facilitate optimization of material selection during design, material tracking during construction and planning resource recovery on decommissioning. As an example, Life Cycle Assessment (LCA) information can be integrated into BIM models[6], so that the design teams can analyze the carbon footprint and recyclability capacity of various building materials at the initial phase. At the same time, combining BIM with Internet of Things (IoT) allows monitoring the use of materials on-site in real-time[7], which minimizes the number of orders made by mistake and waste in the field. This continuity of data between design and deconstruction provides an opportunity to achieve resource circularity across the life cycle of a building. Nonetheless, this vision can be realized only after several obstacles are addressed, such as data standardization, supply chain collaboration, and policy incentives, which implies that further studies should focus more on the integration pathways of BIM in cross-cycle resource management[8].

2.AI for Predictive, Resource-Efficient Planning

AI improves the management of digital projects by providing predictive insights that are beyond human analysis. Machine learning models predict delays and cost deviations, computer vision helps with real - time quality and safety monitoring[9], and natural language tools help classify documentation. When sustainability goals guide it, AI allows for more efficient use of materials, equipment, and labor[10], cutting down unnecessary consumption and improving schedule reliability. Still, AI's accuracy is strongly affected by the quality of BIM - derived data and the flow of information enabled by PMIS[11]. Ethical concerns, algorithmic bias, and high computational energy use could also restrict its contribution to sustainability. So, AI functions as a powerful yet conditional mechanism in a wider digital ecosystem.In addition to schedule and cost forecasting, AI has wide opportunities in sustainable supply chain management and carbon footprint accounting. The machine learning algorithms will be able to process the historical procurement data, logistics information, and market fluctuations to optimize material purchasing plans and transportation routes thus minimizing carbon emissions due to transportations and inventory wastage. At the same time, the AI-based carbon calculation tools can combine component data of BIM models, construction activity data, and energy consumption history to provide real-time estimation and dynamic early warning of project carbon emission. Indicatively, computer vision based site monitoring systems can automatically detect energy-inefficient practices like equipment idling or incorrect storage of materials and make optimization recommendations on time. It is interesting to note that the training data quality directly influences the precision of environmental assessments made by AI which again highlights the fact that BIM is a high-quality source of data. In future, the combination of AI with blockchain technology may also offer a credible data base on carbon credit tracking and green finance.

3.PMIS as an Integrative Management Platform

PMIS tools organize workflows through the organization of communication, documentation, version control and compliance tracking. They offer transparency in teams, define roles and enhance auditability. In terms of sustainability, PMIS enables timely reporting of environmental indicators, controls approval chains and enhances collaboration. Notably, PMIS also incorporates inputs of BIM and AI: BIM models are used to provide information on documentation and change management

processes whereas AI outputs can be used to provide decision alerts and progress dashboards. Nevertheless, organizational culture, digital capabilities and standardization of data structures affect the adoption of PMIS despite these strengths. The system design is not good or there is too much information which may compromise its effectiveness.PMIS is also important in facilitating multi-party cooperation and enhancing accountability. In big sustainable construction projects with many participants and long information chains, PMIS can guarantee transparent reporting and verification of different sustainability indicators (e.g., energy performance, water consumption, waste management) by using such features as permission management, process automation, and audit logs. Moreover, PMIS may be connected to third-party certification systems (e.g., LEED, BREEAM), which automatically matches the project data with the requirements of the certification system to simplify the submission procedure. In terms of governance, PMIS does not serve as an information platform only but rather as an institutional infrastructure that influences collaborative behaviors among stakeholders based on standardized process design and data interfaces. Nevertheless, when system design is too strict or ignores local practices, it might bring the risk of so-called techno-bureaucracy where tools are equated with formal compliance instead of real engines of sustainable innovation.

4.Integrated Framework for Sustainable Performance

The synergistic effect of BIM, AI and PMIS is realized in the form of their complementary roles. BIM provides structured, high-resolution data; AI converts this data into predictive insights; PMIS incorporates these insights into managerial decision-making and inter-organizational coordination. In combination, they affect sustainable performance via four channels: enhanced resource efficiency, less environmental impact, improved cost and schedule control, and better social outcomes like safety and transparency. This interaction takes place through a number of mediating mechanisms, such as decision quality, workflow integration, and knowledge availability. The degree to which these mechanisms result in measurable sustainability results is decided by moderating factors like leadership support, digital literacy, and governance practices.In order to visually explain the synergistic mechanisms of BIM, AI and PMIS, this study suggests a Sustainable Digital Project Management Cyclical Framework. This framework places BIM as the core data layer, AI as the intelligent analytics layer, and PMIS as the collaborative execution layer with bidirectional flows of data between all three layers. Namely:

1.Data Layer (BIM): Provides structured data including geometric information, material properties, and temporal relationships.

2.Analytics Layer (AI): Performs risk prediction, resource optimization, carbon emission simulation, etc.

3.Execution Layer (PMIS): Translates analytical results into task assignments, schedule adjustments, and report generation.

Within this framework, sustainable performance enhancement is achieved through the following sub-mechanisms:

1.Dynamic Optimization Mechanism: AI adjusts resource allocation suggestions in the BIM model based on real-time construction data.

2.Closed-Loop Learning Mechanism: PMIS collects project feedback to refine AI models and BIM templates.

3.Transparent Accountability Mechanism: All decisions and changes are logged within PMIS, facilitating traceability and auditability.

The framework underlines that the iterative evolution of technology and the learning ability of the organization are equally important; only by enhancing both simultaneously can digital transformation really empower sustainable development.

5.Challenges and Critical Conditions

Even though digitalization has its advantages, there are a number of challenges that limit the sustainability potential of BIM, AI and PMIS integration. Inconsistencies in data quality, interoperability constraints, inadequate workforce training and uneven levels of digital maturity among contractors often limit performance improvements. Smaller firms may not have the financial ability to invest in advanced systems, while inconsistent standards make cross - platform collaboration difficult. Furthermore, if governance structures are weak, digital tools might unintentionally add complexity or strengthen existing coordination issues. To get sustainable results, organizations need to put money into data governance, develop common modelling protocols,

build digital competencies, and set up leadership - driven strategies that match technology use with sustainability goals.

To deal with the resource and capability limitations that small and medium - sized enterprises (SMEs) face in digital transformation, this study suggests a phased implementation course:

Phase 1: BIM Foundation: Make the use of BIM to design and clash detection in major projects a priority to gain digital experience.

Phase 2: PMIS Collaboration: Introduce lightweight PMIS tools to strengthen collaborative workflows internally and with key partners.

Phase 3: AI Piloting: Based on accumulated data, pilot AI modules for applications like schedule prediction or safety monitoring.

Concurrently, policymakers and industry associations should play a facilitative role, for example:

1.Establishing regional BIM data-sharing platforms to lower data acquisition costs for SMEs.

2.Introducing digital training subsidies and certification programs to enhance workforce digital literacy.

3.Encouraging large firms to open certain digital tool interfaces to their supply chain partners to foster ecosystem synergy.

Moreover, digital transformation is not an exercise of purchasing technology but rather a process of strategic renewal that needs long-term management commitment, cross-functional team building and supportive incentive systems.

Conclusion

BIM, AI and PMIS, when implemented successfully, offer a robust socio-technical basis to the delivery of sustainable construction projects. Their joint contribution is based on enhancing mechanisms: rich data environments, advanced predictive analytics, structured coordination and enhanced transparency. However, the achievement of these benefits will rely on organizational preparedness, standardized data practices, effective leadership and intentional alignment between digital tools and sustainability objectives. The proposed mechanisms should be empirically tested in future research with various types of projects and evaluate how differences in digital maturity affect sustainable performance. This conceptual article helps make sense of digital project management as an engine of sustainability by clarifying interactions and conditions.Future research can delve into the following directions:

1.Longitudinal Case Studies: Tracking multiple projects from design to operation to analyze the differential contributions of digital tools across various stages.

2.Cross-Cultural Comparisons: Examining the institutional environments and implementation outcomes of BIM-AI-PMIS integration across different countries or regions.

3.Techno-Ethical Dimensions: In-depth exploration of the impacts of AI algorithmic bias, data ownership, and the digital divide on social equity.

Policymakers should consider:

1.Incorporating digital delivery and sustainable performance indicators into the tender requirements for public projects.

2.Supporting the development of cross-industry data standards to facilitate interoperability between construction, manufacturing, energy, and other sectors.

3.Establishing digital transformation funds specifically targeting SMEs and pilot projects for sustainable innovation.

The digital and sustainable transition of the construction industry is a systemic transformation. While technology acts as a catalyst, the true driving force stems from the shared vision, open collaboration, and continuous learning of all industry participants.

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Microservices Architecture Versus Monolithic Architecture: Technical Trade-offs and Economic Analysis of Modularising Human Resources Systems

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KEYWORDS

Human resources system;
Microservices architecture;
Monolithic architecture;
Economic trade-offs modularisation;

ABSTRACT

This paper analyses the technical trade-offs between microservices and monolithic architectures for human resource systems from an economic perspective on human resource management. The research reveals that architectural selection is fundamentally an economic decision concerning modularity, requiring a balance between transaction costs, innovation option value, and asset specificity. It provides an architecture selection framework grounded in economic principles for enterprises of varying scales.

INTRODUCTION

As enterprises deepen their digital transformation journeys, human resource management systems have evolved from traditional back-office support tools into core assets that enhance organisational effectiveness and drive strategic objectives.

1.Research Background and Theoretical Framework

1.1.Research Problem and Perspective

This paper adopts a human resource management economics perspective to construct an analytical framework, defining technological architecture selection as an economic trade-off between long-term costs and benefits.

The research focuses on the impact of system modularity on transaction costs, innovation option value, and asset specificity. Theoretical analysis reveals that for large organisations with complex operations, the initial high investment in microservices architecture can be justified by reducing future change costs and creating more ‘physical options.

Conversely, for small and medium-sized enterprises with stable operations, selecting a monolithic architecture with low initial costs represents a more economical choice. This research provides human resource managers and technology decision-makers with an economics-based assessment tool designed to guide forward-looking decisions[1].

1.2.Background: The Evolving Demands on HR Systems

Against the backdrop of current human resource management systems evolving from record-keeping systems to participatory systems and even intelligent systems, these systems must possess the capability to rapidly respond to emerging demands such as remote working and flexible benefits. The rise of microservices architecture offers a new pathway for system modernisation.

Concurrently, enterprises face the decision of whether to refactor existing systems or adopt microservices directly when building new ones. Existing discussions predominantly focus on technical implementation, lacking a systematic analysis of the long-term cost structures and

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value creation mechanisms associated with architectural choices from an economic perspective. This is precisely the issue addressed by this research.

1.3.Core Concepts: Defining the Architectural Paradigms

Within software engineering, monolithic architecture and microservices architecture represent two fundamentally distinct design paradigms.

Monolithic architectures typically integrate all functional modules of an application within a single process for development, deployment, and scaling. Their lifecycle cost model features relatively low initial development costs, but as system complexity increases, maintenance and functional modification costs exhibit non-linear growth. Microservices architecture advocates constructing applications as a collection of small services, each built around specific business capabilities and capable of independent deployment and scaling.

However, while this architecture delivers flexibility, it also introduces inherent complexities of distributed systems, such as additional costs related to network latency, data consistency, and operational monitoring.

1.4.Theoretical Lens: Modularity and Economic Theories

Modularity theory provides a crucial opportunity to understand the differences between these two architectures. In software engineering, modularity pursues the design principles of high cohesion and low coupling.

Drawing from Baldwin and Clark's discussion in Design Rules, the value of modularity in economics lies in its creation of ‘option value’. This allows individual modules within a system to be independently experimented with, iterated upon, or even replaced without undermining the system's foundations, significantly enhancing its capacity to navigate uncertainty[2].

From the perspective of human resource management and economics, relevant theories offer profound insights into architectural choices. Transaction cost economics indicates that architectural decisions directly influence coordination and communication costs among internal human resource teams, technical development teams, and operations teams. Microservices architecture, by defining clear API contracts, holds promise for reducing internal transaction costs arising from ambiguous module boundaries.

However, it simultaneously introduces new costs associated with service invocation and governance. The theory of real options treats technological investments as ‘options’ that create future growth opportunities. The modular nature of microservices significantly reduces the cost and risk of experimenting with new technologies or business models for independent functional modules such as recruitment, performance management, and learning development, thereby enhancing an organisation's innovation option value.

Furthermore, the theory of asset specificity indicates that within monolithic architectures, HR business logic becomes deeply intertwined with specific technology stacks, creating high asset specificity.

This results in substantial costs for future technological transformation or system upgrades. In contrast, microservices architecture permits technological heterogeneity, effectively reducing this specificity and enabling the selection of the most suitable technical tools for different HR scenarios.

2.Economic Analysis and Decision Model for Architecture Selection

2.1.Economic Trade-off Model

Building upon these theories, we have constructed an economic trade-off model for evaluating HR system architecture choices. This model unfolds across two dimensions: cost and value.

Within the cost dimension, the initial development cost must first be considered.

Typically, monolithic architectures incur lower costs here than microservices, as the latter necessitate meticulous service decomposition and the establishment of complex distributed infrastructure.

Secondly, coordination and communication costs arise: teams within monolithic architectures are highly interdependent, leading to substantial communication expenses; whereas microservices enable team autonomy, though cross-service coordination relies on rigorous contract management, shifting the cost structure.

System operations and monitoring costs are also significant factors: monolithic architectures are relatively simpler to maintain, while microservices demand a mature DevOps culture and robust monitoring systems. Finally, and critically,

change and iteration costs: as monolithic architectures scale, the friction associated with changes increases dramatically; whereas microservices substantially reduce the cost of localised changes, though cross-service modifications may still present challenges.

On the value dimension, agility and time-to-market are paramount. Microservices architecture typically outperforms monolithic structures due to its independent deployment capabilities. System scalability is another key advantage, with microservices enabling granular scaling for high-load services like payroll processing.

Technical resilience and innovation option value form the core of this model. A microservices architecture creates independent experimental options for each HR functional module, whose aggregate value equals the sum of the potential gains from each module's independent innovation multiplied by its probability of success. In contrast, the option value within a monolithic architecture is bundled and difficult to execute.

Furthermore, system stability and fault tolerance must be considered: monolithic architectures carry single points of failure risk, whereas microservices enable fault isolation, though overall fault diagnosis complexity increases[3].

Taking all these factors into account, corporate decision-making should strive to maximise the net present value across the entire system lifecycle. A simplified net present value model may be expressed as the sum of future net revenues discounted at an appropriate rate.

The core advantage of microservices architecture lies in its value components—particularly the value of innovation options—which appreciates significantly over time and with increasing business uncertainty.

Concurrently, its change cost growth curve remains markedly flatter than that of monolithic architectures, potentially rendering it more economically viable from a long-term perspective[4].

Evaluation Dimensions	**Monolithic Architecture**	**Microservices Architecture**	**Economic Interpretation**
Initial Investment Costs	Low	High	Microservices necessitate upfront investment in distributed infrastructure, containerisation, and service meshes, entailing significant fixed costs.
Coordination and Communication Costs	High internal coupling, high communication overhead	Team autonomy, but high governance costs for API contracts	Transaction costs shift from internally ambiguous boundaries to externally defined interfaces, altering cost structures.
Cost Curve of Change	Non-linear escalation with system scale	Low localised change costs, overall controllability	Microservices reduce internal system friction through modularity, stabilising marginal change costs.
Innovation Option Value	Low (option constraints, high execution costs)	High (each service as an independent option)	Microservices create real options, enabling low-risk experimen

			tation and rapid iteration on specific HR functions (e.g., recruitment, performance management).
Technological Flexibility and Asset Specificity	High (deep binding to specific technology stacks)	Low (supports technical heterogeneity)	Microservices reduce the asset specificity of technology stacks, mitigating future risks of technological lock-in and switching costs.
Optimal Application Scenarios	Suitable for stable operations, small scale, rapid validation requirements	The HR function leaps from the operational to the strategic level	The core decision lies in aligning the organisation's current developmental stage with its level of uncertainty to maximise net present value.

Table.1. Comparative Analysis of Economic Characteristics in HR System Architecture

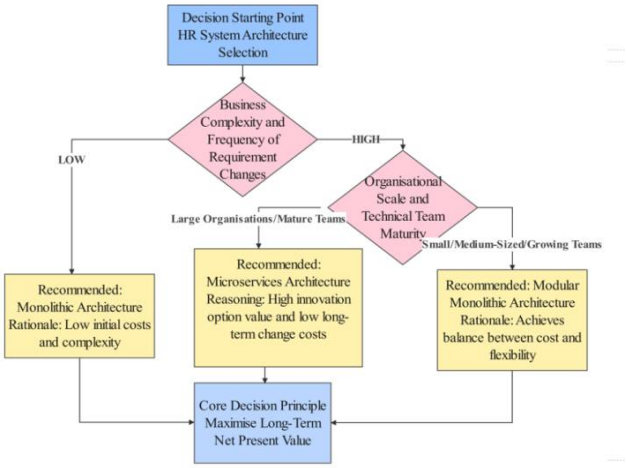

Fig1.HR System Architecture Selection Decision Diagram

2.2.Application Scenarios

Building upon these theories, we have constructed an economic trade-off m

Applying the aforementioned analytical framework to diverse scenarios yields more actionable conclusions. For human resources shared service centres within large conglomerates, the inherent complexity of operations — spanning multiple business models, countries, and high-concurrency environments with fluctuating demands— creates a primary contradiction: the substantial costs of coordination versus the opportunity costs incurred by rigid systems that hinder development. In this context, microservices architecture resolves these issues by decoupling core modules such as personnel management, remuneration, recruitment, and learning. This allows teams across different regions or business units to iterate localised functionalities independently and agilely, while adhering to core data standards. The substantial innovation options value it creates and the long-term change costs it reduces are sufficient to offset the high initial investment, thereby demonstrating significant economic rationality.

For small and medium-sized growth enterprises, whose operations tend to be relatively straightforward, teams compact, and resources constrained, the primary imperative

lies in rapid deployment to validate business models. At this stage, the low initial development costs and reduced coordination complexity inherent in monolithic architectures become decisive factors. Premature adoption of microservices introduces unnecessary distributed system complexity, consuming precious R&D resources. Moreover, the potential innovation option value remains difficult to realise effectively, as the enterprise's developmental direction is still being explored.

2.3.Refactoring Decision

When choosing the path from monolithic to microservices architecture, the decision to refactor should be judged from an economic perspective. It is not a simple question of 'whether to do it,' but rather 'when to do it' most economically. The economic inflection point for refactoring arrives when the marginal change cost of the monolithic system continues to rise and ultimately exceeds the marginal governance cost of a microservices architecture. Investing at this juncture effectively constitutes purchasing a compound option that permits the enterprise to pursue continuous innovation and evolution at lower future costs[5].

2.4.Organisational Alignment (Conway's Law)

Conway's Law classically observes that a system's design architecture replicates the organisation's communication structure. This principle carries profound economic implications within the architectural trade-offs of human resources systems. A tightly coupled monolithic HR system typically corresponds to a traditional HR department structure characterised by functional silos and cumbersome communication processes. Within such an organisational framework, any system-level change necessitates complex cross-departmental coordination, perpetuating exceptionally high internal transaction costs. Conversely, adopting a microservices architecture represents not merely a technical transformation but a strategic investment in organisational design. It necessitates the establishment of cross-functional agile teams aligned with this approach, such as dedicated small feature teams responsible for recruitment operations or compensation management. While the initial restructuring costs of this new organisational model are undoubtedly substantial, once successfully implemented, it significantly reduces subsequent coordination and communication expenses. This enables each team to make rapid decisions and pursue continuous iteration around their independently managed business modules. Therefore, architectural selection fundamentally involves a joint decision between organisational communication costs and technological innovation benefits. When selecting technologies, enterprises must carefully assess whether their existing organisational structure can support a microservices architecture, or whether they are willing to make the necessary investments to build a new organisational structure capable of fully unlocking the value of microservices.

2.5.Three-stage Evolutionary Model

The selection of an HR system architecture is not a static, fixed decision but should be viewed as a dynamic, phased strategic investment process.

To this end, we propose a three-stage evolutionary model to guide enterprises in formulating more forward-looking architectural planning.

During the monolithic initiation phase, business operations typically undergo preliminary validation with relatively straightforward requirements and constrained resources.

The optimal strategy here is to adopt a monolithic architecture for rapid implementation of core HR functions such as employee information management and payroll processing.

The primary objective is to minimise initial investment costs while validating the fundamental business model. It is noteworthy that even at this stage, conscious modular design should be implemented at the programming level.

Within the monolithic system itself, clear boundaries should be established for key business logic such as recruitment and performance management.

This effectively pre-emptively embeds valuable 'options' for potential future decomposition.

When business growth reaches a scale where microservices-based refactoring becomes a decision-making inflection point, operational complexity significantly increases.

Monolithic systems often become difficult to modify, while organisational demand for rapid innovation intensifies. Decision triggers at this stage typically arise when one or more of the following conditions are met:

The marginal cost of modifying the monolithic system exceeds the marginal governance cost of a microservices

architecture; Business growth necessitates rapid, independent experimentation and iteration on specific human resources modules such as learning platforms; or the technical team has expanded sufficiently to support multiple autonomous teams working in parallel. The optimal strategy at this stage is to initiate strategic refactoring, prioritising business value to progressively decouple and transform the most mature, agility-critical functional modules from the monolithic system into independent microservices.

Ultimately, upon completing the microservices transformation, the system enters the microservices governance and value extraction phase. The core task shifts from system construction to efficient governance. Enterprises must establish a mature DevOps culture, a robust API governance framework, and a unified monitoring platform to effectively control and optimise the long-term operational costs of the microservices architecture, thereby maximising its inherent innovation option value[6].

3.Managerial Implications and Practical Recommendations

This study holds significant implications for both human resources managers and technology decision-makers. For human resources managers, it is essential to move beyond viewing technology architecture as purely technical implementation details, instead understanding the economic rationale underpinning its role as a tool for realising human resources strategy. When communicating with technology departments, greater emphasis should be placed on business language such as ‘return on investment, response speed, and operational flexibility’ to jointly evaluate architectural choices.

When selecting HR technology providers, the modernity and modularity of their system architecture should also be a key evaluation criterion.

For technology decision-makers, it is essential to recognise that technology decisions must be closely aligned with the organisation's business strategy and developmental stage, avoiding the pitfall of pursuing technology for technology's sake. Adopt an ‘evolutionary architecture’ mindset. When initially building monolithic systems, consciously design clear interfaces and boundaries for potential future modularisation. This delays major decisions, allowing the natural emergence of the most economically viable refactoring inflection point.

Conclusion

This paper systematically demonstrates that the choice between microservices and monolithic architectures for HR systems is fundamentally an economic trade-off based on modularity.

The core decision lies in prudently evaluating and comparing the long-term cost structures and value creation capabilities of different architectural approaches, where innovation option value plays a particularly critical role in rapidly changing business environments.

For modern HR organisations committed to enhancing agility and innovation capabilities, microservices represent an economically rational choice: strategic upfront investment to secure long-term system evolution capabilities while reducing core change costs. However, this is by no means a universal panacea. Organisations must ground their decisions in their specific scale, operational complexity, and developmental stage, applying economic principles to conduct rigorous evaluations.

This approach enables the selection of technological investments that maximise long-term human resource effectiveness and align most effectively with overarching organisational strategic objectives.

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Belt and Road Trade Cooperation Between Chinese and Kyrgyz Enterprises: Status, Drivers, and Prospects

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KEYWORDS

Belt and road initiative;

China;

Kyrgyzstan;

Trade cooperation;

China-Kyrgyzstan-Uzbekistan railway;

Trade structure

ABSTRACT

China and Kyrgyzstan's trade relationship has grown quickly since the start of the Belt and Road plan. China has been Kyrgyzstan's biggest trade partner and source of imports for years. This paper looks at the current state, traits, and cooperation methods of trade between the two countries' businesses under the Belt and Road plan. The study shows that the total trade between the two countries is growing fast, but it still goes up and down. Their trade structures clearly complement each other; China mainly exports industrial products like textiles, clothing, and shoes, while it imports minerals like gold from Kyrgyzstan. In recent years, high-level diplomacy, strategic alignment, and multi-level cooperation have strongly driven trade cooperation between the two countries.

Big trade problems like trade imbalances, Kyrgyzstan's business situation, and geopolitics remain. Projects like the China-Kyrgyzstan Uzbekistan railway and teamwork in digital economy and green energy can improve trade potential and help ensure a great future.

INTRODUCTION

Kyrgyzstan, located in Central Asia, was a key part of the ancient Silk Road and is now central to the Silk Road Economic Belt. After 2013, with the launch of the Belt and Road Initiative, China and Kyrgyzstan have grown closer, fostering trade and economic ties. By May 2023, the firms were seen as strategic allies, strengthening their business ties. Trade between Chinese and Kyrgyz companies is key to their economic Partnership and illustrates the efficacy of China's BRI is working within Central Asia. Studying this trade helps improve their rapport and business cooperation locally.

1.Current State and Structure of Sino-Kyrgyz Trade

1.1.Trade Volume

After China and Kyrgyzstan started relations in 1992, their trade has grown. The Belt and Road Initiative has led to a quick increase in trade. Kyrgyz numbers show trade between the two countries was $4.8 billion from January to October 2024, up 11.5%. Chinese customs says trade was $23.57 billion from January to October 2025, up 35.4%. China's exports to Kyrgyzstan were $18.41 billion, and imports from Kyrgyzstan were $5.16 billion. Trade has risen a lot since the early days. Trade has a large surplus with Kyrgyzstan, because China's goods are liked for their low cost. Kyrgyzstan is also a key transit point in Central Asia. A lot of Chinese goods go through Kyrgyzstan to other countries, which shows the country's important role as a regional trade hub.

1.2.Trade Structure

Sino-Kyrgyz trade works well because of differences in resources and industries.(Attachment1)

Table 1 shows that China's exports to Kyrgyzstan have shifted from mainly daily consumer goods to more capital and tech-heavy products, such as new energy vehicles and machinery. In contrast, Kyrgyzstan's exports to China are

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mainly minerals and basic agricultural goods, with fewer different product types. This trade setup shows what each country is good at and suggests chances for industry investment and teamwor.

2.Risks Facing Sino-Kyrgyz Trade and Policy Recommendations

Trade between the two nations is increasing due to strong cooperation. Leaders meet regularly and in February 2025, aligned China's Belt and Road plan with Kyrgyzstan's 2026 targets, projecting trade and investments until 2030 for market steadiness.

The countries are working together on customs and standards to increase trade, agreeing in February 2025 to team up on the Belt and Road plan, economic growth, AI, and digital business. A key project is the China-Kyrgyzstan-Uzbekistan railway, started in late 2024, which could change Central Asian transportation by cutting shipping costs and times. Upgrading borders aims to improve traffic, directly supporting trade boosts.

2.1.Challenges and Risks Facing Sino-Kyrgyz Trade

Even with good chances, Chinese and Kyrgyz businesses still have problems. Trade differences might make Kyrgyzstan worry about depending too much on China because Kyrgyzstan doesn't export a broad selection of items to China, so they could be easily hurt by price changes.Kyrgyzstan's commercial laws aren't always stable or clear, and customs can be difficult. Corruption also makes things expensive for businesses. Tax laws change depending on where you are and what you do, which may cause investing complex. Sometimes, people in Kyrgyzstan don't like China because some Chinese projects don't hire enough local people. Even though the governments try to fix misunderstandings, it's important to be careful with what people think. Also, big countries competing in Central Asia could make it harder for businesses to work together.

2.2.Future Prospects and Policy Recommendations

In the future, trade between China and Kyrgyzstan will likely grow closer. China's next five-year plan and Kyrgyzstan's development plan for 2030 are similar, creating chances for future cooperation.

First, diversifying trade is essential. Both countries should keep the green channel for farm goods open and grow Kyrgyzstan's exports of honey and fruit to China. They should also look into service and digital trading in green mining, clean energy, and healthcare to find new ways to grow.

Second, both trade and investment should be promoted. Chinese companies should be encouraged to invest in Kyrgyzstan, building factories for farm processing, construction materials, and electronics assembly. This will help Kyrgyzstan become more industrialized, turning simple trade into industrial partnerships that increase jobs and exports.

Finally, it's important to improve infrastructure and regulations. While pushing big projects like the China-Kyrgyzstan-Uzbekistan railway, the two countries should also work together to share customs data, recognize standards, and build single window systems. Improving these soft connections will lower the costs of doing business.

Conclusion

In conclusion, the Belt and Road Initiative has guided China and Kyrgyzstan to achieve remarkable trade cooperation, expanding trade and improving infrastructure, which lead to great benefits for both countries. Now, the cooperation has entered a crucial phase of quality improvements. Despite challenges like trade imbalances and the business environment, significant political faith between the two governments and very well-matched economic architectures form a solid base for deeper cooperation. As long as both sides stick to the principles of mutual consultation, joint construction, and shared benefits, properly handle risks, and focus on promoting greater trade and investment, economic and trade cooperation between China and Kyrgyzstan will have even broader prospects and become a cooperation model for the Belt and Road Initiative.

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Attachment1

Table.1.Structure of Major Import and Export Goods Between China and Kyrgyzstan

Direction	Main product categories	Specific product examples	Feature
China's exports to Kyrgyzstan	Textiles, Apparel and Footwear	Clothing, footwear, and knitwear	Traditional advantageous product categories account for over 40%.
	Mechanical and electrical equipment and transportation equipment	Automobiles (including electric vehicles), motorcycles, communication equipment, and laptops	The proportion of high value-added products continues to increase
	Miscellaneous products	Furniture, toys, and lamps	A wide variety of products to meet daily consumption needs
Imported from China by Kyiv	Mineral products and precious metals	Gold (China's 7th largest source of imports), copper, antimony and other ores	Resource-intensive, dominating
	Agricultural raw materials	Leather, wool, cotton	Traditional advantages
	Agricultural products	Honey, dried fruit	Exports to China are being expanded through a "green channel".

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Research on The Design And Application of Micro-Expansive Concrete Mix Ratio

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KEYWORDS

Micro expanding concrete;
Mix ratio;
Expanding agent;
Concrete performance;

ABSTRACT

This paper focuses on the mix ratio of micro-expansive concrete, and introduces the types and properties of micro-expansive agents, the working principle of micro-expansive concrete and key construction techniques.

INTRODUCTION

Building structure construction projects are collaborative, systematic projects whose implementation requires high standards for various construction techniques and types. As a common construction material in today's building structures, the advantages of expansive concrete are becoming increasingly prominent. It has a positive impact on project quality, effectively enhancing structural stability and extending the service life of buildings. Expansive concrete incorporating expansive agents can effectively improve internal stress and shrinkage characteristics of the structure, reducing the likelihood of concrete cracks.

In recent years, with the gradual improvement of process evaluation and control methods and standards related to building structure construction, the engineering technology system of expansive concrete has continued to improve. However, in practical applications, expansive concrete technology still faces some problems. Based on this, this paper studies expansive concrete construction technology in combination with the actual construction of building structures. Taking the implementation principles and technical advantages of expansive concrete construction technology as the starting point, it discusses in detail the application process of expansive concrete construction technology in building structure construction and proposes key control points in the actual application of expansive concrete construction technology.

1.Analysis of the advantages of expansive concrete construction technology

Leakage, cracking and other defects are common quality issues in the design and construction of building structures. The application of expansive concrete technology not only improves the overall anti-seepage and anti-cracking properties of the building structure, but also helps reduce project costs [1]. Therefore, it is widely used in actual building structure projects. The main advantages are as follows:

1.1.Good structural crack resistance and anti-seepage effect

Cracks in building structures are primarily caused by excessive structural stress and excessive external construction temperatures. Cracks in concrete structures can seriously impact the strength of the building [2]. Expansive concrete, through the mixing and expansion process during its preparation, creates expansion stress, effectively offsetting the concrete's inherent shrinkage caused by setting. This improves the concrete's internal structure, enhancing its stability and water resistance, and preventing cracks[3].

1.2.Structural seismic effect

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The added expansion agent forms a chemical reaction after mixing with concrete, which has good connectivity. The expanded concrete achieves a good adhesion effect with adjacent materials, thereby effectively improving the earthquake resistance of the building structure and further improving the overall stability of the building structure.

1.3.Long service life of the structure

Concrete achieves stress compensation through shrinkage pressure, effectively improving structural stability and extending the service life of structures. Expansive concrete incorporating expansive agents generates a specific prestress within the concrete, which resists additional stress and provides excellent shrinkage compensation throughout the concrete[4]. Scientifically controlling the initial and final setting times of concrete, and accurately controlling the amount and timing of water spray during concrete maintenance, based on the actual project needs and environmental characteristics, can ensure effective shrinkage compensation, thereby improving overall construction quality and extending service life.

2.Mix design and testing

2.1.Experimental materials and equipment

Test materials and equipment are important components in the study of micro-expansive concrete mix proportions, which determine the accuracy and repeatability of the test. In this study, high-quality raw materials were strictly selected and standardized equipment was used for testing to ensure the reliability of the test results.

The test used a mix design method for slightly expansive concrete with a slump of 180-200 mm and a design strength grade of C25W8F100 as an example. The materials included cement, expansive agent, fly ash, aggregate, and water. P • 042.5 cement was used; the fly ash was Class F II fly ash produced by Manufacturers 1 and 2; the water reducer was GK-3000 retarding high-performance water reducer; the expansive agents were UEA II expansive agent produced by Manufacturer 3 and HME-IV high-efficiency concrete expansive agent produced by Manufacturer 4. Aggregates used were manufactured sand with a fineness modulus of 2.4-2.8 and continuously graded crushed stone with sizes of 5-20 mm and 20-40 mm, as used in the Kara Hydropower Station concrete project[5]; and drinking water that met relevant water quality standards was used to ensure the purity of the concrete. The physical properties of the expansive agent are shown in Tables 1 and 2.

Test items	GB/T 23439-2017 Technical Specifications Type II		Test results	Test conclusion
Magnesium oxide content/%		≤ 5	2.52	qualified
Alkali content/%		≤ 0.75	0.53	qualified
Specific surface area/($m^2.kg^{-1}$)		≥ 200	278	qualified
1.18mm sieve residue/%		≤ 0.5	0.0	qualified
Coagulation time difference/min	Initial condensation	≥ 45	217	qualified
	Initial condensation	≤ 600	243	qualified
Limit expansion rate/%	7d in water	≥ 0.050	0.064	qualified
	21 days in air	≥ -0.010	-0.007	qualified
Compressive strength/Mpa	7d	≥ 22.5	37.4	qualified
	28d	≥ 42.5	47.5	qualified

Table.1. Expansion agent quality inspection results (Manufacturer 3) [6]

Test items	GB/T 23439-2017 Technical Specifications Type II		Test results	Test conclusion
Magnesium oxide content/%		≤ 5	1.90	qualified
Alkali content/%		≤ 0.75	0.53	qualified
Specific surface area/($m^2.kg^{-1}$)		≥ 200	362	qualified
1.18mm sieve residue/%		≤ 0.5	0.0	qualified
Coagulation time	Initial condensat	≥ 45	217	qualified

difference/min	ion			
	Initial condensation	≤ 600	292	qualified
Limit expansion rate/%	7d in water	≥ 0.050	0.064	qualified
	21 days in air	≥ -0.010	-0.006	qualified
Compressive strength/Mpa	7d	≥ 22.5	38.6	qualified
	28d	≥ 42.5	49.9	qualified

Table.2. Expansion agent quality inspection results (Manufacturer 4) [7]

The test equipment includes a cement standard scheduling water consumption meter, a setting time meter, a mortar strength flexural and compressive strength integrated machine, a slump cone, a vibration table, a curing room, an outside micrometer and an electronic scale. The equipment is strictly configured in accordance with relevant standards and can accurately measure various performance indicators of concrete.

2.2.Test mix ratio

Prepare a C25 slightly expansive pumpable concrete mix with a binder dosage of ≥300 kg/m². The water-cement ratio should be between 0.35 and 0.45. The mineral admixture should account for 20% of the binder mass. To prevent segregation, the sand content of pumpable concrete can be slightly higher than that of ordinary concrete to reduce pumping pressure. The key to expansive concrete mix design is ensuring reasonable expansion without compromising strength and workability. The experimental mix of C25 slightly expansive concrete is shown in Table 3.

Experiment number	Concrete material consumption/(Kg.m $^{-3}$)								
	water	cement	fly ash	expansion agent	sand	Xiaoshi	Zhongshi	water reducer	air-entraining agent
JB-144	155	245	69	31	76	607	499	2.2	0.007
JB-145	155	275	78	35	727	604	496	2.519	0.012
	155	314	89	40	688	597	490	2.879	0.018

Table.3. Concrete mix ratio test parameters [6]

Concrete cubes and durability test blocks with different raw material mix ratios were prepared according to standard methods. The compressive strength and durability of the test blocks were measured at 7 days and 28 days, respectively, to evaluate the mechanical properties of concrete at early and late stages. In practice, compressive strength is often used as the main parameter [7] . Concrete frost resistance, impermeability, and limited expansion rate are important indicators for measuring concrete durability [8].

3.Key points in the application of expansive concrete construction technology

3.1.Expansion zone construction

The layout design of the expansion zone is the key to the construction of the expansion zone. An unreasonable layout design will affect the implementation effect of the project. Wire mesh should be laid on both sides of the expansion zone to fix it, so as to ensure the balanced and stable ratio of the expansion concrete and avoid the instability of the expansion zone caused by the mixing of different materials [9] . Strictly control the ratio of the expansion concrete and the amount of various mixed materials in the expansion zone. Add 9% of the expansion agent to the concrete in the middle area of the expansion zone and 7% of the expansion agent to the concrete at the outer end to scientifically improve the uneven stress at both ends of the expansion zone and avoid the occurrence of construction cracks.

The standard expansion band width is set at 2m to ensure operational continuity and subsequent stability. Expansion band pouring construction should be completed according to design standards, and differentiated construction methods should be appropriately selected based on the work area.

3.2.Assembling reinforcement and compensation steel bars

In order to achieve the desired temperature control effect of the expansion zone, necessary temperature control measures should be implemented according to the characteristics of the expansion concrete. By configuring steel bars with binding reinforcement compensation function, not only can the temperature control of concrete construction be achieved, but also the problem of concrete cracking caused by poor material uniformity can be solved. It is necessary to ensure that the selected compensation steel bar material matches the concrete structure steel bar material, and the compensation steel bar diameter should be 1 to 2 grades lower than the structural steel bar diameter [10] .

During the assembly of the compensating reinforcement bars, the reinforcing strip and the compensating bars should be maintained perpendicular to each other, ensuring that the compensating bars are inserted into the concrete to a depth of more than 0.5m. If compensating bars are installed on the top plate, the top plate and the corresponding surface bars should be tied together[11]. For the rear of the wall panel, the same method should be used to tie the corresponding surface bars together. By installing compensating reinforcement bars, the stress-bearing properties of expansive concrete can be effectively improved. By adjusting the radius of the compensating bars, the stress on the expansion strip is uniform, thereby improving the overall stability of the concrete structure.

Conclusion

As a common construction technology in building structure construction, expansive concrete construction technology can effectively improve the earthquake resistance, waterproofness, crack resistance and overall structural stability of conventional concrete, and can effectively reduce construction period and construction costs.

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Digital Transformation and Green Total Factor Productivity of Heavily Polluting Enterprises: The Mediating Role of M&A Activity and the Moderating Role of Green Innovation

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KEYWORDS

Corporate green total factor productivity ;

Digital transformation;

M&A activity;

Corporate green innovation;

Mediating effect;

Moderating effect;

ABSTRACT

Data, as a novel factor of production, brings new opportunities for enterprise development. Using a sample of Chinese heavily polluting listed companies, this study measured corporate green total factor productivity (GTFP) by employing the Super-SBM Malmquist index and explored the underlying mechanism through which digital transformation affects GTFP. This study employs an OLS benchmark regression model to investigate the impact of corporate digital transformation on green total factor productivity (GTFP). Additionally, it constructs mediation and moderation effect models to examine the mechanism through which digital transformation affects GTFP, specifically assessing the mediating role of M&A activity and the moderating role of green innovation. The research results indicate that digital transformation has a positive promoting effect on corporate green total factor productivity. M&A activity plays a partial mediating role between the two, meaning that the impact of digital transformation on corporate green total factor productivity is indirectly generated through M&A activity. Corporate green innovation plays a positive moderating role between the two, meaning that the higher the level of corporate green innovation, the more significant the promoting effect of digital transformation on corporate green total factor productivity. The research results remain valid after considering robustness tests such as variable substitution, model transformation, Sobel-Goodman, and Bootstrap methods. Heterogeneity analysis reveals that the positive effect of digital transformation on corporate green total factor productivity (GTFP) is significantly amplified under three conditions: in non-state-owned enterprises, in regions with superior business environments, and in firms with higher information transparency. For the mediation mechanism, M&A activity exhibits partial mediation in non-state-owned firms and in high-index business environments, but transitions to complete mediation in low-index contexts. Correspondingly, the moderating effect of green innovation is markedly stronger under these same conditions. These contingent findings delineate critical boundary conditions, thereby extending theories of digital transformation and corporate sustainability, while providing empirically grounded insights for regulatory policymakers and corporate managers of heavily polluting enterprises.

INTRODUCTION

In China's rapid economic growth, environmental constraints have emerged as a critical barrier to sustainable development. Enhancing green total factor productivity (GTFP) is crucial for driving industrial transformation. Heavily polluting industries while vital to the economy, account for over 40% of industrial emissions, posing significant ecological challenges. Their green transformation is therefore essential for achieving the "dual carbon" goals and promoting high-quality economic development. Although policies encourage synergy between green innovation and digital

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transformation to support industrial upgrading, these enterprises still face obstacles such as low resource efficiency and high compliance costs. Hence, investigating how digital transformation affects GTFP—and its mechanisms and heterogeneity—holds both theoretical and practical relevance for addressing transformation challenges in these sectors.

This study examines how digital transformation influences GTFP among heavily polluting A-share listed firms in China, focusing on the mediating role of M&A activity and the moderating role of green innovation. The contributions are threefold. First, it enriches the literature on digital transformation and GTFP by empirically demonstrating a positive relationship and introducing the super-efficiency SBM-Malmquist index to quantify effects and uncover underlying mechanisms. Second, it extends understanding of the indirect channels through which digital transformation promotes GTFP, showing that M&A activity acts as a partial mediator—digital transformation boosts GTFP both directly and by stimulating M&A. Third, it identifies green innovation as a positive moderator, indicating that stronger green innovation amplifies the GTFP-enhancing effect of digital transformation, clarifying how technological and environmental strategies interact in heavy polluters. Finally, heterogeneity analyses reveal that the relationship varies with firm ownership, regional business environment, and information transparency, offering both theoretical boundary conditions and practical guidance for managers and policymakers in advancing the green transition of heavy-polluting industries.

1.Literature Review

Scholarly research on corporate digital transformation has yielded substantial findings, focusing on two core areas: First, conceptual connotations and measurement methodologies, with quantification achieved via dummy variables [3], expert scoring [4], textual analysis [5,6], and digital asset proportion [7,8]. Second, economic effects, where digital transformation is shown to impact financial performance [9], green innovation [12], production efficiency [14,15], and supply chain management [19], among other dimensions.

For heavily polluting enterprises, digital transformation is both a response to external pressures and a strategic imperative for high-quality development [21]. Existing studies on the digital transformation-green total factor productivity (GTFP) nexus cover multiple levels. At the macro level, digital economy development and digital village construction have been proven to promote TFP and agricultural GTFP, respectively [22,25], with positive spatial spillovers observed [23,24]. At the regional level, significant heterogeneity exists—digital transformation's GTFP-enhancing effect is more pronounced in eastern China [26], and may exacerbate regional disparities [27]. A U-shaped relationship between digitization and urban GTFP is also identified, constrained by geographic and institutional factors [36].

At the micro level, digital technologies boost productivity by reshaping operational processes and mitigating information asymmetries [28-30]. Theoretically, human-machine collaboration and digital tools drive efficiency gains [31,32]; empirically, digital transformation enhances corporate GTFP through supply chain optimization and green innovation [33,34], with virtual simulation technology adoption reducing R&D costs in manufacturing [37]. Digital finance also promotes GTFP via technological innovation and entrepreneurship, with China's GTFP forming a development pattern centered on Beijing, Shanghai, and Guangdong [38].

However, the digital transformation-GTFP relationship is not uniformly positive. Potential pitfalls include TFP growth hindrance from over-reliance on AI [39], short-term ineffectiveness of digital technologies [40], and resource misallocation from excessive digitization [41].

In summary, existing research reveals the complex nature of digital transformation's impact on GTFP but leaves gaps: insufficient focus on heavily polluting enterprises, and inadequate exploration of specific mechanisms and heterogeneous effects. Investigating this relationship in heavily polluting enterprises is therefore significant, as it broadens the economic consequence discussion of digital transformation and enriches GTFP literature. This study thus focuses on three core questions: the relationship between digital transformation and GTFP in heavily polluting enterprises, the underlying mechanisms, and heterogeneous effects across enterprise types and regions.

2.Research Hypotheses

2.1. Digital Transformation and Corporate Green Total Factor Productivity

First, per the information transmission effect, information asymmetry and incomplete information easily lead to enterprise investment misjudgments [43]. Digital technologies reduce multiple costs (e.g. search, verification) [44], enhance enterprises' informatization capabilities [49], and help them optimize production decisions and reduce resource waste, thereby boosting GTFP [51,52].

Second, based on knowledge spillover theory, data technologies enable enterprises to accurately identify resource needs, promote environmental protection equipment upgrades [53], and curb strategic false disclosures to gain green premiums [55]. They also optimize lifecycle resource use and reshape resource allocation [56,58], improving green innovation efficiency and GTFP.

Third, resource allocation theory holds that digital technology embedded in core processes reshapes business functions and drives production paradigm transformation [61], improving resource allocation efficiency. For resource-intensive enterprises with severe misallocation issues, it enhances information sharing and resource integration [63], thus boosting GTFP. In summary, this study proposes:

H1: Digital transformation can significantly enhance corporate green total factor productivity.

2.2. The Mediating Mechanism of M&A Activity Level

Digital transformation (DT) directly enhances green production, but its full potential hinges on firms' ability to integrate internal/external resources. Grounded in Resource-Based View and Dynamic Capabilities Theory, mergers and acquisitions (M&A) serve as strategic tools for firms to rapidly acquire heterogeneous resources and reconfigure competitive competencies, thereby indirectly promoting green total factor productivity (GTFP) through enhanced M&A activity.

M&A fuels GTFP by optimizing resource allocation, expanding economies of scale, and institutional optimization. It accelerates green technology accumulation, innovation capacity building, and embeds green innovation into production systems, driving fundamental GTFP improvement. High M&A activity enables firms to embed deeper into M&A-constructed networks, efficiently accessing/integrating information, technology, capital, and market resources, enriching knowledge bases, and facilitating creative recombination of green knowledge to form new tech combinations, thus advancing green transformation.

DT reduces M&A transaction costs via data mining, expands decision-making information sources, and deepens value excavation, lowering search costs. It enhances risk-return assessment during M&A execution/supervision, improves green governance efficiency, curbs opportunistic behavior, and boosts firms' competitiveness in M&A markets by elevating management efficiency and legitimacy, further promoting M&A activity. Ultimately, increased M&A activity enables firms to acquire advanced green technologies/management experience, enhancing absorptive capacity for green transformation technologies and forming unique heterogeneous knowledge structures to empower GTFP improvement. This study hypothesizes that DT indirectly promotes GTFP through enhanced M&A activity.

H2: M&A activity level plays a mediating role between digital transformation and corporate green total factor productivity.

2.3. The Moderating Effect of Corporate Green Technology Innovation

Green technology innovation refers not only to new products or processes beneficial to environmental protection [92] but also encompasses systematic changes such as green management and green supply chain optimization [93-95]. Research finds that improvements in green technology efficiency and green innovation compensation are key to promoting GTFP [96, 97]. Applying clean production technologies saves energy and curbs pollution at the source, while using end-of-pipe treatment technologies improves pollutant treatment capacity and energy utilization efficiency [98], directly enhancing green technology efficiency. Green innovation can improve production processes, achieve product differentiation, and through isolation mechanisms and technology spillovers, bring enterprises competitive advantages combining both economic and environmental benefits [99].

Synergistic effects exist between green innovation and digital transformation. Hao et al. (2023), among others,

indicate that digital transformation can enhance an enterprise's GTFP [51]. However, digital transformation itself is complex and highly uncertain, and its impact on GTFP depends on the enterprise's internal capabilities. Jacobides et al. (2018) find that weaker technological innovation capabilities lead to inefficient economic outcomes from digital transformation [100]. This implies that the positive impact of digital transformation on GTFP may not be uniform and largely depends on whether the enterprise possesses the corresponding absorptive and transformative capacity. Firstly, based on absorptive capacity theory, enterprises with higher levels of green innovation often possess stronger technological absorption and resource integration capabilities [101, 102], enabling them to more effectively apply digital technologies such as the Internet of Things and big data to energy saving, emission reduction, and cleaner production processes, thereby amplifying the positive effects of digital transformation. Secondly, based on environmental enablement theory, green innovation has positive externalities and is susceptible to free-riding and opportunistic behavior threats. Digital transformation technologies can effectively prevent such moral hazards [103, 104], ensuring the sustainability of green collaborative innovation, thus creating a more stable and incentive-compatible innovation environment for digital transformation to enhance GTFP. Therefore, in enterprises with high levels of green innovation, digital transformation can integrate more deeply with existing green technological foundations, management systems, and strategic orientations, creating synergistic effects [105, 106], and more significantly optimizing resource utilization efficiency, reducing energy consumption, and ultimately improving GTFP. Conversely, enterprises with low levels of green innovation may lack the technological capability or implementation pathways to fully realize the potential benefits of digital transformation due to weak green knowledge bases. In summary, green innovation plays an important moderating role in the impact of digital transformation on corporate GTFP, strengthening the enhancing effect by optimizing resource allocation, improving management efficiency, promoting technological innovation, and enhancing market image. Based on this, this study proposes the following hypothesis:

H3: Green technology innovation positively moderates the impact of digital transformation on corporate green total factor productivity.

The research framework of this paper is shown in Figure 1.

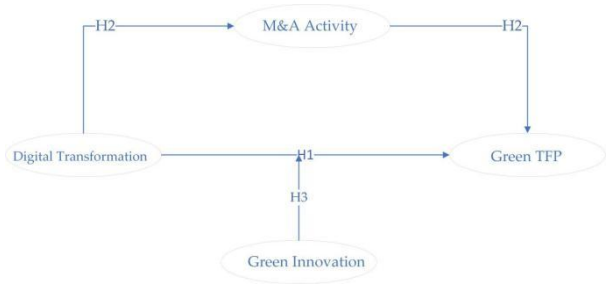

Fig.1. Research framework

3. Model Specification

3.1. Sample and Data

The sample comprises merger and acquisition (M&A) transactions involving Chinese A-share listed companies in heavily polluting industries from 2010 to 2019. Firm-level data are primarily sourced from the CSMAR and WIND databases. Following the methodology of Pan, Liu, and Qiu et al. (2019) [107], firms in industries B06, B07, B08, B09, C17, C19, C22, C25, C26, C28, C29, C30, C31, C32, and D44 are classified as heavily polluting. The data processing procedure includes: (1) excluding firms in the financial and insurance sectors; (2) removing samples labeled as ST or PT; (3) dropping observations with asset-liability ratios less than 0 or greater than 1; (4) excluding related-party transactions; (5) removing deals with transaction values below RMB 1 million; and (6) eliminating observations with missing key financial data. After these filters, the final sample comprises 2,931 observations. To mitigate outlier effects, all continuous variables are winsorised at the 1% level. Data processing and analysis are conducted using STATA 18.0.

3.2.Variable Descriptions

3.2.1.Dependent Variable

Corporate Green Total Factor Productivity ($GTFP_{i,t}$).Following Zhan, Li, and Liu et al. (2022) [108], corporate Green Total Factor Productivity (GTFP) is measured using the Malmquist-Luenberger (ML) index, which is derived from a super-efficiency Slack-Based Measure (SBM) model that incorporates undesirable outputs. The specific input and output variables are constructed as follows:(1) Input Variables: include labor, capital,

intermediate inputs, and energy consumption.Labor: measured by the number of employees at the end of the fiscal year. Capital: represented by the firm's fixed capital stock, calculated using the perpetual inventory method. Intermediate Inputs: comprising operating costs, selling, administrative, and financial expenses. Energy: proxied by the product of the industrial electricity consumption in the firm's host city and the ratio of the firm's employees to the city's total industrial employment. (2) Desirable Output: is measured by the firm's operating revenue. (3) Undesirable Outputs: are represented by industrial waste emissions, specifically sulfur dioxide (SO_2) emissions, wastewater discharge, and soot/dust emissions. Each is estimated as the product of the corresponding city-level industrial emission and the ratio of the firm's employees to the city's total industrial employment.

The SBM-Malmquist index decomposes a firm's green productivity into technical efficiency change (EC) and technological change (TC). Matrices of efficiency and technological change differentials are then constructed from the average values of pairwise firm comparisons.

Assuming the existence of multiple decision-making units , each decision-making unit comprises three vectors: inputs DMU_k (k=1,2,..,K) , desirable outputs, and undesirable outputs, which are represented in matrix form as: $X=(x_1,...,x_n)\in R^{m\times n}$, $Y^g=(y_1^g,...,y_n^g)\in R^{S_1\times n}$ and $Y^b=(y_1^b,...,y_n^b)\in R^{S_2\times n}$,$X>0,Y^g>0,Y^b>0$. Following the approach of Chung, Färe, Grosskopf, et al. (1997) [109], the directional distance function is defined as:

$$\underset{D_0}{\rightarrow}(x,y,b;g)=\sup\{\beta:(y,b)+\beta g\in p(x)\} \quad (1)$$

Where, g is the direction vector, indicating the preference for desirable over undesirable outputs. $g=(y,-b);\beta$ is the value of the directional distance function. Furthermore, we solve for the directional distance function of decision-making units (DMUs) in period t via the linear programming formulation given in Eq. (2):

$$\overrightarrow{D_0^t}(x^t,y^t,b^t;y^t,-b^t)=\max\beta$$
$$\text{s.t.}\begin{cases}\sum_{k=1}^{K}\omega_k^t x_{kn}^t\geq x_{kn}^t, & n=1,2,...,N;\\ \sum_{k=1}^{K}\omega_k^t y_{ks}^t\geq(1+\beta)y_{ks}^t, & s=1,2,...,S;\\ \sum_{k=1}^{K}\omega_k^t b_{km}^t\geq(1+\beta)b_{km}^t, & m=1,2,...,M;\\ \omega_k^t, & k=1,2,...,K;\end{cases} \quad (2)$$

Based on the directional distance function, the Malmquist-Luenberger (ML) productivity index from period t to period t+1 can be derived as follows:

$$ML_t^{t+1}=\left\{\frac{\left[1+D_0^t(x^t,y^t,b^t;g^t)\right]}{\left[1+D_0^t(x^{t+1},y^{t+1},b^{t+1};g^{t+1})\right]}\times\frac{\left[1+D_0^{t+1}(x^t,y^t,b^t;g^t)\right]}{\left[1+D_0^{t+1}(x^{t+1},y^{t+1},b^{t+1};g^{t+1})\right]}\right\}^{\frac{1}{2}} \quad (3)$$

If ML>0, it indicates that green total factor productivity (GTFP) shows an upward trend from period t to period t+1; otherwise, it exhibits a downward trend. Specifically, the ML productivity index can be further decomposed into the green technical efficiency change index (ML_EFFCH) and the green technological progress change index (ML_TECH). The former reflects the contribution of improvements in technical efficiency to GTFP, while the latter represents the contribution of shifts in the production frontier to productivity. Their specific expressions are as follows:

$$ML\_EFFCH_t^{t+1}=\frac{\left[1+D_0^{t+1}(x^t,y^t,b^t;g^t)\right]}{\left[1+D_0^{t+1}(x^{t+1},y^{t+1},b^{t+1};g^{t+1})\right]} \quad (4)$$

$$ML\_TECH_t^{t+1}=\left\{\frac{\left[1+D_0^{t+1}(x^t,y^t,b^t;g^t)\right]}{\left[1+D_0^t(x^t,y^t,b^t;g^t)\right]}\times\frac{\left[1+D_0^{t+1}(x^{t+1},y^{t+1},b^{t+1};g^{t+1})\right]}{\left[1+D_0^t(x^{t+1},y^{t+1},b^{t+1};g^{t+1})\right]}\right\}^{\frac{1}{2}} \quad (5)$$

Following these steps, the obtained ML index is converted into Green Total Factor Productivity (GTFP). The growth trend of the average GTFP for the sample firms is shown in Figure 2.

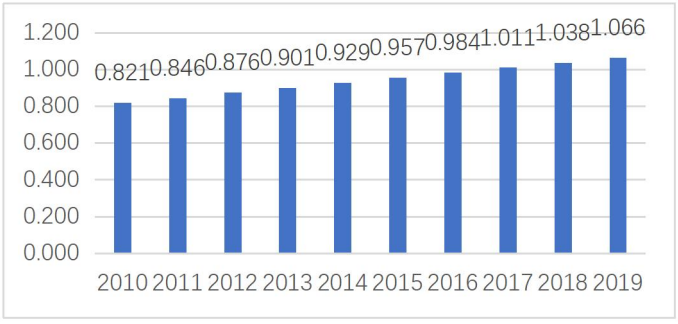

Fig.2. Trend of Average Green Total Factor Productivity in Heavily Polluting Enterprises

3.2.2.Explanatory Variable: Digital Transformation($DCG_{i,t}$)

The degree of corporate digital transformation is measured by the proportion of digital-technology-related intangible assets to total intangible assets. Following the approach of Zhang, Li, and Xing (2021) [7], this metric is constructed using the detailed breakdown of year-end intangible assets disclosed in the notes to the financial statements. Specifically, items related to digital technologies-such as networks, software, intelligent platforms, client-side systems, and management systems-are identified and aggregated. The ratio of this digital-technology-related portion to the total book value of intangible assets serves as the proxy.

3.2.3.Mediating Variable

M&A Activity($SMA_{i,t}$)following Zhang, Song, and Liu (2023) [110] and Zhang, Yao, and Du (2021) [111], this variable is measured by the number of merger and acquisition (M&A) deals completed by sample firm *i* in year *t*.

Corporate Innovation($RD_{i,t}$)following the methodologies of Beladi et al. (2022) and Xue et al. (2023) [112,113], we measure corporate innovation using the natural logarithm of the total count of invention patents, utility models, and design patents plus one (ln(total patents + 1)).

3.2.4.Control Variables

Drawing on established literature, this study controls for a set of firm- and region-level characteristics, including firm size, leverage, board independence, board size, ownership concentration, property rights, and the business environment index. Detailed definitions of these variables are provided in Table 1.

3.3.Model Specification

To test Hypotheses 1, 2, and 3, Models (6) through (9) are constructed as follows:

$$GTFP_{i,t} = \alpha_0 + \alpha_1 DCG_{i,t} + \alpha_2 Size_{i,t} + \alpha_3 Lev_{i,t} + \alpha_4 Indep_{i,t} + \alpha_5 Board_{i,t} + \alpha_6 ShareTop_{i,t} + \alpha_7 Board_{i,t} + \alpha_8 ShareTop_{i,t} + \alpha_9 Envir_{i,t} + \varepsilon_{i,t} \quad (6)$$

$$SMA_{i,t} = \beta_0 + \beta_1 DCG_{i,t} + \beta_2 Size_{i,t} + \beta_3 Lev_{i,t} + \beta_4 Indep_{i,t} + \beta_5 Board_{i,t} + \beta_6 ShareTop_{i,t} + \beta_7 Board_{i,t} + \beta_8 ShareTop_{i,t} + \beta_9 Envir_{i,t} + \varepsilon_{i,t} \quad (7)$$

$$GTFP_{i,t} = \chi_0 + \chi_1 DCG_{i,t} + \chi_2 SMA_{i,t} + \chi_3 Size_{i,t} + \chi_4 Lev_{i,t} + \chi_5 Indep_{i,t} + \chi_6 Board_{i,t} + \chi_7 ShareTop_{i,t} + \chi_8 Board_{i,t} + \chi_9 ShareTop_{i,t} + \chi_{10} Envir_{i,t} + \varepsilon_{i,t} \quad (8)$$

$$GTFP_{i,t} = \delta_0 + \delta_1 DCG_{i,t} + \delta_2 RD_{i,t} + \delta_3 DCG_{i,t} \times RD_{i,t} + \delta_4 Size_{i,t} + \delta_5 Lev_{i,t} + \delta_6 Indep_{i,t} + \delta_7 Board_{i,t} + \delta_8 ShareTop_{i,t} + \delta_9 Board_{i,t} + \alpha_{10} ShareTop_{i,t} + \delta_{11} Envir_{i,t} + \varepsilon_{i,t} \quad (9)$$

$$GTFP_{i,t} = \eta_0 + \eta_1 DCG_{i,t} + \eta_2 GRD_{i,t} + \eta_3 DCG_{i,t} \times GRD_{i,t} + \eta_4 Size_{i,t} + \eta_5 Lev_{i,t} + \eta_6 Indep_{i,t} + \eta_7 Board_{i,t} + \eta_8 ShareTop_{i,t} + \eta_9 Board_{i,t} + \eta_{10} ShareTop_{i,t} + \eta_{11} Envir_{i,t} + \varepsilon_{i,t} \quad (10)$$

Among these, Model (6) tests the positive impact of corporate digital transformation on green total factor productivity (GTFP). Building on Model (6), Models (7) and (8) examine the mediating effect of M&A activity. Models (9) and (10) test the moderating effects of firm innovation and green innovation, respectively. Dependent Variable $GTFP_{i,t}$ represents corporate green total factor productivity (GTFP); Explanatory Variable $DCG_{i,t}$ represents the degree of corporate digital transformation; Mediating Variable $SMA_{i,t}$ represents M&A activity; Moderating Variable $RD_{i,t}$, $GRD_{i,t}$ respectively represent corporate innovation and corporate green innovation; Control variables include: firm size $Size_{i,t}$, Financial Leverage $Lev_{i,t}$, Board Independence $Indep_{i,t}$, Board Size $Board_{i,t}$, Ownership Concentration $Share_{i,t}$, Ownership Nature $State_{i,t}$ Environment Index $Envir_{i,t}$; *Industry* represents industry fixed effects; *Year* represents fixed effects; $\varepsilon_{i,t}$ represents the random error term.

3.4.Model Specification

(I) Descriptive Statistics of Key Variables

This study's sample comprises 2,931 observations. Table 2 reports the mean, standard deviation, median, maximum, and minimum values for the key variables. Green Total

Factor Productivity($GTFP_{i,t}$)has a mean of 0.950 and a median of 0.951, indicating a roughly symmetric distribution. Its values range from 0.800 to 1.092, with a standard deviation of 0.080, suggesting limited variation in GTFP across sample firms. Digital Transformation($DCG_{i,t}$)shows a mean of 0.047 and a median of 0.002, with a standard deviation of 0.160. This indicates a generally low level of digital adoption among most firms, while a few outliers exhibit significantly higher levels (maximum = 1), resulting in a pronounced right-skewed distribution. M&A Activity(has a mean of 1.176 and a median of 1, implying that most firms undertake few M&A transactions. However, the maximum value reaches 34, and the standard deviation is 1.913, reflecting highly active M&A engagements by a small subset of firms and a strongly right-skewed distribution. Corporate Innovation($RD_{i,t}$)presents a mean of 1.075 and a median of 0, revealing that half of the sample firms report no R&D investment. The wide range (maximum = 8.280) and substantial standard deviation (1.866) highlight a highly uneven distribution of R&D expenditure, with a minority of firms investing significantly above the average. Firm Size ($Size_{i,t}$)has a mean of 22.47 and a standard deviation of 1.402, indicating a relatively concentrated distribution. Financial Leverage($Lev_{i,t}$)shows a mean of 0.519, close to its median of 0.521, suggesting a moderate level of indebtedness among sample firms. Regarding board characteristics, Board Independence ($Indep_{i,t}$) has a mean (value) of 37.3%,Board Size ($Board_{i,t}$) averages 8.831 members, which is in line with typical corporate governance structures. Ownership Concentration, ($ShareTop_{i,t}$)measured by the shareholding ratio of the largest shareholder, shows a mean of 34.4% and a maximum of 90%, indicating highly concentrated ownership in a portion of the sample firms. According to the results for Ownership Nature, 5($State_{i,t}$)53.8% of the sample firms are state-owned, suggesting a balanced composition. The Environment Index ($Envir_{i,t}$)has a mean value of 0.496, suggesting that approximately half of the sample firms face a certain degree of regulatory pressure in their business environment.

(II) Correlation Analysis of Main Variables

This study employs Pearson correlation coefficients to test the correlations among variables, with the results presented in Table 3. Green Total Factor Productivity ($GTFP_{i,t}$) shows a significantly positive correlation with Digital Transformation ($DCG_{i,t}$) (r=0.079, p<0.01) and with M&A Activity ($SMA_{i,t}$) (r=0.195, p<0.01). GTFP is also significantly positively correlated with Corporate Innovation ($RD_{i,t}$) and Corporate Green Innovation ($GRD_{i,t}$) (r=0.183, p<0.01; r=0.217, p<0.01), suggesting a synergistic effect of technology-driven factors on corporate green total factor productivity. Firm Size ($Size_{i,t}$) is significantly positively correlated with ($GTFP_{i,t}$) (r=0.178, p<0.01), whereas Financial Leverage () is significantly negatively correlated with $GTFP_{i,t}$ (r=-0.165, p<0.01), reflecting the constraining effect of financial structure on innovation. Ownership Nature ($State_{i,t}$) is significantly negatively correlated with $GTFP_{i,t}$ (r=-0.197, p<0.01), indicating that state-owned enterprises exhibit weaker green total factor productivity. Among the control variables, Board Size ($Board_{i,t}$) shows a significantly negative correlation (r=-0.106, p<0.01), while Board Independence $Indep_{i,t}$ shows a significantly positive correlation (r=0.099, p<0.01), reflecting the differential impacts of governance structure. The Environmental Index($Envir_{i,t}$) shows a weakly positive correlation with (r=0.047, p<0.05), suggesting that policy pressure from the operating environment may stimulate innovation. Furthermore, all inter-variable correlation coefficients are below 0.5, and Variance Inflation Factor

(VIF) tests indicate no severe multicollinearity issues, meeting the requirements for subsequent regression analysis.

3.5.Multicollinearity Test

Table 4 presents the results of the Variance Inflation Factor (VIF) test. The VIF values for all variables range from 1.03 to 1.58, with a mean VIF of 1.21, which is well below the conventional threshold of 10. This indicates the absence of severe multicollinearity in the model. Furthermore, the tolerance values (1/VIF) all exceed 0.6 (the minimum being 0.634), providing additional confirmation of the independence among the explanatory variables.

3.6.Regression Analysis

1. Baseline Regression Analysis

This study estimates the baseline model, with results presented in Table 5. Column (1) reports the baseline regression results for the impact of corporate digital transformation on Green Total Factor Productivity (GTFP). The estimated coefficient for digital transformation is 0.039 and is statistically significant at the 1% level (t = 4.27). This indicates that for heavily polluting enterprises, a one-percentage-point increase in the degree of digital transformation is associated with a 0.039-percentage-point increase in GTFP. This finding suggests that enhanced digital capability significantly promotes GTFP, providing initial support for Hypothesis H1.Columns (2) through (6) progressively introduce control variables. Although the coefficient for digital transformation declines slightly (from 0.039 to 0.028), it remains statistically significant at the 1% level (with t-statistics all greater than 3.28). This demonstrates the robust positive effect of digital transformation on GTFP, strongly supporting Hypothesis 1.Regarding the control variables in Column (6): Firm Size (Size) exerts a significant positive influence on GTFP (coefficient = 0.019, t = 17.90), suggesting that economies of scale may provide resource support for green productivity. Financial Leverage (Lev) shows a significant negative effect (coefficient = -0.074, t = -11.35), indicating that high debt levels may constrain GTFP. Board Independence (Indep) has a significant positive impact (coefficient = 0.079, t = 2.96), implying that improved corporate governance aids GTFP. The Nature of Property Rights (State) exhibits a significant negative influence (coefficient = -0.029, t = -9.99), which suggests that non-state-owned enterprises (private firms) tend to achieve higher levels of GTFP.

2. Tests for Mediating and Moderating Effects

Following the three-step mediation test procedure proposed by Wen et al. (2014), the total effect of digital transformation on Green Total Factor Productivity (GTFP) is shown in Column (8) of Table 6. The total effect of the core explanatory variable (DCG) on GTFP is 0.028 (t=3.29), which is statistically significant at the 1% level, satisfying the first step of the mediation test. Column (1) of Table 6 examines the impact of digital transformation on the mediating variable, M&A activity (SM). The results show that the coefficient of DCG on SM is 0.958 (t = 3.25), significant at the 1% level, indicating that digital transformation significantly enhances M&A activity (supporting the path DCG → SM). In Column (2) of Table 6, the coefficient of SM on GTFP is 0.005 (t = 6.93), also significant at the 1% level, confirming that M&A activity significantly promotes GTFP (supporting the path SM → GTFP). The mediating effect is calculated as 0.00479 (0.958 × 0.005), accounting for 17.1% (0.00479 ÷ 0.028) of the total effect. The coefficient for the direct effect of DCG on GTFP is 0.023 (t = 2.72), significant at the 1% level, suggesting that a partial mediation may exist. Given that the total effect equals the sum of the mediating and direct effects (0.00479 + 0.023 ≈ 0.028), the results confirm a significant partial mediation effect, thereby supporting Hypothesis 2. Column (3) of Table 6 reports the regression results for Hypothesis 3. Column (3) introduces the interaction term between corporate innovation and digital transformation to test its moderating effect. The result shows that the estimated coefficient for on Green Total Factor Productivity is 0.012 and is statistically insignificant. This indicates that the level of corporate innovation does not significantly motivate or enhance the promoting effect of digital transformation on corporate green innovation. Column (4) introduces the interaction term between green innovation and digital transformation to test the moderating effect of green innovation. The result shows that the estimated coefficient for on GTFP is 0.033, which is statistically significant at the 5% level (t = 2.51). This indicates that a higher level of green innovation strengthens the positive impact of digital transformation on GTFP, thereby supporting Hypothesis 3b.

3.7.Robustness Test

To examine the robustness of our conclusions, this study conducts the following robustness checks.

1. Robustness Test: Alternative Variable Measures

To ensure the robustness of the baseline regression results, this study employs alternative measures for the key variables. Following the approach of Wu, Hu, and Lin et al. (2021) as well as Zhang and Du (2023) [31], Columns (1) and (2) in Table 7 utilize an alternative proxy for digital transformation. This proxy is constructed by using Python's web scraping functionality to identify and count feature words related to digital transformation in firms' annual financial reports. The search covers five key technology categories: Artificial Intelligence, Blockchain, Cloud Computing, Big Data, and Digital Technology Applications. A higher frequency of these feature words indicates a greater degree of corporate digital transformation. Furthermore, to address the right-skewed distribution of the raw word frequency data, we apply a logarithmic transformation by taking the natural logarithm of the word count plus one (ln(word frequency + 1)).The results in Columns (1) and (2) show that the estimated coefficients for are 0.037 (t = 14.81) and 0.027 (t = 11.10), respectively, both statistically significant at the 1% level. This provides further robust support for Hypothesis 1.

2. Robustness Test: Alternative Model Specification

Column (3) employs a Tobit model for estimation. The regression results show that the estimated coefficients for are 0.039 (t = 4.27) and 0.028 (t = 3.28), respectively, both statistically significant at the 1% level. This finding provides further support for Hypothesis 1.

3. Sobel-Goodman Mediation Test

The Sobel-Goodman method is applied to test the significance of the mediating effect of M&A activity. As presented in Table 8, the Sobel test results show that the estimated value of the indirect effect is 0.005 (z = 3.771), with a p-value less than 0.01, indicating that the mediating effect of M&A activity is statistically significant. The Aroian test yields highly consistent results (z = 3.744, p = 0.000), providing further support for the significance of the mediating effect. Similarly, the Goodman test result, with a slightly higher z-value (z = 3.799, p = 0.000), also confirms a significant indirect effect. The decomposition of the total effect into direct and indirect effects shows p-values less than 0.01 and satisfies the relationship: Total Effect = Direct Effect + Indirect Effect (0.023 + 0.005 $\approx$ 0.028).

4. Bootstrap Test

The Bootstrap method, by employing repeated resampling, helps reduce reliance on the normality assumption and enhances the reliability of the results. Table 9 presents the results for the mediating effect of M&A activity using the Bootstrap method with 1,000 resampling repetitions. The results show that the indirect effect of the independent variable $DCG_{i,t}$ on the dependent variable $GTFP_{i,t}$ through the mediator $SMA_{i,t}$ is 0.005, with a Bootstrap standard error of 0.002, a z-value of 3.09 (p = 0.002), and a 95% confidence interval of [0.002, 0.008]. This indicates a significant indirect effect whose confidence interval does not contain zero, thereby confirming the presence of a mediating effect. Meanwhile, after controlling for the mediator, the direct effect of $DCG_{i,t}$ on $GTFP_{i,t}$ is 0.023 (Bootstrap standard error = 0.008, z = 2.80, p = 0.005), with a 95% confidence interval of [0.007, 0.039], indicating that the direct effect is also statistically significant.

These results are highly consistent with the findings from the earlier Sobel test (indirect effect = 0.005, direct effect = 0.023), further supporting the robustness of the conclusion. As both the direct and indirect effects are significant and point in the same direction (both positive), this suggests that $SMA_{i,t}$ plays a partial mediating role in the relationship between $DCG_{i,t}$ and $GTFP_{i,t}$. That is, $DCG_{i,t}$ influences $GTFP_{i,t}$ both indirectly through $SMA_{i,t}$ and also has a direct positive effect on it. While the Bootstrap method enhances result reliability by reducing dependency on the normality assumption, future research could further increase the number of resampling repetitions to improve the precision of interval estimates and examine the adequacy of control variables to ensure model completeness.

3.8.Heterogeneity Analysis

1. Heterogeneity by Ownership Type Compared to private enterprises, state-owned enterprises (SOEs) tend to adopt a more conservative approach toward M&A decisions. Heavily polluting firms with different property rights face varying degrees of government intervention and bear different policy burdens, which may lead to heterogeneous effects of digital transformation on their Green Total Factor

Productivity (GTFP). This study splits the sample into two subsamples—SOEs and non-SOEs—and separately examines the relationship between digital transformation and GTFP, as well as the mediating role of M&A activity and the moderating role of green innovation. The results are presented in Table 10. Columns (1) to (4) in Table 10 report results for the SOE subsample. The estimated coefficients for digital transformation $DCG_{i,t}$ are 0.019, 0.409, 0.016, and 0.021, respectively, none of which are statistically significant. Columns (5) to (8) present results for the non-SOE subsample. Here, the estimated coefficients for $DCG_{i,t}$ are 0.033, 1.220, 0.028, and 0.029, respectively, all significant at the 1% level. In Column (7), the coefficient for M&A activity $SMA_{i,t}$ is 0.004, significant at the 1% level. In Column (8), the coefficient for the interaction term $DCG_{i,t} \times GRD_{i,t}$ is 0.049, significant at the 5% level. The results clearly indicate that digital transformation has a more pronounced and significant positive effect on GTFP in non-state-owned heavily polluting enterprises, whereas its effect on state-owned counterparts is insignificant. Furthermore, the mediating effect of M&A activity and the moderating effect of green innovation are both significant and effective specifically within the non-SOE subsample.

2.Heterogeneity by Business Environment Index. Drawing on the empirical analysis of Kopka and Grashof (2022) [114], whether digital transformation can reduce energy consumption is highly contingent upon local contextual factors. When a firm operates in a region with a higher business environment index, it typically exhibits more advanced management practices and technological capabilities. The motivation for M&A in such contexts is often driven by strategic goals related to technology acquisition and market power enhancement. The progressive deepening of enterprise digitalization accelerates technological empowerment, which optimizes M&A processes, elevates corporate green total factor productivity (GTFP), and helps narrow the technological gap between regions with superior and inferior business environments. To test the differential effects of digital transformation, M&A activity, and green innovation on the GTFP of heavily polluting enterprises across regions with varying business environment indices, this study utilizes the business environment index from the China Provincial Business Environment Index Report 2017 as the benchmark. The sample is divided into two groups-firms in regions with a higher-than-average business environment index and those with a lower-than-average index. The results are presented in Table 11.A comparison between Column (1) and Column (5) in Table 11 reveals that the estimated coefficient for digital transformation $DCG_{i,t}$ in Column (1) is 0.037 (t = 2.90, p < 0.01), which is notably larger than the coefficient of 0.020 (t = 1.70, p < 0.10) in Column (5). This finding indicates that digital transformation exerts a more pronounced positive effect on GTFP for heavily polluting enterprises located in regions with a superior business environment. Examining the mediating role of M&A activity by comparing Columns (2)-(3) with Columns (6)-(7) shows that, with the exception of Column (7), the coefficients for $DCG_{i,t}$ are significantly positive. This pattern suggests that M&A activity plays a partial mediating role in high-index regions, whereas it appears to function as a complete mediator in low-index regions. Finally, a comparison of the moderating effect between Column (4) and Column (8) demonstrates that the estimated coefficient for the interaction term $DCG_{i,t} \times GRD_{i,t}$ is statistically significant only for the high-index group. This result implies that the moderating effect of green innovation is effective exclusively under conditions of a more favorable business environment.

3. Heterogeneity by Information Transparency

M&A activity and green innovation initiatives inherently involve risk and uncertainty. Firms with lower information transparency face greater financing constraints due to the associated informational asymmetry. Conversely, firms with higher transparency can effectively convey objective and comprehensive information about their M&A and innovation activities to the external market. In such a high-transparency context, investors can clearly assess the firm and make timely investment decisions, thereby providing crucial funding support [115]. Following existing literature, this study employs the modified Jones model to measure corporate information transparency. After taking the absolute value of the calculated measure, the sample is split at the median into two groups—high and low information transparency—for subgroup regression analysis. The results are presented in Table 12.

In Columns (1) to (4) of Table 12, which correspond to the high-transparency group, the estimated coefficients for digital transformation $DCG_{i,t}$ are 0.045, 0.904, 0.040, and 0.053, respectively, all statistically significant at the 1% level. In Column (3), the coefficient for M&A activity $SMA_{i,t}$ is 0.005 (significant at the 1% level), confirming its mediating role. However, in Column (4), the coefficient for the interaction term $DCG_{i,t} \times GRD_{i,t}$ is 0.013 and statistically insignificant. These results indicate that for firms with higher information transparency, digital transformation significantly enhances GTFP, M&A activity serves as a mediator in this relationship, but the moderating effect of green innovation is not observed. Turning to the low-transparency group, in Column (5), the coefficient for $DCG_{i,t}$ is 0.012 and insignificant, suggesting that digital transformation does not significantly promote GTFP when information transparency is low. Interestingly, Column (8) reveals that although the coefficient for $DCG_{i,t}$ itself is insignificant, the coefficient for the interaction term $DCG_{i,t} \times GRD_{i,t}$ is significant. This finding implies that under the influence of green innovation, digital transformation can exert a positive effect on GTFP even in low-transparency firms.

4.Results Conclusions

4.1.Main Findings

As a central feature of the digital economy, digital transformation is playing an increasingly significant role in enhancing total factor productivity within heavily polluting enterprises. This study, based on a sample of Chinese listed companies in heavily polluting industries from 2010 to 2019, investigates the impact of digital transformation on corporate green total factor productivity (GTFP), as well as the mediating role of M&A activity and the moderating role of green innovation. The key findings are as follows: First, the degree of corporate digital transformation exerts a significant positive effect on GTFP. Deeper digital adoption is associated with higher levels of green productivity. Second, M&A activity plays a partial mediating role in this relationship. The positive impact of digital transformation on GTFP is partially and indirectly channeled through enhanced M&A activity. Third, green innovation acts as a positive moderator. Specifically, a higher level of green innovation amplifies the positive effect of digital transformation on GTFP. Finally, these core results exhibit significant heterogeneity across firm ownership, regional business environment, and information transparency. The positive effect of digital transformation on GTFP is more pronounced—and both the partial mediation of M&A activity and the moderation of green innovation hold—for firms that are non-state-owned, operate in regions with a superior business environment, or maintain higher information transparency. In contrast, the effect is statistically insignificant for state-owned enterprises. In regions with a lower business environment index, digital transformation still promotes GTFP, but the effect size is significantly smaller than in high-index regions; here, M&A activity appears to function as a complete mediator, while the moderating effect of green innovation is absent. For firms with lower information transparency, digital transformation alone does not significantly promote GTFP; however, in the presence of green innovation, it exerts a positive influence on GTFP.

4.2.Implications

From a practical standpoint, the conclusions of this study offer valuable empirical evidence and policy insights for corporate decision-makers and government regulators. For corporate decision-makers, the implications are threefold.

To begin with, heavily polluting enterprises should intensify their digital transformation efforts. This can be achieved by adopting advanced digital technologies-such as artificial intelligence and blockchain-and by investing in digital skills training for employees. These steps can enhance overall information competency and the practical application of digital tools, thereby boosting GTFP. Furthermore, attention should be paid to M&A activity. Firms should foster the coordinated development of digital transformation and M&A strategy, leveraging digitalization to facilitate transactions, reduce associated costs, optimize resource allocation, and improve post-merger integration-all contributing to higher GTFP. Lastly, it is crucial to refine incentive mechanisms for green innovation. By promoting the synergistic development

of digital transformation and green innovation, companies can fully harness the potential of digitalization to advance GTFP. This involves incentivizing in-house R&D capabilities to drive improvements in green productivity. For government regulators, two main courses of action are suggested. Firstly, relevant authorities can formulate and implement supportive policies for corporate digital transformation, including fiscal subsidies and financial support. Creating a favorable policy environment will encourage greater investment in digital technologies. Secondly, regulators should strengthen supervision and guidance over corporate M&A activities and green innovation initiatives to ensure compliant operations. Simultaneously, policy formulation must account for the heterogeneous effects stemming from differences in firm ownership, regional business environment, and information transparency. Moreover, while encouraging M&A and green innovation, policies should emphasize sustainable development to mitigate potential adverse environmental and social impacts.

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Attachment 1

Tab.1. Description of Main Variables

Variable Category	Variable Name	Symbol	Definition
Dependent Variable	Green Total Factor Productivity	$GTFP_{i,t}$	Enterprise green total factor productivity, calculated using ML method
Explanatory Variable	Digital Transformation	$DCG_{i,t}$	Measured by the proportion of intangible assets related to digital technology
Mediating Variable	M&A Activity	$SMA_{i,t}$	Number of mergers and acquisitions of firm *i* in year *t*
Moderating Variable	corporate Innovation	$RD_{i,t}$	Measured by the logarithm of (total number of invention patents, utility models, and design patents + 1)
	corporate Green Innovation	$GRD_{i,t}$	
Control Variable	Firm Size	$Size_{i,t}$	Logarithm of (total assets + 1)
	Financial Leverage	$Lev_{i,t}$	Ratio of liabilities to total assets
	Board Independence	$Indep_{i,t}$	Proportion of independent directors in the total number of board members
	Board Size	$Board_{i,t}$	Total number of board members
	Ownership Concentration	$ShareTop_{i,t}$	Shareholding ratio of the largest shareholder
	Ownership Nature	$State_{i,t}$	Dummy variable: 1 for state-controlled firms, 0 otherwise
	Environment Index	$Envir_{i,t}$	Dummy variable: 1 if above national average index, 0 otherwise

Attachment 2

Tab.2. Descriptive Statistics of Key Variables

Variable	Mean	Max	S.D.	Med	Min
$GTFP_{i,t}$	0.950	1.092	0.0800	0.951	0.800
$DCG_{i,t}$	0.047	1	0.160	0.002	0
$SMA_{i,t}$	1.176	34	1.913	1	0
$RD_{i,t}$	1.075	8.280	1.866	0	0
$GRD_{i,t}$	0.753	5.357	1.058	0	0
$Size_{i,t}$	22.47	26.50	1.402	22.41	15.60
$Lev_{i,t}$	0.519	1.897	0.228	0.521	0.00710
$Indep_{i,t}$	0.373	0.714	0.0579	0.333	0
$Board_{i,t}$	8.831	18	1.748	9	0
$ShareTop_{i,t}$	0.344	0.900	0.150	0.320	0.0263
$State_{i,t}$	0.538	1	0.499	1	0
$Envir_{i,t}$	0.496	1	0.500	0	0

Attachment 3

Tab.3. Correlation Matrix of Key Variables

变量	$GTFP_{i,t}$	$DCG_{i,t}$	$SMA_{i,t}$	$RD_{i,t}$	$GRD_{i,t}$	$Size_{i,t}$	$Lev_{i,t}$	$Indep_{i,t}$	$Board_{i,t}$	$ShareTop_{i,t}$	$State_{i,t}$	$Envir_{i,t}$
$GTFP_{i,t}$	1											
$DCG_{i,t}$	0.079***	1										
$SMA_{i,t}$	0.195***	0.103***	1									
$RD_{i,t}$	0.183***	-0.047*	0.0320	1								
$GRD_{i,t}$	0.217***	-0.088***	0.047*	0.405***	1							
$Size_{i,t}$	0.178***	-0.016	0.094***	0.237***	0.237***	1						
$Lev_{i,t}$	-0.165***	-0.001	0.0270	-0.0180	-0.0180	0.303***	1					
$Indep_{i,t}$	0.099***	0.042*	0.038*	0.0100	0.0100	0.00400	-0.00400	1				
$Board_{i,t}$	-0.106***	-0.009	-0.054**	0.086***	0.086***	0.254***	0.109***	-0.347***	1			
$ShareTop_{i,t}$	-0.062***	-0.069***	-0.044*	0.066***	0.066***	0.260***	0.088***	-0.0170	0.040*	1		
$State_{i,t}$	-0.197***	-0.101***	-0.208***	0.038*	0.038*	0.211***	0.181***	0.00600	0.199***	0.206**	1	
$Envir_{i,t}$	0.047*	0.010	0.098***	0.0270	0.0270	-0.085***	-0.120***	-0.0110	-0.053**	-0.058*	-0.147***	1

Notes: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. The same applies to the following tables.

Attachment 4

Tab.4. Multicollinearity Test

Variable	VIF	1/VIF
$Size_{i,t}$	1.58	0.633956
$GRD_{i,t}$	1.45	0.689360
$Board_{i,t}$	1.28	0.784052
$RD_{i,t}$	1.21	0.826579
$State_{i,t}$	1.20	0.834306
$Indep_{i,t}$	1.16	0.862243
$Lev_{i,t}$	1.14	0.874843
$ShareTop_{i,t}$	1.11	0.900847
$SMA_{i,t}$	1.09	0.919525
$Envir_{i,t}$	1.05	0.956876
$DCG_{i,t}$	1.03	0.969450
Mean VIF	1.21	

Attachment 5

Tab.5. Baseline Regression Results

变量	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
				$GTFP_{i,t}$				
$DCG_{i,t}$	0.039***	0.041***	0.041***	0.039***	0.040***	0.036***	0.028***	0.028***
	(4.27)	(4.50)	(4.67)	(4.47)	(4.58)	(4.19)	(3.28)	(3.29)
$Size_{i,t}$		0.010***	0.014***	0.014***	0.016***	0.018***	0.019***	0.019***
		(9.92)	(13.69)	(13.72)	(15.17)	(16.33)	(17.37)	(17.90)
$Lev_{i,t}$			-0.085***	-0.085***	-0.083***	-0.083***	-0.075***	-0.074***
			(-13.07)	(-13.10)	(-12.96)	(-12.97)	(-11.85)	(-11.35)
$Indep_{i,t}$				0.129***	0.064**	0.059**	0.079***	0.079***
				(5.34)	(2.48)	(2.32)	(3.12)	(2.96)
$Board_{i,t}$					-0.006***	-0.006***	-0.005***	-0.005***
					(-7.07)	(-7.34)	(-5.58)	(-5.44)
$ShareTop_{i,t}$						-0.060***	-0.044***	-0.044***
						(-6.22)	(-4.58)	(-4.48)
$State_{i,t}$							-0.030***	-0.029***
							(-10.24)	(-9.99)
$Envir_{i,t}$								0.002
								(0.74)
截距	0.948***	0.717***	0.667***	0.620***	0.655***	0.641***	0.607***	0.605***
	(617.57)	(30.79)	(29.05)	(25.26)	(26.38)	(25.87)	(24.70)	(24.63)
Year	YES	YES	YES	YES	YES	YES	YES	YES
样本量	2,931	2,931	2 931	2 931	2 931	2 931	2 931	2 931
R-squared	0.006	0.038	0.092	0.100	0.115	0.127	0.157	0.157

Robust t-statistics in parentheses，*** p<0.01, ** p<0.05, * p<0.1(the same below).

Attachment 6

Tab.6. Results of the Mediating and Moderating Effect Tests

Variable	Mediating Effect		Moderating Effect	
	(1) $SMA_{i,t}$	(2) $GTFP_{i,t}$	(3) $GTFP_{i,t}$	(4) $GTFP_{i,t}$
$DCG_{i,t}$	0.958***	0.023***	0.021**	0.022**
	(3.25)	(2.72)	(2.36)	(2.40)
$SMA_{i,t}$		0.005***		
		(6.97)		
$RD_{i,t}$			0.005***	
			(6.68)	
$DCG_{i,t} \times RD_{i,t}$			0.012	
			(1.56)	
$GRD_{i,t}$				0.011***
				(7.48)
$DCG_{i,t} \times GRD_{i,t}$				0.033**
				(2.51)
$Size_{i,t}$	0.211***	0.018***	0.005***	0.005***
	(5.58)	(16.36)	(6.94)	(6.96)
$Lev_{i,t}$	0.302*	-0.076***	0.016***	0.014***
	(1.78)	(-12.08)	(14.40)	(11.49)
$Indep_{i,t}$	0.715	0.075***	-0.071***	-0.072***
	(1.28)	(3.01)	(-11.39)	(-11.48)
$Board_{i,t}$	-0.046**	-0.005***	0.072***	0.076***
	(-1.98)	(-5.34)	(2.89)	(3.08)
$ShareTop_{i,t}$	-0.400	-0.042***	-0.005***	-0.005***
	(-1.49)	(-4.38)	(-5.75)	(-5.68)
$State_{i,t}$	-0.815***	-0.025***	-0.042***	-0.041***
	(-10.01)	(-8.55)	(-4.50)	(-4.44)
$Envir_{i,t}$	0.304***	0.000	-0.025***	-0.026***
	(4.27)	(0.17)	(-8.59)	(-8.84)
intercept	-3.205***	0.622***	-0.000	-0.001
	(-3.81)	(25.22)	(-0.02)	(-0.35)
sample size	2 931	2 931	2,931	2 931
R-squared	0.080	0.171	0.188	0.194

Attachment 7

Tab.7. Robustness Tests for the Baseline Mode

Variable	Alternative Explanatory Variable		TOBIT Model Specification	
	(1) $GTFP_{i,t}$	(2) $GTFP_{i,t}$	(3) $GTFP_{i,t}$	(4) $GTFP_{i,t}$
$DCG_{i,t}$	0.037***	0.027***	0.039***	0.028***
	(14.87)	(11.10)	(4.27)	(3.28)
$Size_{i,t}$		0.017***		0.019***
		(15.99)		(17.41)
$Lev_{i,t}$		-0.070***		-0.074***
		(-11.23)		(-11.76)
$Indep_{i,t}$		0.062**		0.079***
		(2.49)		(3.14)
$Board_{i,t}$		-0.004***		-0.005***
		(-5.04)		(-5.57)
$ShareTop_{i,t}$		-0.041***		-0.044***

		(-4.40)		(-4.57)
$State_{i,t}$		-0.026***		-0.029***
		(-8.95)		(-10.11)
$Envir_{i,t}$		0.001		0.002
		(0.41)		(0.74)
Constant	0.940***	0.634***	0.948***	0.605***
	(604.81)	(25.98)	(617.80)	(24.51)
Number of Observations	2,931	2 931	2 931	2 931
R^2/Log likelihood	0.070	0.188	3255.232	3497.054

Attachment 8

Tab.8. Sobel-Goodman Mediation Test

	Est	Std_err	z	P> | z |
Sobel	0.005	0.001	3.771	0.000
Aroian	0.005	0.001	3.744	0.000
Goodman	0.005	0.001	3.799	0.000
Path a : $DCG_{i,t} \rightarrow SMA_{i,t}$	0.958	0.214	4.484	0.000
Path b: $SMA_{i,t} \rightarrow GTFP_{i,t}$	0.005	0.001	6.969	0.000
Indirect effect: a×b	0.005	0.001	3.771	0.000
Direct effect	0.023	0.009	2.717	0.007
Total effect	0.028	0.009	3.278	0.001

Attachment 9

Tab.9. Bootstrap Test

	Coef.	Std.	z	P> | z |	Normal-based [95% conf. interval]	
Indirect effect	0.005	0.002	3.09	0.002	0.002	0.008
Direct effect	0.023	0.008	2.80	0.005	0.007	0.039

Attachment 10

Tab.10. Heterogeneity Analysis Results by Ownership Type

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	State-owned				Non-state-owned			
	$GTFP_{i,t}$	$SMA_{i,t}$	$GTFP_{i,t}$	$GTFP_{i,t}$	$GTFP_{i,t}$	$SMA_{i,t}$	$GTFP_{i,t}$	$GTFP_{i,t}$
$DCG_{i,t}$	0.019	0.409	0.016	0.021	0.033***	1.220***	0.028***	0.029***
	(1.32)	(1.58)	(1.14)	(1.32)	(3.06)	(3.71)	(2.56)	(2.58)
$SMA_{i,t}$			0.006***				0.004***	
			(4.71)				(5.07)	
$GRD_{i,t}$				0.016***				0.007***
				(7.95)				(3.08)
$DCG_{i,t} \times GRD_{i,t}$				0.017				0.049**
				(0.93)				(2.51)

$Size_{i,t}$	0.018***	0.129***	0.017***	0.012***	0.020***	0.310	0.018***	0.017***
	(12.18)	(4.75)	(11.61)	(6.96)	(12.31)	(6.38)	(11.37)	(9.88)
$Lev_{i,t}$	-0.076***	-0.095	-0.075***	-0.069***	-0.072***	0.660**	-0.075***	-0.070***
	(-8.28)	(-0.57)	(-8.26)	(-7.66)	(-8.18)	(2.46)	(-8.58)	(-7.92)
$Indep_{i,t}$	0.072**	-0.036	0.072**	0.067**	0.110***	2.411*	0.099	0.118***
	(2.26)	(-0.06)	(2.28)	(2.15)	(2.60)	(1.87)	(2.36)	(2.82)
$Board_{i,t}$	-0.006***	-0.027	-0.006***	-0.006***	-0.002	-0.042	-0.002	-0.002
	(-5.61)	(-1.42)	(-5.47)	(-6.20)	(-1.41)	(-0.87)	(-1.31)	(-1.29)
$ShareTop_{i,t}$	-0.049***	-0.799***	-0.044***	-0.049***	-0.035**	0.161	-0.036**	-0.036**
	(-3.89)	(-3.47)	(-3.49)	(-3.98)	(-2.42)	(0.36)	(-2.49)	(-2.47)
$Envir_{i,t}$	-0.001	0.223***	-0.003	-0.006*	0.006	0.370***	0.004	0.007*
	(-0.39)	(3.32)	(-0.78)	(-1.75)	(1.44)	(2.91)	(1.05)	(1.63)
Constant	0.609***	-1.630***	0.619***	0.747***	0.549***	-6.448***	0.578***	0.597***
	(18.60)	(-2.74)	(19.01)	(20.40)	(13.79)	(-5.32)	(14.50)	(14.40)
Number of Observations	1 578	1,578	1578	1578	1353	1353	1353	1353
R^2	0.120	0.026	0.132	0.161	0.132	0.061	0.148	0.147

Attachment 11

Tab.11. Heterogeneity Analysis Results by Business

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	superior business environment				inferior business environment			
	$GTFP_{i,t}$	$SMA_{i,t}$	$GTFP_{i,t}$	$GTFP_{i,t}$	$GTFP_{i,t}$	$SMA_{i,t}$	$GTFP_{i,t}$	$GTFP_{i,t}$
$DCG_{i,t}$	0.037***	1.039***	0.033***	0.026*	0.020*	0.700***	0.014	0.026**
	(2.90)	(2.73)	(2.59)	(1.89)	(1.70)	(3.21)	(1.21)	(2.11)
$SMA_{i,t}$			0.004***				0.008***	
			(4.57)				(6.01)	
$GRD_{i,t}$				0.007***				0.017***
				(3.11)				(7.93)
$DCG_{i,t} \times GRD_{i,t}$				0.077***				0.002
				(3.61)				(0.15)
$Size_{i,t}$	0.019***	0.384***	0.018***	0.016***	0.019***	0.069**	0.018***	0.013***
	(11.82)	(8.00)	(10.71)	(8.84)	(12.69)	(2.44)	(12.43)	(8.19)
$Lev_{i,t}$	-0.086***	0.488*	-0.087***	-0.081***	-0.064***	0.036	-0.065***	-0.061***
	(-9.06)	(1.73)	(-9.32)	(-8.59)	(-7.46)	(0.22)	(-7.59)	(-7.18)
$Indep_{i,t}$	0.031	-0.165	0.032	0.022	0.105***	1.133*	0.096***	0.112***
	(0.81)	(-0.14)	(0.84)	(0.58)	(3.08)	(1.77)	(2.84)	(3.33)
$Board_{i,t}$	-0.008***	-0.092**	-0.008***	-0.008***	-0.003***	-0.002	-0.003***	-0.003***
	(-5.59)	(-2.18)	(-5.36)	(-5.72)	(-2.78)	(-0.09)	(-2.80)	(-3.07)
$ShareTop_{i,t}$	-0.045***	0.241	-0.046***	-0.047***	-0.048***	-0.868***	-0.041***	-0.017***
	(-3.53)	(0.63)	(-3.63)	(-3.71)	(-3.30)	(-3.17)	(-2.83)	(-3.27)
$State_{i,t}$	-0.029***	-0.959***	-0.025***	-0.031***	-0.028***	-0.673***	-0.022***	-0.026***
	(-7.03)	(-7.76)	(-6.02)	(-7.50)	(-6.72)	(-8.64)	(-5.31)	(-6.31)
Constant	0.655***	-6.280***	0.680***	0.725***	0.572***	-0.299	0.575***	0.684***
	(17.36)	(-5.59)	(17.96)	(17.57)	(17.32)	(-0.48)	(17.60)	(19.36)

Number of Observations	1453	1,453	1453	1,453	1478	1478	1478	1478
R^2	0.168	0.095	0.180	0.186	0.1511	0.077	0.172	0.190

Attachment 12

Tab.12. Terogeneity Analysis Results by Information Transparency

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	higher information transparency				lower information transparency			
	$GTFP_{i,t}$	$SMA_{i,t}$	$GTFP_{i,t}$	$GTFP_{i,t}$	$GTFP_{i,t}$	$SMA_{i,t}$	$GTFP_{i,t}$	$GTFP_{i,t}$
$DCG_{i,t}$	0.045***	0.904***	0.040***	0.053***	0.012	0.951***	0.007	0.005
	(3.70)	(2.71)	(3.33)	(4.09)	(1.04)	(3.65)	(0.56)	(0.40)
$SMA_{i,t}$			0.005***				0.006***	
			(5.58)				(5.03)	
$GRD_{i,t}$				0.015***				0.008***
				(7.06)				(3.69)
$DCG_{i,t} \times GRD_{i,t}$				0.013				0.045**
				(0.67)				(2.51)
$Size_{i,t}$	0.017***	0.313***	0.015***	0.011***	0.021***	0.128***	0.020***	0.018***
	(10.10)	(6.83)	(9.08)	(5.96)	(14.44)	(4.08)	(13.93)	(11.29)
$Lev_{i,t}$	-0.081***	0.374	-0.083***	-0.071***	-0.069***	0.195	-0.070***	-0.068***
	(-8.44)	(1.42)	(-8.72)	(-7.51)	(-8.19)	(1.06)	(-8.40)	(-8.12)
$Indep_{i,t}$	0.043	0.937	0.038	0.052	0.111***	0.711	0.106***	0.108***
	(1.17)	(0.93)	(1.05)	(1.44)	(3.20)	(0.94)	(3.10)	(3.15)
$Board_{i,t}$	-0.005***	-0.063*	-0.005***	-0.005***	-0.004	-0.029	-0.004***	-0.004***
	(-4.09)	(-1.84)	(-3.87)	(-4.43)	(-3.62)	(-1.10)	(-3.50)	(-3.76)
$ShareTop_{i,t}$	-0.028**	0.159	-0.029**	-0.026**	-0.059***	-1.073***	-0.052***	-0.062***
	(-2.11)	(0.44)	(-2.20)	(-2.01)	(-4.31)	(-3.58)	(-3.85)	(-4.53)
$State_{i,t}$	-0.028***	-0.986***	-0.023***	-0.029***	-0.030***	-0.644***	-0.026***	-0.030***
	(-6.87)	(-8.75)	(-5.54)	(-7.20)	(-7.14)	(-7.11)	(-6.14)	(-7.26)
$Envir_{i,t}$	-0.002	0.359***	-0.004	-0.003	0.007*	0.228***	0.006	0.005
	(-0.61)	(3.40)	(-1.11)	(-0.91)	(1.80)	(2.65)	(1.46)	(1.35)
Constant	0.661***	-5.450***	0.689***	0.777***	0.555***	-1.399**	0.564***	0.618***
	(17.39)	(-5.23)	(18.15)	(19.01)	(17.08)	(-1.97)	(17.47)	(17.41)
Number of Observations	1,510	1,510	1,510	1,510	1421	1421	1421	1421
R^2	0.135	0.096	0.153	0.168	0.191	0.079	0.206	0.207

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Historiographical Review of Chinese Research on Political Literacy of University Students

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KEYWORDS

Political literacy;
University students;
Higher education;
Iideological and political education;
Curriculum integration;
Digital citizenship

ABSTRACT

This review synthesizes Chinese research on the political literacy of university students from 1990 to 2025 using a historiographical design anchored in major Chinese databases and policy documents. The field exhibits four phases: 1990 to 2005 established a normative foundation within ideological and political education; 2006 to 2015 translated aims into competency frameworks and indicators; 2016 to 2019 embedded political literacy in professional curricula and practice; 2020 to 2025 integrated digital participation, media use, and learning analytics with attention to privacy and data governance. Across phases the literature moves from conceptual aims to measurable constructs, curricular integration, and engagement in online publics. The review identifies priorities for validated and transparent instruments, cohort tracking across undergraduate years, and embedded evaluations that link learning designs to changes in student knowledge, competencies, and behavior while safeguarding consent and privacy.

INTRODUCTION

Political literacy in Chinese higher education is commonly understood as an integrated capacity that joins knowledge of constitutional and institutional arrangements, value orientation and identity formation, civic competencies such as information discernment and deliberation, and observable behaviors in campus governance and social participation. In practice it has been cultivated within the long standing system of ideological and political education while gradually extending into professional curricula and co curricular settings, which gives the construct both normative and pedagogical significance [1]. This review adopts a historiographical perspective to trace how Chinese scholarship has conceptualized and measured political literacy among university students from the 1990s to 2025, and how teaching and assessment practices have evolved across four identifiable phases. It clarifies the movement from foundational definition to competence based indicators, then to curriculum embedded and practice oriented approaches, and finally to digital contexts where online participation, media use, and data governance influence both opportunities and risks for student development [2]. By consolidating representative scholars and verifiable contributions within each phase, the review aims to provide a coherent map of concepts, methods, and evidence that can guide future research design, scal.

Materials and Methods

This review adopts a historiographical design that combines systematic searching with narrative synthesis. The primary sources were Chinese language journals and dissertations retrieved from CNKI, CSSCI indexed journals and Wanfang. Policy and curriculum documents relevant to ideological and political education in universities were consulted to anchor turning points in the field. The time window ran from January 1990 to November 2025 so that recent outputs on digital participation and learning analytics were fully covered. Searches were conducted in Chinese and English using combinations of the following terms and their close variants: political literacy, political quality, university students, higher education, ideological and political education, curriculum ideological political, digital

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citizenship, and media literacy.

Inclusion required a clear focus on university students in mainland China and an explicit contribution to the definition, measurement, cultivation, or evaluation of political literacy. Conceptual essays, empirical studies, and curriculum or governance reforms were eligible. Studies were excluded if they addressed only basic education, were limited to general public opinion without a higher education context, or lacked substantive relevance to political literacy. Titles and abstracts were screened first, followed by full text review. Each included item was coded for research type, institutional setting, sample features, instruments and indicators, and principal claims. Additional fields captured links to national or sector policies, the presence of teacher development components, and attention to digital environments.

Periodization was derived from clusters of publication themes and from policy milestones in higher education. Representative scholars were identified through citation patterns, authorship of widely used textbooks or comprehensive reviews, and visible influence on institutional practice. Methodological quality was recorded rather than scored, with notes on reliability and validity reporting for scales, on sampling strategies, and on the use of longitudinal or experimental designs. The synthesis proceeded by phase specific narration that aligns features, scholars, and claims. As this work synthesizes publicly available texts and does not involve human participants, no ethical approval was require.

Results

1.1990s－2005: Foundational Normative Phase

In the early years of the field, Chinese scholarship on the political literacy of university students was framed as a normative project within ideological and political education. Core writings defined political literacy as a composite of knowledge of political institutions and history, value orientation aligned with national goals, and guided participation in campus and community settings. The dominant method was theoretical exposition supported by analysis of policy and curricular documents, with limited use of systematic empirical designs. Influential contributors such as Zhang Yaocan and Chen Wanbo articulated the objects, contents, and carriers of ideological and political education and positioned political literacy as an outcome of value formation and political socialization in higher education. Subsequent international analyses describe this stage as one of institutional consolidation in which universities established party led structures, standardized courses, and a nationwide delivery system for ideological and political education, while empirical validation of outcomes remained sparse [1]. Recent thematic reviews corroborate the observation that early work favored prescriptive argument and descriptive reporting, laying the conceptual groundwork but leaving questions of measurement quality and causal effects largely open for later phases [3].

2.2006－2015: Competency and Measurement Turn

During this decade, Chinese scholarship on university students' political literacy moved from value transmission toward demonstrable competencies and measurable outcomes. Researchers operationalized political literacy as a bundle of knowledge, belief, efficacy, and participation, and began to translate these constructs into item banks and scales with attention to reliability and validity. Survey culture expanded in teacher education institutes and student affairs units, where Likert instruments, factor analysis, and item discrimination tests were used to calibrate indicators such as political cognition, civic competence, and internal or online political efficacy. Quality assurance also improved inside universities through pretesting, multi university sampling, and the routine reporting of Cronbach alpha and model fit indices. This measurement turn did not abandon normative aims but tied them to evidence on communication effect, curriculum exposure, and media use. In later consolidation studies that reflect this tradition, scholars model how internet literacy and contact shape the communication effect of ideological and political education among university students, which retroactively validates the competence centered approach of the period [4]. Parallel work uses structural equation modeling to link curriculum based ideological and political education to student psychological outcomes, exemplifying the mature use of latent constructs and validated indicators that grew out of this decade [5].

3.2016－2019: Curriculum-Embedded and Practice-Oriented Phase

During this period universities moved from stand alone civic

instruction toward embedding political literacy across majors and courses, an approach widely described as curriculum ideological and political. The reform stressed course level alignment of objectives, content, teaching links, and evaluation so that professional knowledge, values education, and application could be taught together. Reviews that synthesize recent evidence characterize this shift as a turn to implementation within disciplines accompanied by difficulties of assessment design and teacher capacity, which clarifies the practical orientation of the 2016 to 2019 phase and its emphasis on linking classroom learning with concrete tasks and field practice [6]. Case studies in engineering and resource curricula document explicit insertion of ideological and political elements into lectures, design assignments, and practice activities, together with process evaluation and project based learning, which illustrates how political cognition, social responsibility, and law awareness were cultivated inside professional teaching rather than only in dedicated theory classes .

4.2020 – 2025: Digitalization, Platform Participation and Ethics

In this period research on the political literacy of Chinese university students shifted into digital contexts where online participation, platform use, and data driven assessment interact with classroom and campus practice. Scholars integrated digital citizenship, media literacy, and platform behaviors into the construct of political literacy and used validated instruments and structural models to link media use, self efficacy, and civic intention, which positioned political literacy as both competence and behavior in converged media environments [2]. Studies on misinformation documented that many Chinese college students perceive tangible psychological risks arising from false content and uneven source evaluation skills, which strengthened calls for ethics aware pedagogy and institutional safeguards that protect consent, privacy, and psychological safety while cultivating responsible participation . Designs increasingly paired questionnaires with learning platform logs or other process data to capture engagement and outcomes, although protocols for transparency and data minimization remain uneven across institutions. A compact map of digital themes, indicators, and ethics foci is provided here, see Table 1, which summarizes constructs frequently used in studies from 2020 to 2025.

Theme	Typical indicators used in studies	Ethics focus	Theme
Digital participation	Frequency of online discussion, civic intention, political efficacy, self regulation, official media use	Consent and privacy, accountability	Digital participation
Learning analytics in courses	Log events, time on task, forum contribution, quiz attempts, linkage of assessment to participation	Transparency, data minimization, informed access	Learning analytics in courses
Misinformation resilience	Accuracy checks, source evaluation, correction intention, reporting behavior, perceived impact on mood	Psychological safety, support pathways, educator guidance	Misinformation resilience

Table.1. Digital themes and examples for political literacy 2020 to 2025

Conclusion

This review shows a clear evolution in Chinese research on the political literacy of university students from 1990s to

2005 as a foundational normative phase, through 2006 to 2015 with emphasis on competencies and measurement, then 2016 to 2019 with curriculum embedded and practice oriented work, and finally 2020 to 2025 with digitalization, platform participation, and ethics at the center. Across these phases, the literature moved from goal setting and conceptual framing toward operational indicators, classroom integration, and attention to online publics. The most recent studies extend the construct to include digital citizenship and data governance, which strengthens relevance but also heightens ethical demands. The field now needs validated and openly described instruments, cohort tracking across the undergraduate years, and embedded evaluations that link teaching designs to specific gains in knowledge, competencies, and behavior. It also requires sustained teacher development for discipline based integration and careful protocols for consent, privacy, and transparency in learning analytics. Greater attention to vocational institutions, private universities, and minority regions will improve generalizability and fairness..

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Research on Innovative Environmental Management Models of Leading Agricultural Industrialization Enterprises in Liaoning Province

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KEYWORDS

Agricultural industrialization;
Leading enterprises;
Innovation in environmental management models;

ABSTRACT

Under the background of the 'dual carbon' goals and the green transformation of agriculture, the innovation of environmental management modes in leading agricultural enterprises in Liaoning Province has become a key factor in promoting regional agricultural sustainable development. Based on theories such as circular economy and technological innovation, this paper addresses issues such as passive environmental protection and insufficient technology application in enterprises in Liaoning Province, and designs a three-level environmental management innovation model of 'internal enterprise closed loop – industry chain collaboration – regional resource sharing.' An empirical test is conducted using Sanyou Agriculture as a case study. The data show that after implementing this model, the enterprise significantly outperformed the industry average in environmental performance, economic performance, and technological adaptability, achieving a win-win situation of 'enhanced efficiency through environmental protection.' The research findings not only enrich the theoretical framework at the intersection of agricultural economics and environmental management but also provide practical references for the green transformation of leading agricultural enterprises in Liaoning Province and for relevant policy-making.

1.INTRODUCTION

1.1Research background and significance

Against the backdrop of intensifying global climate change and tightening resource constraints, green, low-carbon, and circular development has emerged as a core issue reshaping the global industrial landscape. As a fundamental sector of the national economy, the green transformation of agriculture is directly tied to the ecological security and sustainable development foundation of regions and even the entire country. The implementation of China's "dual carbon" strategy—carbon peaking by 2030 and carbon neutrality by 2060—has laid out a clear path for the low-carbon and ecological transformation of traditional agriculture, while also imposing higher requirements on the environmental governance capabilities of agricultural production and operation entities.

As key hubs connecting smallholder farmers to large markets, leading agricultural industrialization enterprises are core carriers of the modern agricultural management system. Their level of environmental operation not only determines their own potential for sustainable development but also profoundly influences the green transformation of the entire agricultural industrial chain. Liaoning Province, a major grain-producing area in Northeast China and an advantageous region for characteristic agricultural products, boasts a solid industrial foundation for leading agricultural industrialization enterprises in sectors such as grain processing, animal husbandry, and specialty edible fungi and vegetable cultivation. However, their environmental operation practices exhibit obvious lag. In reality, most leading agricultural enterprises in the province remain at the

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level of "passive compliance" in environmental protection, lacking the strategic awareness to deeply integrate environmental management with industrial upgrading. Meanwhile, the penetration rate of green innovation tools such as circular agriculture technologies and digital environmental protection systems is relatively low, and the technical adaptability and systematization of environmental operation models are insufficient. This not only restricts the improvement of enterprises' own economic benefits and brand value but also slows down the province's agricultural transition to a green and low-carbon paradigm, creating a prominent contradiction with the demand for high-quality agricultural development under the background of the revitalization of Northeast China's old industrial bases. In this context, exploring an environmental operation model for leading agricultural industrialization enterprises that suits Liaoning's regional characteristics has become an inevitable choice to address the coordinated challenge of agricultural ecological protection and industrial efficiency improvement.

Theoretically, this study holds significant academic value. First, it systematically sorts out core theories including value creation-oriented environmental management theory, environmental operation paradigm transformation theory, and green culture-environmental operation interaction theory, and establishes a theoretical application framework in the context of agricultural industrialization. This fills the theoretical gap in existing research on environmental operation of meso-level entities (provincial leading agricultural enterprises) and promotes the improvement of the theoretical system at the intersection of agricultural economics and environmental management. Second, through literature integration, theoretical deduction, and coupling analysis with Liaoning's regional characteristics, it constructs an analytical paradigm for environmental operation model innovation that aligns with Liaoning's agricultural industrial endowments, providing a reference analytical framework for theoretical research on environmental operation of leading agricultural enterprises in similar regions.

In practical terms, the value of this study is reflected in dual empowerment. On one hand, taking Liaoning Sanyou Agricultural Biotechnology Co., Ltd. as a typical case, it diagnoses the existing pain points in its environmental operation and constructs an environmental operation model featuring "technological innovation-driven, internal circular closed-loop, and regional resource coordination". This provides a replicable and promotable practical model for leading specialty agricultural product processing enterprises in Liaoning, helping them transform "environmental protection investment" into "value output" and achieve a win-win situation of both environmental and economic performance. On the other hand, the research results can serve as a decision-making reference for local agricultural authorities to formulate agricultural green transformation policies and optimize environmental protection support mechanisms for leading enterprises, driving Liaoning's agricultural sector to realize the simultaneous improvement of ecological benefits and industrial competitiveness under the "dual carbon" goals.

1.2.Literature Review and Research Gaps

Foreign academic research on leading agricultural industrialization enterprises initially focused on the evaluation of enterprises' comprehensive development level and regional adaptability analysis, and in recent years has gradually extended to the dimensions of competitiveness deconstruction and development potential research. In the aspect of regional adaptability evaluation, ang Ying and Yadong Fan (2010) took leading agricultural industrialization enterprises in Heilongjiang Province as research samples, constructed a comprehensive evaluation system from dimensions such as industrial layout rationality, interest linkage mechanism improvement, and resource integration capability, analyzed the development characteristics and core constraints of leading enterprises under the background of cold-region agriculture, and provided a basic analysis framework for the cultivation and development of leading agricultural enterprises in high-latitude regions [1]. In the field of enterprise competitiveness research, GUO Yubing et al. (2023) selected 28 leading agricultural industrialization enterprises in Shanxi Province as research objects, built a competitiveness evaluation model covering dimensions such as industrial driving capacity, resource allocation efficiency, and technological innovation level, clarified the competitiveness shortcomings of different types of leading enterprises through empirical analysis, and put forward cultivation paths and optimization strategies for core leading enterprises, providing practical references for improving the competitiveness of regional leading agricultural enterprises [2]. Overall, foreign research in this field mostly takes

specific regions as samples, forming a research paradigm of "evaluation system construction - development bottleneck diagnosis - optimization strategy proposal", but there is still a lack of special exploration on the environmental operation dimension of leading enterprises.

The enabling effect of digital technology on agricultural industrialization has been a research hotspot in the field of foreign agricultural economy in recent years, and scholars have conducted in-depth discussions from the dual perspectives of productivity innovation and industrial sustainable development. In terms of improving agricultural green productivity, the research of Zeng F et al. (2024) confirmed that rural digitalization can achieve a leap-forward improvement in agricultural green total factor productivity through paths such as optimizing the allocation of production factors, reconstructing agricultural production processes, and improving the efficiency of resource recycling. The research also pointed out that the enabling effect of digitalization on agricultural green transformation has regional and industrial format heterogeneity, and the enabling effect is more significant in the fields of characteristic agricultural product planting and processing [3]. In the dimension of rural industrial sustainable development, Gao S et al. (2023) combined digital empowerment, rural entrepreneurship, and deep learning technology to construct a logical framework for digital technology-driven sustainable development of rural industries, empirically tested the core value of digital technology in expanding industrial boundaries, reducing production energy consumption, and strengthening industrial chain collaboration, and also revealed practical bottlenecks restricting the landing of digital technology such as technical thresholds and data security [4]. These studies have clarified the enabling path of digital technology for agricultural industrialization, but have not deeply coupled digital technology with the environmental operation model of leading agricultural enterprises, and lack the design of digital environmental operation schemes for leading enterprises.

Foreign research on environmental operation started early, forming a research system centered on the evaluation of environmental management system effectiveness and the measurement of enterprise ecological carrying capacity. At the level of the practical value of environmental management systems, Sroufe R (2003) through empirical research on enterprises in multiple industries, confirmed that a sound environmental management system can significantly optimize enterprise environmental management practices and production and operation processes, which can not only reduce the intensity of enterprise pollutant emissions but also effectively control production costs by improving resource utilization efficiency. The research also clarified the adaptability differences of environmental management systems in enterprises of different scales and formats [5]. In the agricultural field, Yi Ling Liu and Song Qing Li (2014) constructed an ecological carrying capacity evaluation system for leading agricultural industrialization enterprises, designed quantitative indicators from dimensions such as resource consumption, pollution emissions, and ecological contributions, and clarified the core influencing factors of the ecological carrying capacity of leading agricultural enterprises through empirical research, filling the theoretical gap in the quantitative evaluation of the ecological carrying capacity of agricultural enterprises [6]. However, existing research mostly focuses on a single dimension of environmental operation, failing to form a systematic environmental operation model covering the enterprise interior, industrial chain, and region, and there is an obvious gap in research on the adaptability of environmental operation of leading agricultural enterprises in cold regions.

Based on the above research results of foreign literature and combined with the practical needs of the development of leading agricultural industrialization enterprises in Liaoning Province, there are still three significant theoretical and practical gaps in the field of environmental operation of leading agricultural industrialization enterprises.

First, the systematic lack of research perspectives; existing research mostly focuses on a single dimension of environmental operation, for example, Sroufe R (2003) only focuses on the practical effectiveness of the internal environmental management system of enterprises, and Yi Ling Liu et al. (2014) focuses on the single indicator measurement of enterprise ecological carrying capacity, failing to build a multi-dimensional collaborative environmental operation theoretical framework of "enterprise interior - industrial chain - region", which is difficult to meet the systematic environmental governance needs of leading agricultural industrialization enterprises as the chain leaders of the industrial chain. Second, the blank of the cold-region dimension in regional adaptability; although ang Ying et al. (2010) paid attention to the development characteristics of leading agricultural enterprises in cold

regions, they did not extend to the field of environmental operation; and existing environmental operation technologies and schemes are mostly designed based on temperate or tropical agricultural endowments, without fully considering the regional characteristics such as winter low-temperature constraints in Northeast cold regions and the rigid demand for black soil protection. The adaptability research of cold-region-specific agricultural waste recycling technology, low-temperature cultivation energy-saving technology, etc., is blank, leading to the serious lack of landing of existing models in Liaoning Province and other Northeast cold regions. Third, the insufficient synergy of technology integration; although Zeng F et al. (2024) and Gao S et al. (2023) confirmed the enabling value of digital technology for agricultural green transformation, they did not cross-integrate digital technology with theories such as circular economy and industrial chain integration, nor did they form a practical path for environmental operation of leading agricultural enterprises driven by digital technology, making it difficult to solve the practical problems of insufficient application of green technology and low digitalization level of environmental operation of leading agricultural enterprises in Liaoning Province.

In response to the above research gaps, this study forms innovative breakthroughs in three aspects: in terms of subject focus, this study locks on leading agricultural industrialization enterprises in Liaoning Province as meso-level subjects, constructs an environmental operation model suitable for the provincial regional agricultural industrial pattern, thereby filling the gap in theoretical and practical research on environmental operation at the meso level, and opening up the connection channel between macro-policy implementation and micro-subject practice; in terms of regional adaptability, based on the climatic characteristics of Northeast cold regions and the demand for black soil protection, develop cold-resistant edible fungi cultivation technology, cold-region waste high-efficiency conversion technology and other cold-region-specific agricultural recycling technologies, design environmental operation schemes that fit regional endowments, and solve the technical adaptability problem of agricultural green transformation in cold regions; in the dimension of theoretical integration, construct a three-level environmental operation model of "internal enterprise closed loop - industrial chain collaboration - regional resource sharing", realize the cross-field integration of circular economy, industrial chain integration and cold-region agricultural technology innovation theories, and form a provincial agricultural leading enterprise green transformation solution with both theoretical depth and practical value.

2.Theoretical Basis and Concept Definition

2.1Leading Agricultural Industrialization Enterprises

According to the relevant identification standards of the Ministry of Agriculture and Rural Affairs, leading agricultural industrialization enterprises refer to agricultural enterprises that take the production, processing, and circulation of agricultural products as their core business, realize large-scale and intensive operation through models such as "enterprise + farmer" and "enterprise + cooperative + farmer", have a significant driving effect on agricultural industrial development, and are recognized by governments at all levels. Its core characteristics include: large operation scale, strong industrial chain integration capability, close interest linkage with farmers, and a prominent role in driving regional agricultural economic development. Leading agricultural industrialization enterprises in Liaoning Province mostly focus on fields such as grain processing, animal husbandry, and characteristic agricultural product development, and are the core subjects of regional agricultural modernization and green transformation.

2.2.Innovation of Environmental Operation Modes

2.2.1.Academic Controversy and Conceptual Analysis

At present, the academic circle has not yet formed a unified consensus on the definition of environmental operation model innovation, and the core of the controversy focuses on two levels: innovation dimension and value orientation. From the perspective of innovation dimension, some scholars believe that environmental operation model innovation should focus on the technical level. For example, Dong Xiaodong et al. (2014) proposed that its core is the embedding of low-carbon technology and recycling technology in the production link, which is the green iteration of the enterprise's technical system; another part of

scholars emphasizes the collaboration at the industrial chain dimension. Zhang Changjiang et al. (2020) pointed out that environmental operation model innovation needs to cover the upstream and downstream of the industrial chain, and realize the maximization of ecological benefits through the integration of the entire chain of resources, and the technological innovation of a single enterprise is difficult to achieve systematic environmental improvement. From the perspective of value orientation, some studies advocate "ecology first" as the core, taking environmental performance as the primary assessment indicator of model innovation; while scholars such as Gan Changsheng (2025) adhere to the dual value orientation of "environment - economy", believing that environmental operation models separated from economic performance do not have a sustainable promotion foundation.

2.2.2.Concept Definition of This Study

Combined with the development characteristics and research needs of leading agricultural industrialization enterprises in Liaoning Province, this study defines environmental operation model innovation as: taking circular economy as the underlying logic, technological innovation as the core support, and industrial chain integration as the implementation path, leading agricultural industrialization enterprises break through the traditional environmental management model of "passive compliance", integrate internal and external resources of the enterprise, and form a new type of operation structure and operation mechanism that "converts environmental constraints into development momentum". Its core connotation includes three aspects: first, the meso attribute of the innovation subject, focusing on provincial leading agricultural industrialization enterprises as the chain leader of the industrial chain; second, the systematicness of the innovation dimension, covering three levels: enterprise interior, industrial chain, and region; third, the synergy of innovation goals, ultimately realizing the dual goals of sustainable enterprise development and regional ecological protection, specifically reflected in practical forms such as the application of circular economy models, digital technology empowering environmental management, and green integration of the entire industrial chain.

Dong Xiaodong et al. (2014) based on Kuhn's "Structure of Scientific Revolutions" theory proposed that the enterprise operation paradigm needs to iterate with changes in external environmental constraints. In the context of low-carbon economy and "dual carbon" goals, enterprises need to shift from the traditional paradigm of "economy first" to the environmental operation paradigm of "environment and economy coordination". This theory provides a paradigm transformation perspective for the research: leading agricultural industrialization enterprises in Liaoning Province need to break through the traditional operation thinking of "emphasizing production over environmental protection", fully integrate environmental factors into all links such as strategic planning, production and operation, and industrial chain integration, and complete the systematic transformation of the operation paradigm.

2.3.Industrial Chain Integration Theory

The industrial chain integration theory emphasizes optimizing the division of labor and cooperation by integrating upstream and downstream resources of the industrial chain, and improving the overall efficiency and competitiveness of the industry. Agricultural industrial chain integration covers the coordinated linkage of links such as means of production supply, agricultural production, agricultural product processing, and circulation and sales. Combined with environmental operation goals, green industrial chain integration needs to integrate environmental protection requirements into all links to achieve efficient resource utilization and environmental risk management and control. This theory provides path guidance for the innovation of environmental operation models of leading agricultural industrialization enterprises in Liaoning Province - by integrating regional agricultural resources, building a green industrial chain of "planting - processing - waste recycling - sales", and improving the systematicness and synergy of environmental operation.

2.4.Technological Innovation Theory

The technological innovation theory holds that technological progress is the core driving force for industrial upgrading and enterprise development. In the field of environmental operation, green technological innovation (such as low-carbon production technology, recycling technology, digital environmental protection technology, etc.) is the key to improving environmental performance. Studies by Yu Sidong et al. (2025) and Fu Bo et al. (2025) have confirmed

that innovative means such as "Internet +" and digital technology can empower the quality and efficiency improvement of agricultural industrialization. This theory provides technical dimension support for the research: leading agricultural industrialization enterprises in Liaoning Province need to break through the technical bottlenecks of environmental operation through green technology research and development and application, and promote the iterative upgrading of environmental operation models.

2.5.Theoretical Integration Framework

This study constructs a three-dimensional theoretical integration framework of "circular economy as the underlying logic + industrial chain integration as the implementation path + technological innovation as the core support". Each theory does not act independently, but intersects and collaboratively supports the construction of the three-level environmental operation model. The specific logic is as follows:

(1) Circular economy theory lays the core criteria of the model

The core principles of circular economy, "reduce, reuse, and recycle", delineate the underlying logical boundary of the three-level environmental operation model. At the level of the internal enterprise closed loop, it guides enterprises to build a material and energy circulation chain of "resources - products - renewable resources" to realize the nearby resource utilization of waste; at the level of industrial chain collaborative circulation, it requires chain leader enterprises to extend the circular concept to the upstream and downstream, creating a full-chain circular system of "green supply - clean processing - low-carbon circulation"; at the level of regional resource sharing and circulation, it promotes the overall utilization of waste across enterprises and industries, realizing the efficient circulation of resources at the regional level and solving the problem of the limited circulation scope of a single subject.

(2) Industrial chain integration theory clarifies the model implementation path

The industrial chain integration theory provides an expansion path of "from single point to system" for the three-level model. For the single-point breakthrough of the internal enterprise closed loop, this theory guides enterprises to first integrate resources in internal production, processing, waste treatment and other links; on this basis, relying on the chain leader status of leading enterprises, integrate upstream farmers/cooperatives, downstream distributors and other industrial chain subjects to realize industrial chain collaborative circulation; finally extend to the regional level, integrate resources across industries and subjects, build a regional sharing platform, complete the model expansion from micro to meso, and ensure the systematicness and synergy of environmental operation.

(3) Technological innovation theory consolidates the model landing support

The technological innovation theory provides technical feasibility guarantee for the three-level model. In view of the special regional conditions of Northeast cold regions, the technological innovation theory guides enterprises to develop adaptive technologies such as low-temperature-resistant cultivation and high-efficiency conversion of waste mushroom sticks to solve the technical pain points of the internal enterprise closed loop; at the level of industrial chain collaboration, support enterprises to introduce clean production technologies such as Internet of Things monitoring and waste heat recovery to realize precise environmental management and control of the entire chain; at the level of regional resource sharing, help build a digital resource allocation platform, improve the efficiency and accuracy of regional resource integration, and ensure the transformation of the three-level model from theoretical design to practical landing.

The cross-integration of the three theories forms a complete theoretical system of "logical guidance - path planning - technical support", providing a comprehensive theoretical basis for the construction and verification of the three-level environmental operation model of leading agricultural industrialization enterprises in Liaoning Province, avoiding the limitations and fragmentation problems of the application of a single theory.

3.Design of Environmental Operation Model Innovation from the Perspective of Circular Economy

Based on the core principles of circular economy of "reduce, reuse, and recycle", combined with the industrial endowment of leading agricultural industrialization enterprises in Liaoning Province and the regional ecological needs of Northeast cold regions and major grain-producing areas, this study constructs a three-level progressive

environmental operation innovation model system of "internal enterprise closed loop - industrial chain collaborative circulation - regional resource sharing", and the specific design is as follows:

3.1.Internal Enterprise Closed-Loop Circulation Model: Focusing on Single-Point Breakthrough of "Resources - Products - Renewable Resources"

To address the pain points of resource waste and ineffective control of waste emissions in the enterprise production link, with the core goal of "cost reduction, efficiency improvement, and environmental load reduction", build an internal material and energy circulation system for enterprises to realize the nearby resource utilization of waste, reduce the dependence on external resources, and enterprises of different industrial types can form differentiated circulation paths:

(1) Circulation sub-model for grain processing enterprises

Build a closed loop around the "full value chain development of rice/corn", forming a circulation link of "raw grain - main products - by-products - renewable resources - waste - energy/fertilizer". Specifically, rice husks can be burned for power generation through biomass boilers, meeting 30%-50% of the enterprise's production electricity demand; the ash residue generated from power generation is mixed with rice bran meal to process into organic carbon-based fertilizer, which is fed back to the enterprise's cooperative planting base, forming an internal resource closed loop of "processing - energy - planting".

(2) Circulation sub-model for animal husbandry enterprises

With the "full resource utilization of breeding waste" as the core, build a circulation chain of "feed formulation - livestock and poultry breeding - manure collection - biogas project - biogas residue/biogas slurry processing - planting". The biogas produced by anaerobic fermentation of breeding manure can be used for enterprise heating, canteen gas or connected to the local gas pipeline network; biogas residue is processed into commercial organic fertilizer, and biogas slurry is used to irrigate supporting silage corn bases after harmless treatment, which not only solves the problem of breeding manure pollution but also reduces feed procurement costs, realizing a self-sufficient cycle of "breeding - energy - planting".

(3) Circulation sub-model for characteristic agricultural product processing enterprises

For the edible fungi and fruit and vegetable processing industries, design a circulation path of "culture medium/raw materials - products - waste mushroom sticks/fruit residue - renewable resources". Taking edible fungi enterprises such as Liaoning Sanyou Agriculture as an example, waste mushroom sticks can be crushed and mixed with straw and livestock manure to process into organic cultivation substrate or organic fertilizer, which is reused for edible fungi production or sold to surrounding farmers, realizing the closed-loop operation of "production - waste - reproduction", with the waste resource utilization rate reaching more than 90%.

3.2.Industrial Chain Collaborative Circulation Model: Promoting Full-Chain Linkage of "Upstream - Midstream - Downstream"

Taking leading enterprises as chain leaders, integrate upstream and downstream resources of the industrial chain, and implement the circular economy concept throughout the entire process of agricultural production, processing, and circulation, realizing the coordinated linkage of "upstream green supply - midstream clean processing - downstream low-carbon circulation", and solving the limitations of a single enterprise's limited circulation scope and insufficient resource utilization:

(1) Upstream green supply link

Leading enterprises sign green production agreements with cooperatives and family farms through the interest linkage mechanism of "order agriculture + technical guidance", uniformly supply biological pesticides, organic fertilizers, high-quality improved seeds, and provide standardized technical training. For example, Dalian Hanwei Group provides cooperative farmers with green feed formulas and ecological breeding technologies in the egg industrial chain, requiring the unified recycling and treatment of breeding manure, which not only ensures the green and safety of raw materials but also provides a stable source of waste for the entire industrial chain circulation.

(2) Midstream clean processing link

Leading enterprises promote the technological transformation of "reduction and resource utilization" in the processing link, and adopt clean production processes to realize the cascade utilization of energy and the recycling of

water resources. For example, Liaoning Goubangzi Smoked Chicken Group has introduced a waste heat recovery system, which uses the waste heat of processing steam for workshop heating and raw material preheating, greatly reducing production energy consumption.

(3) Downstream low-carbon circulation link

Jointly with terminal sellers to build a circular circulation system of "green packaging - low-carbon transportation - waste packaging recycling". Taking Panjin Dingxiang Rice Industry as an example, it uses degradable corn starch packaging materials, builds packaging recycling outlets with chain supermarkets, and the recycled packaging is crushed and used as feed or organic fertilizer auxiliary materials to feed back to upstream planting; in the transportation link, new energy vehicles or railway transportation are preferred to reduce logistics carbon emissions, forming an industrial chain circular closed loop of "processing - sales - recycling".

3.3.Regional Resource Sharing and Circulation Model: Realizing Cross-Enterprise and Cross-Industry Resource Integration

To address the problems of weak investment capacity in environmental protection facilities of small and medium-sized leading enterprises and scattered regional resources, following the principles of "sharing, efficiency, and intensification", under government guidance and led by leading enterprises, build a regional shared circular economy platform, integrate resources and waste across enterprises and industries, and improve the overall efficiency of regional environmental operation.

(1) Regional waste treatment sharing platform

Led by large leading enterprises such as Liaoning Hefeng Animal Husbandry, build regional organic fertilizer processing centers and biomass energy stations to centrally dispose of livestock manure from surrounding small and medium-sized breeding enterprises and rice husks and rice bran and other by-products from grain processing enterprises, reducing the investment cost of environmental protection facilities for small and medium-sized enterprises and realizing the centralized and resource utilization of regional agricultural solid waste.

(2) Cross-industry circulation platform for black soil protection

Combined with Liaoning Province's strategic positioning as a major grain-producing area, integrate resources in the fields of "planting - breeding - processing - agricultural machinery services", and build a regional circulation system of "black soil conservation tillage - waste returning to the field - organic planting". Specifically, provincial leading grain processing enterprises, together with agricultural machinery cooperatives, implement a conservation tillage model of "straw crushing returning to the field + organic fertilizer application"; breeding enterprises supply manure resources, and processing enterprises provide organic auxiliary materials such as waste mushroom sticks, jointly supplying green fertilizers for the planting link, which not only improves black soil fertility but also realizes the full circulation of regional agricultural waste, reducing chemical fertilizer usage by more than 30%.

3.4.Core Supporting Elements of Model Design

To ensure the landing of the environmental operation model from the perspective of circular economy, three core supporting elements need to be matched to solve the key bottlenecks in the model operation. First, technical support; focusing on the characteristics of agriculture in Northeast cold regions, develop low-cost circular technologies suitable for local conditions. At the same time, introduce digital technologies, such as installing intelligent monitoring systems in biogas projects to monitor gas production efficiency and pollutant emissions in real time, improving the accuracy of the circulation process. Second, premium incentives for upstream farmers to participate in green production. Establish a "circulation benefit sharing mechanism", leading enterprises implement "minimum purchase price + 5%-10% green price increase"; regional sharing platforms adopt "fee based on quantity + profit sharing" to reduce the environmental protection costs of small and medium-sized enterprises. Third, standard support; formulate special standards for agricultural circular economy in Liaoning Province, covering "technical specifications for waste resource utilization", "green production standards for the entire industrial chain", "operation and management standards for regional circulation platforms", etc., clarify circulation indicators for different industries such as grain processing and animal husbandry, and ensure the standardized and quantifiable operation of the model.

3.5.Analysis of Model Applicability Boundaries

The three-level environmental operation model of "internal enterprise closed loop - industrial chain collaboration - regional resource sharing" designed in this study is mainly applicable to the following three types of leading agricultural industrialization enterprises in Liaoning Province:

Characteristic agricultural product processing enterprises: such as edible fungi and fruit and vegetable processing enterprises. The waste generated in the production process of such enterprises, such as waste mushroom sticks and fruit residues, has high resource value. They can rely on the internal closed-loop model to realize waste reuse, and at the same time, integrate surrounding resources such as straw and livestock manure through industrial chain collaboration and regional sharing to improve circulation efficiency. The practice of Liaoning Sanyou Agriculture has verified the adaptability of this model.

Grain processing enterprises: such as rice and corn processing enterprises. The by-products generated in their production, such as rice husks and rice bran, can be used for energy and fertilizer utilization through internal closed loops. As the core subject of the regional grain industrial chain, they can take the lead in building industrial chain collaboration and regional sharing platforms, promoting the full-chain circulation of "planting - processing - returning to the field", which is in line with Liaoning Province's industrial positioning as a major grain-producing area.

Large-scale animal husbandry enterprises: such as pig and layer breeding enterprises. They can realize the biogas conversion and organic fertilizer processing of breeding manure through internal closed loops, and at the same time link with surrounding planting enterprises to form an industrial chain circulation of "breeding - energy - planting", and also rely on regional sharing platforms to solve the manure treatment problem of small and medium-sized breeding entities.

4.Case Analysis and Empirical Test

To ensure the representativeness and promotion value of the case study conclusions, this study selects Sanyou Agriculture as the core case object, and its typicality is mainly reflected in three aspects: first, industrial representativeness, the enterprise focuses on the edible fungi processing field in Northeast cold regions, and the edible fungi industry is one of the core formats of characteristic agricultural product processing in Liaoning Province. The pain points it faces, such as "difficulty in adapting to cold-region cultivation and low resource utilization rate of waste mushroom sticks", are consistent with the common predicament of most leading enterprises of the same type in the province; second, subject-level representativeness, Sanyou Agriculture is a provincial leading agricultural industrialization enterprise, with the resource integration capability of the industrial chain leader, covering the entire process of "strain research and development - cultivation production - processing and sales - waste recycling", which is fully in line with the meso-subject positioning of provincial leading agricultural industrialization enterprises focused on this study; third, model adaptability representativeness, the enterprise has fully implemented the three-level environmental operation model of "internal enterprise closed loop - industrial chain collaboration - regional resource sharing", covering all core links from internal intelligent cultivation circulation to regional centralized treatment of waste mushroom sticks, which can provide a complete practical sample for verifying the effectiveness of this model. In addition, to further verify the universality of the model, this study also selects 1 leading grain processing enterprise and 1 leading animal husbandry enterprise in Liaoning Province for supplementary comparison to confirm the adaptability of the three-level model in different agricultural formats.

4.1.Enterprise and Industry Pain Points

The traditional model of Liaoning's edible fungi industry has three core problems: first, the cultivation link relies on manual regulation, and the accuracy of parameters such as temperature and humidity is low, leading to high energy consumption; second, most of the waste mushroom sticks generated in edible fungi production are landfilled, with a resource utilization rate of less than 20%, causing environmental pollution and resource waste; third, under the low-temperature environment in winter in Northeast cold regions, the growth cycle of edible fungi is extended by 30%, and the nutrient loss of the cultivation substrate is fast, affecting yield and quality. Before 2019, Sanyou Agriculture was also restricted by this, with environmental operation investment accounting for only 1.2% of operating income, the annual cost of waste mushroom stick treatment

exceeding 500,000 yuan, and the market share of green products less than 15%.

4.2.Design of Environmental Operation Model

Internally, the enterprise focuses on the entire process of "cultivation substrate - edible fungi production - waste mushroom sticks - renewable resources", creating a closed loop of "resources - products - waste - renewable resources". It independently developed an intelligent edible fungi cultivation system, which monitors and intelligently regulates cultivation environment parameters in real time through sensors; the waste mushroom sticks generated in production are crushed and mixed with straw and livestock manure to process into organic cultivation substrate or organic fertilizer, which is fed back to the enterprise's self-built 200-mu edible fungi planting base and surrounding farmers' farmland, realizing the internal circulation of "cultivation - waste - reproduction".

In view of the characteristics of Northeast cold regions, develop low-temperature-resistant edible fungi cultivation technology and waste mushroom stick high-efficiency conversion technology to solve the problems of "poor low-temperature adaptability and low waste conversion efficiency" in the traditional model; introduce digital technology, deploy Internet of Things monitoring equipment in the cultivation workshop to realize real-time collection and optimization of energy consumption and environmental parameters.

Establish cooperation with 5 small and medium-sized edible fungi enterprises and 3 straw recycling cooperatives in the surrounding area, share intelligent cultivation technology and waste treatment equipment, centrally treat waste mushroom sticks in the region, and the processed organic fertilizer is supplied to surrounding grain growers, forming a collaborative network of "characteristic agricultural product processing - regional resource circulation".

4.3.Empirical Test:Analysis of Model Effectiveness Based on Data

4.3.1.Data Collection and Indicator Design

Focusing on the three dimensions of "environmental performance - economic performance - technical adaptability", collect core data of Sanyou Agriculture in 2019 (before model implementation), 2023 (after model implementation), and 2024 (after optimization), and compare with the average level of similar edible fungi processing enterprises in Liaoning Province to verify the effectiveness of the model. The specific indicators and data are as follows:

Dimension Classification	Specific Indicators	Sanyou Agriculture in 2019 (before model)	Sanyou Agriculture in 2023 (after model)	Sanyou Agriculture in 2024 (after optimization)	Average of similar enterprises in Liaoning Province (2024)
Environmental Performance	Resource utilization rate of waste mushroom sticks	18%	92%	100%	38%
	Energy consumption per unit output (kWh/mu)	8200	5100	4800	7500
	Water resource reuse rate	22%	58%	62%	32%
	Organic fertilizer replacing chemical fertilizer (tons) |	0	3200	4500	950
	Qualified rate of production "three	75%	100%	100%	88%

	wastes" discharge				
Economic Performance	Proportion of environmental operation investment in revenue	1.2%	2.5%	2.8%	2.0%
	Cost of waste mushroom stick treatment	52	18	15	42
	Proportion of green product revenue	14%	48%	55%	28%
	Annual total output value (10,000 yuan)	3200	7500	12000	4800
	Profit rate per unit product	8.5%	15.2%	18.6%	10.2%
Technical Adaptability	Popularization rate of intelligent cultivation technology	0%	100%	100%(full-process digitalization)	28%
	Survival rate of low-temperature cultivation in cold regions	72%	95%	96%	80%
	Technology R&D investment (10,000 yuan/year)	85	260	350	130
	Number of scientific research cooperation institutions	3	8	12	4
	Number of patents owned (items)	2	15	22	6

Table.1. Data Collection

4.3.2.Verification of Model Effectiveness Based on Data

(1) Environmental performance: achieving a leap from "passive emission reduction" to "active circulation", with significantly better results than industry benchmarks

First, waste resource utilization has achieved a full closed loop. From 2019 to 2024, the resource utilization rate of the enterprise's waste mushroom sticks increased from 18% to 100%, 62 percentage points higher than the average level of similar enterprises in Liaoning Province (38%), completely eliminating the soil pollution problem caused by the traditional landfill model. Its core driving force is the "waste mushroom sticks - organic substrate - organic fertilizer" circulation system built by the enterprise, which directly confirms the ecological value of the internal closed-loop model.

Second, resource utilization efficiency has achieved step-by-step optimization. The cumulative reduction in

energy consumption per unit output reached 41.5%, and the water resource reuse rate increased by 40 percentage points, both of which are significantly ahead of the industry average; in 2024, the amount of organic fertilizer replacing chemical fertilizer reached 4,500 tons, 4.7 times the industry average, which not only reduced agricultural non-point source chemical pollution but also conformed to Liaoning Province's policy orientation of black soil protection and development, realizing the coordinated development of enterprise production and regional ecology.

Third, pollution control has achieved both compliance and ecological standards. The qualified rate of production "three wastes" discharge increased from 75% to 100%, and has maintained stable compliance for two consecutive years, 12 percentage points higher than the industry average (88%), highlighting the stability and reliability of the model in pollution control.

(2) Economic performance: environmental investment is transformed into value-added momentum, achieving a win-win pattern of "environmental protection and efficiency improvement"

First, the cost structure has achieved refined optimization. Although the proportion of environmental operation investment in revenue increased from 1.2% to 2.8%, the cost of waste mushroom stick treatment decreased by 71.2%, and the profit rate per unit product increased by 10.1 percentage points; in 2024, the enterprise's total output value exceeded 120 million yuan, an increase of 275% compared with 2019, far exceeding the industry average scale of 48 million yuan, confirming that environmental investment is not a "cost burden" but a core element driving enterprise value creation.

Second, the premium capacity of green products has been significantly improved. The proportion of green product revenue of the enterprise reached 55%, 27 percentage points higher than the industry average. This achievement stems from the enterprise's strategic practice of obtaining organic certification and laying out high-end markets relying on environmental performance advantages; combined with the industry trend of a 52.29% year-on-year increase in edible fungi exports in Anshan in 2024, the market competitiveness of its green products has been further released.

Third, the scale expansion effect has accelerated. The growth rate of the enterprise's total output value from 2023 to 2024 reached 60%, much higher than the industry's average annual growth rate of 25%, indicating that after the model matures, the brand value and cost advantages generated by environmental performance have been transformed into the core driving force for scale expansion, verifying the economic feasibility of the "circular economy + market-oriented" model.

(3) Technical adaptability: the collaboration between cold-region technological breakthroughs and digital empowerment builds core competitive barriers

First, the effect of cold-region adaptive technology is prominent. The survival rate of low-temperature cultivation of edible fungi in the enterprise reached 96%, 16 percentage points higher than the industry average, which benefits from the targeted research and development of low-temperature-resistant strains and intelligent temperature control technology, solving the industry pain point of a sharp decline in edible fungi output in winter in Northeast cold regions, and confirming the core conclusion that "technical adaptability is the key premise for the landing of environmental operation models".

Second, innovation capability and achievement transformation efficiency are ahead of the industry. The growth rate of technology R&D investment reached 311.8%, the number of patents owned increased to 22, and the number of scientific research cooperation institutions expanded to 12 (including professional colleges such as Shenyang Agricultural University), all indicators are far ahead of the industry average; in 2024, full-process digital coverage increased production scheduling efficiency by another 15%, further consolidating the enterprise's technical barriers.

Third, the technical scheme has strong industry promotion value. The popularization rate of intelligent cultivation technology reached 100%, 72 percentage points higher than the industry average (28%). The "cold-region digital circulation technology scheme" developed by the enterprise has been included in the 2024 agricultural green technology promotion catalog by the Department of Agriculture and Rural Affairs of Liaoning Province, and has a practical foundation for replication and promotion among similar cold-region agricultural enterprises.

In summary, based on the comprehensive research and judgment of data from three dimensions of environment, economy, and technology from 2019 to 2024, the environmental operation model constructed by Sanyou Agriculture has achieved a coordinated leap in environmental and economic performance through the logical link of "technical adaptability - environmental

circulation - economic value-added", and the results have continued to lead the industry average level. This practice not only verifies the adaptability of the model to leading edible fungi processing enterprises in Liaoning Province but also proves that the environmental operation system with "technological innovation as the core, circular economy as the path, and market orientation as the support" is a feasible paradigm for leading agricultural industrialization enterprises to achieve green transformation and high-quality development.

Conclusion

In the critical stage of the in-depth advancement of the "dual carbon" strategy and the green transformation of agriculture, the environmental operation level of leading agricultural industrialization enterprises in Liaoning Province has become a core variable restricting the sustainable development of regional agriculture. In response to the practical pain points of enterprises in the province such as passive environmental protection and insufficient adaptability of green technology, this study, supported by theories such as circular economy, technological innovation, and industrial chain integration, constructs a three-level innovative environmental operation model of "internal enterprise closed loop - industrial chain collaboration - regional resource sharing", and selects Liaoning Sanyou Agricultural Biotechnology Co., Ltd., a leading enterprise in characteristic agricultural product processing in Northeast cold regions, for empirical testing.

This study first clearly defines core concepts such as leading agricultural industrialization enterprises, environmental operation, and environmental operation model innovation, systematically sorts out the adaptability of theories such as value creation-oriented environmental management, environmental operation paradigm transformation, and green industrial chain integration, and establishes the core logic of environmental operation transformation from "passive compliance" to "value creation". At the model design level, the internal enterprise closed-loop model constructs differentiated circulation paths for different industrial types, grain processing enterprises form a closed loop of "raw grain - processing - energy - planting", animal husbandry enterprises build a self-sufficient cycle of "breeding - biogas - planting", and characteristic agricultural product processing enterprises realize the resource reuse of "cultivation - waste mushroom sticks - regenerated substrate"; the industrial chain collaborative model takes leading enterprises as chain leaders to connect the full-chain greening of upstream green supply, midstream clean processing, and downstream low-carbon circulation; the regional resource sharing model realizes the intensive allocation of resources across enterprises and industries by building sharing platforms such as waste treatment and black soil protection, and at the same time supports the model landing with three supporting elements: technology research and development, income incentives, and standard specifications. The case empirical results of Sanyou Agriculture show that from 2019 to 2024, under the empowerment of the new model, the resource utilization rate of the enterprise's waste mushroom sticks increased from 18% to 100%, the energy consumption per unit output decreased by 41.5%, the water resource reuse rate increased by 40 percentage points, the amount of organic fertilizer replacing chemical fertilizer reached 4,500 tons, and the production "three wastes" discharge achieved 100% compliance; at the economic level, although the proportion of environmental operation investment increased to 2.8%, the cost of waste mushroom stick treatment decreased by 71.2%, the proportion of green product revenue increased to 55%, the annual total output value increased by 275% compared with 2019, and the profit rate per unit product increased by 10.1 percentage points; in terms of technical adaptability, the survival rate of low-temperature cultivation in cold regions reached 96%, intelligent cultivation technology realized full-process coverage, the number of patents owned increased to 22, and the relevant technical scheme has been included in the provincial agricultural green technology promotion catalog, all indicators are significantly better than the average level of similar enterprises in Liaoning Province, successfully achieving the dual goals of "environmental protection and efficiency improvement".

In summary, the theoretical contribution of this study is to improve the theoretical system at the intersection of agricultural economy and environmental management and build an analysis framework for environmental operation of meso-level subjects; the practical value is reflected in providing a replicable green transformation plan for leading agricultural industrialization enterprises in Liaoning Province, and its cold-region adaptive technology and three-level circulation model provide a typical model for the

green revitalization of agriculture in the old industrial base of Northeast China, and also provide a scientific basis for local agricultural authorities to formulate targeted support policies and optimize the regional agricultural ecological governance system.

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lastic Properties of High-Performance Recycled Concrete: Materials–Structure

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KEYWORDS

High performance;
Recycled concrete;
Elastic properties

ABSTRACT

This review synthesises recent evidence on elastic properties of high performance recycled concrete from a materials to structure perspective. At comparable strength, static elastic modulus decreases with increasing recycled coarse aggregate. Typical penalties are about 0 to 10% at 0 to 30% replacement, about 5 to 20% at 30 to 60% replacement, and about 15 to 30% at 60 to 100% replacement. Low water to binder ratio with silica fume or slag improves the interfacial transition zone and reduces the loss. Dynamic modulus from resonance or ultrasonic methods exceeds static values by about 5 to 15% at 28 days under similar moisture. Poisson ratio is usually about 0.16 to 0.23. Fibres do not raise modulus at equal strength but can moderate losses at high replacement. The review compares empirical, micromechanics, numerical representative volume element and data driven models, and proposes a concise reporting and validation protocol to support serviceability focused design.

INTRODUCTION

Elastic properties, especially elastic modulus and Poisson's ratio, govern member stiffness, crack development and deflection control in structural design, so they are central to the engineering use of high performance concrete and its recycled variant. From a materials viewpoint, a low water to binder ratio combined with mineral admixtures and high range water reducers produces a dense paste and an improved interfacial transition zone, which together raise stiffness at a given strength level. When recycled aggregates are introduced, lower aggregate modulus, adhered mortar and higher water absorption increase porosity and weaken the interfacial transition zone, so at comparable compressive strength a reduction of static elastic modulus is frequently observed. The magnitude of this reduction depends on replacement level, recycled aggregate quality indices such as density, absorption and adhered mortar fraction, paste composition, curing regime, age and moisture state, and on the test method used to report static or dynamic values [1]. For structural applications, these material changes affect serviceability checks for deflection and crack width, and they motivate clear reporting of mixture features and recycled aggregate quality so that results can be compared across studies and used in practice [2]. This review follows a materials to structure logic, compiles compact numeric windows for elastic properties by replacement band and quality class, and organises prediction approaches into empirical relations, micromechanics models, numerical representative volume element simulations and data driven learners, with an emphasis on transferability to high performance recycled concrete [1,2].

Materials and Methods

This study is a structured literature review. Scopus, Web of Science Core Collection and Google Scholar were searched for the years 2000 to 2025 using combinations of the terms high performance concrete, recycled concrete, elastic modulus, Poisson ratio, recycled aggregate and interfacial transition zone. Titles and abstracts were screened first, followed by full texts. Eligible sources were peer reviewed journal articles and standards that reported numerical elastic modulus or Poisson ratio together with mixture details and

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test procedures. Exclusions were non structural materials, theses, abstracts or posters, and items without numerical results. To enable comparison, we recorded for each source the concrete strength class and whether elastic modulus was static or dynamic.

Data extraction followed a predefined template. Mixture variables captured were water to binder ratio, binder system and mineral additions, replacement ratios for coarse and fine recycled aggregates, and recycled aggregate quality indices including density, water absorption, adhered mortar fraction and flakiness. Test and conditioning variables captured were curing regime and age, moisture state at test, specimen geometry, strain range and the named test method. All values were converted to SI units. Static and dynamic elastic moduli were reported separately without conversion unless an explicit relation was provided by the source. Poisson ratio values were retained only when the age, moisture state and method were stated. To summarise trends for practice, records were grouped by replacement bands of 0 to 30%, 30 to 60% and 60 to 100% and by recycled aggregate quality class. Where three or more records were available in a group, we reported the range with a central tendency. For engineering context, measured values were also compared with code type relations based on strength and density, and deviations were expressed as simple percentage errors. The grouped results support the numeric ranges in Table 1 and the workflow in Figure 1.

Results

At comparable compressive strength, the static elastic modulus of high performance recycled concrete decreases with increasing recycled coarse aggregate. The magnitude depends on replacement level and recycled aggregate quality. In mixes with low water to binder ratio and silica fume or slag, the loss is smaller because the interfacial transition zone is improved. The compact ranges that follow from the screened studies are summarised in Table 1 [3 – 5]. Dynamic modulus obtained from resonance or ultrasonic methods is higher than static modulus measured from stress strain tests. The difference is typically 5 to 15% at 28 days when moisture state is similar. Poisson ’ s ratio remains comparatively stable in the range 0.16 to 0.23 with modest sensitivity to replacement and quality. The combined picture for modulus and Poisson’ s ratio by replacement band and quality class is given in Table 1 [5]

Replacement band, coarse RA (%)	RA quality class	Binder and curing note	Static elastic modulus change at matched strength (%)	Dynamic vs static at 28 d (%)	Poisson’s ratio at 28 d
0 to 30	high quality, low absorption and low adhered mortar	silica fume or slag; standard curing	0 to −10	dynamic greater by 5 to 10	0.18 to 0.22
30 to 60	moderate quality	fly ash or slag; standard curing	−5 to −20	dynamic greater by 5 to 15	0.18 to 0.22
60 to 100	mixed or low quality	silica fume and extended curing	−15 to −30	dynamic greater by 10 to 20	0.19 to 0.23

Table.1. Elastic modulus and Poisson ’ s ratio of high performance recycled concrete by replacement band and recycled aggregate quality [3 – 5,8]

Notes. Static values come from compressive stress – strain tests. Dynamic values come from resonance or ultrasonic methods. Ranges depend on density, absorption and adhered mortar fraction, on water to binder ratio, and on moisture state and strain range at test.

Model behaviour follows a consistent pattern. Empirical equations based on strength and density reproduce the central tendency for low to moderate replacement but lose accuracy at high replacement unless density or a quality proxy is added. Micromechanics three phase schemes capture changes caused by modulus contrast and adhered mortar but require inputs that are not always reported.

Numerical representative volume element studies support mechanism insight and can generate synthetic data for calibration. Data driven learners such as gradient boosting reduce bias across heterogeneous datasets when features include absorption, adhered mortar fraction, binder descriptors and age. The evidence synthesis and model comparison steps used in this review are shown in Figure 1 [3,4,6,7].

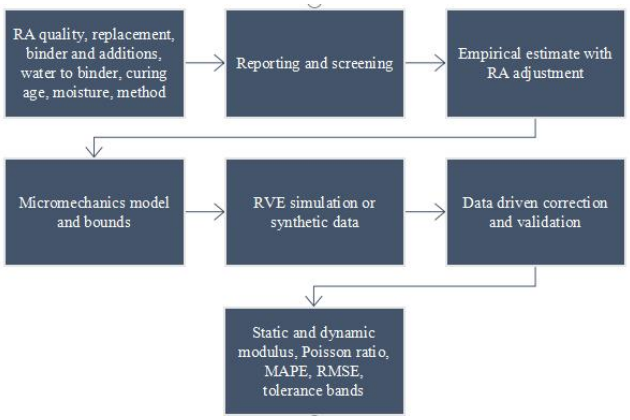

Fig.1. Evidence synthesis and model comparison workflow for elastic property prediction in high performance recycled concrete

Studies that include steel or recycled steel fibers indicate that fibers do not systematically raise elastic modulus at constant strength. They can moderate the loss at high replacement by improving matrix continuity and crack stability, especially with medium quality recycled aggregate and silica fume in the binder. When models are evaluated on independent sets, unified or machine learning equations tailored to recycled aggregate features achieve mean absolute percentage errors near 6 to 10%, which is an improvement over code type relations calibrated for natural aggregate concrete.

Conclusion

This review links materials choices to elastic response in high performance recycled concrete. At similar strength, static elastic modulus decreases as recycled aggregate content rises, with the loss governed by replacement band and aggregate quality. Dynamic modulus exceeds static by about 5 to 15% at comparable age and moisture, while Poisson's ratio remains about 0.16 to 0.23. Table 1 summarises compact ranges and Figure 1 shows the workflow used to organise evidence and models. For prediction, empirical relations suit low to moderate replacement, micromechanics and representative volume elements add interpretability when phase data exist, and data driven learners benefit from quality descriptors. A hybrid scheme with micromechanics priors and data driven correction, supported by standardised reporting and stratified validation, improves comparability and supports serviceability focused design.

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Toward a New Financial Paradigm: A System-Activity Approach

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KEYWORDS

System-activity approach;

Finance, virtual essence of finance;

Systemic model;

Virtual construct;

Paradigm;

Continuity of the activity process;

ABSTRACT

This article argues that the dichotomy prevalent in modern financial theory between the domestic view of finance as "economic relations" and the Western view as "capital management" is a consequence of a fragmented understanding of the process itself.It is argued that the transition from the traditional understanding of financial activity and finance to a new paradigm requires a systemic representation of it, as a combination of cognitive and material activity. Finance is viewed as a virtual valuation of assets involved in economic circulation. This representation overcomes the discrepancy between traditional, fragmented understandings of financial activity and the general scientific principle of continuity. As a result, conceptual and universal graphical models of the process of activity and socioeconomic development with an anthropocentric focus have been constructed.From a scientific perspective, the obtained results advance economic theory and create the preconditions for the development of a wide range of research in new scientific areas. From a practical perspective, the research results will find wide application in education, as well as in the study of systemic financial risks.

ВВЕДЕНИЕ

Известно, что мировая экономика может быть представлена как гетерогенная система, элементы которой находятся в неравновесном состоянии. Это подтверждается, например, как различающейся динамикой платежных балансов стран, так и степенью нелинейности динамики их экономического развития [1;2;3]. Тем не менее, экономическая наука смогла выработать универсальную парадигму описания экономических процессов на макро- и микроуровнях, основанную на понятийном аппарате, разделяемом большинством мирового научного сообщества и используемом в теории и практике.

Известно также, что мировая финансовая системы представляет собой инфраструктурный элемент в системе деятельности по обслуживанию процесса общественного развития. При этом, финансовая система является одним из основных факторов, определяющих эффективное функционирование системы мировой экономики. Однако, в отличие от экономической науки, до настоящего времени финансовая наука обладает ярко выраженной неоднозначностью понятийного аппарата в глобальном экономическом пространстве – отсутствием глобальной парадигмы финансов. Кроме того, наблюдается парадокс финансовой науки, когда практический финансовый инструментарий обслуживания экономических процессов фактически унифицирован на глобальном уровне, а теоретические аспекты финансов противоречивы, сущность и содержание таких категорий как финансы и финансовая деятельность не имеют однозначного определения и, как следствие, сферы функционирования финансов и денег не разделены [4].

Основная часть

Антропоцентричность модели социально-экономического развития.

Системный анализ работ Л. Моргана [5], Ф. Энгельса [6], А.А. Богданова [7], В.И. Вернадского [8], Б.М. Кедрова [9], М. Алле [10], В.С. Степина [11;12], И.П. Меркулова [13], В.С. Автономов [14], Р. Талера [15] и других авторов позволил выделить

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причинно-следственные связи факторов и построить универсальную антропоцентричную модель общественного развития, приведенную на рис.1.

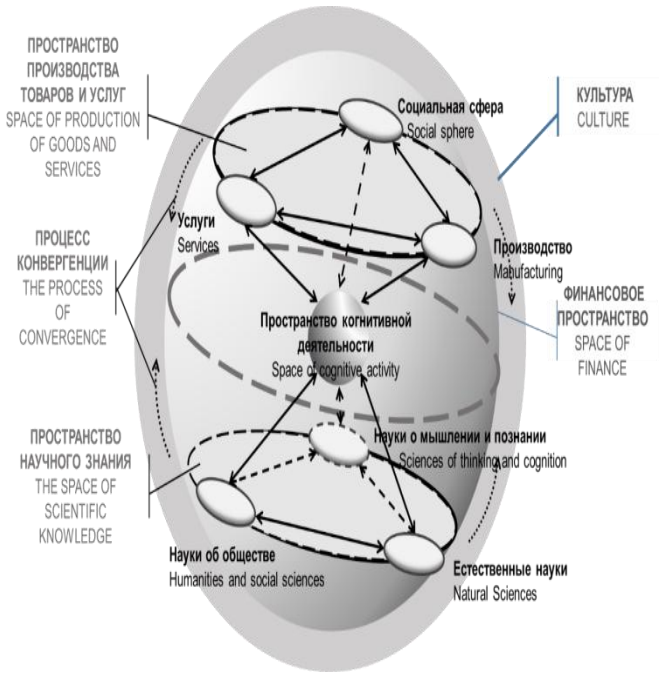

Рис.1.Универсальная антропоцентричная модель общественного развития

Как видно из рис.1., центральным элементом в представленной модели является Человек, а точнее когнитивная деятельность как неотъемлемый атрибут Человека. В эволюционном аспекте общественного развития можно говорить о том, что когнитивная деятельность сформировала сферу культуры как первичный элемент безопасности при коммуникациях за удовлетворение первичных потребностей человека в борьбе за выживание. Следующим этапом общественного развития, в заданной риторике, стало формирование финансовой сферы – финансовое пространство, как элемент оценки ценности вещей (стоимость) необходимых для выживания при их обмене. Дальнейшее развитие общества привело к формированию экономики (пространство производства товаров и услуг), как сферы материального производства и поиску универсального товара – всеобщего эквивалента оценки стоимости или денег. В дальнейшем, ускорение общественного развития привело к выделению науки в самостоятельное пространство (пространство научного знания). Потребности производственной сферы в научных знаниях, а сферы научного знания в продуктах производства явились основой формирования процесса их конвергенции. В плане когнитивной деятельности это выражается в потребности инженерии: необходимости системного и междисциплинарного подхода к организации процесса деятельности [16].

Анализ причинно-следственных связей элементов модели, представленных на рис.1, выявил ряд противоречий в конвенциональном представлении финансов и финансовой деятельности, в частности, противоречие общенаучному принципу континуальности. Это позволило сформировать гипотезу о виртуальной сущности финансов в отличие от конвенциального их представления как экономические отношения в отечественной риторике или деньги, капитал и управление ими в риторике западных специалистов.

Методологические основания гавого подхода к финансам и финансовой деятельности

Отечественные и иностранные специалисты с разных позиций определяют понятие финансы. Если для иностранных специалистов финансы есть деньги, капитал и способы управления им, то для отечественных специалистов финансы есть система экономических отношений [4]. Это объективно создает препятствия для интеграции специалистов в программы по разработке теории финансов и финансовых технологий будущего, более глубокого понимания сущности и роли финансов в глобальном мире.

Междисциплинарный анализ сложившейся в финансовой науке ситуации позволил сделать предположение, что разрешение противоречий в теории финансов лежит в области создания новой научной рациональности в сфере финансов, основанной на системном представлении деятельности в общем и финансовой деятельности, в частности. В отличие от конвенциального представления процесса деятельности, основанного на анализе эмпирических данных, концепция системного представления процесса деятельности предполагает наличие двух комплементарных элементов, связанных строгими причинно-следственными связями. Во-первых, это

элемент когнитивной деятельности, результатом которой является виртуальный конструкт, как видение будущего. Во-вторых, это элемент материальной (практической) деятельности, результатом которой является воплощение на практике виртуального конструкта – построение будущего. То есть сделано предположение о существовании объективной закономерности развития – построение будущего, как процесса деятельности, имеющего два последовательных этапа. Это этап формирования в сознании субъекта виртуальной реальности (конструкта будущего) и этап превращения этого конструкта в реальность – будущее. Такая концептуальная модель процесса деятельности приведена на рис. 2.

Рис.2.Концептуальная (системная) модель процесса деятельности

Сделанное предположение о системности процесса деятельности имеет объективные основания и опирается на результаты работ таких философов как И. Кант [17], В.С. Степин [18], основоположников системного анализа А.А. Богданова и Л. фон Берталанфи, а также Б.М. Клейнера [19], акцентирующего внимание на системности экономики, приверженцев методологии междисциплинарности в анализе предмета исследования М. Алле и М.В. Ковальчука, работы Д. Канемана, Т.Тверски, Р.Талера, в области поведенческой экономики, И.П. Меркулова в части когнитивных аспектов деятельности и основоположника виртуалистики Н.А. Носова, а также на многие другие исследования отечественных и зарубежных специалистов.

Основы настоящего исследования были заложены при формировании финансовой модели пенсионной системы, как многомерного виртуального пенсионного пространства и модели расчета скрытого пенсионного долга [20]. В рамках рассмотрения «закона экспансии разума» [21] была показана уникальная роль когнитивной деятельности как основного фактора общественного развития. Позже, была сформулирована позиция автора по поводу определения понятия «финансы», радикально отличающаяся от конвенциальной [22]. На примере рассмотрения лизинговой деятельности было показано, что ее основой является не финансовый, а организационный аспект, связанный с когнитивной деятельностью [24]. Завершилось формирование «фундамента» нового подхода к рассмотрению финансов и финансовой деятельности двумя работами [25; 26], среди которых особо следует выделить статью «О новой парадигме финансовой деятельности», опубликованной в «Белорусском экономическом журнале» [25]. Эта работа определила методологию исследования такого феномена, как финансы и в ней, впервые, была представлена системная модель финансового процесса как целого, в отличие от фрагментарного конвенционального подхода. Более того, был поставлен вопрос о разделении в финансовой деятельности виртуального и реального, а также вопрос о том, что экономические отношения вторичны по отношению к когнитивной деятельности и являются одним из результатов материализации виртуального конструкта, сформированного в сознании субъекта.

Необходимость развития конвенциональных представлений об экономике и отход от чисто

эмпирического ее анализа переходит в разряд актуальной тематики [26]. Так, Ю.М. Осипов считает, что вся экономика заключена в сфере сознания, то есть в головах людей и она «измысливается» и сводится к особого рода оцифрованной и словесно выраженной информации — стоимостной, денежной, ценовой. То есть она есть не что иное, как метафизическое энерго-информационное поле [27, с.9] или в контексте модели (рис.1) – это системное пространство науки, производства и когнитивной деятельности, объединенное в единую систему пространством финансов. Однако процесс отказа от традиционных представлений об экономике и переход на качественно новый уровень мышления , по утверждению Н.П. Ващекина и Е.Н. Пасхина, потребует коренной переориентации сознания людей на новое, отказ от многих современных стереотипов мышления, общепринятых ценностей и потребностей, которые еще до недавнего времени рассматривались как нерушимые и общечеловеческие [28, с.266], это с одной стороны. С другой стороны, не готовность к изменениям и духовная незрелость общества, по мнению А. Урсула, может привести к возникновению глобального антропологического кризиса, как следствие действия еще недостаточно познанных нами закономерностей взаимодействия природы и общества, которые еще несколько десятилетий назад почти однозначно оценивались как закономерности прогресса» [29, С.8].

В основе предложенного системного подхода к процессу деятельности лежит когнитивно-субстанциональное толкование стоимости, финансов денег, цен, капитала в контексте построений И Ката. Он из совокупности окружающих нас вещей (вещи в себе) – как универсального пространства - выделяет «действительные предметы», способные быть толчком к познанию [17,С.105]. Они, в нашей риторике, активизируют когнитивную деятельность, которая формирует образы, составляющие хаос ощущений реальных и возможных (виртуальных). Следуя логике И. Канта, хаос ощущений, образует тот материал, из которого пространственная и временная формы чувственного созерцания формируют предметы чувственного опыта (виртуальные конструкты), то есть формируют вещи «как предметы возможного опыта». Совокупность предметов «возможного опыта», упорядоченная с помощью категорий рассудка, «есть собственно то, что мы здесь называем природой» [17,С.114]. Результатом воздействия вещи в себе на процесс познания получается явление - виртуальный образ (конструкт) как «суть простого представления чувственности», того, что мы ощущаем в реальности и воображении, а не простого отображения свойств вещей в себе [17,С.105]. Вещи в себе формируют эмпирическую реальность и, с точки зрения процесса познания (развития), создают условия для формирования виртуальных конструктов будущего, представляющих собой не простое отражение настоящего, но его развитие в явление, в соответствии с чувствами и представлениями субъекта. Таким образом, явление субъективно и является имманентным свойством процесса деятельности. Субъективность явления определяется когнитивными способностями субъекта в построении виртуальной реальности (виртуального конструкта). Следуя этой логике, сделаем вывод о том, что когнитивная деятельность и когнитивные способности есть имманентное свойство процесса деятельности, определяющее во многом ее результат.

Этот факт и послужил основанием того предположения, что конвенциональная модель процесса деятельности в общем и финансовой деятельности, в частности, построенная только на основе реальности является фрагментарным представлением деятельности и по объективным основаниям требует развития в соответствии современным уровнем знания - дополнения когнитивным элементом.

Преодоление разрыва континуальности в традиционном представлении финансовой деятельности и финансов

Поэлементная структура конвенционального и предложенного концептуального представления процесса деятельности рассмотрена в более ранних работах [2;4] Анализ функционирования концептуальной модели дал возможность выявить закономерность процесса деятельности, в том числе и финансовой. В общем случае, закономерность процесса развития, заключается в системности: осмыслении реальной ситуации и построении в сознании виртуального конструкта будущего с последующим его воплощением в новой реальности, то есть четкой

последовательности и причинно-следственной связи виртуального и реального [2, С.135, 140]. При этом, анализ процесса деятельности в контексте концептуальной модели сделки как совокупности виртуального и реального позволил выявить противоречие конвенциональной модели сделки общенаучному принципу континуальности, а также разграничить области функционирования финансов и денег, что схематично показано на рис. 3.

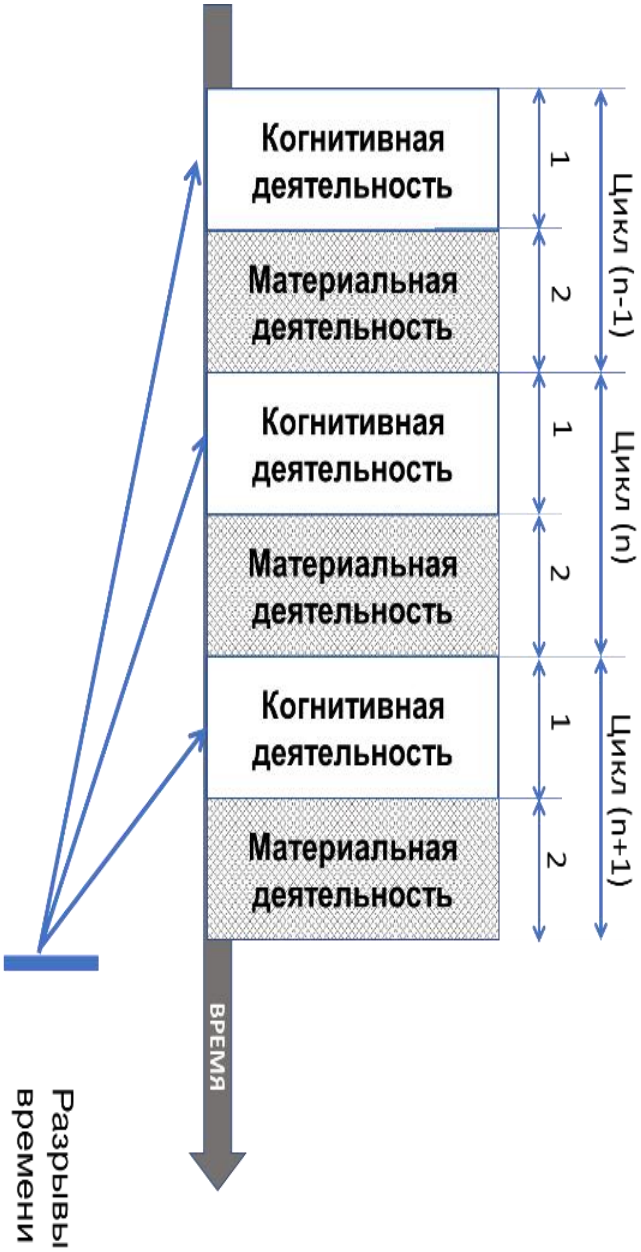

Рис.3.Процесс развития как система

Как видно из рис.3., процесс развития как системная сущность формируется из циклов деятельности, которые также имеют системную природу. То есть, структура цикла включает два последовательных этапа: 1 – когнитивная деятельность и 2 – материальная деятельность. В риторике статьи, конвенциальная модель деятельности представлена исключительно этапом материальной деятельности (заштрихованный элемент на рис.3), поскольку оперирует исключительно с эмпирическими данными. Акцентируем внимание на том, что когнитивная деятельность, хотя и присутствует в реальности, однако, в рамках конвенциального представления из рассмотрения выпадает. Этот факт эквивалентен разрыву континуальности при рассмотрении процесса деятельности в конвенциональной риторике [4]. Этот факт представлен на рис.3 в виде светлого элемента. Из этого следует, что конвенциональное представление процесса деятельности является фрагментарным и не соответствует общенаучному принципу континуальности, тогда как предложенная концепция системного подхода к представлению процесса деятельности более совершенна и может быть использована для более глубокого анализа такого предмета исследования как финансы.

Системное представление деятельности и позволило выдвинуть гипотезу о виртуальной сущности финансов и разделении сфер функционирования финансов и денег как виртуального и реального.

О виртуальной сущности финансов

Объединяющим началом отечественных и иностранных исследований является использование традиционного (конвенционального) подхода к структуре экономической и в том числе финансовой деятельности, основанного на его внешнем наблюдении в рамках эмпирической реальности.

Следует подчеркнуть, что в рамках исследования финансовая деятельность рассматривается как системный процесс, включающий два последовательных элемента. Первый из них – это элемент когнитивной деятельности. Ее результатом является формирование в сознании субъекта виртуального конструкта будущего как новой виртуальной реальности. Основанием для этого является некая идея - цель, сформированная в настоящей эмпирической реальности как необходимость дальнейшего существования. Второй элемент – процесс материализации новой виртуальной реальности

(виртуального конструкта) в новую эмпирическую реальность, т. е. преобразование виртуального образа будущего в новую реальность – будущее.

В рамках данной концепции финансы определяются как виртуальная денежная оценка стоимости ресурсов (имущества, обремененного и принадлежащего на правах собственности), вовлекаемых в экономический оборот с целью достижения позитивного социально значимого результата – цели деятельности (развития). В этом ключе финансы являются стоимостной категорией и обладают свойством объективности непрерывного бытия, что не нарушает общенаучного принципа континуальности.

Представление финансов как совокупности денежных отношений, принятое в риторике отечественных исследователей, не обладает этим свойством по нескольким причинам. Во-первых, экономические отношения являются вторичными по отношению к когнитивной деятельности, так как планируются в виртуальной реальности, и не обязательно реализуются в эмпирической реальности. Во-вторых, эти отношения имеют прерывистый характер и могут появиться только в рамках материального элемента деятельности (рис. 3), нарушая континуальность процесса деятельности. В-третьих, понятия «деньги» и «денежные отношения» существенно у́ же и определяют только часть финансовых возможностей и ресурсов экономического агента (субъекта), которые могут быть вовлечены в хозяйственный оборот. Деньги, а в общем случае – финансовые активы, формируют систему инструментов, механизмов и технологий финансовой деятельности [30].

Финансовая же деятельность представляется как финансовое планирование, отличительным признаком которого является виртуальная природа. Сущность виртуальной деятельности заключается в формировании (конструировании) виртуальной финансовой модели (виртуального конструкта) будущего как новой реальности, а также путей, инструментов и механизмов ее создания. Отсюда происходит и зарождение процесса инженерии, в общем и финансовой инженерии, в частности [16]. Акцентируем внимание на распределительном (перераспределительном) и фондовом характере финансовой деятельности. Для достижения поставленной цели формируются виртуальные фонды денежных ресурсов (денежная оценка) и осуществляется распределение и перераспределение виртуальных ресурсов между этими фондами. Заметим, что все эти процессы происходят в виртуальной сфере. В практическом аспекте эта деятельность, в общем виде, заключается в построении будущего бухгалтерского баланса предприятия, бюджета домашнего хозяйства или государственного бюджета. В идеальном случае это может быть, например, актуарный баланс экономического агента, в котором учитываются его специфические риски. В то же время могут реализовываться и функции контроля – сравнение новой виртуальной реальности как конструкта будущего (актуарный бухгалтерский баланс) с новой константной реальностью как новой действительностью (фактический бухгалтерский баланс) и анализом факторов полученного результата.

Таким образом проводится четкое однозначное разделение сферы влияния финансов и финансовой деятельности (как когнитивной аспект деятельности с построением виртуального конструкта, а так же виртуальной логистики и инструментария его реализации) и сферы влияния денег. Сфера влияния денег является сферой материализации виртуального финансового конструкта и практического использования соответствующих финансовых инструментов и механизмов. Граница раздела финансовой сферы и денег отделяет виртуальное от материального, соответственно. Следует заметить, что в рамках данной риторики деньги понимаются в широком смысле как финансовые активы, поскольку любая трансакция с ними завершается в денежной форме и в денежном виде отражается в бухгалтерском балансе. Деньги представляются носителем финансов (стоимости), а в случае расчетов наличными средствами – материальным носителем финансов. План организации денежных потоков по перераспределению финансов (стоимости) – финансовая логистика формируется в виртуальной области и материализуется на основании и в соответствии с обязательствами экономических агентов, возникающими в рамках экономической деятельности по реализации соответствующей сделки.

Предложенная концепция финансов и финансовой деятельности универсальна, обладает свойством объективной непрерывности бытия и не имеет ограничений ни в пространстве, ни во времени, т. е. носит глобальный характер. В ней четко прослеживается

возможность установления связи с прошлым опытом, на основании которого в настоящем строится модель будущего.

В рамках предложенной концепции имеется реальная возможность ее эмпирической проверки. Эта возможность реализуется в форме прогнозирования результатов финансовой деятельности и их эмпирической проверки на стадии реализации функции контроля – сравнение прогнозных и реальных данных.

Например, использование финансовой модели планирования ресурсов предприятия ERP (Enterprise Resource Planning) позволяет построить несколько виртуальных сценариев (планов) деятельности предприятия на основе формирования и регулирования виртуальных денежных потоков. Все операции предприятия описываются не в натуральном, а в финансовом выражении (денежная оценка стоимости). Такие построения модели предприятия в рамках финансовой риторики являются виртуальными моделями (конструктами) деятельности предприятия, но они привязаны к результатам реальной деятельности. Таким образом, посредством применения ERP-моделей можно разработать несколько альтернативных сценариев и выбрать для практической реализации наиболее приемлемый для конкретных условий. Очевидно, что принятое решение о материализации конкретного сценария может быть проверено на практике: после завершения запланированного реального производственного цикла виртуальное может быть преобразовано в реальность. Это наглядная демонстрация связи виртуального и реального, а также возможности контроля виртуального на практике.

Наши рассуждения не противоречат утверждению К.Э. Переса и М. Верненго о том, что современные финансы имеют концептуально единое теоретическое ядро, которое включает в себя гипотезу эффективного рынка (EMH – The efficient market hypothesis) и математические модели взаимосвязи между риском и доходностью на основе ценообразования капитальных активов (CAPM – Capital Asset Pricing Model), теоремы Модильяни-Миллера (M&M – Modigliani-Miller theorems) и (BSM approach to option pricing) подходу Блэка Шоулза-Мертона к ценообразованию опционов [31, P.2]. Все эти математические модели представляют собой виртуальные оценки экономических параметров ситуации при проведении экономическим агентом финансовых операций. Они могут использоваться в практических целях, и на их основе может прогнозироваться (оцениваться) виртуальный финансовый результат деятельности, проверка которого возможна эмпирически. Таким образом, выдвинутая гипотеза о виртуальной сущности финансов доказана.

Представленная концепция открывает возможность для согласования позиций отечественных и иностранных исследователей по вопросу выработки единой парадигмы финансов и финансовой деятельности – семантического ядра финансовой науки. Не секрет, что значительные расхождения в понимании отечественными и иностранными специалистами теории и практики финансовой деятельности и финансов приводят к замедлению развития этого сектора экономики. Это обстоятельство особенно остро проявляется в современном обществе в связи с развитием и широким распространением во всех сферах человеческой деятельности информационно-коммуникационных технологий и развитием систем искусственного интеллекта. Эта глобальная тенденция обусловила и тот факт, что и Международный валютный фонд ставит вопрос о необходимости формирования для всех специалистов финансовой сферы общих понятий, т. е. разработки единой парадигмы финансов, возводя эту проблему в разряд актуальной тематики глобальных исследований. Очевидно, что разработка единого семантического ядра финансов и финансовой деятельности будет обеспечивать также единые подходы и к пониманию, и к обеспечению финансовой стабильности на глобальном уровне, поскольку «…финансы имеют фундаментальное отличие от других экономических функций, таких как обмен, производство и распределению ресурсов» [32, с.11].

Заключение

Культура, как продукт когнитивной деятельности, является основой общественного развития. Понятие финансы, изначально как оценка ценности продуктов собирательства и их обмена, а затем оценка стоимости продуктов труда, выраженная в единицах какого-то универсального товара, эволюционировали до современного уровня оценки стоимости в деньгах. В этой риторике финансы явились катализатором

производства товаров и услуг и, в конечном итоге, современной социально-экономической системы. Однако до настоящего времени когнитивный аспект финансов и финансовой деятельности оставался вне поля зрения исследователей, сосредоточивших свое внимание на их эмпирическом, конвенциональном аспекте.

Анализ логики причинно-следственных связей в определениях понятия финансы отечественных и зарубежных специалистов в конвенциональной риторике позволил выдвинуть и доказать гипотезу о виртуальной природе финансов, как продукта когнитивной деятельности, используя системный и междисциплинарный подход к анализу понятия финансы и финансовая деятельность – предмету анализа.

Концептуальное, системное представление процесса финансовой деятельности как закономерности процесса развития, включающей два взаимосвязанных элемента – когнитивная деятельность и материальная деятельность, дает возможность перейти к формированию новой научной рациональности в сфере финансов. То есть, это позволяет сформировать новый образ экономического мышления, основанный на разграничении сфер действия финансов и денег и предложить новую парадигму финансов. Более того, такое представление деятельности позволяет определить финансы как виртуальную категорию – виртуальную денежную оценку стоимости имущества, вовлекаемого в экономический оборот, а деньги рассматривать как носитель финансов при распределении или перераспределении его стоимости.

Показано, что в отличие от конвенциального подхода к финансам и финансовой деятельности, рассмотренная в статье концепция системного представления деятельности: выявляет закономерность процесса развития в форме системного представления процесса деятельности как его имманентного свойства; обладает свойством объективности непрерывного бытия за счет устранения фрагментарности представления процесса деятельности и не противоречит общенаучному принципу континуальности; создает объективные предпосылки для формирования новой глобальной парадигмы финансов – новой научной рациональности; создает объективные условия для дальнейшего развития экономической теории и теории финансов.

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К новой парадигме финансов: системно-деятельностный подход

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Аннотация

В статье утверждается, что, преобладающая в современной финансовой теории дихотомия между отечественным взглядом на финансы как на "экономические отношения" и западным взглядом как на "управление капиталом" является следствием фрагментарного понимания самого процесса деятельности.

Обосновано, что переход от традиционного понимания финансовой деятельности и финансов к новой парадигме требует ее системного представления, как совокупности процесса когнитивной деятельности и деятельности материальной. При этом, финансы рассматриваются как виртуальная оценка стоимости активов, вовлекаемых в экономический оборот. Такое представление преодолевает несоответствие традиционных, фрагментарных представлений финансовой деятельности, общенаучному принципу континуальности. Как результат, построены концептуальные и универсальные графические модели процесса деятельности и социально-экономического развития антропоцентрической направленности.

В научном плане, полученные результаты развивают экономическую теорию и создают предпосылки развития широкого спектра исследований по новым научным направлениям. В практическом плане результаты исследования найдут широкое использование в образовательной сфере, а также в области исследования системных финансовых рисков.

Ключевые слова: системно-деятельностный подход, финансы, виртуальная сущность финансов, системная модель, виртуальный конструкт, парадигма, континуальность процесса деятельности

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Research on the intervention mechanism of sustainable physical exercise on obesity among vocational college students

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KEYWORDS

College students of vocational schools;

Sustainable physical exercise;

Obesity problem

ABSTRACT

Adolescent obesity is worsening globally, and the obesity rate among Chinese college students keeps rising, which has become the leading cause of their failure in physical fitness assessments and also triggers psychological issues like inferiority and depression. To tackle this problem, this study constructs a multidimensional, integrated theoretical framework for sustainable physical exercise intervention based on physical-mental synergy, and designs a systematic intervention mechanism focusing on energy metabolism and mental health regulation. It further proposes implementation strategies under the tripartite synergy of universities, teachers and students, explores diverse exercise models, and innovatively develops a "vocational education-integrated" model suitable for higher vocational education with clear campus implementation paths. This research provides a scientific and feasible solution for alleviating college students' obesity and improving their physical and mental health.

1.INTRODUCTION

According to the 《2024 World Obesity Report》, if no obesity interventions are implemented globally, the number of overweight or obese adolescents (aged 5-19) is projected to rise from 435 million (22% of the global population in this age group) to 770 million by 2035. Among them, 27 million will develop high blood sugar, and 69 million will suffer from hypertension, primarily concentrated in middle-income countries. The National College Student Physical Fitness and Health Survey indicates a continuous increase in obesity rates among Chinese university students. The 2021 findings from the Eighth National Student Physical Fitness and Health Survey, released by the Ministry of Education, reveal that by 2020, approximately 30% of university students failed to meet physical fitness standards. Obesity has become the primary reason for failing these standards, as it not only affects students' appearance but also directly or indirectly leads to psychological issues such as low self-esteem and depression. Data from the 《National College Student Health Survey Report (2024)》 show that anxiety detection rates among university students reached 23.5%, while depression detection rates stood at 19.2%. Additionally, obesity poses a severe threat to students' health, which is one of the reasons why the pass rate for physical fitness tests remains stagnant.

1.Analysis of the Current Obesity Status Among Vocational College Students

1.1.Analysis of the Current Obesity Situation

1.1.1.Imbalanced Diet and Lack of Knowledge

The daily dietary patterns of college students exhibit a notably unhealthy tendency, characterized by the following key features: Severe dietary imbalances, predominantly marked by excessive caloric intake. According to a survey by《China Urban News》, college students face structural issues such as overconsumption of meat, eggs, cooking oil, and salt, while inadequately consuming vegetables, fruits, dairy, and fish. Generally low nutritional knowledge levels, accompanied by a significant "disconnect between knowledge and behavior." Widespread irregular eating habits,

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including frequent skipping of breakfast, late-night snacking, and heavy consumption of sugary beverages. These behavioral factors have become the primary drivers of obesity among college students. A Shanghai-based study revealed that 91.43% of respondents agreed that "irregular eating and binge eating" are the main causes of obesity, creating a striking "cognitive-behavioral" contradiction with their 77% self-consciousness about body shape.

1.1.2.Insufficient Physical Activity and Excessive Screen Time

Physical inactivity is a prominent issue currently faced by college students, rooted in the "systemic lack of opportunities for exercise." This phenomenon manifests specifically as a coexistence of insufficient active exercise and a sedentary lifestyle. Survey data from Sun Guiju's team in Nanjing, Jiangsu Province, reveals that although 60.1% of college students engage in at least 10 minutes of high-intensity exercise weekly, their average daily screen time (including computer and mobile phone usage) reaches as high as 9.24 hours. The extended screen time is primarily attributed to academic tasks and digital entertainment activities, which have become a norm in campus life and severely encroach upon students' time for active physical exercise.

1.1.3.Disordered sleep patterns and psychological stress

College students generally face problems of insufficient sleep and poor sleep quality. According to a survey conducted by Sun Guiju's team, the average sleep duration of this group is 7.3 hours, with 13.3% of students sleeping less than 6 hours, and as many as 44.9% of students experiencing various sleep problems. The important triggers behind it are psychological factors such as academic pressure and employment anxiety, which can lead to disrupted sleep patterns and subsequently lower sleep quality. In addition, research has confirmed that frequent mental health issues such as depression and stress are significantly associated with weight changes. Data shows that over 80% of students have the phenomenon of staying up late (only 19.29% have a regular schedule). In summary, the combination of unhealthy diets, widespread sleep disorders, and sedentary professional learning patterns creates a high-risk breeding ground for obesity.

1.2.The hazards of obesity among vocational college students

1.2.1.Health risks: comprehensive erosion from physiology to psychology

The harm of obesity to the health of college students manifests as a dual erosion of physiology and psychology, forming a vicious cycle of mutual influence.

At the physiological level, obesity is the pathological basis and initiating factor of various chronic diseases. First, it significantly increases the risk of metabolic syndrome, leading to diabetes, hypertension and dyslipidemia. The traditional concept of "middle-aged and elderly" diseases is showing a trend towards younger age groups, which seriously restricts the healthy lifespan of adults. Secondly, obesity triggers changes in biological factors, with excessive weight continuously increasing the mechanical load on weight-bearing joints such as the knee and ankle joints, accelerating cartilage wear, and subsequently causing osteoarthritis and chronic pain. This not only limits physical activity, but also hinders daily walking. Thirdly, obesity directly damages cardiovascular and pulmonary function, manifested as long-term overload of the heart and decreased lung function reserves, as well as common clinical symptoms such as shortness of breath and severe lack of endurance after physical activity, making it difficult to tolerate sustained physical activity. Fourthly, obesity can lead to dysfunction of the endocrine system, which is closely related to diseases such as polycystic ovary syndrome in women and abnormal estrogen levels in men. In addition, chronic low inflammation often associated with obesity can lead to immune system disorder and increase the risk of infectious diseases.

On a psychological level, the pressure brought by obesity cannot be ignored. In the youth group that highly values appearance, obesity is prone to become a focus of social discrimination, peer ridicule, and self denial, seriously damaging individual self-esteem and becoming an important source of inferiority and depression. The social anxiety caused by body type anxiety, as well as concerns about academic prospects and future development, collectively exacerbate the risk of anxiety and depression. At a deeper level, individuals may experience severe dissatisfaction and cognitive distortion with their body image, which can trigger two extreme behaviors - either excessive dieting or binge

eating, leading to a self reinforcing vicious cycle of "psychological pain behavioral loss control weight gain psychological distress".

1.2.2.Academic and career risks: directly affecting core competitiveness

Obesity has a profound negative impact on vocational college students, directly eroding their academic performance and career development potential. At the academic level, studies have shown that obesity may have adverse effects on neurocognitive function, leading to a decline in core cognitive abilities such as memory, attention, and executive function, which in turn affects learning efficiency and academic performance. Meanwhile, health issues related to obesity, such as fatigue and physical discomfort, can directly lead to an increase in absenteeism rates; Especially in practical courses that emphasize hands-on abilities, students often feel frustrated due to insufficient physical flexibility and difficulty in completing standardized operations, and even avoid class, resulting in a significant decrease in classroom participation.

At the level of career development, its impact is even more severe. Vocational education aims to cultivate high-quality technical and skilled talents in the production, construction, and service front lines. Many corresponding positions (such as mechanical maintenance, CNC operation, cooking, construction, nursing, etc.) have clear requirements for practitioners' physical endurance, strength, agility, and sustained standing ability. Obesity directly leads to insufficient physical reserves in such professions, which constitutes a fundamental obstacle to their ability to perform in future work. In the training environment, delayed response and limited mobility significantly increase the risk of obese students encountering work-related accidents such as mechanical scratches, slips, burns, etc. Ultimately, in the job market, when companies recruit for these frontline positions, they take into account the physical and health conditions of their employees. Obesity may become an "implicit screening criterion," putting students at a disadvantage in interviews and physical fitness tests, directly limiting their employment competitiveness and career prospects.

1.2.3.Social Adaptation and Development Risks: Invisible Deprivation of Opportunities

The negative impact of obesity on vocational college students further extends to their social adaptation and personal development, forming profound comprehensive risks. At the social level, obese students often actively avoid social scenes such as group activities and teamwork due to fear of negative evaluations or limited mobility. This self isolation behavior can easily lead to marginalization, making it difficult to establish and develop a healthy interpersonal network, resulting in innate weakness of college students' social adaptation capital.

At the developmental level, the undergraduate period is a crucial stage for accumulating human capital and social relationships. However, the lack of energy and social withdrawal caused by obesity make it difficult for students to fully participate in extracurricular activities such as clubs, competitions, and social practices. The lack of these key experiences directly hinders the cultivation of non cognitive skills such as organizational coordination, communication expression, and leadership, resulting in limited development of comprehensive qualities.

For vocational college students, obesity is a complex problem that combines health crises, academic obstacles, career bottlenecks, psychological burdens, and social dilemmas. It fundamentally erodes the core competitiveness of vocational college students as "future craftsmen", namely healthy physical fitness and sustainable professional fitness, posing a systematic threat to their personal development and social integration.

2.Exploration of sustainable sports exercise intervention mechanism

2.1.Concept of Sustainable Development

The "environmental" sustainability of intervention mechanisms refers to creating supportive physical and institutional environments for physical exercise. For example, ensuring sufficient sports facilities, open hours, creating a positive campus sports culture atmosphere, and institutionalizing intervention measures such as incorporating them into the curriculum system and credit recognition.

The 'social' sustainability of intervention behavior: its core lies in students' intrinsic motivation and health equity. The

intervention mechanism cannot rely solely on coercion, but should focus on stimulating students' intrinsic interests, such as project interest, sense of belonging to clubs, etc; Satisfy their social and psychological needs, such as companionship support, sense of achievement, etc; Ensure that all students, including obese students, can participate fairly and benefit from it.

The "economic" sustainability of intervention systems refers to the feasibility and long-term viability of intervention programs in terms of resource investment. It should not be a "bonsai project" that consumes huge amounts of money and relies on short-term projects, but should be low-cost, efficient, and easy to promote. For example, utilizing existing faculty and facilities, cultivating student sports backbone, and designing sports programs.

Sustainable physical exercise is a long-term, not a one-time activity. Can integrate into campus daily life and systems, rather than exist in isolation. It can help students transition from passive participation to active persistence, cultivating their lifelong exercise habits and abilities.

2.2.Exploration of Sustainable Sports Exercise Intervention Mechanism

2.2.1.Health Promotion Type

The core objective of this mechanism is to improve students' physical health indicators, with a focus on optimizing physical health parameters such as body fat percentage, blood pressure, and muscle mass. The typical practice form is the "college student health exercise prescription" mechanism, which is based on individual physical health assessment and health risk assessment results, and professional teachers develop personalized and periodic exercise plans, and dynamically adjust them according to the stage assessment results. This mechanism emphasizes the scientific and targeted nature of exercise, and is combined with a digital health management platform to achieve precise monitoring and feedback of the exercise process through technological empowerment.

2.2.2.Interest cultivation type

The fundamental goal of this mechanism is to stimulate students' interest in sports and cultivate long-term exercise habits, emphasizing the emotional experience and intrinsic motivation cultivation during the process of physical exercise. The approach is to rely on two organizational forms, namely "sports course selection" and "sports clubs", to provide diversified and personalized sports projects including rock climbing, aerobics, tug of war, etc., emphasizing students' autonomy and fun experience in the participation process, rather than solely focusing on skill achievement, thus promoting their transformation from "passive participation" to "active participation".

2.2.3.Integration of Vocational Education (Characteristics of Higher Vocational Education)

This mechanism is an important path to reflect the characteristics of higher vocational education, with the goal of integrating physical exercise with the physical fitness required for students' future careers, and enhancing their physical adaptability to their professional positions. The practical form is to construct a "vocational physical fitness training" system, designing exercise content with "quasi professional" characteristics based on typical job tasks and physical fitness needs corresponding to different professional groups.

2.2.4.Suggestions for the Construction of Sustainable Physical Exercise Intervention Mechanism in Vocational Colleges

Promote systematic integration and build a composite educational ecosystem. We should abandon fragmented and isolated ways of organizing sports activities, and instead systematically integrate the four elements of "clubs, courses, events, and environment" at the top-level design level to build a composite campus sports education ecosystem that is interconnected and functionally complementary. By laying the foundation through courses, deepening interests through clubs, providing exhibition platforms for competitions, and creating a supportive atmosphere in the environment, a collaborative and efficient educational force is formed.

Deepen the integration of vocational education and strengthen the development of internal drive. Different from ordinary universities, vocational colleges should vigorously develop and promote the "vocational education integration" physical exercise mode, closely combining physical training with the specific physical literacy required for students' future careers. This model transforms physical exercise into

an effective way to enhance professional competence, which can significantly stimulate students' motivation to participate and achieve a cognitive transformation from 'I want to exercise' to 'I want to exercise'.

Promote technological empowerment, achieve precise management and incentives. We should actively introduce digital tools such as intelligent mobile applications and wearable devices to alleviate the relative shortage of professional physical education teachers. Through technological means, personalized tracking, data-driven analysis, and real-time feedback of students' exercise process can be achieved, improving the level of refined management and providing visual progress incentives for students. Improve incentive feedback mechanisms to meet diverse needs. Build a diversified incentive system that includes institutional incentives, data feedback, and spiritual honor. Incorporate physical exercise into credit recognition, generate personalized exercise reports through digital platforms, and establish various sports honors and awards to meet students' different needs in achievement recognition, ability proof, and social respect, and continuously consolidate their exercise behavior.

3.Principle of intervention mechanism

3.1.Aerobic exercise regulation intervention

3.1.1.Principles of Energy Metabolism Regulation

The core mechanism of this principle is to establish a sustained negative energy balance through scientific exercise intervention, thereby directly promoting fat consumption. The specific pathways of action include:

Direct fat oxidation during exercise: In moderate to low-intensity, long-term aerobic exercise, the body oxidizes and decomposes fat as the main energy source under sufficient oxygen supply conditions, effectively reducing body fat storage;

Excessive oxygen consumption after exercise: After exercise, the body maintains a high oxygen consumption rate to restore internal homeostasis, continuously burning calories and fat. This phenomenon is called "excessive oxygen consumption after exercise", which helps to increase 24-hour total energy expenditure and fat consumption;

Improvement of basal metabolic rate: Long term regular aerobic exercise can help increase lean body mass, improve mitochondrial structure and function, and moderately increase resting metabolic rate, enhancing energy expenditure ability in non exercise states.

3.1.2.Principles of Endocrine and Metabolic Regulation

The core of this principle lies in improving the metabolic regulatory environment of the body through exercise, enhancing insulin sensitivity, and optimizing lipid metabolism pathways. The mechanism mainly includes:

Enhance insulin sensitivity: aerobic exercise can promote the uptake and utilization of glucose in skeletal muscles, reduce insulin resistance, and play a key role in preventing and improving type II diabetes, especially for obese students;

Regulating lipid metabolism related hormones: Exercise can inhibit the secretion of hormones that promote fat synthesis, while activating hormones that promote fat breakdown, such as catecholamine release, thereby improving body fat metabolism balance.

3.1.3.Principles of cardiovascular and cardiopulmonary function regulation

This principle aims to enhance the efficiency of oxygen delivery and utilization in the body through aerobic exercise, thereby improving overall exercise tolerance. The mechanism mainly includes: enhancing myocardial function, exercise training can improve myocardial contractility, increase cardiac output per stroke, and improve cardiac pumping efficiency; The improvement of aerobic capacity is manifested as an increase in maximum oxygen uptake, which is the standard for evaluating cardiopulmonary function. The increase in maximum oxygen uptake means an increase in oxygen utilization efficiency, a reduction in fatigue during exercise, an improvement in exercise tolerance, and thus contributes to the long-term persistence of physical exercise behavior.

3.1.4.Principles of psychological and behavioral regulation

This principle focuses on the positive impact of physical exercise on the psychological state and behavioral patterns of college students, promoting the formation and

maintenance of exercise habits. The mechanism mainly includes: neuroendocrine regulation, sustained moderate to low intensity aerobic exercise can stimulate the release of endorphins, generate pleasant emotions, relieve stress and anxiety, thereby reducing emotional overeating and eating behavior; Improving self-efficacy, by achieving phased exercise goals such as running distance, energy consumption, etc., students can receive immediate achievement feedback and enhance their self belief in "I can do it", which is the key psychological foundation for persisting in physical exercise; The behavioral habituation mechanism embeds regular aerobic exercise into daily life rhythms, forming stable behavioral patterns that help improve the persistence of physical exercise, promote the automation and long-term persistence of exercise behavior.

4.Construction of intervention mechanism

4.1.Construction of Systematic Intervention Mechanism for Aerobic Exercise

The personalized exercise prescription regulation mechanism, as the core link of aerobic exercise systematic regulation intervention, is based on the FITT principle to construct a personalized plan. The specific regulation mechanism is as follows: exercise intensity regulation. To avoid homogenization of exercise intensity, an individualized setting method is adopted, mainly based on the heart rate interval method, such as controlling within 60% -70% of the maximum heart rate, that is, the fat efficient oxidation interval or subjective fatigue sensation scale, to ensure that exercise stimulation is within a safe and effective range. In the early stages of intervention, it is recommended to start with low intensity to reduce the risk of sports injuries and psychological distress. Time and frequency adjustment, according to the "American Physical Activity Guidelines", the initial goal is to exercise 3-5 times a week, each time lasting more than 30 minutes, and support phased accumulation, such as 10 minutes each time, completing 3 times for a total of 30 minutes. With the gradual improvement of students' physical fitness adaptation, the ultimate goal is to accumulate 150 minutes of moderate intensity aerobic exercise per week.

The advanced load regulation module is designed based on the physiological principle of "over recovery", aiming to gradually increase the load, continuously optimize the training effect, and prevent the occurrence of plateau period. The specific mechanism is to establish a dynamic evaluation and load adjustment mechanism, implement physical fitness assessment every 4-8 weeks, and gradually increase exercise duration, frequency, or intensity based on the assessment results to maintain the fun and effectiveness of exercise stimulation.

The diversified adjustment module for types and scenarios aims to enhance interest and behavioral compliance in sports participation. Through the design of diversified sports types and scenarios, it alleviates the monotony of the exercise process. The specific implementation mechanism includes building an aerobic exercise resource library that covers projects such as campus jogging, brisk walking, swimming, spinning bikes, aerobic fitness exercises, dance, and skipping rope; And combined with the campus physical environment, club organization activities, and technology platforms, enhance the fun and participation appeal of aerobic exercise.

The monitoring and feedback regulation module, based on behavior reinforcement theory, enhances students' exercise motivation through systematic data monitoring and result feedback, and provides empirical evidence for prescription adjustment. The specific mechanism includes: process monitoring, guiding students to use tools such as heart rate wristbands and exercise apps, and systematically recording key indicators such as heart rate, exercise duration, distance, and energy consumption; Consequential feedback: Regularly generate individual exercise health reports, correlate process data with physical indicators, and analyze changes in weight, body fat percentage, waist circumference, and cardiopulmonary function to enable students to intuitively recognize exercise effectiveness and construct a positive stimulation closed-loop system of "behavior data feedback reinforcement".

4.2.Health Behavior Habitation Module

This module is based on the theory of habit formation and aims to promote the automation and long-term maintenance of healthy exercise behavior through systematic behavior design. Specific implementation strategies include:

Execution intention training, physical education teachers guide students to develop "if then" plans, such as "if I feel increased stress and have a desire to eat, then I will take a 10 minute walk", transforming abstract exercise intentions into

automated behavioral responses in specific contexts, enhancing the clarity and immediacy of behavior execution.

Habit connection and environmental reconstruction guide students to connect new exercise behaviors with existing daily habits, such as "completing 10 squats immediately after brushing teeth every day", and optimize the external environment in which the behavior occurs, such as "preparing sportswear before bedtime for morning jogging", to reduce the resistance to behavior initiation and promote the effective solidification of new behavior patterns.

Construction of a process oriented incentive system, establishing a non weight centered incentive system with effort and behavior persistence as the core, and strengthening students' positive behavior during exercise through the establishment of honorary titles such as "Full Attendance Participation Award" and "Stage Progress Award", rather than solely relying on weight changes as evaluation criteria, thereby enhancing intrinsic motivation and behavioral sustainability.

4.3.Positive body image construction module

This module aims to improve physical cognition and self acceptance, and alleviate psychological and behavioral disorders caused by physical dissatisfaction through cognitive reconstruction and media critical education

Body function appreciation training, by assigning the task of writing a "body function diary", guides students to record a valuable activity completed by their body every day, such as "successfully completing a three kilometer run", gradually shifting their focus from external physical form to body function and ability, and establishing a sense of respect for the body based on function.

Body image media literacy education aims to help students identify and resist irrational social comparisons by analyzing the constructiveness and unreality of the "ideal body" image in mass media and social platforms, cultivate their understanding and acceptance of body diversity, and reduce the impact of appearance anxiety on sports participation.

5.Reshaping Sustainable Physical Exercise Literacy

The core goal of the implementation strategy for reshaping sustainable physical exercise literacy is to internalize physical exercise from an external mandatory "task" into students' conscious and lifelong "literacy" and "lifestyle". This requires the collaborative efforts of schools, teachers, and students to form a complete educational ecosystem.

5.1.School level

Top level design and supportive environment shaping, schools are the "engine" and "soil" of this mechanism, responsible for providing institutional, resource, and cultural guarantees. Incorporate 'health first, lifelong sports' into the official development plan of the school to enhance the strategic position of sports work. The school has established a "Healthy Campus Committee": led by school leaders, with the participation of the Sports Department, Student Affairs Office, Academic Affairs Office, Logistics, Medical Office, and various secondary colleges, to break down departmental barriers and coordinate resources. For students: Promote the "Sports Comprehensive Literacy Credit", which not only looks at physical test scores, but also includes attendance rate, progress, participation in clubs and competitions, and sports theory knowledge in the assessment, achieving a combination of process and outcome evaluation. For departments/classes: Incorporate the rate of students' physical health compliance and participation in sports activities into the work assessment of departments and counselors, and form an incentive mechanism.

Resource integration and conditional support strategies are used to create a physical and digital environment for students that is "dynamic, active, and convenient to move". Hardware upgrade and intelligence, adding, updating, and maintaining sports venues and equipment. Introduce the "Smart Playground" system, which automatically records student movement data through facial recognition and IoT devices, and connects with the academic system. Diversified funding support, establishment of special activity funds for sports clubs and reward funds for on campus and off campus sports events, and encouragement of social resources to participate. Micro updates in time and space ensure that venues are fully open during spare time. Set up a "fragmented fitness corner" on campus open space and equip dormitory buildings with simple equipment such as yoga mats.

Cultural creation and brand activity strategies aim to make physical exercise the most trendy cultural symbol on campus. Create a brand sports festival, hold annual events such as "Sports Culture Festival", "Campus Marathon", "Fun Tug of War", "Physical Challenge", etc., and give it a unique sense

of ceremony and honor system. Empower sports clubs, encourage and support students to establish diversified sports clubs such as cycling clubs, street dance clubs, and rock climbing clubs, and provide professional guidance, activity funding, and exhibition platforms to make them a source of vitality for sports culture. Stereoscopic promotion, utilizing campus media, vigorously promoting the stories of "exercise experts" and "progressive stars", and shaping positive role models.

5.2.Teacher level

Role transformation and ability enhancement, teachers are the "catalysts" and "guides" of this mechanism, and need to transform from "command issuers" to "interest motivators, method guides, and growth partners".

Teaching philosophy and role transformation strategy, from "teaching physical education" to "teaching people to achieve health and growth through physical education". Promote a student-centered teaching method, respect individual differences, shift from "command based" teaching to "guided" and "encouraging" teaching, and focus on students' sense of experience, achievement, and learning pleasure. A "sports mentor" is not only a teacher in the classroom, but also a consultant for students' sports life, helping them develop personalized exercise plans and solve the difficulties they encounter in the process of persistence.

Innovative strategies for teaching content and methods to make physical education classes "useful, interesting, and selective". Develop "modular" courses, break the traditional single course model, and offer "weight loss and shaping classes", "physical fitness enhancement classes", "outdoor expansion classes", "fitness and bodybuilding classes", etc., allowing students to choose independently based on their interests and needs.

Deepen the integration of vocational education, cooperate with various majors, and develop targeted "vocational physical training" content, such as neck and lumbar spine health exercises for IT majors, allowing students to intuitively experience the value of physical exercise for future careers.

Integrating health theory education: Systematically teaching knowledge such as sports physiology, nutrition, injury prevention, and sports psychology in physical education classes to cultivate students' "sports and health concepts".

Collaborative education and attention to individual strategies, building a sports support network that involves all members. Collaborate with counselors, regularly communicate, and jointly pay attention to the physical exercise and psychological status of special student groups such as obesity and frailty. Train student sports backbone, cultivate "sports committee members" or "sports leaders" in classes and clubs, and play the role of peer education and role models.

5.3.Student level

The cultivation of subject consciousness and behavior, students are the "ultimate subjects" and "practitioners" of this mechanism, and the awakening of their internal motivation and changes in behavior are the fundamental signs of strategic success.

Cognitive arousal and goal management strategies help students transform from passive participants to active planners. Carry out "self diagnosis of sports literacy", through questionnaire surveys and interpretation of physical test data, to enable students to have a clear understanding of their physical condition, exercise ability, and health risks, and stimulate their intrinsic motivation for change. Guide the development of a "personal exercise prescription" and guide students to set clear, measurable, achievable, related, and time limited personalized exercise goals based on the SMART principle, such as "losing 5 pounds through jogging this semester" and "increasing the number of pull ups from 0 to 3".

Strategies for mastering skills and solidifying habits, teaching students the ways and methods of motor skills, and helping them become accustomed to sports behavior. Encourage students to deepen their learning and master at least one sport they truly love during their school years, as a carrier of lifelong exercise. Learn the "micro habit" cultivation method, teach students to start with small goals such as "exercising for 10 minutes every day", lower the threshold for starting exercise, and use the "habit stacking" method to integrate exercise into daily life rhythm. Make good use of digital tools, encourage students to use sports apps to record check-in, join online sports communities, and use the power of technology to obtain guidance, feedback, and social motivation.

Community integration and positive mindset strategies enable students to find a sense of belonging and achievement within the collective. Encourage students to

join a sports club or group based on their interests, using peer pressure and social fun to overcome laziness. Cultivate a 'growth mindset', guide students to view the bottlenecks and setbacks in exercise correctly, shift their focus from 'why am I so fat' to 'I ran one more lap today than yesterday', and celebrate every small progress. Practice 'body function appreciation', reduce anxiety about appearance, and instead appreciate and appreciate every improvement in physical movement ability.

These three levels of strategies are interdependent and mutually reinforcing. Schools create the overall environment and possibilities, with teachers as key guides and enablers, and students as active participants and practitioners, ultimately forming the value endpoint and source of vitality of the entire system. Only through the collaboration of three parties and the formation of a joint force can we truly achieve a deep reshaping of the sustainable physical exercise literacy of vocational college students.

Conclusion

Theoretical framework and mechanism innovation: This study goes beyond the simple initiative of "multi sport" and constructs a multidimensional, integrated, and mind body co governance sustainable physical exercise intervention theoretical framework. This framework is based on the physiological principle of "energy metabolism regulation" to ensure the scientific and effective intervention; Using "mental health regulation" as an internal engine, by stimulating intrinsic motivation, reconstructing cognition, and cultivating positive body images, we can break through the psychological bottleneck of behavioral persistence; In the end, each link was concretized and systematized through an intervention mechanism that included motivational stimulation, content methods, and support guarantees, ensuring the integrity and operability of the intervention.

Implementation strategy and subject collaboration: To ensure the implementation of the mechanism, this study proposes an implementation strategy driven by the collaboration of three major subjects: schools, teachers, and students. At the school level, a supportive 'big environment' has been constructed through top-level design, resource integration, and cultural creation; At the teacher level, they play a key "catalyst" role through role transformation, teaching innovation, and collaborative education; At the student level, their core position as "active practitioners" has been established through cognitive awakening, skill mastery, and community integration. These three levels are interconnected, weaving together a three-dimensional network that promotes the reshaping of sustainable physical exercise literacy.

Pattern exploration and path design: The study deeply explores diversified sustainable sports exercise patterns such as community socialization, technological empowerment, event honors, and environmental guidance, and innovatively proposes a "vocational education integration" pattern that fits the characteristics of higher vocational education. On this basis, this study has planned a campus implementation path from top-level design to comprehensive promotion, ultimately achieving normalized operation, providing a clear roadmap for the intervention plan to move from blueprint to reality.

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Guided by Sustainable Development Theory: Research on Hierarchical Cultivation Path in Dance Activities for 3-6 Year old Children

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KEYWORDS

Stratified training;
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Dance movements

ABSTRACT

During the critical growth stage of children aged 3–6, dance education plays a prominent role in their physical, cognitive, emotional and social development. Based on the concept of sustainable development, this study systematically reviews theories of early childhood education, physical literacy and dance education, clarifies the connotation and requirements of the concept in early childhood dance education, and identifies gaps in existing research. Guided by principles such as developmentality, it constructs a hierarchical physical literacy training path for young children's dance learning, categorizing children by age and ability with tailored teaching methods. The findings provide a scientific framework for early childhood dance teaching, enhance teaching effectiveness, stimulate children's learning interest, facilitate teachers' professional growth, and offer insights for the scientific advancement of early childhood education.

INTRODUCTION

During the critical period of young children's growth, dance education, as a unique and diverse educational approach, plays an undeniable role in the development of children aged 3-6. From the perspective of physical development, young children are in a stage of rapid bone and muscle development. Various movements in dance activities, such as walking, running, jumping, and spinning, can effectively exercise children's muscle strength, enhance joint flexibility and agility, promote the coordinated development of large and small muscle groups, and lay the foundation for children's good body posture and exercise ability. At the level of cognitive development, young children's thinking is mainly based on concrete and visual thinking. Dance, through vivid movements, cheerful rhythms, and rich contexts, can stimulate children's observation, attention, and memory. For example, when learning a dance that imitates small animals, young children need to carefully observe the shape and movement characteristics of the animals, remember the order and key points of the dance, which helps to improve their cognitive abilities. In terms of emotional and social development, dance provides young children with an outlet to express their emotions, allowing them to release their emotions and enhance their confidence through dance. Collective dance activities can also cultivate children's teamwork awareness and social skills, allowing them to learn how to collaborate, share, and communicate with peers.

With the development of society and the updating of educational concepts, the concept of sustainable development has gradually penetrated into various fields of education. Integrating the concept of sustainable development into early childhood dance education is of great significance. The concept of sustainable development emphasizes the long-term benefits, comprehensiveness, and harmonious coexistence between individuals and the environment of education. Incorporating this concept into early childhood dance education can help break the short-term utilitarian goals that may exist in traditional

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dance education, such as simply pursuing training in dance skills, but placing more emphasis on the comprehensive and long-term development of children's physical literacy. Guided by the concept of sustainable development, early childhood dance education can pay attention to the individual differences and developmental rhythms of each child, provide them with a sustainable dance learning environment and content, and promote their sustainable growth in physical, psychological, emotional, and other aspects. This is not only beneficial for the healthy development of young children in their early childhood stage, but also lays a solid foundation for their future learning and life, and has a positive demonstration effect on promoting the scientific development of the entire field of early childhood education.

1.Current research status of early childhood dance education

In China, research on early childhood dance education is gradually receiving attention, and related research results are constantly emerging. In terms of educational goals, many scholars emphasize that early childhood dance education should not only focus on imparting dance skills, but also pay attention to the comprehensive development of young children. Through dance education, cultivate children's aesthetic ability, creativity, expressiveness, and emotional expression ability. In terms of teaching content, research suggests that dance materials should be selected based on the age characteristics and interests of young children, such as selecting child friendly dances, ethnic and folk dances, etc., so that the dance content is close to the children's life experience and stimulates their learning interest. In terms of teaching methods, advocating diversified teaching methods such as story introduction method, game teaching method, situational teaching method, etc., to improve children's learning enthusiasm and initiative. For example, by telling an interesting story and incorporating dance movements into the story, children can learn dance in context, enhancing the fun of dance learning.

Research on early childhood dance education in foreign countries started earlier and has accumulated rich experience in educational concepts and teaching practices. In terms of educational philosophy, it emphasizes putting young children at the center, respecting their individual differences and developmental needs, and focusing on cultivating their self-learning ability and innovative spirit. In teaching practice, diversified teaching modes are adopted, such as improvisational dance teaching, creative dance teaching, etc., to encourage children to unleash their imagination and creativity, and freely express their emotions and ideas. Foreign countries also place great emphasis on the integration of dance education with other disciplines, such as combining dance with music, art, literature, and other subjects to broaden children's artistic horizons and cultivate their comprehensive artistic literacy.

However, existing research on the cultivation of physical literacy in early childhood dance education still has certain shortcomings. In terms of training objectives, although the importance of early childhood dance education for children's physical development is recognized, there is a lack of comprehensive and systematic planning for the training objectives of various elements of physical literacy. Often, the focus is only on training dance skills, while neglecting the cultivation of physical fitness, sports cognition, and emotional attitudes. In terms of teaching content, the design and arrangement of dance movements focus more on the artistic and ornamental aspects of dance, and there is insufficient research on how to effectively enhance children's physical literacy through dance activities. In terms of teaching methods, there is a lack of personalized teaching methods tailored to the different developmental stages and levels of physical literacy in young children, making it difficult to meet the learning needs of each child.

2.Layered cultivation path design in preschool dance activities

2.1.Path design principles

Based on the theory of sustainable development, when designing a layered training model for dance activities for children aged 3-6, it is necessary to follow the important principles of development, differentiation, fun, and comprehensiveness to ensure the scientific, effective, and appropriate path.

The first principle of path design is development. Children are in a stage of rapid physical and cognitive development, and dance activities should fully consider their developmental potential, providing them with appropriate movement training and cognitive development. The teaching content and difficulty should gradually progress according to

the age and physical development level of young children, from simple basic movement training to complex dance combination exercises, constantly stimulating their physical potential and promoting the continuous improvement of their physical abilities. In dance teaching for 3-4 year old children, the focus should be on cultivating their basic motor skills, such as the correct posture and sense of rhythm for walking, running, and jumping; As age increases, the difficulty and complexity of dance movements can gradually increase in the 5-6 year old stage, introducing movements that require body coordination and balance, such as rotation, jumping, etc., to meet the needs of young children's physical development.

The second principle of path design is diversity, which emphasizes paying attention to individual differences of young children, including physical conditions, interests, learning abilities, and other aspects. Every child is a unique individual, with varying rates and characteristics of physical development. Therefore, path design should be layered based on the differences of young children, and personalized teaching objectives, content, and methods should be developed for different levels of young children. For young children with good physical fitness and strong athletic abilities, more challenging dance training content can be provided to cultivate their dance skills and expressive abilities; For young children with relatively weak physical fitness and slower development of physical abilities, emphasis should be placed on training their basic physical abilities and cultivating their interests, using milder and gradual teaching methods to help them gradually improve their physical abilities.

The third principle of path design is fun, and the fun principle is the key to attracting young children to actively participate in dance activities. Children's attention and interest are easily diverted, and only interesting dance activities can stimulate their learning enthusiasm and initiative. In dance teaching, various interesting teaching methods such as games, stories, and role-playing can be used to integrate dance movements into interesting contexts. By playing the game "Action Imitation Show", children can imitate the movements of various animals and plants, such as small rabbits jumping and small trees standing tall, and learn and practice dance movements in the game. This allows children to experience the joy of dance in a relaxed and pleasant atmosphere, and improve their physical literacy.

The fourth principle of path design is comprehensiveness, which requires dance activities to not only focus on a certain aspect of children's physical abilities, but also comprehensively consider the development of multiple dimensions such as physical fitness, motor skills, motor cognition, and emotional attitudes. Dance teaching content should cover various forms and elements of dance, while combining knowledge of physical exercise, health education, and other aspects to promote the comprehensive development of children's physical and mental health. In dance classes, some simple sports games can be added, such as relay races, obstacle jumps, etc., to exercise children's physical fitness; At the same time, by explaining knowledge such as body structure and movement principles, children's motor cognition level can be improved. Pay attention to cultivating children's emotional cognition, encourage them to express their emotions and feelings in dance, enhance their confidence and teamwork spirit.

2.2.Path layering basis and hierarchical division

Age is an important stratification criterion. There are significant stage differences in physical and cognitive development among children aged 3-6. Children aged 3-4 are in the basic stage of physical development, with poor coordination and flexibility of movements, and their cognitive abilities are mainly based on concrete and intuitive thinking. Children at this stage are more suitable for learning simple and basic dance movements, such as basic steps, hand positions, etc., in dance activities, and improving the accuracy and stability of movements through repeated practice. Children aged 4-5 have improved physical coordination and motor skills, and begin to develop a certain sense of rhythm and imitation ability. In dance teaching, the difficulty and diversity of dance movements can be appropriately increased, and some simple dance combinations can be introduced to cultivate children's sense of rhythm and expression. Children aged 5-6 have further developed various physical abilities, able to understand complex dance movements and instructions, and possess strong creativity and imagination. At this time, dance teaching can focus more on training dance skills and rehearsing dance works, encouraging children to unleash their creativity and perform dance.

The level of physical ability development is also a key factor

in stratification. By evaluating the physical fitness, athletic ability, and physical cognition of young children, they can be classified into different levels. Children with good physical fitness, strong athletic abilities, and high levels of physical cognition can be classified as high-level; Children with moderate physical fitness and athletic ability, as well as average physical cognitive level, are considered at the intermediate level; Children with weaker physical fitness, slower development of athletic abilities, and lower levels of physical cognition belong to the lower level. For high-level young children, more challenging dance training can be provided, such as difficult dance technique exercises, complex dance rehearsals, etc., to further enhance their physical abilities. Middle level children are taught dance with moderate difficulty, focusing on consolidating and improving their physical fitness and athletic abilities. Low level children mainly receive basic dance training and physical fitness exercises to help them gradually improve their physical fitness and keep up with the teaching progress.

Interests and hobbies cannot be ignored in terms of hierarchical division. The level and direction of children's interest in dance will affect their participation and learning outcomes in dance activities. Children who have a strong interest in dance and demonstrate high talent can receive more attention and training, providing richer dance learning resources and exhibition opportunities. For children with average interests, it is necessary to stimulate their interest and guide them to actively participate in dance activities through diverse teaching methods and interesting teaching content. Some children are interested in ethnic dance, while others enjoy modern dance. Teachers can provide corresponding dance teaching content based on children's interests and hobbies to meet their personalized needs.

Based on the above stratification criteria, children are divided into three levels: low, medium, and high. The characteristics of low-level children are relatively weak physical fitness and motor ability, poor physical coordination and flexibility, and limited cognitive and understanding abilities of dance. The physical fitness and athletic ability of middle level children have developed to a certain extent, with improved physical coordination and flexibility, as well as enhanced recognition and understanding of dance. High level young children have good physical fitness, strong athletic ability, excellent physical coordination and flexibility, and have a deep understanding and knowledge of dance, as well as a certain degree of creativity and expressiveness.

2.3.Training objectives and content architecture

Developing specific and targeted physical literacy training objectives for children of different levels, and constructing a comprehensive and systematic content framework, are the key to achieving hierarchical training.

For low-level children, the goal of physical ability development mainly focuses on improving their basic physical fitness and stimulating their interest in dance. In terms of physical fitness, children can enhance their muscle strength, joint flexibility, and body coordination through simple sports games and dance exercises. Encourage young children to engage in simple activities such as jumping and stretching to exercise their upper and lower limb strength, coordination, and flexibility. In the cultivation of dance interest, vivid and interesting teaching methods such as story introduction and game teaching are adopted, allowing children to experience the joy of dance in a relaxed and pleasant atmosphere. In terms of content framework, the basic knowledge of dance section focuses on helping young children understand the basic concepts, types, and characteristics of dance, such as ethnic dance, ballet, modern dance, etc. By watching dance videos, teacher demonstrations, and other methods, children can have a preliminary understanding of dance. Skill training mainly focuses on learning basic dance movements, including correct standing posture, walking steps, simple hand and foot positions, etc. These movements are the foundation of dance, and through repeated practice, they help young children master the correct body posture and movement norms. In the process of improving physical fitness, arrange some simple sports activities such as short distance running, simple climbing, balanced walking, etc., to exercise children's physical abilities.

The training objectives for middle level children have further improved in terms of physical ability and dance skills. In terms of physical ability, it is required that young children have significant improvements in strength, speed, endurance, coordination, and other aspects. Enhance children's physical fitness through more challenging sports games and dance training, such as freestyle skipping rope, kicking shuttlecock, and more complex dance combination exercises. In terms of dance skills, emphasis is placed on cultivating the

standardization, fluency, and expressiveness of dance movements. Teach young children to grasp the rhythm of dance, coordinate and transform movements, and improve the overall quality of dance. In the content framework, the learning of basic dance knowledge is more in-depth, and young children need to understand the history and cultural background of dance, as well as the basic principles of dance creation. By learning the history and culture of different ethnic dances, young children can experience the cultural connotations of dance. In the skill training section, we will increase the training content of dance techniques, such as learning simple skills such as rotation, jumping, and flipping, while strengthening the practice of dance combinations to improve children's dance performance. In terms of improving physical fitness, some sports activities that require physical coordination and teamwork should be carried out, such as indoor basketball, mini soccer and other ball games, to cultivate children's teamwork spirit and physical coordination.

The training objectives for high-level young children focus on the mastery of dance skills and the full expression of creativity. In terms of dance skills, children are required to be proficient in high difficulty dance movements such as complex jumps, rotations, somersaults, etc., and possess excellent dance expression and artistic appeal. In terms of cultivating creativity, encourage young children to create dance works and unleash their imagination and innovative thinking. In the content framework, basic knowledge of dance involves aesthetic appreciation of dance art and analysis and evaluation of dance works. By appreciating classic dance works, guiding young children to analyze the artistic characteristics, expression techniques, and emotional expressions of the works, we aim to enhance their aesthetic abilities. Skill training mainly focuses on the training of high difficulty dance techniques, while also emphasizing the grasp and expression of dance styles. The creativity cultivation stage provides rich creative materials and free creative space, allowing children to create dance according to their own interests and ideas, and organizing dance work exhibitions and communication activities to improve children's creative ability and confidence.

2.4.Teaching Methods and Strategies

In order to achieve the physical ability development goals of children at different levels, it is necessary to adopt diverse and personalized teaching methods and strategies.

Dance game teaching method is an effective teaching method suitable for dance education of young children at all levels. Games can stimulate children's interest in learning, allowing them to learn dance movements in a relaxed and enjoyable atmosphere. For low-level children, simple dance games can be designed, such as "Dance Movement Imitation Show", where basic dance movements are choreographed into different shapes and content, and children complete the movements one by one. This not only exercises children's basic movement abilities, but also enhances the fun of the game. Middle level children can participate in more challenging dance games, such as "dance puzzles", which break down dance movements into several movement shapes. By completing the movement shape puzzle, children can learn the sequence of dance movements, improve their dance memory and sense of rhythm. High level young children can engage in dance creative games, such as "improvisational dance creation". Given a theme or music, young children can engage in improvisational dance creation within a specified time frame, unleashing their creativity and imagination.

The situational teaching method creates vivid dance scenarios to allow children to experience the charm of dance and improve their dance performance. For low-level children, fairy tale scenarios can be created, such as "Little Red Riding Hood's Dance Journey", where children play Little Red Riding Hood and imitate her movements and plot in the dance, enhancing the fun and situational sense of the dance. Middle level children can participate in dance teaching in historical and cultural contexts, such as the "Ancient Palace Dance Experience", allowing them to understand the characteristics and cultural background of ancient palace dance, learn and perform palace dance in the context, and improve their dance cultural literacy. High level young children can engage in dance creation in real-life situations, such as "campus life dance", allowing them to observe scenes and characters in campus life, transform them into dance movements and plots, create and perform dance works, and cultivate their observation ability and artistic expression.

Heuristic teaching method focuses on guiding young children to think and explore independently, cultivating their innovative thinking and problem-solving abilities. In dance teaching, teachers can inspire children to think about changes and innovations in dance movements through questioning, guidance, and other methods. For low-level children, teachers can ask 'If you were a little bird, how

would you fly?' to guide children to use their imagination and create their own dance movements. Middle level children, teachers can ask more challenging questions, such as "How to connect these two dance movements more smoothly?" to encourage children to think and try different ways of connection, improving their dance skills. For high-level young children, teachers can guide them to conduct in-depth analysis and reflection on dance works, such as "What emotions does this dance work express? How can you better express this emotion through dance movements?" to stimulate their innovative thinking and artistic expression.

Personalized guidance is an important teaching strategy to meet the individual differences of young children. Teachers should pay attention to the learning situation and developmental needs of each child, and provide personalized guidance based on the characteristics of children at different levels. For low-level children, teachers should provide more patience and encouragement, pay attention to their mastery of basic movements, and correct erroneous movements in a timely manner. For middle level children, teachers can provide more specific guidance in dance skills and expression, helping them break through bottlenecks and improve their dance level. For high-level young children, teachers should focus on inspiring their creativity and artistic cultivation, providing professional advice and guidance, and promoting the improvement of their dance creation and performance abilities.

Group cooperative learning is also an effective teaching strategy. Through group cooperation, young children can learn and communicate with each other, cultivate teamwork spirit and social skills. In dance teaching, children can be divided into groups to rehearse and perform dance works together. Low level preschool groups can practice simple dance combinations, learn from each other, and correct movements. Middle level preschool groups can collaborate to choreograph a small dance piece, divide tasks and work together to complete the planning, rehearsal, and performance of the dance. High level preschool groups can engage in more complex dance creation and performance. Through group discussions and cooperation, each child's strengths can be leveraged to create better dance works.

3.Practical problems and improvement measures of the path

In the practical process, when encountering problems, it is necessary to solve them in a timely manner to further improve the hierarchical cultivation model. The adaptation problem of teachers to hierarchical teaching is particularly prominent. Some teachers are accustomed to the traditional "one size fits all" teaching model, and when implementing hierarchical teaching, it is difficult to provide personalized teaching based on the characteristics and needs of children at different levels. There are certain deviations in the selection of teaching content and the application of teaching methods, resulting in unsatisfactory teaching outcomes. To solve this problem, it is necessary to strengthen the training and guidance of teachers, regularly organize teachers to participate in training courses and seminars on hierarchical teaching, and invite experts to give lectures and guidance. Establish a teacher communication platform to allow teachers to share their experiences and insights on layered teaching, and jointly explore problems and solutions encountered in teaching. Encourage teachers to continuously learn and explore, flexibly apply teaching methods based on the actual situation of young children, and improve the quality of hierarchical teaching.

The understanding and support of parents are also issues that need to be addressed in the practical process. Some parents lack understanding of the concept and methods of hierarchical education, and are concerned that hierarchical teaching may bring psychological pressure to children and affect their learning enthusiasm. Some parents pay too much attention to their children's academic performance and competition awards, and do not attach enough importance to their children's physical ability development and interest cultivation. To address these issues, it is necessary to strengthen communication and exchange with parents. Through parent meetings, parent lectures, parent WeChat groups, and other means, we can introduce the design concept, teaching objectives, and implementation methods of the hierarchical training path to parents, so that they understand the importance of hierarchical teaching for the development of their children's physical abilities. Regularly provide feedback to parents on their children's performance and progress in dance activities, allowing them to see their children's growth and changes, and enhancing their confidence and support for tiered teaching. Guide parents to

establish correct educational concepts, pay attention to their children's comprehensive development, encourage their children to actively participate in dance activities, and cultivate their interests and talents.

In addition, it was found in the practical process that there are some unreasonable aspects in the allocation and utilization of teaching resources. There are certain differences in teaching resources for different levels of classes, such as dance textbooks, teaching equipment, and teaching staff, which affect the fairness and quality of teaching. To solve this problem, it is necessary to optimize the allocation of teaching resources and allocate dance textbooks, teaching equipment, and other resources reasonably according to the teaching needs of different levels of classes. Strengthen the construction of the teaching staff, improve the professional competence and teaching ability of teachers, and ensure that every class can receive high-quality teaching services. Establish a teaching resource sharing platform to enable teachers to share teaching resources and improve the efficiency of their utilization.

4.Conclusion and Prospect

4.1.Research Summary

In terms of theoretical research, a comprehensive review and analysis were conducted on the application of sustainable development concepts in early childhood education, theories related to children's physical literacy, and the current research status of early childhood dance education. The connotation and requirements of sustainable development concept in early childhood dance education have been clarified, which focuses on the comprehensive and long-term development of children's physical literacy, respects individual differences of children, and promotes harmonious coexistence between children and the environment. In depth analysis of the constituent elements and developmental characteristics of young children's physical abilities provides a solid theoretical foundation for the design of hierarchical training paths. Through the analysis of the current research status of early childhood dance education at home and abroad, the shortcomings in the cultivation of physical literacy in current research have been pointed out, providing direction for future research.

In terms of model design and practice, based on the concept of sustainable development, following the principles of development, differentiation, fun, and comprehensiveness, a hierarchical training path for physical literacy in dance activities for 3-6 year old children has been constructed. Based on factors such as the age, physical literacy development level, and interests of young children, they are divided into three levels: low-level, intermediate level, and high-level. Clear training objectives and content frameworks have been developed for each level. Adopting diverse teaching methods and strategies such as game based teaching, situational teaching, heuristic teaching, personalized guidance, and group cooperative learning to meet the learning needs of children at different levels.

The research results have important application value in early childhood dance education. The hierarchical cultivation path provides a scientific and systematic teaching path for early childhood dance education, which can help teachers better teach according to the actual situation of young children and improve teaching effectiveness. Diversified teaching methods and strategies can stimulate children's interest and initiative in learning, allowing them to learn dance and improve their physical abilities in a happy environment. Through this study, teachers' understanding and application ability of sustainable development concepts and hierarchical teaching have been improved, promoting their professional growth.

4.2.Research Shortcomings and Prospects

Although this study has achieved certain results, there are also some shortcomings. In terms of research samples, this study has a relatively small sample size and a limited sample range. This may result in the research findings not being representative enough to fully generalize to all 3-6 year old children. In terms of the universality of the path, although the hierarchical training path has achieved good results in practice, there are differences in the educational environment and resources of different regions and kindergartens, and the model may need to be appropriately adjusted and optimized for application in other kindergartens.

Future research can be conducted in the following directions. One is to further expand the research sample and select 3-6 year old children from different regions and types of kindergartens for research, in order to improve the representativeness and reliability of the research results. Through multi center and large sample research, we aim to

gain a deeper understanding of the developmental characteristics and needs of children's physical literacy under different backgrounds, providing richer data support for the improvement of hierarchical training paths. The second is to conduct long-term follow-up research and observe the children who participate in the practice to understand the long-term impact of hierarchical training paths on the development of children's physical literacy. Pay attention to the changes in physical abilities of young children at different age groups, as well as the sustained role of dance education in their future learning and life, providing a basis for long-term planning of dance education for young children. The third is to strengthen the optimization and promotion research of the path, and according to the actual situation of different kindergartens, make personalized adjustments and optimizations to the hierarchical training path, improve the universality and operability of the path. By organizing training, seminars and other activities, we will promote the hierarchical training path to more kindergartens and teachers, and promote the overall development of early childhood dance education. Further exploration can be conducted on the integration of early childhood dance education with other fields, such as drama, music, language, and other subjects, to expand children's learning areas and promote their comprehensive development.

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Study on the Influencing Factors of Carbon Emissions in China's Air Cargo Transportation Industry

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KEYWORDS

Air cargo;

Carbon emissions;

Influencing factors;

SPSS model

ABSTRACT

This paper focuses on the identification of key drivers of carbon emissions in China's air cargo industry and the construction of a prediction model, with the aim of providing a precise decision-making basis for the green transformation of the civil aviation industry under the "dual-carbon" goal. The study selects the data from 2006-2019 and 2023-2024 (avoiding the abnormal disturbance of COVID-19 epidemic), and analyzes the macroeconomic variables such as GDP index, investment in fixed assets of the whole society, the level of consumption of the residents, total retail sales of consumer goods, and the total amount of imports and exports by multiple stepwise linear regression analysis using SPSS statistical software. The empirical results show that the investment in fixed assets is the core variable that explains the variation of air cargo and mail transportation, and reveals the transmission mechanism of economic expansion on air logistics demand and carbon emission through the path of investment in fixed assets, which confirms that the path of carbon peaking of air cargo transportation is deeply coupled with macroeconomic policies. The study further points out that under the constraint of the 2030 peak carbon target, it is necessary to optimize the structure of fixed asset investment as a key hand to reduce emissions, guide capital to tilt towards low-carbon technology areas such as sustainable aviation fuels and electrified equipment, and establish a linkage threshold mechanism between the investment growth rate and the decline of the industry's carbon intensity. This study provides a quantitative analysis framework for the formulation of precise emission reduction policies for the air cargo industry, but in the future, further integration of energy consumption data is needed to construct a direct carbon emission prediction model, and scenario analysis is introduced to assess the policy effects of different carbon neutralization paths.

INTRODUCTION

Global climate change is one of the major challenges facing humankind today, and reducing greenhouse gas emissions has become a consensus of the international community. With the signing of the Paris Agreement, a number of countries have committed themselves to keeping global average temperatures below a 2° C rise from pre-industrial levels and to working to limit warming to 1.5° C. To achieve this goal, countries have set up timetables and implementation strategies for carbon peaking and carbon neutrality. China, as the world's largest carbon emitter, has proposed the goal of achieving carbon peaking by 2030 and carbon neutrality by 2060 , which points out the direction for the development of various industries. As an energy-consumption-intensive industry, the aviation transportation industry is an important source of carbon emissions in the transportation sector. According to ICAO's Global Aviation Environment Report 2024, CO_2 emissions from the aviation industry will account for 2.5% of the global total in 2023, and will rise to 3.5% in 2050, which makes the pressure to reduce emissions urgent. China's "14th Five-Year Plan" explicitly calls for the construction of a green and low-carbon industrial system and the

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promotion of green transformation of the civil aviation industry.

However, the carbon peak path of the air cargo industry is affected by a variety of factors. Most of the existing air cargo carbon emission studies have stopped at qualitative discussions or simple correlation analyses in terms of carbon emission measurement[1-7], identification of carbon emission influencing factors [8-12], and emission reduction strategies [13-17], and lack of rigorous measurements of the net effect of multifactor covariance interference. Therefore, this study aims to conduct standardized statistical and modeling analysis based on the SPSS model, aiming at identifying the key factors affecting China's air cargo carbon emissions and establishing a prediction model based on them, so as to provide a strong basis for promoting the development of China's civil aviation industry.

1.Research Methodology and Data Processing

1.1.Variable Selection and Data Sources

In this paper, the main factors affecting the development of China's aviation logistics are selected: GDP index, investment in the whole society's fixed assets, the level of residents' consumption, the total retail sales of consumer goods, and the total amount of imports and exports. Among them, the data of GDP index, total retail sales of social consumer goods, residents' consumption level and total fixed assets are from the National Bureau of Statistics, and other data are from the Ministry of Transportation and Communications.

Since the air transportation industry is seriously affected by COVID-19 during the period of 2020-2022. In view of this, the cargo and mail transportation volume and its influencing factors in 2006-2019 and 2023-2024 are selected in the study of this paper, which can more accurately reflect the typical characteristics and long-term development trend of China's air transportation industry, and also effectively avoid the anomalous perturbation caused by COVID19.

1.2.SPSS Analysis Methods

SPSS (Statistical Package for the Social Sciences) is the most widely used statistical analysis software for time series analysis, regression analysis, categorical forecasting etc. The choice of the method was based on the need for robustness in variable screening. In the initial construction of the regression model, the direct use of Ordinary Least Squares (OLS) is likely to lead to distorted parameter estimates. Stepwise regression automatically eliminates redundant variables that do not contribute sufficiently to the margin of the dependent variable or are highly overlapping with other independent variables through the “forward-backward” iteration mechanism, ensuring that only independent and statistically significant core factors are retained in the final model. The second is based on the theoretical fit of the linear relationship. The transmission mechanism from infrastructure investment to air cargo demand is approximately linear in the short run - for every unit increase in fixed asset investment, the demand for transportation of raw materials, components and finished products increases in a stable proportion through the ripple effect of the industrial chain. SPSS scatterplot matrix and curve estimation (Curve) module preliminarily verified that the air cargo and mail transportation volume and the whole society's fixed asset investment satisfy the Pearson linear assumption.

2.Empirical Results and Analysis

2.1.Correlation analysis and initial screening of variables

The study firstly measures the correlation strength between air cargo and mail transportation volume and macroeconomic factors through SPSS correlation analysis module, and the results show that the Pearson correlation coefficients of investment in fixed assets, total retail sales of consumer goods, and air cargo and mail transportation volume have exceeded the threshold value of 0.90, which is highly significant and positively correlated, and the correlation coefficients of the GDP index and the total amount of imports and exports have reached more than 0.85, and the correlation coefficient of the level of consumption of residents is slightly lower(r=0.76). The correlation coefficient of GDP index and total imports and exports also reaches above 0.85, and only the correlation coefficient of consumer level is slightly lower(r=0.76), which confirms the strong coupling between the demand for air cargo transportation and the macroeconomic prosperity, and provides the basis for variable screening in the subsequent regression modeling.

	Freight and mail transportation volume	
	Person	Sig(2-tailed)
GDP index	.960**	<.001
Total retail sales of consumer goods	.964**	<.001
Total imports and exports	.914**	<.001
Consumption level of the population	.946**	<.001
Social fixed asset investment	.968**	<.001

Table.1.Correlation coefficients between cargo and mail transportation volumes and other influencing factors

2.2.Multiple Stepwise Regression Modeling and Variable Optimization

With air cargo and mail transportation volume as the dependent variable and five types of economic indicators as the independent variables, the prediction model is constructed by stepwise regression method, and SPSS performs a total of three rounds of iterative screening: the first round of the system prioritizes the inclusion of the whole society's investment in fixed assets, and the model adjusts the R-square that reaches 0.932, and the F-test statistic is 342.67 with the significance level less than 0.001, which indicates that the single variable can independently explain 93.2% of the variance of the dependent variable, and the model as a whole is highly significant; in the second round of attempting to introduce the GDP index, the tolerance drops to 0.08 and the variance inflation factor VIF=12.5, triggering the multiple covariance elimination mechanism, so the variable is automatically removed; in the third round of the retail sales of consumer goods, due to the level of significance of p=0.062 (>0.05) does not satisfy the criteria for entering the model. terminated the screening, and the final model was determined to be univariate structure.

Model	R	R^2	Adjusted R^2	D-W
1	.968[a]	.937	.932	1.933

Table.2.Summary of air cargo and mail traffic model

2.3.Model Diagnostics and Statistical Tests

To ensure the robustness of the model, three classical econometric tests were performed on the final model: the heteroskedasticity test was performed using the Breusch-Pagan method, and the results did not show significant heteroskedasticity; the diagnostic of multiple covariance was performed by retaining only univariate variables, with the VIF value of 1.0 to thoroughly circumvent covariate interference; and the autocorrelation test with the Durbin-Watson statistic of 1.847, which indicating no serial correlation of residuals, and all tests were done in the SPSS diagnostic module.

3.Establishment of forecasting models

Through SPSS stepwise regression iterative screening and three econometric tests, the final air cargo and mail transportation volume forecasting model is established with social fixed asset investment as the only core independent variable, in which the significance level is less than 0.001, the tolerance and variance inflation factor VIF are both 1.000, which completely avoids the interference of multiple covariance, and the standardized coefficient Beta=0.968 shows that the driving strength is close to complete positive correlation. Its standardized coefficient Beta=0.968 indicates that the driving strength is close to full positive correlation, and the adjusted R-squared value shows that the model can independently explain more than 93% of the variance of the dependent variable, and the model as a whole passes the F-test and the Durbin-Watson statistic falls in the no-autocorrelation interval, which is of robust predictive validity. The construction process of other derivative models is exactly the same as this one, including the linear time model of average air cargo and mail transportation distance and the linear time model of the whole society's fixed asset investment, which adopts the same step-by-step regression strategy, test criteria and diagnostic process. The final model of air cargo and mail transportation volume is:

Predictive modeling of individual influencing factors	
Air cargo and mail traffic	Y=273.790200+0.001082a
GDP index	$Y= -132549.209 + 1.658\times10^{-5}$ （c）^{3}
Average air cargo and mail distance	Y=2329.302402+0.314544d
Social fixed asset investment	Y=-49221274.063115+24589.458803c

Table.3.Predictive model for each influencing factor

a: Social fixed asset investment

c: Year

d:GDP index

The results indicate:

1. **Significant macroeconomic correlation characteristics:** The strong correlation ($r>0.9$) between air cargo and mail transportation volume and the whole society fixed asset investment, total retail sales of consumer goods and other indicators shows that the carbon emissions of the air cargo industry are highly tied to the activity of the national economy, and the growth of fixed asset investment in the period of economic expansion directly pulls the demand for air logistics, which in turn exacerbates the pressure on carbon emissions.
2. **Fixed Asset Investment as the Core Explanatory Variable:** The regression model screening results show that only the whole society fixed asset investment enters the final equation, and its regression coefficient is 0.001082 ($p<0.001$), indicating that for every 100 million yuan increase in fixed asset investment, the volume of air cargo and mail transportation grows by an average of about 10.82 tons, which verifies its significant influence as a key driving factor.
3. **Reliable model prediction efficacy:** The adjusted R^2 =0.932 indicates that the model can explain 93.2% of the variation in air cargo volume, which has strong prediction ability. However, it should be pointed out that the model does not directly incorporate environmental variables such as carbon emission intensity and fuel efficiency, and the actual carbon emission prediction needs to be combined with the data on energy consumption per unit of transportation volume for the secondary conversion.
4. **Structural Impact of Epidemic Shock:** By excluding the 2020-2022 data, the study finds that the continuity of data between the pre-epidemic pattern and the post-epidemic era (2023-2024) is basically valid, but the recovery of air cargo after 2023 may be accompanied by changes in carbon emission intensity, which needs to be continuously monitored.

Conclusion

In this study, SPSS modeling verifies the decisive impact of social fixed asset investment on China's air cargo and mail traffic, a finding that provides a quantitative basis for analyzing the peak carbon path of the air cargo industry. This finding provides a quantitative basis for analyzing the carbon peak path of the air cargo industry, which should be the focus of policymakers under the constraints of the "dual-carbon" goal:

1. Optimize the investment structure and direct fixed asset investment towards low-carbon aviation technologies to reduce carbon emission intensity at source.
2. Establishing a dynamic monitoring mechanism, linking and analyzing the growth rate of fixed-asset investment with the carbon emission factor of air cargo, and setting a threshold for the decline of carbon intensity in the industry.
3. Improve cross-sectoral synergies, given the deep coupling of air cargo transportation with the national economy, and the need to incorporate civil aviation emission reduction targets into the macroeconomic regulatory policy system.
4. Strengthen the data infrastructure, supplement the complete annual data after the epidemic as soon as possible, and incorporate carbon emission direct accounting variables to enhance the model's ability to support environmental decision-making.

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Internal Audit Independence in the Context of Big Data A Study on the Impact of Dynamic Competitiveness on State-Owned Enterprises

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KEYWORDS

Internal Audit Independence

ABSTRACT

This study employs panel data of A-share listed companies on the Shanghai and Shenzhen Stock Exchanges from 2018 to 2022 as the baseline sample to empirically examine the impact of internal audit independence on corporate competitiveness in the current year (2018–2022), one-year lag (2019–2023), and two-year lag (2020–2024). Furthermore, it investigates whether this impact exhibits significant heterogeneity across firms with different ownership structures. The results indicate that internal audit independence exerts a significantly positive effect on corporate competitiveness in the current year: specifically, a one-unit increase in internal audit independence is associated with an approximate 8.869-unit rise in competitiveness. This positive impact persists in the one-year lag period but weakens substantially (as reflected by reduced coefficient magnitude and statistical significance). By the third year, however, the effect of internal audit independence on corporate competitiveness becomes statistically insignificant. Further analysis reveals significant ownership-based heterogeneity in the aforementioned relationship: the enhancement of internal audit independence only significantly boosts the current competitiveness of state-owned enterprises (SOEs), while exerting no notable influence on that of non-SOEs. This suggests that strengthening the independent status of internal audit in SOEs constitutes an effective governance mechanism to improve their short-term competitive capacity and responsiveness. Additionally, the moderating role test of data element utilization efficiency shows that this efficiency significantly amplifies the positive impact of internal audit independence on the one-year lagged competitiveness of SOEs. In other words, a higher level of data element utilization efficiency enables internal audit independence to promote corporate competitiveness more effectively in the second year. Nevertheless, this moderating effect becomes ineffective for SOEs in the third year, implying that SOEs can gain substantial short-term audit synergy benefits from improved data element utilization efficiency, but the sustainability of such effects is limited.

INTRODUCTION

(1) Research Background

As a critical management activity, internal audit serves as a robust pillar for improving the supervision system of state-owned assets and an organizational guarantee for state-owned enterprises (SOEs) to achieve benchmarking management against world-class enterprises and fulfill high-quality development goals. In October 2013, at the Executive Meeting of the State Council, Premier Li Keqiang put forward the important requirement of implementing full-coverage auditing. In December 2013, Liu Jiayi, then Auditor-General, emphasized at the National Audit Work Conference that to meet the overall objectives and requirements of audit work, efforts should be made to realize full-coverage of audit supervision, continuously enhance the deterrence and effectiveness of auditing, and ensure in accordance with the law that all public funds, state-owned assets, and state-owned

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resources are within the scope of audit supervision without leaving any supervision blind spots or gaps.

In 2014, the Fourth Plenary Session of the 18th Central Committee of the Communist Party of China further incorporated the economic responsibility audit of leading cadres into the scope, explicitly proposing to improve the audit system and implement full-coverage auditing for four key areas: public funds, state-owned assets, state-owned resources, and the performance of economic responsibilities by leading cadres. On December 8, 2015, the General Office of the State Council issued the Implementation Opinions on Carrying out Full-Coverage Auditing, which put forward specific requirements and implementation suggestions for the practice of full-coverage auditing.

Since the concept of full-coverage auditing was proposed and put into practice, it has become a core strategic requirement for China's audit work, while the economic responsibility audit targeting leading cadres has emerged as a new focus of this full-coverage initiative. In 2017, the General Office of the Communist Party of China Central Committee and the General Office of the State Council issued the Several Opinions on Deepening the Audit Supervision of State-owned Enterprises and State-owned Capital, explicitly proposing the establishment of a regular audit system for enterprise state-owned capital and the implementation of full-coverage audit supervision over state-owned assets.

In May 2018, General Secretary Xi Jinping delivered an important speech at the First Meeting of the Central Audit Commission, putting forward the requirement to "strengthen the coordination of national audit work, optimize the allocation of audit resources, ensure that all entities subject to audit are audited, all audits are conducted strictly, and accountability is enforced rigorously, striving to build a centralized, unified, fully covered, authoritative, and efficient audit supervision system." In 2020, the State-owned Assets Supervision and Administration Commission of the State Council (SASAC) issued the Notice on Carrying Out the Action to Improve Management by Benchmarking World-Class Standards and the Implementation Opinions on Deepening the Internal Audit Supervision of Central Enterprises, emphasizing that central enterprises should establish a centralized, unified, fully covered, authoritative, and efficient audit supervision system adapting to the new era, new situation, and new requirements, and build a long-term closed-loop mechanism for risk prevention and control. Table 1 lists the major documents issued by state authorities regarding the governance reform of state-owned enterprises, the development of internal audit, and the utilization of data elements since the deepening of state-owned enterprise reform in 2015.

Strengthening internal audit is not only an inevitable requirement for advancing the modernization of the national governance system and governance capacity, but also an objective necessity for propelling high-quality economic development. Existing literature has demonstrated that internal audit can enhance the quality of financial reports (Abbott et al., 2016; Tao, 2016; Lü & Wang, 2021; Christensen, 2022; Wang & Chen, 2024), identify audit risks (Zhang et al., 2024; Huang, 2024), reduce improper managerial behaviors (Ege, 2015), lower audit fees and improve audit efficiency by assisting external auditors in annual report audits (Abbott et al., 2012; Pizini et al., 2015; Li, 2025), mitigate internal control deficiencies (Lin et al., 2011; Guo, 2017; Wu et al., 2021), reduce risks and enhance organizational value (Carcello et al., 2020), drive value creation (Emett et al., 2024; Xiang & Zhou, 2025; Zhang et al., 2025; Xie et al., 2025), improve economic performance (Jiang et al., 2020; He et al., 2025), and facilitate the development of new-quality productive forces (He, 2025).

As a production factor, data has restructured the business models, management paradigms, and organizational governance structures of modern enterprises. Due to the "disintermediation" effect triggered by digitalization, networking, and intelligentization in the economic field, enterprises face increased environmental uncertainty, complexity, and risks, with their competitive and profit margins correspondingly compressed (Chen et al., 2020; Jia et al., 2020). Traditional production organizations, transaction models, and corporate governance structures—such as internal audit—must undergo adaptive adjustments to respond to these new changes (Luo et al., 2017). Morakanyane et al. (2017) reviewed existing literature and summarized the research progress on the digital transformation of business organizations from dimensions including definitions, characteristics, driving factors, key areas, and economic impacts. They emphasized that corporate digital transformation should be regarded as a dynamic and continuous evolutionary process, which requires integrating digital resources of enterprises and reshaping the corporate ecosystem in terms of business models, operational processes, and organizational structures. Therefore, breaking organizational inertia, integrating digital technologies, and

restructuring organizational structures have become strategic choices for enterprises to achieve successful digital transformation (Matt et al., 2015; Hess et al., 2016; Vial, 2019). As the "third line of defense" for corporate organizations, the internal audit management system faces the demand for digital organizational restructuring. However, there remain numerous gaps to be filled in the digital transformation of internal audit (Qin, 2014, 2018; Liu et al., 2019; Li & He, 2019; Wang, 2020; Zhang et al., 2020). Big data auditing focuses more on the reapplication of audit techniques and operational models, while the digital transformation of internal audit is not only the implementation of information technologies such as online auditing, big data analytics, blockchain-based independent auditing, and AI-assisted auditing, but also a top-down systematic project with a broader scope. It involves comprehensive digital structural reforms, including the positioning of internal audit objectives, management systems and monitoring methods, the construction of information platforms, evidence-gathering models and technical methods, the application of audit results, the allocation of interdisciplinary talents, and institutional guarantees. Based on this, this study will, against the backdrop of II. Research Significance

(2.1) Theoretical Significance

Against the backdrop of big data, this study explores the impact of internal audit independence on SOEs' dynamic competitiveness, enriching the theoretical system of corporate governance and auditing. Traditional audit independence focuses on organizational and personnel dimensions, while this study extends it to data independence (e.g., objectivity of data acquisition, neutrality of algorithms) and combines it with technological empowerment (blockchain-based evidence preservation, automated analysis), providing a new perspective for audit theory (Zhang et al., 2024). Meanwhile, internal audit has shifted from "post-event supervision" to "in-process early warning" and "pre-event prevention" (Yang, 2025), and independent audit institutions can actively participate in strategic decisions, promoting the transformation of audit functions from compliance supervision to value creation (Zhi et al., 2021).

This study constructs a theoretical framework of dynamic competitiveness, revealing the transmission mechanism between auditing and competitiveness. Independent internal audit can monitor operational risks in real time through big data, improve risk response speed, and enhance dynamic competitiveness (Duan, 2023). Additionally, it promotes interdisciplinary integration: at the intersection of auditing and information economics, big data reduces information asymmetry, and data authenticity relies on independence, expanding the application scenario of "signaling theory" (Yang, 2025); at the intersection of organizational studies and strategic management, independent audit breaks departmental barriers, enhances organizational agility, and supports dynamic competitiveness (Zhang et al., 2024).

(2.2) Practical Significance

First, it optimizes SOEs' governance structure, strengthens audit authority, advances the reform of separating management from auditing, and improves audit credibility. Second, it enhances risk prevention and control capabilities and decision-making effectiveness. Independent audit institutions integrate multi-source data, identify anomalies such as fund misappropriation through big data models, and realize the transformation from "post-event rectification" to "pre-event prevention" (Zou, 2022). Third, it promotes SOEs' sustainable development. Through full-process supervision (e.g., asset handover, merger and acquisition restructuring), independent internal audit reduces corruption and inefficient investment (Zhang et al., 2017), preventing the loss of state-owned assets. In complex market environments, it evaluates the risks and returns of innovative projects, ensuring enterprises' compliance and dynamic competitiveness.

1. Literature Review at Home and Abroad

1.1.Research on Internal Audit

1.1.1. Evolution of Internal Audit

Research on internal audit has evolved from traditional financial supervision to modern governance empowerment. Early studies focused on internal control and compliance: Mautz and Sharaf (1961) emphasized the reliability of financial information, and Chambers (1995) positioned internal audit as a "management tool." With the rise of corporate governance theory, Cohen et al. (2004) confirmed that internal audit enhances organizational value through risk identification; Sarens and Abdolmohammadi (2011) found that audit committee independence affects internal audit effectiveness. In the technology-driven era, Vasarhelyi et al. (2020) proposed a continuous auditing framework, and AI and blockchain enabled real-time risk monitoring (Brown-Liburd et al., 2021). In China, the "triple-audit synergy

mechanism" (Liu, 2021) and the Provisions on Internal Audit Work (2018) have strengthened supervisory synergy (Wang, 2022). Current research focuses on technological empowerment (Zhang, 2023), governance synergy (Li, 2023), and emerging fields (Kolk & Perego, 2014).

1.1.2.Supervisory Functions of Internal Audit

Research on internal audit's supervisory functions focuses on effectiveness and influencing factors. Influencing factors include functional positioning (Mei, 2018), leadership style (Dal Mas & Barac, 2018), and personnel allocation (Wang et al., 2014). Internal audit departments subordinate to audit committees and concurrent leadership of audit heads can improve independence (Wang, 2018). In terms of effectiveness, collaboration between internal and external auditors reduces audit costs (Wang & Yang, 2009; Al-Dhamari, 2018), and internal audit improves financial report quality (Prawitt et al., 2009; Gros et al., 2017). Mei (2018) pointed out that internal auditors' communication skills moderate the relationship between independence and supervision quality.

1.1.3.Economic Consequences of Internal Audit

Internal audit's economic consequences mainly involve corporate value and governance effects. It achieves value addition through reasonable assurance and consulting services (Zhao, 2008), and positive interaction with other governance mechanisms enhances this effect (Chen et al., 2016). In terms of governance, it supports internal control (Vijayakumar & Nagaraja, 2012), improves financial report quality (Wang et al., 2010), and inhibits irregularities (Chen et al., 2016). However, existing research has limitations: poor adaptability of Western theories to China's context (Yang, 2022), over-reliance on questionnaire surveys (Sarens, 2021), and lag in emerging field standards (Mock et al., 2023). Future research should construct a "national governance—organizational governance—technological governance" framework (Liu, 2024) and innovate evaluation indicators (Cao et al., 2023).

1.2. Literature Review on Corporate Competitiveness

1.2.1. Evolution of Corporate Competitiveness Research

Corporate competitiveness research has evolved from single financial performance to a comprehensive framework including knowledge accumulation, dynamic capabilities, and niche breadth. Xu (2020) proposed a three-tier knowledge structure model; Li (2024) found that digital transformation enhances competitiveness through improving production efficiency. In evaluation methods, Qian (2022) used text mining to construct a competitiveness identification model; Zhang (2019) combined grey relational analysis and dynamic efficacy coefficient method to develop a shipbuilding enterprise competitiveness index. This evolution continues Barney's (1991) Resource-Based View and integrates Teece's (1997) Dynamic Capability Theory in China.

1.2.2. Influencing Factors of Competitiveness

Policy and institutional factors: Yang and Gong (2025) verified that the "leader recruitment system" improves corporate innovation and competitiveness; Lu (2025) found that fintech pilot policies promote digital transformation and competitiveness. Digital economy and technological innovation: Sun et al. (2025) confirmed that data element marketization enhances core competitiveness; Cao et al. (2025) pointed out that digital technology innovation reduces supply chain concentration and increases product differentiation. AI and big data: Chen and Liao (2025) found that AI promotes profitability and operational capabilities; Zheng et al. (2025) revealed an inverted U-shaped relationship between big data applications and manufacturing competitiveness. Industrial and enterprise characteristics: Ma (2025) found that basic research investment promotes high-tech industry competitiveness; Zhang et al. (2025) verified a U-shaped correlation between carbon information disclosure and green competitiveness. Corporate governance and social responsibility: Shi et al. (2025) found that ESG performance promotes competitiveness through charitable donations and TFP; Yu (2025) pointed out that CSR reduces customer concentration.

2. Path Mechanisms of Corporate Competitiveness

Three core driving mechanisms are identified: Technological dimension—AI enhances competitiveness by improving TFP (Du et al., 2024), but there is an inverted U-shaped relationship due to "financial distress" risk (Pan, 2023); Institutional dimension—digital finance alleviates financing constraints (Zhang, 2023), while resource allocation distortion inhibits competitiveness (Jiang, 2025); ESG dimension—green innovation promotes competitiveness (Wang, 2023), but social responsibility investment has a "resource crowding-out effect" (Yang, 2022), and industry technological intensity plays a moderating role (Li, 2025).

These findings deepen the understanding of the "technology-institution-environment" interaction in Porter's (1990) Diamond Model.

3. Measurement of Corporate Competitiveness

Scholars have proposed various evaluation methods. Tang & Liu (2010) used financial indicators; Gao et al. (2023) constructed a comprehensive index from seven dimensions; Zeng (2023) included scale, growth, profitability, and innovation capacity. Literature on agricultural listed companies' competitiveness evaluation is scarce, and variable selection varies. This study measures micro-level dynamic competitiveness using financial indicators.

III. Theoretical Analysis and Research Hypotheses

1. Internal Audit Improves Financial Quality

Internal audit oversees financial reports and monitors operational management, identifying aggressive accounting practices, reducing managerial interference, and safeguarding financial report quality (Wang et al., 2010; Kaawaase et al., 2021), contributing to SOEs' high-quality development.

2.nternal Audit Alleviates Principal-Agent Problems

As a professional and independent internal supervision department, internal audit supervises agents on behalf of principals, curtails managers' myopic behaviors, prevents shareholder expropriation, improves governance efficiency and quality, and supports SOEs' long-term development.

3. Internal Audit Improves Internal Controls

First, it fosters a corporate culture of excellence, providing institutional guarantees for competitive advantage. Second, it ensures timely and accurate communication of internal control information, improving operational efficiency (Yan & Xu, 2023). Third, it optimizes the balance between centralization and decentralization, cultivating a results-oriented attitude. Fourth, it supervises and evaluates internal controls, identifying deficiencies and proposing optimization solutions.

Research Hypothesis (H): Internal auditing positively promotes enterprises' dynamic competitiveness, and this promotional effect is more pronounced in state-owned enterprises.

IV. Research Design

(1) Data Source and Sample Selection

The initial sample includes A-share listed companies on the Shanghai and Shenzhen Stock Exchanges from 2018 to 2024. Samples are screened as follows: excluding those with asset-liability ratio outside 0-1, ST/*ST/PT companies, and those with missing data. Finally, 20,117 observation samples are obtained, with all variables winsorized at the 1% level. Data are sourced from the CSMAR Database, processed using Stata 18.0. Base period data (2018-2022) are used to calculate competitiveness in Ti+1 and Ti+2.

Control variables: (1) Actual controller type (1=SOE, 0=non-SOE); (2) Controlling shareholder ownership ratio; (3) Managerial ownership; (4) Board size; (5) Supervisor board size; (6) Independent director ratio; (7) Independent director network centrality.

(2) Variable Selection

1.Enterprise Dynamic Competitiveness: Referring to Jin & Zhang's method, factor analysis is used to evaluate static competitiveness in the current and lagged two years, and a dynamic evaluation model is constructed.

1.Explanatory Variable — Internal Audit Independence (Indep_Audit): Referring to Specific Standards for Internal Auditing No. 22 and existing literature, it is measured by organizational structure: 1 if the number of audit committee members ⩾ industry average, otherwise 0.

1.Moderating Variable—Data Element Utilization Efficiency: A lexicon is constructed from policy documents and literature, Word2Vec is used to expand it, and machine learning extracts word frequencies from annual reports. The natural logarithm of total word frequency (after adding 1) is used as the indicator.

1.Control Variables: Firm size (natural logarithm of employees), ownership type, controlling shareholder ownership ratio, managerial ownership, board size, supervisory board size.

Independent Director Ratio: The ratio of independent directors to the total number of directors, which reflects the degree of board independence and is positively correlated with the effectiveness of the board's oversight and advisory functions.

Independent Director Network Centrality: A comprehensive indicator measuring the importance of independent directors' positions within the overall director network. A higher network centrality indicates that the company possesses greater discourse power and stronger resource integration capabilities in the independent director network.

Detailed variable descriptions are provided in Table 2.

Currently, there is no consensus in the academic community on how to measure static corporate competitiveness. Using a single indicator is highly one-sided, while adopting a multi-

indicator evaluation also presents numerous challenges. Through in-depth analysis and drawing on the evaluation and analysis methods for corporate competitiveness developed by the Service Industry Survey Center of the National Bureau of Statistics of China, this study selects the following indicators:
Profitability indicators: Return on Assets (ROA), Return on Equity (ROE), Return on Invested Capital (ROIC);
Solvency indicators: Leverage Ratio (LEV, i.e., asset-liability ratio), Current Ratio (CR), Quick Ratio (QR), Cash Asset Ratio (CAR);
Operational efficiency indicators: Current Asset Turnover (CAT), Total Fixed Asset Turnover (TRFA);
Growth capacity indicators: Sustainable Growth Rate (SGR).
A comprehensive evaluation index system for dynamic corporate competitiveness is constructed, consisting of 4 first-level indicators and 10 second-level indicators.

In conducting the comprehensive evaluation of corporate competitiveness, the primary step is to normalize moderate indicators to ensure they are positively oriented (i.e., direction alignment). Failure to implement such positive orientation will affect the analysis process and its results. There are various methods for normalizing moderate indicators (e.g., taking the opposite number, taking the reciprocal), and this study adopts the method of taking the opposite number for positive orientation.

The specific positive orientation method for moderate indicators in this study is as follows:

(1)Public factors, along with their corresponding factor eigenvalues, variance contribution rates, and cumulative variance contribution rates, were calculated using SPSS 20.0. The results indicate that within the corporate competitiveness measurement index system, the asset-liability ratio (LEV) falls into the category of moderate indicators. For enterprises, a higher asset-liability ratio increases their debt-servicing pressure, while an excessively low ratio hinders the effective use of financial leverage. This prevents minimizing the weighted average cost of capital (WACC) and adversely impacts the firm's market value. Therefore, for manufacturing enterprises, the optimal value of the asset-liability ratio is typically 0.5.

(2)In measuring corporate competitiveness, this study adopts the widely used and objective factor analysis method to construct a comprehensive score function. Prior to conducting factor analysis, the Kaiser-Meyer-Olkin (KMO) test and Bartlett's Test of Sphericity were performed to verify the suitability of the sample variables for factor analysis, using SPSS 20.0.

As shown in Table 3, the KMO statistics are 0.628, 0.641, and 0.634, respectively, all exceeding 0.6—indicating that the data are suitable for factor analysis. The Bartlett's Test of Sphericity yields large chi-square values with 45 degrees of freedom, and all results are statistically significant. This confirms the appropriateness of factor analysis for the data. Across the three sample periods, the approximate chi-square values of the test are 157,750.457, 172,778.095, and 174,074.784, respectively, with corresponding significance levels of 0.000 (far below the 0.01 significance threshold). These results strongly reject the null hypothesis that the correlation matrix among variables is an identity matrix, demonstrating significant correlations between the variables in this study—providing a fundamental prerequisite for factor analysis.

Statistic Year		Year T	Year T+1	Year T+2
KMO Measure of Sampling Adequacy		.628	.641	.634
Bartlett's Test of Sphericity	Approximate Chi-Square	157750.457	172778.095	174074.784
	Degrees of Freedom	45	45	45
	Significance	.000	.000	.000

Table.3. KMO and Bartlett's Test

Table 4 presents the total variance explained by each component factor in the factor analysis of corporate competitiveness indicators for the base period (Year T). Through dimensionality reduction via factor analysis, three public factors were extracted based on the criterion of eigenvalue > 1, with a cumulative variance contribution rate of 59.274%. This indicates that the extracted factors retain most of the information from the original data. The weight of each public factor is defined as the ratio of the variance contribution rate of the respective factor to the cumulative variance contribution rate. Calculations show that the weights of the three public factors are 0.4627, 0.3611, and 0.1761, respectively.

Table 5 presents the total variance explained by each component factor in the factor analysis of corporate competitiveness indicators for the one-year lagged period (Year T+1). Through dimensionality reduction via factor analysis, three public factors were extracted based on the

criterion of eigenvalue > 1, with a cumulative variance contribution rate of 61.510%. This indicates that the extracted factors retain most of the information from the original data. Calculations show that the weights of the three public factors are 0.4543, 0.3770, and 0.1688, respectively.

Table 5 presents the total variance explained by each component factor in the factor analysis of corporate competitiveness indicators for the two-year lagged period (Year T+2). Through dimensionality reduction via factor analysis, three public factors were extracted based on the criterion of eigenvalue > 1, with a cumulative variance contribution rate of 61.214%. This indicates that the extracted factors retain most of the information from the original data. Calculations show that the weights of the three public factors are 0.4582, 0.3702, and 0.1715, respectively.

Figure 1 presents the scree plot of the common factors, where the horizontal axis represents the factor serial numbers and the vertical axis denotes the factor eigenvalues. The plot indicates that the eigenvalues of the first three factors are generally high, forming a relatively steep line segment. In contrast, the eigenvalues of factors beyond the third are generally low, connecting to form a flat line segment. Thus, extracting three common factors is deemed appropriate.Based on the extraction of principal component factors, Table 7 presents the component score coefficient matrix obtained through SPSS analysis.

Factor		Component in Year T			Components of Year T+1			Components of Year T+2		
		1	2	3	1	2	3	1	2	3
LEV	X1	-.264	.057	-.022	-.261	.044	-.026	-.263	.051	-.038
CAR	X2	.210	.050	.023	.212	.039	.011	.208	.047	-.016
QR	X3	.342	-.004	.022	.336	.001	.035	.337	-.002	.045
ROA	X4	.013	.430	.001	.012	.393	-.009	.015	.399	.004
ROE	X5	-.021	.279	-.043	-.018	.317	-.034	-.023	.306	-.066
ROIC	X6	-.014	.440	-.009	-.013	.410	-.015	-.014	.417	-.019
CAT	X7	-.113	.059	.405	-.126	.061	.375	-.120	.054	.397
TRFA	X8	.083	-.016	.891	.069	-.001	.907	.078	-.006	.888
SGR	X9	.003	.054	.062	.001	.043	.046	.003	.085	.072
CR	X10	.342	-.001	.021	.336	.003	.034	.337	.000	.043

Table.7. Component Score Coefficient Matrix

The comprehensive score function for Year T is as follows：

$$F_1=-0.264X_1+0.210X_2+0.342X_3+0.013X_4-0.21X_5 -0.014X_6-0.113X_7+0.083X_8+0.003X_9+0.342X_{10} \quad (1)$$

$$F_2=0.057X_1+0.050X_2-0.04X_3 +0.430X_4+0.279X_5+0.440X_6+0.059X_7 -0.016X_8+0.054X_9-0.001X_{10} \quad (2)$$

$$F_3=-0.022X_1+0.023X_2+0.022X_3 +0.001X_4-0.043X_5-0.009X_6+0.405X_7 +0.891X_8+0.062X_9+0.021X_{10} \quad (3)$$

The comprehensive score function for Year T+1 is as follows:

$$FF_1 = -0.261\ X_1 + 0.212\ X_2 + 0.336\ X_3 + 0.012\ X_4 - 0.018\ X_5 - 0.013\ X_6 - 0.126\ X_7 + 0.069\ X_8 + 0.001\ X_9 + 0.336\ X_{10} \quad (4)$$

$$FF_2 = 0.044\ X_1 + 0.039\ X_2 + 0.001\ X_3 + 0.393\ X_4 + 0.317\ X_5 + 0.410\ X_6 + 0.061\ X_7 - 0.001\ X_8 + 0.043\ X_9 + 0.003\ X_{10} \quad (5)$$

$$FF_3 = -0.026\ X_1 + 0.011\ X_2 + 0.035\ X_3 - 0.009\ X_4 - 0.034\ X_5 - 0.015\ X_6 + 0.375\ X_7 + 0.907\ X_8 + 0.046\ X_9 + 0.034\ X_{10} \quad (6)$$

The comprehensive score function for Year T+2 is as follows

$$FFF_1 = -0.263\ X_1 + 0.208\ X_2 + 0.337\ X_3 + 0.015\ X_4 - 0.023\ X_5 - 0.014\ X_6 - 0.120\ X_7 + 0.078\ X_8 + 0.003\ X_9 + 0.337\ X_{10} \quad (7)$$

$$FFF_2 = 0.051\ X_1 + 0.047\ X_2 - 0.002\ X_3 + 0.399\ X_4 + 0.306\ X_5 + 0.417\ X_6 + 0.054\ X_7 - 0.006\ X_8 + 0.085\ X_9 \quad (8)$$

$$FFF_3 = -0.038\ X_1 - 0.016\ X_2 + 0.045\ X_3 + 0.004\ X_4 - 0.066\ X_5 - 0.019\ X_6 + 0.397\ X_7 + 0.888\ X_8 + 0.072\ X_9 + 0.043\ X_{10} \quad (10)$$

Using the above nine formulas, the common factor scores of the samples can be calculated via Stata 18.0. Subsequently, the composite scores of corporate competitiveness for the base period, one-year lagged period, and two-year lagged period of the samples can be computed respectively using Formulas (3)–(5), (6)–(8), and (9)–(11).

$$CC_T=0.4627*F_1+0.3611*F_2+0.1761*F_3 \quad (12)$$

$$CC_{T+1}=0.4543*FF_1+0.3770*FF_2+0.1688*FF_3 \quad (13)$$

$$CC_{T+2}=0.4582*FFF_1+0.3702*FFF_2+0.1715*FFF_3 \quad (14)$$

(III) Regression Model Design

To test the research hypothesis regarding the impact of internal audit independence on corporate dynamic competitiveness, the following regression model is constructed:：

$$CC_T / CC_{T+1} / CC_{T+2} = \alpha_0 + \alpha_1 indep\_audit + \alpha_{2-n} \sum Controls + \varepsilon \quad (15)$$

In the model, α 0 denotes the constant term; α_1、α_2、……、αn is the regression coefficient；CC_T、CC_{T+1}、CC_{T+2}denote

corporate competitiveness in the base period, one-year lagged corporate competitiveness, and two-year lagged corporate competitiveness, respectively.; indep_auditindep_audit represents a firm's internal audit independence; Controlsdenotes a set of control variables; and is the random error term.

V. Empirical Results and Discussion

(1) Internal Audit Independence and Enterprises' Dynamic Competitiveness

The empirical results in Table 8 indicate that the impact of internal audit independence on corporate competitiveness exhibits a distinct characteristic of "short-term promotion and long-term attenuation."

Column (1) shows that after controlling for other factors, the improvement of internal audit independence significantly enhances enterprises' current-year competitiveness. The coefficient is 8.869 and statistically significant at the 1% level, indicating that higher internal audit independence is associated with stronger current-year competitiveness. Specifically, a one-unit increase in internal audit independence leads to an approximate 8.869-unit increase in current-year competitiveness.

Column (2) reports a coefficient of 4.589 for internal audit independence, which is statistically significant at the 10% level (t = 1.93). The positive impact of internal audit independence on competitiveness persists in the one-year lagged period but weakens substantially (the coefficient decreases from 8.869 to 4.589), with the significance level dropping from 5% to 10%. This suggests that the driving effect of internal audit independence has short-term momentum but cannot alone sustain strong medium-term growth.

Column (3) presents a coefficient of -0.054, which is completely insignificant (t = -0.15). By the third year, internal audit independence no longer has any statistically identifiable impact on corporate competitiveness. These findings demonstrate that the effect of internal audit independence on competitiveness is temporary rather than permanent; the long-term performance of corporate competitiveness depends more on other structural or strategic factors.

In summary, internal audit independence acts as a "short-term catalyst" rather than a "long-term engine" for corporate competitiveness. It can bring immediate improvements in corporate governance and operational efficiency, but sustaining long-term competitiveness requires integration with other long-acting mechanisms.

Heterogeneous Impacts of Control Variables

Firm Size: Exhibits a complex dynamic impact on competitiveness. Column (1) shows a significantly negative coefficient of -5.410 at the 1% level, which may reflect the "large enterprise syndrome"—expansion leading to bureaucracy and delayed decision-making, thereby inhibiting short-term competitiveness. Column (2) reports a significantly positive coefficient of 1.509 at the 1% level, indicating that the positive effects of scale begin to dominate. Column (3) shows that the significant positive impact of firm size disappears, suggesting that the scale effect itself is a dynamic adjustment process, and its long-term impact is overshadowed by other more complex factors.

Ownership Type: Demonstrates a robust long-term positive impact on corporate competitiveness. Results in Columns (2) and (3) indicate that the coefficient of ownership type is significantly positive in both the second and third years with relatively large values. This suggests that state-owned enterprises (SOEs) play a decisive role in enhancing medium- and long-term competitiveness through their advantages in resource acquisition, policy support, and stability maintenance.

Board Size: Shows dynamic changes in its impact on competitiveness. Column (1) reports a significantly negative coefficient of -1.448 at the 5% level, reflecting the inefficiency in decision-making caused by overly large boards. Column (3) presents a significantly positive coefficient of 0.311 at the 1% level, supporting the "resource dependence theory"—in the long run, larger boards can bring more external resources and information, facilitating corporate stability and development.

Supervisory Board Size: Displays a short-term positive and long-term negative impact on competitiveness. Column (1) shows a significantly positive coefficient of 2.015 at the 5% level, indicating that the supervisory function of the supervisory board plays an active role in the current year. Column (3) reports a significantly negative coefficient of -0.202 at the 10% level; similar to board size, it may generate certain governance costs in the long run.

Managerial Ownership: Exhibits a short-term negative impact on competitiveness. Column (1) presents a significantly negative coefficient of -0.123 at the 1% level, which may imply an "entrenchment effect" rather than an "interest alignment effect"—managers may make decisions that are not conducive to short-term competitiveness to protect personal interests (e.g., risk avoidance).

Practical Implications

For Enterprises: They should strengthen short-term governance, attach great importance to and safeguard the independence of internal auditing, and regard it as a key tool to improve short-term operational efficiency and risk control capabilities. Meanwhile, enterprises should layout long-term strategies, integrating optimized corporate governance structures with long-term technological innovation and market strategies to build sustainable competitive advantages. Enterprises should view scale rationally, guard against the "large enterprise syndrome" during expansion, and stimulate organizational vitality through internal management reforms to convert scale advantages into sustained competitiveness.

For Regulators: They should continue to introduce policies to encourage and regulate the construction of enterprise internal audit systems, especially setting clear requirements for independence. This is of positive significance for improving the quality and short-term performance of microeconomic entities in the entire market.

In conclusion, these more comprehensive regression results clearly depict a picture: internal auditing is an effective "governance emergency injection," while the long-term "healthy physique" of enterprises relies on a comprehensive and dynamically adjusted governance system and strategic layout.

Variable	(1) Competitiveness in Year T	(2) Competitiveness in Year T+1	(3) Competitiveness in Year T+2
Internal Audit Independence	8.869***	4.589*	-0.054
	(3.36)	(1.93)	(-0.15)
Firm Size	-5.410***	1.509***	-0.033
	(-8.58)	(2.66)	(-0.40)
Ownership Nature	2.202	14.492***	5.308***
	(1.06)	(7.76)	(19.39)
Controlling Shareholder Ownership Ratio	-4.786	-8.479*	0.521
	(-0.95)	(-1.88)	(0.79)
Controlling Shareholder Ownership Ratio	-0.123***	0.029	-0.000
	(-2.75)	(0.72)	(-0.05)
Board Size	-1.448**	-0.388	0.311***
	(-2.34)	(-0.70)	(3.81)
Supervisory Board Size	2.015**	-0.041	-0.202*
	(2.19)	(-0.05)	(-1.66)
Independent Director Ratio	-24.589	6.278	3.289
	(-1.51)	(0.43)	(1.53)
Independent Director Network Centrality	-1.387	-1.036	0.160
	(-0.63)	(-0.52)	(0.55)
Intercept	64.372***	-7.268	-2.056
	(6.17)	(-0.77)	(-1.49)
Observations	20,117	20,117	20,117
R-squared	0.005	0.006	0.030

Table.

(2) Internal Audit Independence and State-Owned Enterprises' Competitiveness

Table 9 presents the results of subgroup regression analysis based on enterprise ownership type, aiming to examine the heterogeneous impacts of internal audit independence on the dynamic competitiveness of state-owned enterprises (SOEs) in the current period (Year T), short term (Year T+1), and medium term (Year T+2).

SOE Subgroup

Within the SOE subgroup, internal audit independence exhibits a significant short-term promotional effect on corporate competitiveness. Specifically, in the current period (Year T), the coefficient of internal audit independence is 17.212, which is statistically significant at the 1% level (t = 2.87). This indicates that enhancing internal audit independence in SOEs can immediately strengthen their

current-period competitiveness. However, this positive impact is time-bound: in Years T+1 and T+2, the coefficients are 8.492 and -0.340, respectively, neither of which is statistically significant. This suggests that the impact of internal audit independence is primarily concentrated in the short term and fails to persist into the medium and long terms.

Non-SOE Subgroup

In contrast, the impact of internal audit independence in non-SOEs presents a distinctly different pattern. In Years T, T+1, and T+2, the coefficients are -1.113, -0.121, and -0.008, respectively—all negative but statistically insignificant.

Key Findings and Implications

These results confirm significant ownership-based heterogeneity in the impact of internal audit independence on corporate competitiveness. Specifically, enhancing internal audit independence significantly boosts the current-period competitiveness of SOEs but exerts no significant effect on that of non-SOEs.

For SOEs, strengthening the independent status of internal auditing constitutes an effective governance mechanism to improve short-term competitiveness and responsiveness. Regulators and SOE managers should strive to ensure the independence of internal audit departments through institutional design, organizational structure optimization, and resource allocation, thereby unlocking their potential in corporate governance and value creation. However, given the short-term nature of this impact, SOEs need to complement internal audit independence with other long-acting governance mechanisms to sustain competitive advantages.

For non-SOEs, the drivers of competitiveness may stem more from market mechanisms, entrepreneurial spirit, or alternative governance arrangements. The standalone enhancement of internal audit independence is not a critical lever for improving their competitiveness.

Table.10.abc	State-Owned	Non-State-Owned	State-Owned	Non-State-Owned	State-Owned	Non-State-Owned
	Corporate Competitiveness in Year T		Corporate Competitiveness in Year T+1		Corporate Competitiveness in Year T+2	
Internal	17.212	-	8.492	-	-	-
Audit Independence	***	1.113		0.121	0.340	0.008
	(2.87)	(-0.55)	(1.42)	(-0.77)	(-0.39)	(-0.46）
Firm Size	-9.377***	-3.321***	4.491**	0.043	-0.095	-0.002
	(-5.05)	(-8.53)	(2.43)	(1.42)	(-0.35)	(-0.60)
Controlling Shareholder Ownership Ratio	-16.259	-0.512	-32.002**	-0.031	1.440	0.010
	(-1.03)	(-0.17)	(-2.05)	(-0.13)	(0.63)	(0.36)
Managerial Ownership	-0.663	-0.134***	-0.167	0.000	-0.030	-0.000
	(-1.13)	(-5.79)	(-0.29)	(0.01)	(-0.35)	(-0.30)
Board Size	-1.147	-1.390***	-1.410	0.019	0.814***	-0.004
	(-0.69)	(-3.44)	(-0.85)	(0.61)	(3.34)	(-0.96)
Supervisory Board Size	3.787*	-0.450	-0.101	-0.021	-0.434	-0.003
	(1.91)	(-0.58)	(-0.05)	(-0.35)	(-1.50)	(-0.39)
Proportion of Independent Directors	-40.842	-10.928	9.556	-0.0263	5.303	0.005
	(-0.93)	(-1.02)	(0.22)	(-0.31)	(0.82)	(0.06)
Independent Director Network Centrality	0.071	-2.582*	-2.403	-0.157	0.496	0.011
	(0.01)	(-	(-	(-	(0.50)	(0.94)

		1.93)	0.35)	1.50)		
Intercept	101.189***	49.2386	-2.192	1.332	-1.065	1.127***
	(3.65)	(6.87)	(-0.08)	(2.37)	(-0.26)	(17.39)
Observations	5,756	14361	5,756	14361	5,756	14361
R-squared	0.008	0.0096	0.002	0.0008	0.003	0.0004

Table.

(3) Moderating Role of Data Element Utilization Efficiency

Table 9 indicates that the positive impact of internal audit independence on state-owned enterprises (SOEs)' competitiveness tends to weaken over time. To further explore the influence of data element utilization efficiency, we introduce it as a moderating variable and examine its moderating effect on the relationship between internal audit independence and SOEs' competitiveness in the one-year lagged (T+1) and two-year lagged (T+2) periods. The results are presented in Table 10.

Column (1): SOE Subgroup (T+1 Period)

The coefficient of the interaction term "Internal Audit Independence × Data Element Utilization Efficiency" is 3.853, which is statistically significant at the 5% level (t = 2.14). This suggests that in SOEs, data element utilization efficiency significantly strengthens the positive impact of internal audit independence on corporate competitiveness. In other words, a higher level of data element utilization efficiency amplifies the promotional effect of internal audit independence on enterprises' short-term competitiveness (Year T+1). A plausible explanation is that SOEs place greater emphasis on optimizing audit systems when enhancing data element utilization, thereby magnifying the value of internal audit independence.

Column (2): Non-SOE Subgroup (T+1 Period)

The coefficient of the interaction term "Internal Audit Independence × Data Element Utilization Efficiency" is 0.005, which is statistically insignificant (t = 0.28). This indicates that in non-SOEs, data element utilization efficiency does not significantly moderate the relationship between internal audit independence and corporate competitiveness. Possible reasons include: (1) the internal audit mechanisms of non-SOEs are inherently more flexible, leading to a smaller marginal effect of data element utilization efficiency; or (2) non-SOEs' competitiveness is more strongly driven by market factors.

Column (3): SOE Subgroup (T+2 Period)

The coefficient of the interaction term "Internal Audit Independence × Data Element Utilization Efficiency" is 0.326, which is statistically insignificant (t = 1.23). This demonstrates that the moderating effect of data element utilization efficiency on internal audit independence disappears in the medium term (Year T+2), indicating that such an effect is likely short-lived. Potential explanations are: (1) the effect of data element utilization efficiency in SOEs attenuates over time; or (2) the role of internal audit independence is offset by other factors.

Column (4): Non-SOE Subgroup (T+2 Period)

The coefficient of the interaction term "Internal Audit Independence × Data Element Utilization Efficiency" is 0.001, which is statistically insignificant (t = 0.43). This reconfirms that data element utilization efficiency exerts no significant moderating effect in non-SOEs, either in the short or medium term.

Summary of Moderating Effect Results

Table 10 reveals that data element utilization efficiency exerts a significant positive moderating effect on the relationship between internal audit independence and SOEs' short-term competitiveness (Year T+1), but this effect dissipates in the medium term. In non-SOEs, data element utilization efficiency shows no significant moderating effect whatsoever. These findings indicate that ownership type serves as a key boundary condition: SOEs may derive greater audit synergy benefits from data element utilization, but the sustainability of such benefits is limited.

Table.10.abc	(1) State-Owned	(2) Non-State-Owned	(3) State-Owned	(4) Non-State-Owned
	Competitiveness in the One-Year Lagged Period (Year T+1)		Competitiveness in the Two-Year Lagged Period	
Internal Audit Independence × Data Element Utilization Efficiency	3.853**	0.005	0.326	0.001
	(2.14)	(0.28)	(1.23)	(0.43)

Data Element Utilization Efficiency	-0.156	-0.001	-0.013	0.001
	(-0.27)	(-0.51)	(-0.16)	(0.64)
Internal Audit Independence	0.198	-0.137	-1.043	-0.011
	(0.03)	(-0.81)	(-1.00)	(-0.58)
Firm Size	4.439**	0.043	-0.100	-0.002
	(2.40)	(1.41)	(-0.37)	(-0.58)
Controlling Shareholder Ownership Ratio	-31.537**	-0.033	1.480	0.010
	(-2.02)	(-0.14)	(0.64)	(0.37)
Managerial Ownership	-0.162	0.001	-0.029	-0.001
	(-0.28)	(0.01)	(-0.34)	(-0.31)
Board Size	-1.554	0.019	0.801***	-0.003
	(-0.93)	(0.60)	(3.28)	(-0.95)
Supervisory Board Size	-0.183	-0.021	-0.441	-0.002
	(-0.09)	(-0.35)	(-1.52)	(-0.36)
Proportion of Independent Directors	7.949	-0.267	5.166	0.006
	(0.18)	(-0.32)	(0.80)	(0.06)
Proportion of Independent Directors	-1.854	-0.159	0.543	0.011
	(-0.27)	(-1.51)	(0.55)	(0.94)
Intercept	0.200	1.346**	-0.861	1.125***
	(0.01)	(2.39)	(-0.21)	(17.33)
Observations	5,756	14361	5,756	14361
R-squared	0.003	0.001	0.003	0.001

Table.

4.Research Conclusions and Implications

4.1.Research Conclusions

Based on empirical data of Chinese listed firms, this study explores how internal audit independence affects enterprises' dynamic competitiveness and the moderating role of ownership type. Full-sample regression and subgroup tests yield core findings:

Internal audit independence exerts a significant short-term boost on current dynamic competitiveness, but this positive effect fades and becomes statistically insignificant by Year T+3, constrained by long-term strategic factors. Subgroup analysis shows heterogeneous impacts: in state-owned enterprises (SOEs), internal audit independence strongly drives competitiveness (coefficient=17.212), far exceeding the full-sample average, as it mitigates principal-agent problems and ensures state-owned asset efficiency. In non-SOEs, however, its effect is insignificant due to flexible governance structures and competitiveness relying more on entrepreneurship, market opportunities and innovation. Control variables like firm size also show heterogeneous effects across models, reflecting the systematic nature of competitiveness formation.

(2) Research Implications

This study offers targeted implications: For SOEs, strengthen internal audit independence via top-level design, shift its function from financial compliance to value creation, and integrate it with digital transformation. For non-SOEs, avoid copying SOE governance models; instead, embed internal audit into core business risk management. For policymakers, adopt classified regulatory guidance—impose mandatory independence requirements on SOEs and provide principle-based guidelines for non-SOEs.

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Release Date	Issuing Authority	Document Title	Core Tenets of the Document
August 2015	Central Committee of the Communist Party of China (CPC) and the State Council	Guidelines on Deepening the Reform of State-owned Enterprises	We will improve the supervision system and mechanisms for state-owned capital auditing, implement full-coverage auditing supervision over enterprise state-owned assets, and establish a regular auditing system for enterprise state-owned capital.
January 2018	National Audit Office, PRC	Provisions of the National Audit Office on Internal Audit Work	This constitutes a major initiative to implement the guiding principles of the CPC Central Committee and the State Council on strengthening internal audit work and giving full play to its role. It is of great significance for promoting audited entities to standardize internal management, improve

			internal control, mitigate risks, and enhance quality and efficiency.
November 2018	SASAC	Guidelines for Compliance Management of Central State-owned Enterprises (Trial Implementation	To promote central state-owned enterprises (CSOs) to comprehensively strengthen compliance management, accelerate the improvement of law-based and compliant operation and management capabilities, strive to build law-based central enterprises, and ensure the sustainable and healthy development of enterprises.
December 2019	State-owned Assets Supervision and Administration Commission of the State Council	《Official Notice on Matters Concerning the Improvement and Oversight of the Internal Control Systems of Central Enterprises in 2020	All Central Enterprises shall take "strengthening internal control, preventing risks, and promoting compliance" as the goal, and establish a comprehensive, full-staff, whole-process, and whole-system risk prevention and control mechanism.
January 2020	State-owned Assets Supervision and Administration Commission of the State Council	Official Notice on Matters Concerning the Conduct of Internal Audit Work in Central Enterprises in 2020	Promote Central Enterprises to give full play to the supervisory and inspection role of internal audit in "facilitating management, controlling risks, and strengthening supervision", and continuously enhance enterprises' internal "immunity".
January 2020	State-owned Assets Supervision and Administration Commission of the State Council (SASAC)	Official Notice on Accelerating the Digital Transformation of State-owned Enterprises	Promote organizational and management reforms of enterprises oriented toward digital transformation, coordinate the development of new digital capabilities, and earnestly advance digital transformation efforts with a "nail-sticking spirit" to ensure consistent implementation of the overall blueprint.
September 2020	State-owned Assets Supervision and Administration Commission of the State Council	Implementation Opinions on Deepening the Internal Audit Oversight of Central Enterprises	Focusing on the formation of a state-owned asset supervision system centered on capital management, promote Central Enterprises to establish an internal audit leadership and management system that meets the requirements of the modern enterprise system with Chinese characteristics.
September 2020	State-owned Assets Supervision and Administration Commission of the State Council	Opinions on Further Deepening the Construction of Law-Based Central Enterprises	Deepen the informatization and digitalization of key areas such as contract management, case management, and compliance management; embed legal review into the processes of major decision-making and important business management; and realize the online identification, analysis, evaluation, and prevention and control of legal and compliance risks through big data and other means.
June 2025	State-owned Assets Supervision and Administration Commission of the State Council	Measures for the Administration of Development Planning of Central Enterprises	The State-owned Assets Supervision and Administration Commission of the State Council (SASAC) supervises and inspects the implementation of development plans, the progress of major engineering projects, and the completion of key tasks of Central Enterprises. For issues such as significant deviations in development direction, serious delays in implementation progress, and low development quality, it shall issue reminders, conduct interviews, or circulate notices in accordance with relevant provisions; for cases of blind investment deviating from the development plan direction, it shall impose assessment score deductions based on the severity of the circumstances.

Table.1. Relevant Documents on Internal Audit and Data Element Utilization Since 2015

Type	Variable	Definition
Dependent Variable	Corporate Dynamic Competitiveness	Comprehensive Index
Independent Variable	Internal Audit Independence	It is assigned a value of 1 if the number of audit committee members is greater than or equal to the industry average, and 0 otherwise.
Moderating	Data Factor Utilization Rate	Ln (Number of Data Factor Utilization-related Words + 1)

Variable		
Control Variable	Firm Size	Ln (Number of Employees + 1)
	Ownership Nature	Dummy variable: assigned a value of 1 for state-owned enterprises (SOEs), and 0 otherwise.
	Shareholding Ratio of Controlling Shareholders	(Number of Shares Held by Controlling Shareholders) / (Total Share Capital)
	Managerial Ownership Ratio	(Number of Shares Held by Managers) / (Total Share Capital)
	Board Size	Ln (Number of Board Members + 1)
	Proportion of Independent Directors	(Number of Independent Directors) / (Total Number of Board Members)
	Independent Director Network Centrality	The network centrality of independent directors' positions in the overall director network

Table.2. Variable Description

Component	Initial Eigenvalues			Sum of Squared Loadings			Rotated Sum of Squared Loadings		
	Total	Percentage of Variance	Cumulative %	Total	Percentage of Variance	Cumulative %	Total	Percentage of Variance	Cumulative %
1	2.780	27.799	27.799	2.780	27.799	27.799	2.743	27.431	27.431
2	2.118	21.181	48.980	2.118	21.181	48.980	2.141	21.405	48.837
3	1.029	10.294	59.274	1.029	10.294	59.274	1.044	10.437	59.274
4	.995	9.953	69.227						
5	.879	8.791	78.018						
6	.780	7.798	85.817						
7	.734	7.342	93.159						
8	.560	5.601	98.760						
9	.110	1.098	99.857						
10	.014	.143	100.000						

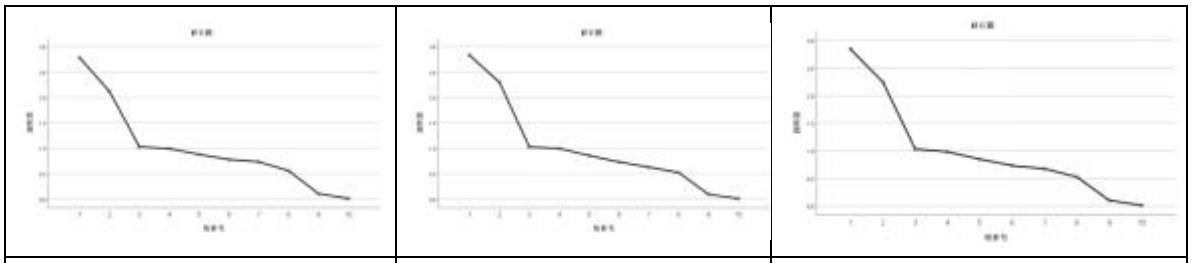
Table.4. Total Variance Explained in Base Year T

Component	Initial Eigenvalues			Sum of Squared Loadings			Rotated Sum of Squared Loadings		
	Total	Percentage of Variance	Cumulative %	Total	Percentage of Variance	Cumulative %	Total	Percentage of Variance	Cumulative %
1	2.827	28.273	28.273	2.827	28.273	28.273	2.794	27.942	27.942
2	2.296	22.965	51.238	2.296	22.965	51.238	2.318	23.184	51.126
3	1.027	10.272	61.510	1.027	10.272	61.510	1.038	10.384	61.510
4	.996	9.964	71.474						
5	.858	8.585	80.059						
6	.731	7.311	87.369						
7	.631	6.306	93.675						
8	.524	5.239	98.914						
9	.096	.955	99.870						
10	.013	.130	100.000						

Table.5. Total Variance Explained for T+2 Year

Component	Component			Component			Component		
	Total	Percentage of Variance	Cumulative %	Total	Percentage of Variance	Cumulative %	Total	Percentage of Variance	Cumulative %
1	2.843	28.432	28.432	2.843	28.432	28.432	2.805	28.050	28.050
2	2.246	22.457	50.889	2.246	22.457	50.889	2.266	22.664	50.715
3	1.032	10.325	61.214	1.032	10.325	61.214	1.050	10.499	61.214
4	.982	9.815	71.029						
5	.849	8.487	79.515						
6	.732	7.321	86.837						
7	.674	6.743	93.580						
8	.528	5.277	98.857						
9	.103	1.027	99.884						
10	.012	.116	100.000						

Table .6. Total Variance Explained for T+2 Year



Scree Plot of Year T	Scree Plot of Year T+1	Scree Plot of Year T+2

Figure. 1. Scree Plot of Common Factors

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Digital Human Resources: Literature Review and Research Prospects

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KEYWORDS

Digital human resources;

Digital transformation;

Digital intelligence;

Collaborative development

ABSTRACT

Comprehensive digitalization is profoundly changing people's production, life, work and learning styles. The rapid development of the digital economy also prompts enterprises to carry out profound digital transformation. Human resources work is an important part that affects the organizational structure and business activities of enterprises. Digital human resources has become an important factor for the success of enterprise transformation. Scholars at home and abroad have conducted in-depth research on the definition and characteristics, mode mechanisms, risk countermeasures, etc. of digital human resources. Therefore, this article will sort out and look forward to the concept characteristics and the current status of research and development at home and abroad.

INTRODUCTION

The term "digital human resources" first appeared in the "Deloitte 2016 Global Human Capital Trends" report, which argued that digital human resources represented a revolution rather than a slow evolution. In 2021, General Secretary Xi Jinping emphasized during a collective study session that "the digital economy is becoming a crucial force in reorganizing global factor resources, reshaping the global economic structure, and altering the global competitive landscape. Developing the digital economy is a strategic choice for seizing the new opportunities presented by the new round of scientific and technological revolution and industrial transformation"[1]. In 2024, the state introduced the "Action Plan for Accelerating the Cultivation of Digital Talent to Support the Development of the Digital Economy (2024-2026)". This plan emphasized that digital talent can boost the development of the digital economy and accelerate the development of new forms of productive forces. With the rapid development of China's digital economy and the continuous upgrading of network infrastructure and intelligent terminal industries[2], the support of technology drives organizational change. Digital human resources management, through new-generation digital technologies such as mobile Internet, cloud computing, big data, and artificial intelligence, creates a unified digital workplace, realizes the process and automation of human resources management, enhances the employee experience, helps organizations make scientific human resources management decisions, and the digital development of human resources has become an inevitable development trend.

The development trend of digital human resources shows that digital intelligence will become the core strategy for organizations to improve efficiency and also a powerful weapon for seizing the talent dividend. As the new generation enters the workplace and becomes the main force in organizations, having grown up with mobile Internet technology, they will accelerate the digital intelligence of all employees in the organization and serve as a guarantee for enhancing digital capabilities. At the same time, with the continuous growth of human resources data, digital human resources management will become a shining star among the value creators of organizations. In summary, the development of digital human resources is not only a manifestation of the technological revolution but also a new journey of human progress. Against the backdrop of

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digitalization, change, opportunities, talent, and integration, the transformation of the foundation of digital human resources management is of great significance for improving organizational effectiveness, optimizing the talent structure, and promoting innovative development.

Facing the profound changes that digitalization is bringing to the ways people produce, live, work, and learn, the rapid development of the digital economy is also driving enterprises to undergo deep digital transformation. Human resources (HR) functions are a critical component influencing organizational structure and business activities, and digital HR has become a key factor in the success of enterprise transformation. Scholars have conducted extensive research on the definition and characteristics, models, mechanisms, risks, and countermeasures related to digital HR. Therefore, this paper aims to review and summarize its conceptual features and the current state of research development, while also providing an outlook for future directions.

1.Concept Definition and Characteristics

The conceptual landscape of modern management theory is often punctuated by seminal figures and foundational texts, yet the emergence of Digital Human Resources (Digital HR) as a significant paradigm defies such a neat origin story. Unlike other classic organizational theories with clear progenitors — such as Taylor's Scientific Management or Mayo's Human Relations approach—Digital HR cannot be attributed to a single founder or a definitive inaugural proposition. It is, instead, a contemporary and evolving mode of human resource management that has been gradually conceived and shaped organically within the crucible of the Information Age. Its genesis is inextricably linked to the rapid, wave-like advancement of information and communication technologies, a force that has fundamentally reshaped the socioeconomic fabric. This management paradigm is thus less an invention and more an adaptive response, emerging as the logical confluence and deep integration of technological capability with the enduring functions of human capital management. It represents a quintessential product of its time, evolving in lockstep with digital transformation trends that permeate all aspects of organizational life. Moreover, these activities are carried out simultaneously and intertwined with each other[3]. This viewpoint expounds the connotation of digital human resources from a relatively broad perspective and emphasizes the simultaneity of its activity scope and technological application. In China, after extensive research and practice, the currently widely accepted definition is: Digital human resources is a new type of management mode that actively applies digital technology and information means in human resources management practices to effectively manage the human resources of enterprises. This definition not only clarifies that the management scope of digital human resources is corporate human resources but also emphasizes that its core lies in using digital technology and information means to ensure the effectiveness of management. Further analysis shows that digital human resources have some distinct characteristics, including digital-driven, agility, intelligent decision-making, self-service, and cost-effectiveness, etc.[4]. Digital-driven means that the management process takes data as the core and relies on the collection, analysis, and application of data to drive decision-making and management activities; agility reflects that this management mode can quickly adapt to the changes in the internal and external environments of the enterprise and flexibly adjust human resources strategies; intelligent decision-making relies on advanced algorithms and data analysis tools to provide a scientific basis for the enterprise's human resources decisions; self-service enables employees and managers to independently complete relevant human resources management operations to a certain extent, improving efficiency; cost-effectiveness highlights that through digital means, it is possible to effectively reduce the cost of human resources management while ensuring the quality of management.

The scholarly inquiry into Digital HR reveals a fascinating tapestry of perspectives, distinctly colored by the academic environments, cultural contexts, and practical realities in which researchers are situated. Scholars across the globe, while examining the same broad phenomenon, have cultivated different research trajectories and underlying value systems, leading to a rich, if sometimes fragmented, body of literature. Internationally, a notable contribution comes from scholar Alan, whose viewpoint frames Digital HR as a complex and comprehensive organizational process. This process, in Alan's conceptualization, is characterized by the holistic application of digital technologies across the entire spectrum of human resource management activities. It encompasses a continuum from initial recruitment and selection, through onboarding, performance management,

learning and development, and extends to compensation, benefits, and payroll administration. Crucially, Alan emphasizes that these activities are not sequential or isolated but are conducted simultaneously and are deeply interdependent, woven together by shared digital platforms and data streams. This perspective offers a broad, process-oriented understanding of Digital HR, highlighting its integrative nature and the synchronicity of its technological application and managerial scope.

In contrast, within the Chinese academic and professional context, extensive research and practical experimentation have converged upon a definition that, while aligned in spirit, carries distinct nuances. The widely accepted definition positions Digital HR as a new management model that actively employs digital technologies and information methodologies within HR practices to achieve effective governance and optimization of an enterprise's human resources. This definition performs two critical functions. First, it explicitly demarcates the domain of Digital HR: the human resources of the enterprise itself. Second, and more importantly, it centers the core mechanism of this model: the strategic use of digital and informational tools as the primary enablers of management efficacy. The emphasis is squarely on leveraging technology to attain effectiveness, implying a focus on outcomes such as improved decision quality, operational efficiency, and strategic alignment.

Delving deeper, this model is operationalized through a constellation of interrelated and defining characteristics that distinguish it from traditional HRM. A closer analytical examination reveals these core attributes:

Data-Driven Core: At the heart of Digital HR lies a fundamental shift from intuition-based to evidence-based management. The process is intrinsically data-centric, relying on the systematic collection, sophisticated analysis, and strategic application of people analytics. Data becomes the primary fuel for decision-making and the steering mechanism for management interventions, spanning from predicting talent attrition to optimizing workforce planning.

Agility: Reflecting the volatile, uncertain, complex, and ambiguous (VUCA) nature of the modern business environment, Digital HR is characterized by organizational agility. This refers to the capacity of the HR system and its associated strategies to respond rapidly and flexibly to shifts in both the internal organizational climate and the external market, regulatory, and competitive landscapes. It enables proactive rather than reactive adjustments to talent management approaches.

Intelligent Decision-Making:Moving beyond basic data reporting, this characteristic entails the use of advanced algorithms, machine learning models, and predictive analytics tools. These technologies transform raw data into actionable insights and foresight, providing a scientific, empirical basis for strategic HR decisions. This could manifest in AI-powered candidate matching, personalized learning path recommendations, or models identifying high-potential employees.

Self-Service Empowerment:Digital HR architectures often feature integrated platforms (e.g., Enterprise Resource Planning or dedicated HR Information Systems) that enable delegation of routine administrative tasks. Employees can manage personal data, request leave, access payslips, and enroll in training, while managers can handle approvals, conduct performance check-ins, and generate team reports. This decentralization of transactions improves operational efficiency, enhances user experience, and frees HR professionals for more strategic roles.

Cost-Effectiveness: A compelling pragmatic attribute is the emphasis on optimizing the economic equation of HR service delivery. Through automation of repetitive tasks, streamlining of processes, reduction of administrative overhead, and improved allocation of HR investments based on data, digital means offer the potential to significantly lower the operational costs of human resource management. Crucially, this is achieved not by diminishing service quality but often by enhancing it through greater speed, accuracy, and accessibility.

In synthesis, Digital HR emerges as a historically contingent concept born from technological progress, interpreted through diverse scholarly lenses that reflect regional and pragmatic emphases. Its operational essence, however, is captured in a cohesive model defined by a data-driven nucleus, augmented by agility, intelligence, user empowerment, and a strong imperative for value-driven efficiency. This conceptual framework provides the foundation for both understanding its current implementation and guiding its future evolution as a cornerstone of modern organizational management.

2.Literature Review of Digital Human Resources at Home and Abroad

Through sorting out relevant literatures, it is found that the

main research directions of domestic scholars on digital human resources mainly focus on five aspects: studying the importance and specific paths of digital human resources from the perspective of managers or enterprises, discussing the impacts brought by digitization at the employee level, researching the impacts of digital technology on human resources starting from digitization itself, putting forward suggestions on the combination of people and digital technology, and finally expounding the changes and challenges brought about in the digital era. Analyzing and discussing from the perspective of managers or enterprises, scholars Guo Jinhua and Zhu Chengliang, from the enterprise level, by citing the "value chain theory", put forward the necessity of digital human resources transformation of manufacturing enterprises and the improvement of enterprise added value. They also promoted the high added value at both ends of the "smile curve" of manufacturing enterprises from two aspects: upstream research and development innovation and downstream service operation, and proposed practical path choices[5]. Scholars such as Ma Qian took start-up enterprises and incubation platforms as the breakthrough points. By introducing digital technology, which brought opportunities and development to the above-mentioned enterprises, they proposed the digital enabling service path mechanism of "digital technology support service + organizational management optimization service co-creation ecosystem embedding mechanism", clarified the characteristics and differences of different stages of digitalization of innovative enterprises, and provided specific ideas for the selection of digital human resources of Xi'an Zhongke Chuangxing Technology Incubator Co., Ltd. through specific case analysis[6]. Discussing from the perspective of employees, scholars such as Li Shaolong proposed that in the digital era, human resources should adopt digital gamification management, that is, HRM. This group of scholars believes that in the situation where traditional incentive methods are gradually declining, more efforts should be made to stimulate employees to establish internal incentive motives, and gamified human resources under the digital environment is a novel and effective attempt[7]. Scholars Wang Shaojie and Li Jing, in management practice, recognized the change of employees from the "robots" established in the industrial era to the "digital people" with the advent of big data, and proposed that digital people will become the masters of organizational human resources[8].In terms of digital development, scholars such as Li Yanping adopted the digital-HRM research method and proposed that human resources should rapidly develop digitally to improve organizational management efficiency and enhance employees' technical capabilities. They also emphasized the urgency and inevitability of enterprises' digital transformation[9]. Scholars such as Zhang Zhipeng discussed that digital transformation has completely subverted human resources services, and analyzed the impacts of digital technology on organizational human resources from three dimensions: the digitalization of business resources, the scenario-based application of data resources, and the intelligence of data resources[10]. In terms of the integration of people and technology, scholars such as Xie Xiaoyun explored new practices of digital technology and human resources, sorted out and summarized dimensions such as training and development, assessment and supervision, reward and punishment mechanisms, the relationship between organizations and employees, human intelligence and machine intelligence, etc., and proposed the five major tensions in digital human resources. Scholars such as Li Ping proposed at the organizational structure level that artificial intelligence (objective intelligence) and human intelligence (subjective intelligence) have become a unity of opposites like yin and yang[11]. Regarding the changes and challenges brought to small and medium-sized enterprises (SMEs) in the context of the digital era, scholar Lei Jiewei discussed the changes and challenges faced by digital human resources from two aspects. On the one hand, technologies such as big data are used to achieve enterprise benchmark recruitment and improve the accuracy of human resources analysis. On the other hand, it is difficult for enterprises to carry out the top-level design of digital human resources, and there is a lack of relevant high-end digital professionals[12]. Scholars such as Lü Fen affirmed that SMEs are important contributors to China's economic development and used fsQCA to analyze how to promote the digital technology innovation capabilities of SMEs to adapt to the development of the times[13].

Foreign scholars have studied digital human resources in two parts according to the time series, taking the COVID-19 pandemic as a dividing line. Before the pandemic, most foreign scholars focused their research directions on the impact of the configuration of the digital employee model against the backdrop of the digital society and economy. For example, Fuchs proposed new digital labor forms such as

digital labor and digital work[14]. After experiencing the pandemic, foreign scholars have taken digital human resources as the key research focus and analyzed the impacts brought by digitization from different dimensions. Regarding the changes in the digital workplace, as the management gradually accepts new technologies, the workplace also needs to be adjusted accordingly. This new leadership style has introduced concepts such as flexibility. In this context, flexibility specifically means that the workspace is no longer limited to a specific physical location. Scholars such as Maral believe that during the pandemic, remote work and hybrid work have been widely adopted. They studied the impact of the shift in work patterns on office workers and analyzed the development potential of the future sustainable work environment. They analyzed the opportunities and challenges brought by the digital workplace from the perspectives of individuals, teams, and leadership, and concluded that in order to achieve the expected work patterns and value benefits, employers need to provide support and redesign the physical digital workplace to meet the diverse needs of employees[15].

In terms of the digital transformation of human resources, Villajos believes that over time, in order to enable organizations to adapt to more intense market competition, the focus of human resources needs to shift from traditional strategic management methods to sustainable management methods, and digitization is a necessary measure for human resources reform[16]. Standing at the level of human resources leadership, scholar Zervas discussed how to effectively promote the development of digital skills, enhance organizational resilience, and drive economic development, and concluded the necessity of digital practices carried out by human resources leaders[17]. Scholars such as Divya, through bibliometric methods, revealed the research trends in the fields of digital transformation and human resources management, providing references for subsequent research[18].

3.A renowned theoretical study

In addition, there exists a renowned theoretical model that provides a clear and systematic explanation of the dynamic relationship between organizations and talent mobility.Based on the "Attraction-Selection-Attrition" (ASA) theoretical model proposed by Schneider (1987), the illustrated diagram vividly reflects the dynamic process of how organizations and individuals achieve mutual adaptation through attraction, selection, and attrition — thereby shaping organizational homogeneity.

The ASA model highlights a crucial phenomenon: organizations tend to recruit and retain individuals who are similar to existing members, thereby reinforcing organizational homogeneity. Over time, this may lead to a lack of diversity in perspectives and thinking, potentially hindering innovation and adaptability. Therefore, modern organizations should strive to strike a balance between maintaining cultural consistency and introducing appropriate diversity while applying the ASA framework. For instance, during the attraction stage, organizations can showcase not only their cultural strengths but also their openness and inclusiveness. During the selection phase, assessment tools can be designed to evaluate not only job skills but also whether candidates can bring new perspectives and experiences. In the attrition stage, organizations should establish mechanisms for feedback and adjustment, allowing individuals who do not fully fit in but possess unique value to have opportunities for adaptation and growth.Furthermore, with the rise of digital human resource management, the application of the ASA model has gained new possibilities. For example, organizations can use data analytics to more accurately assess the degree of match between individuals and the organization; intelligent recruitment systems can simulate organizational culture and work scenarios, allowing candidates to experience them in advance; and employee retention analysis models can help identify attrition risks early and intervene. These digital tools not only enhance the efficiency of attraction, selection, and attrition but also make these processes more scientific and precise.

In summary, the ASA model provides a profound analytical framework for understanding the interaction between individuals and organizations. In practical applications, organizations should remain vigilant against the potential negative effects of excessive homogeneity, flexibly adjusting human resource management strategies to achieve a dynamic balance between organizational consistency and individual diversity.

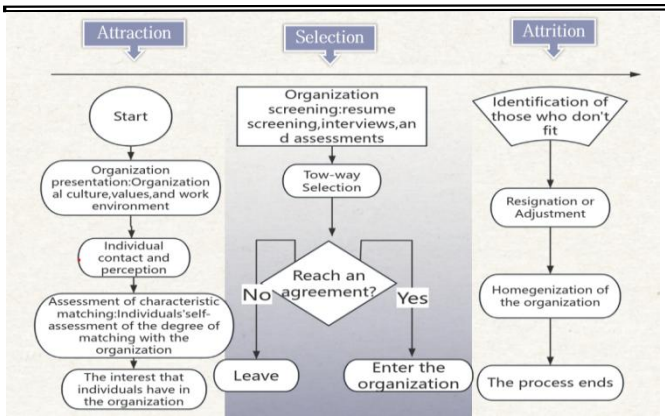

Fig.1.

Building upon the "Attraction-Selection-Attrition" (ASA) model, digital human resources (Digital HR) is revitalizing this classic framework by infusing it with unprecedented dynamism, granularity, and strategic value, allowing it to evolve from a descriptive explanation of organizational homogeneity into a prescriptive engine for managed diversity and adaptive resilience. While the traditional ASA model is often critiqued for potentially fostering static, insular organizations in today's volatile and complex business landscape, Digital HR intervenes precisely at this intersection of legacy theory and modern practice, transforming each phase through data-driven innovation. In the Attraction phase, organizations move beyond broad cultural messaging to targeted, predictive engagement — leveraging analytics from platforms like LinkedIn and Glassdoor for hyper-targeted employer branding, using algorithms to analyze digital footprints of successful employees to build "ideal fit" profiles for proactive candidate identification, and offering immersive pre-experiences through VR tours and AI chatbots to strengthen the quality of initial engagement. The Selection phase is elevated from subjective assessment to an augmented, bias-aware intelligence process, where AI-powered screening tools analyze contextual evidence of skills and problem-solving approaches, structured digital interviews provide data-rich insights into communication styles and cognitive preferences, and carefully designed AI systems help mitigate bias in job descriptions and evaluations — enabling organizations to select for "cultural add" rather than mere "cultural fit." In reimagining Attrition, Digital HR redefines it from a passive exit endpoint into a continuous feedback loop for organizational learning and talent agility, utilizing predictive attrition risk modeling by integrating data from HRIS, engagement surveys, and productivity tools to identify employees at high risk of leaving, while AI-powered internal talent marketplaces transform potential attrition into dynamic internal redeployment by mapping employees' capabilities and aspirations to new roles or projects, and continuous cultural sensing through sentiment analysis and collaboration pattern monitoring ensures that organizational homogeneity evolves adaptively rather than stagnantly. Ultimately, under Digital HR's influence, the ASA model becomes an interconnected, data-rich cycle that consciously manages the core paradox of building a strong, coherent culture while actively incorporating diverse skills and perspectives, revitalizing it as a framework for "Intelligent Organizational Adaptation" that guides organizations in attracting aligned talent, selecting candidates who thrive and healthily challenge the status quo, and interpreting attrition signals as opportunities for learning and agile restructuring — fostering culturally cohesive yet dynamically diverse organizations equipped to innovate and compete in the 21st century, with the theory's new vitality lying in its enhanced capacity to explain and shape the modern, data-infused interplay between individuals and organizations.

Review and Research Prospects

In the contemporary era, the field of digital human resources (Digital HR) finds itself in a continuous and dynamic process of scholarly exploration and practical application. Its developmental trajectory is not characterized by radical disruption but rather by a more nuanced pattern of gradual, cumulative progress. This trend is substantiated by the observable, year-on-year increase in academic and professional literature dedicated to the subject. The proliferation of such research output signifies a maturing field, with the volume of studies presenting an increasingly rich and multifaceted discourse. The substantive findings and theoretical contributions embedded within this growing corpus of literature are progressively transcending the confines of abstract theory. They are being operationalized and integrated into the practical workflows of enterprises and organizations worldwide, thereby introducing novel paradigms and methodologies to the domain of human resource management.

A comparative analysis of domestic and international research landscapes on Digital HR reveals distinct and significant paradigmatic differences, each with its own strengths and limitations. The perspective dominant in much

of domestic research tends to coalesce around two primary focal points. Firstly, it strongly emphasizes the urgency and strategic imperative of HR digital transformation, positioning it as a critical, non-negotiable element for the competitiveness and survival of modern enterprises in the digital economy. Secondly, it undertakes a multi-faceted analysis of the impacts of digital technologies across the entire HR value chain, meticulously examining changes in processes from recruitment and talent acquisition, through learning and development, to performance management and compensation. However, a prevalent critique of this body of work is that a substantial portion remains at a relatively descriptive or surface level. It often presents what can be termed a "digitization + HRM" model — layering digital tools onto existing HR processes — without delving sufficiently into the deeper, transformative implications. This surface-level engagement manifests in several specific methodological and theoretical shortcomings: the absence of a widely accepted, robust theoretical framework to ground empirical studies; insufficient integration of macro-level contextual factors (e.g., national digital infrastructure, labor market dynamics, regulatory environments) into the research design; a lack of clarity in research pathways and logical progression; and a notable deficit in rigorous empirical analysis and longitudinal data to validate proposed models and outcomes. This constellation of challenges naturally prompts critical reflection on the future developmental trajectory of Digital HR as a discipline. Key questions emerge: How can Digital HR research transcend its current limitations to construct more sophisticated, predictive, and sustainable theoretical models? In practice, how can enterprises move beyond mere tool adoption to leverage Digital HR strategically, thereby enhancing overall management quality and securing a decisive advantage in hyper-competitive markets? These pressing questions underscore the urgent need for enrichment, methodological refinement, and theoretical deepening in subsequent scholarly inquiry.

In contrast, the international research perspective offers a distinct, though not unproblematic, approach to understanding digital transformation. Foreign scholars have cultivated unique conceptual understandings and research trajectories, often segmenting the transformation journey into discernible phases, such as digitization (converting analog to digital), digitalization (using digital data to streamline processes), and digital transformation (fundamentally rethinking business models). This phased model provides a valuable heuristic for understanding organizational maturity. However, a noteworthy and critical observation is the tendency among some scholars to conflate or simplistically equate "digitization" with "digital intelligence" or full automation. This conflation can be viewed as a reductionist stance, as it risks marginalizing the enduring and crucial role of human agency, judgment, and strategic oversight within digitally enabled HR systems. It overlooks the socio-technical dimension where technology augments rather than wholly replaces human decision-making and relational aspects of management.

Despite this particular conceptual pitfall, the international research corpus presents numerous aspects worthy of considered (reference). Strengths often include a stronger tradition of interdisciplinary research (merging HR studies with data science, information systems, and organizational theory), a greater emphasis on constructing and testing theoretical frameworks, and more extensive use of empirical, often quantitative, research designs. As the global community of scholars and practitioners ventures further into the complexities of the Digital HR domain, it is imperative to uphold an objective, critical, and scientifically rigorous attitude. The path forward involves a judicious synthesis: reasonably drawing upon and adapting the robust methodologies and theoretical advances from international research while discarding overly simplistic or technologically deterministic assumptions. Simultaneously, domestic research must build on its applied strengths by deepening theoretical rigor and empirical validation. The ultimate goal should be to seek common ground — shared fundamental questions about technology, people, and organization — while respecting and learning from different contextual perspectives. It is on this foundation of critical synthesis and methodological advancement that the future of Digital HR research, both in China and globally, can achieve deeper, more impactful, and sustainable development, ultimately guiding organizations to foster workplaces that are not only technologically advanced but also humane, adaptive, and strategically astute.

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Waste-Free Recycling Technologies – A Step Towards Sustainable Production Development

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KEYWORDS

Tin-lead slag;
High-grade solders;
Lead-free solders;
Tin chloride;
Salt slag;
Regeneration

ABSTRACT

This paper presents the results of research into the production of high-grade solders from tin-containing slag recycled from the melt. Excess copper is removed by filtering the rough solder over a specific temperature range, yielding POS61 solder. The resulting filter residue is used for alloying gray cast iron. To produce lead-free solders, lead is removed by mixing SnCl2 into the melt at a 10:1 ratio. Regeneration of the resulting salt slag to extract SnCl2 and reuse it is carried out using fractional crystallization in water, taking into account the different solubility of SnCl2 and PbCl2 at low temperatures.

ВВЕДЕНИЕ

Отсутствие в Республике Беларусь собственных месторождений оловянных руд требует бережного отношения к оловосодержащим отходам, образующимся в результате утилизации средств автоматизации и электроники, где используются припои на основе олова. Потребление олова в производстве припоев в последнее время растет, особенно в КНР, что связано с расширением выпуска продукции электронной промышленности. Спрос на олово расширяется благодаря увеличению потребления припоев, не содержащих свинец, которые более перспективны с точки зрения экологии. Припои, которые обычно содержали около 63 % олова, заменяются припоями с концентрацией олова более 95 %, что способствует росту спроса и цен на олово. Согласно стандартам SN100MA-S и DIN35229 содержание свинца в припоях не должно превышать 0,05 %.

Цены на металл с марта 2020 года выросли в 2,5 раза, установив исторический максимум на уровне 36797 долларов за тонну. С 2021 года запасы олова на биржевых складах упали примерно в 23 раза, что свидетельствует о жестком его дефиците на рынке. При этом половина спроса на олово приходится на припой [1].

В Республике Беларусь среди оловосодержащих отходов большой объем составляет оловянно-свинцовая изгарь, при рециклинге которой получают сплавы с повышенным содержанием примесей, в первую очередь меди и железа. Причиной накопления этих элементов в составе получаемого сплава является смешивание оловосодержащих отходов разного состава в процессе их накопления и заготовки [2], а также образование их в технологическом процессе пайки.

Основная часть

Усилиями сотрудников научно-исследовательской лаборатории литейных технологий филиала БНТУ «НИПИ» разработана технология получения качественного припоя из продуктов рециклинга оловянно-свинцовой изгари путем удаления из расплава меди и железа до допустимых пределов [3, 4]. В результате фильтрации чернового расплава ПОС61М получен эвтектический припой, соответствующий марке ПОС61 с остаточным содержанием меди не более 0,10 %,

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а железа и никеля – менее 0,10 %, который по своему составу и свойствам соответствует требованиям производства [5]. Образующиеся фильтр-остатки, содержащие олово и медь, используются для легирования серых чугунов с целью повышения их механических свойств и марки чугуна. При этом добавка олова составляет 0,06–0,1 %, а для меди 0,4–0,6 % для получения марок чугуна выше СЧ25.

В последние годы в целях защиты потребителей бытовой техники от контакта со свинецсодержащими материалами в странах ЕС запрещено использовать аналогичные припои. Поэтому появилась необходимость обеспечить отечественных производителей холодильников, стиральных машин и различных электрических приборов бессвинцовым припоем. При этом в качестве основы такого припоя можно использовать продукт рециклинга оловянно-свинцовой изгари. Из металлургии тяжелых цветных металлов известно, что удалить свинец из расплава на основе олова можно за счет организации обменной реакции:

$$Pb + SnCl2 \leftrightarrow PbCl2 + Sn,$$

протекающей слева направо при температуре ниже 450 ºС [6]. Практически процесс стараются вести при минимально возможной температуре (240–250 ºС), с расходом хлористого олова от 6 до 80 кг на 1 кг свинца. Возможно также прямое удаление свинца из чернового олова обработкой элементарным хлором при температуре 250–270 ºС, но данная технология требует дорогостоящих защитных сооружений и высокой технологической дисциплины. Поэтому разрабатывалась технология удаления свинца из оловосодержащего сплава с использованием хлористого олова.

В качестве объекта исследования использовали отработанный припой на основе олова с содержанием 0,185 % свинца. Исходный состав припоя массой 1 кг расплавляли в чугунном тигле печи сопротивления при температуре 250±5 ºС и замешивали соль SnCl2 в соотношении с расплавом 10:1 (10 кг). Замешивание проводили специальной мешалкой в течение 5-45 минут, используя каждый раз свежие составы.

После снятия хлористых съемов с поверхности расплава его разливали в слитки и проводили анализ на остаточное содержание свинца, железа и меди. Результаты изменения концентрации свинца от времени замешивания в расплав SnCl2 приведены на рисунке 1. Из графика следует, что время замешивания SnCl2 в расплав существенно влияет на остаточное содержание свинца в припое и уже после 15 минут обеспечивается его приемлемая концентрация. Одновременно за это время изменяется и содержание в припое других примесей (таблица 1).

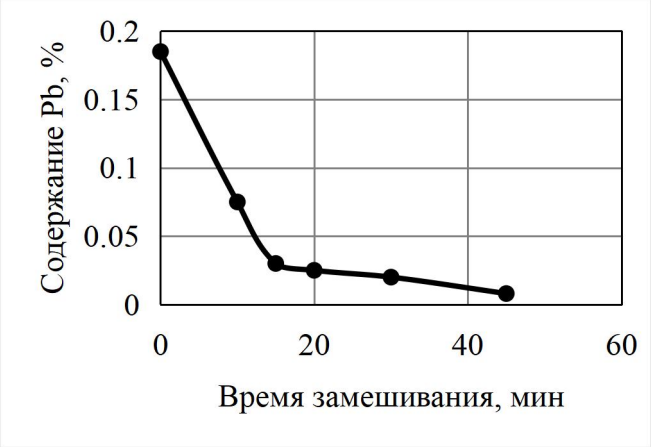

Рисунок.1.Влияние времени замешивания SnCl2 на остаточное содержание свинца в припое

Припой	Содержание элементов, %						
	Pb	Sb	Bi	Cu	Ni	Ag	Sn
Исходный	0,185	0,009	0,007	0,94	0,14	0,003	остальное
Рафинированный	0,03	0,009	0,005	0,03	0,05	–	остальное

Таблица.1.Химический состав припоя до и после рафинирующей обработки в течение 15 минут

Эффективно сказалась обработка также на примесях меди, никеля и серебра. Содержание сурьмы и висмута не изменилось, но оно не превышало допустимых пределов. Увеличение времени замешивания SnCl2 в расплав припоя до 45 минут обеспечило снижение содержания свинца до 0,008 % при соотношении свинца в сплаве к олову в шлаке равным 1:100. Однако следует ограничиться 15 минутами перемешивания из экономических соображений.

Для реализации такой технологии на производстве необходимо решить вопрос о регенерации образующихся солевых смесей SnCl2– PbCl2 с целью дальнейшего использования SnCl2 при рафинировании олова от свинца, учитывая его высокую стоимость. С этой целью изучали растворимость солей SnCl2 и PbCl2

в воде в зависимости от температуры.

PbCl2 слабо растворим и не подвержен гидролизу в процессе растворения как в малом, так в избыточном количестве воды. Растворимость его составляет 0,673 г при 0 ºС и 3,25 г при 100 ºС. SnCl2 (безводный, плавленый) имеет растворимость 83,9 г при 0 ºС и 269,8 г при 100 ºС. В избытке воды он подвержен сильному гидролизу с выпадением осадка. В малом количестве воды SnCl2 растворяется без труда, но склонен к окислению на воздухе и эти процессы ускоряются при повышении температуры. Поэтому было принято решение растворять шлаковую смесь солей в небольшом избытке воды с соотношением воды к солям 3:1 при температуре не более 20 ºС и интенсивном перемешивании. Для стабилизации раствора использовали 1 % HCl в присутствии металлического олова, содержащегося в шлаковой смеси солей в виде корольков. Это обеспечило достаточно полный переход SnCl2 в раствор.

Разделение совместного раствора SnCl2 и PbCl2 проводили способом дробной кристаллизации в полиэтиленовой таре при температуре +4…-5 ºС выстаиванием в течение 24 часов с последующей декантацией раствора хлорида олова с осадка кристаллов хлорида свинца. Суспензия кристаллов последнего фильтровалась на гравитационном бумажном фильтре до получения влажного осадка. Очищенный раствор хлорида олова с примесями никеля и меди подвергался упариванию до состояния плава и кристаллизовался при последующем охлаждении. Таким способом удалось понизить содержание PbCl2 в шлаковом расплаве хлоридов с 1 % до 0,05 %, что позволяет повторно использовать регенерированный SnCl2 в виде кристаллогидрата при добавке 50 % в смеси с чистым SnCl2·2H2O для рафинирования оловянных припоев с содержанием свинца 0,10–0,15 %. При очистке припоев, содержащих до 0,5 % свинца, двух стадийной обработкой на первой стадии возможно применение флюса, полностью состоящего из регенерированного хлорида олова, а на второй стадии – использовать смесь регенерата с чистым SnCl2 в соотношении 50 : 50 %.

Отработанная технология рафинирования оловянных припоев позволяет получать марочные составы бессвинцовых припоев и рационально использовать SnCl2 [7].

Учитывая, что чистое олово склонно к саморазрушению при низких температурах из-за «оловянной чумы», припои на основе олова дополнительно легируют в небольших количествах медью, никелем и другими элементами. В качестве варианта снижения в них содержания меди можно использовать способ обработки расплава серосодержащими флюсами.

Заключение

В результате проведенных исследований разработана безотходная технология рециклинга оловосодержащих отходов с получением марочных бессвинцовых припоев, востребованных отечественными предприятиями. Это обеспечило возможность поставки производимой продукции на экспорт и стабилизировать их работу. Предложенная технология регенерации образующегося солевого шлака позволила возвращать в производство SnCl2 и извлекать PbCl2, используемый при производстве аккумуляторных батарей.

С использованием результатов исследований в 2024 году переработаны оловосодержащие отходы в оловянно-свинцовые и бессвинцовые припои для ОАО «Минский часовой завод» и ПК ООО «Литопласт» на сумму более 6500 рублей.

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БЕЗОТХОДНЫЕ ТЕХНОЛОГИИ РЕЦИКЛИНГА – ШАГ К УСТОЙЧИВОМУ РАЗВИТИЮ ПРОИЗВОДСТВА

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В работе приведены результаты исследований по получению марочных припоев из продуктов рециклинга оловосодержащей изгари. Удаление избыточной меди обеспечивается путем фильтрации чернового припоя в определенном диапазоне температур с получением припоя ПОС61. Образующиеся фильтр-остатки используются для легирования серого чугуна. При получении бессвинцовых припоев свинец удаляется при замешивании в расплав $SnCl_2$ в соотношении к расплаву 10:1. Регенерация образующегося солевого шлака для извлечения $SnCl_2$ и его повторного применения проводится с использованием дробной кристаллизации в воде с учетом разной растворимости $SnCl_2$ и $PbCl_2$ при низких температурах .

Ключевые слова: Оловянно-свинцовая изгарь, марочные припои, бессвинцовые припои, хлорид олова, солевой шлак, регенерация.

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Big Data Analysis Of Common Grammar Errors Among EFL Learners: A Basis For Improving English Writing Instruction Aligned with SDG 4 (Quality Education)

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KEYWORDS

Corpus-based research;

EFL writing;

Grammar error analysis;

NLP-assisted tools;

Data-informed instruction;

Sustainable development Goal 4

ABSTRACT

The increasing availability of digital learner data has opened new possibilities for enhancing the quality of English as a Foreign Language (EFL) instruction. This study investigates recurring grammar error patterns in EFL learners' writing using a corpus-based, big data-informed approach. Grounded in Error Analysis Theory and Interlanguage Theory, the study analyzes a large digital corpus of learner- written texts to identify systematic grammatical difficulties, including errors in verb tense, article usage, prepositions, subject-verb agreement, and sentence structure.

The findings reveal these grammar errors are not random performance mistakes but consistent indicators of learner's developing interlanguage system. Unlike traditional grammar instruction, tends to look at small scales or small samples like a few essays, maybe one class and limited classroom samples while digital corpora and NLP-assisted analysis enables to see and identify thousands of texts and writings. Big data does not work as a substitute for teachers, but as a tool that strengthens instructional insight through large-scale evidence. To allow us to move from assumptions to evidence and from guessing to knowing.

By informing data-driven curriculum design, supporting AI-assisted feedback practices, and enhancing teacher decision-making, the study demonstrates how large-scale learner data analysis can contribute to more effective and inclusive EFL writing instruction.

In alignment with Sustainable Development Goal 4 (Quality Education), this research highlights the potential of evidence-based and learner-centered teaching approaches to promote more effective, inclusive, and equitable EFL writing instruction across diverse educational contexts.

INTRODUCTION

In the 21st century, education has entered the era of data. Every sentence written by a student becomes part of a larger story that can reveal how language is acquired and developed. Yet, in the world of teaching specifically language teaching, we are often guided with intuition and limited classroom observation rather than empirical evidence. This study was inspired by a simple and real classroom experience: behind every grammar mistake is a learning opportunity. However, it gives the idea and realization that there are some failed strategies in traditional teaching. So, big data analysis enters the classroom, not to replace the teachers but one that allows educators to empower insights

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drawn from thousands of learner output. Traditional approaches to grammar instruction usually rely on small classroom samples and teacher intuition. While these approaches are valuable, they may not capture broader tendencies across learners and tasks. With the increasing use of digital writing platforms, it has become possible to test learner writing in larger numbers. This creates an opportunity to move beyond isolated examples and toward a more comprehensive understanding of grammar errors.

In many EFL classroom, students are able to generate meaningful ideas but struggle to present them accurately and comprehensively in written English. Teachers often spend considerate time correcting grammar, yet similar errors continue to appear ibn students' work. This situation raises an important question: are grammar errors simply mistakes, or do they reflect deeper patterns in how learners develop written language?

Learning English as a foreign language can be challenging, especially in writing. Many students make similar grammar mistakes that can affect their ability to communicate clearly. Furthermore, it looks at the most common grammar errors made by EFL learners in their writing. Understanding these mistakes will help teachers improve how they teach English writing, making learning easier and more effective.

Many students learning English as a second language struggle with grammar when writing. These errors can slowdown their progress and make communication vague. By analyzing common grammar errors found in EFL learners' writing, this research aims to support and improve better teaching methods that address these challenges effectively.

Writing can be a challenge filled with many grammar errors. These errors often result from misunderstanding of English rules. It collects and looks at those frequent errors to guide educators and language advocates in developing clearer and more helpful writing instruction.

This paper examines how data-based analysis can be used to identify common grammar error patterns among EFL learners and how these insights can help improve English writing instruction. By focusing on recurring errors rather than isolated mistakes, the study aims to provide a clearer basis for improving English writing instruction. In doing so, it seeks to support teaching practices that are more responsive to learner needs and aligned with the objectives of SDG 4, particularly in promoting effective, inclusive, and quality education.

1.THEORETICAL FRAMEWORK

This research is anchored on three major theories that explain why learners make grammar errors and large-scale data can provide deeper insight into their writing performance. The framework integrates Corder's Error Analysis Theory, Selinker's Interlanguage Theory, and the Big Data Analytics Model. Together, these theories guide the analysis, interpretation, and application of findings for improved English writing instruction.

1. Corder's Error Analysis Theory (1967) main idea that leaners' errors are not sign of failure but valuable evidence of learning in progress. It points out that classifying errors into systematic categories such as verb tense, articles, prepositions, S-V agreement, and sentence structure. Big data strengthens Corder's theory by allowing researchers to examine thousands of errors at once, making error patterns more reliable and visible.
2. Selinker's Interlanguage Theory (1972) introduced thew concept of interlanguage-which is influenced by both their first language (L1) and the target language (L2). Interlanguage is a temporary, evolving system that changes as learners gain more exposure and feedback. Interlanguage contains:

(1) The learner's first language (L1)
(2) General learning strategies
(3) Rules invented by the learner to fill the gaps in their knowledge
(4) Errors are signs that the interlanguage system is developing and self-adjusting over time.

This research, Interlanguage Theory helps explain:

(1) Why certain errors are common across L1 groups?
(2) Why some grammar forms develop earlier or later?
(3) How learners' internal rules influence their writing?
(4) Why predictable patterns appear consistently in the data?

By analyzing errors of writing samples, big data allows us to observe how interlanguage forms and evolves on a large scale.

Connection between the two theories:

Corder's theory tells us why it's important to study learners' errors, while Selinker's theory explains how those errors

form and evolve. Together, they provide the theoretical foundation for using big data analysis to trace and understand patterns of grammar errors among EFL learners.

2.PURPOSE OF THE STUDY

The purpose of this study is to examine recurring grammar error patterns in the written work of EFL learners using a big data-informed analytical approach. By identifying common areas of grammatical difficulty across learner texts, the study aims to provide a clearer basis for improving English writing instruction. Specifically, the study seeks to move beyond learners' level error correction and toward a deeper understanding of how grammar errors reflect learners' language development. The findings are intended to support more effective and inclusive writing pedagogy, in line with the goals of quality education under SDG 4.

3.RESEARCH QUESTIONS

1. What types of grammar errors commonly appear in the written texts of EFL learners?
2. Which grammar error categories occur most frequently across leaner text samples?
3. In what ways can a big data-informed approach contribute to more effective and inclusive EFL teaching practices aligned with SDG 4?

4.RELATED LITERATURE

Many experts believe that technology will not replace teachers, but rather will transform the role of teachers. In the past, teachers were the main source of information and knowledge. The future teacher will be more like a coach, helping students to find and use information for themselves (*Ashrafimoghari,2022)*. It is through helping educators and designers redesign and enhance their instructional insights and lesson accordingly. Learning analytics is a data-driven approach to understand how people learn, so that you can help them learn better (*Ashrafimoghari,2022*). It is design to analyze thousands of students writing and outputs.

Errors are the deviations or wrong forms of a language reflecting the competence of the learner. There can be various causes of errors. One of the causes of errors is the ignorance of appropriate rule in the foreign language. (Dr. Neupane cited Corde, 1999) Errors are not merely a deviation but rather, a reflection of growth and cognitive development. Error analysis is the systematic study and analysis of the errors committed by second language learners (Richards & Selinker, 2008). Grammatical error for language learners has recently attracted increasing interest in the Natural Language Processing (NLP) community. Grammatical error has the potential to create commercially viable software tools for the large number of students around the world who are studying a foreign language, in particular the large number of students of English as a Foreign Language (EFL) (Dahlmeier et al). NLP is a tool use detect large scale of student's writings and can help teachers detect errors which are in five categories: verb tenses, subject – verb agreement, preposition, articles, and sentence structure. The results show that verb tense was the most frequent. Article omission and preposition errors were also common, especially among learners whose first language differ structurally from English. As suggested by Corder (1967), mistakes are related to problems in performance, just like a slip of the tongue or pen. However, errors are systematical complications that indicate competence-related problems, contributing to the learner's progress (Gazioglu et al., 2024 cited Corder,1967). The most important is that these patterns were consistent across thousands of texts, and it is systematic, predictable, and teachable.

The biggest obstacle for grammatical error correction has been that until recently, there was no large, annotated corpus of learner text that could have served as a standard resource for empirical approaches to grammatical error correction. (Dahlmeier cited Leacock et al.,2010). Through hard work and consistency, they were able to create the UNS Corpus of Learner English (NUCLE), a large, annotated corpus of learner texts that freely available for research purposes. which can also be used as a tool. NUCLE can examine over thousands of students essays with a total of over one million words which are completely interpreted with error tags and corrections. Though, NUCLE has been there and available for two years now, there has been no reference paper that describe the details of the corpus.

Natural Learning Processing (NLP) tools handle tasks like text analysis, tagging, and pattern recognition in large datasets, such as learner text for grammar error detection. In EFL research, they automate error identification in writing samples, far beyond manual counts. Tools like AntConc or Wmatrix exemplify this by generating words and frequency stars from big data. Some common options for conceptual

works include:

1. AntConc – free software for words, collocations, and keyword extraction; ideal for spotting verb tense issues in EFL texts (Gazioglu, M., & Aydin, S. (2024)
2. Wmatrix – web interface with semantic tagging (USAS/CLAWS); compares sub-corpora to track learner progress. (Wmatrix7 onwards)
3. Sketch Engine – commercial tool for word sketches and grammar profiling; supports multilingual error analysis (Kilgarriff, A et al., 2004)

These are some tools which detect students' writing errors and can enhance teacher's insights at scale and teaching strategies. Another tool is spaCy designed for industrial -strength natural language processing (NLP), excelling in tasks like tokenization, part-of-speech tagging, dependency parsing, and named entity recognition. spaCy automates grammar profiling via dependency parsing (Honnibal & Montani,2017), pairing with AntConc for hybrid EFL analysis.

Research indicates that the use of digital learning tools such as e-books can enhance language learning achievement by overcoming physical barriers between teachers and students and fostering a deeper understanding of learners' learning contexts (Songkhro et al., 2025). These findings support the present study's argument that technology -assisted and data-informed approaches can promote and enhance more inclusive and effective EFL instruction. Though e-books are not classified as big -data, their use in digital learning gives large-scale learner interaction data, which can be analyzed to inform data-driven and EFL teaching methods and practices.

5.METHODOLOGY

This study adopts a qualitative descriptive research design supported by a corpus-based, big data-informed analytical approach. The design focuses on identifying recurring and systematic grammar error patterns in EFL learners' written texts rather than evaluating errors one by one.

This approach is for examining real learner language and aligns with Error Analysis Theory (Corder,1967) and Interlanguage Theory (Selinker,1972), which emphasize systematic patterns of learner errors as evidence of language development.

DATA COLLECTION

The data consisted of a large collection of learner-written texts which include essays, reports, reflections, and academic papers produced and collected from EFL university learners at Shinawatra University, Thailand representing a range of proficiency levels. Specifically, the data is comprised approximately 300 essays written by Chinese EFL students by open argumentative topics like "Technology Role in Education" to encourage learners to produce original output. The use of a large dataset allows the study to move beyond isolated classroom samples and toward a more comprehensive understanding of grammatical difficulties experienced by learners. All learner texts were collected from regular coursework, anonymized prior to analysis, and used only for research purposes, with no impact on students' academic evaluation and performance.

ERROR CATEGORIES

Grammar errors were identified and classified into five major categories based on frameworks in Error Analysis Theory (Corder,1967) and Interlanguage Theory (Selinker,1972). The analysis focused on the following:

1. Verb tense
2. Subject -verb agreement
3. Article usage
4. Prepositions
5. Sentence structure and word order

These categories were selected because they are widely recognized as persistent problem areas in EFL writing and frequently associated with first language transfer effects.

ANALYTICAL PROCEDURE

We used Python- based natural language processing (NLP) tools, including spaCy assist in identifying grammatical errors, which were interpreted within established error analysis frameworks.

The analytical procedure involved are the following steps:

1. Compilation of learner -all learner written text were compiled into a digital corpus suitable for computational analysis.
2. Automated Error Detection – Python -based Natural Language Processing (NLP) tools, particularly spaCy were used to process corpus, it performed tasks such as

tokenization, part-of-speech tagging, and dependency parsing to identify grammatical deviations related to the error categories.

3. Error Classification – identified grammatical patterns and deviations were grouped according to five categories.
4. Manual interpretation – automated results were manually reviewed to ensure pedagogical relevance and theoretical alignment. This helped identify systematic errors from occasional mistakes and ensured accurate interpretation of findings.

6. DATA ANALYSIS

Although frequency tendencies were observed, the study does not aim to provide statistical generalization but rather qualitative pattern identification across large-scale learner data. This section presents the analysis of grammar errors identified in the EFL learners' written texts using a corpus -based, big data-informed approach. Rather than examining individual learner performance, the analysis focuses on recurring and systematic grammar error patterns across a large collection of learner texts.

Digital learner corpus was examined using NLP – assisted corpus analysis tools to identify frequently occurring grammatical forms and deviations into predefined categories based on established error analysis frameworks. The analysis emphasizes patterns, frequency tendency, and persistent errors, rather than precise numerical measurement.

The results confirmed what many teachers observe, but now supported by strong data. Verb tense misuse was the most frequent error type, especially with perfect tenses. These errors included inconsistent tense usage within sentences and inappropriate tense use in written discourse. Such error patterns are common aspect which are often influenced by learners' first language structures.

Article omission was extremely common among learners whose native language have no article system like Thai and Chinese. Many learners have demonstrated difficulty in exercising definite and indefinite articles accurately, because they never use them in their first language. This finding s supports interlanguage theory that learners develop internal rules that may not fully align what is being used normally in English language.

Preposition confusion was another major challenge especially using "in," "on," and "at." Learners frequently used incorrect preposition and confused them entirely.

Errors related to subject-verb agreement were also observed, specifically in complex sentence structures.

Finally, sentence fragments and run-ons are also present which is due to difficulty in organizing ideas in a second language.

7.DISCUSSION

The findings of this study indicate that grammar errors in EFL learners' writing are systematic and consistent rather than random. The frequent occurrence of errors related to verb tense, article usage, prepositions, subject-verb agreement, and sentence structure suggests that these areas represent persistent challenges in English writing world. These results reinforce the view that grammar errors should be understood as part of learners' linguistic development rather than as isolated mistakes.

We need to shift our focus from simply identifying errors one by one to understanding them. When we hear our student say "she go to school every day", are not signs carelessness or laziness but it is a reflection of learners' evolving internal rule systems. Large-scale learner data makes it possible to observe how grammatical errors evolve over time, offering insights to learners' movement toward more target-like language use. This supports Corder's (1967) argument that errors provide valuable evidence of learning in progress.

How can we apply this?

The study supports **data-informed curriculum design**, enables educators to prioritize instructional content based on recurring grammar error patterns identified through large-scale learner data. Common grammar errors like verb tense, article usage, and sentence structure, can be integrated into writing curricula, ensuring that teaching content directly addresses learner's most persistent difficulties.

In addition, the integration of **AI-powered feedback tools** and NLP-assisted corpus analysis offers practical support for EFL writing instruction. Integrate writing platforms that analyze student errors in real time to help teachers and provide instant, personalized feedback. AI powered tools, such as ChatGPT, can generate immediate, detailed, and personalized feedback on student writing, potentially alleviating the workload of educators and providing timely assitstance to learners (Guo et al.,2024; Lee and Moore,2024)

The use of big data and NLP tools also contributed to teacher empowerment. Teachers can use error analytics dashboards to visualize which grammar topics cause the most difficulty enabling targeted remediation. Enhancing approach such workshops and ongoing support, aligning with SDG 4's teacher developing targets.

1. Corpus Training- teachers query sub-corpora for authentic examples, creating tailored drills example: depend on vs depend in.
2. AI Integration – freeing time for mentoring on cross-linguistic contrasts.
3. Collaborative Design – peer forums share Sketch Engine outputs, refining rubrics.

Cross- linguistic awareness, teachers should understand how a student's first language shapes their English grammar and address those predictable transfer errors explicitly. By understanding how learner's first language influences English writing, teachers can interpret errors more constructively and adopt inclusive, learner-centered strategies. This is what big data offers: clarity, precision, and personalization.

In alignment with Sustainable Development Goal 4 (Quality Education), the findings emphasize how data-informed approaches can support more effective, equitable and sustainable EFL teaching. Rather than replacing human insight, large-scale data analysis amplifies teachers' professional judgement by providing clearer, evidence-based perspectives on learner needs.

Big data is about amplifying teacher's strategies and methodologies. It helps us see learners as unique data stories, each mistake a clue, each sentence a step toward fluency.

Grammar instruction should be informed by authentic learner data rather than assumptions. By focusing on frequent and persistent errors, teachers can design more effective and targeted writing instruction. Big data can be of big help to improve writing instruction and improve common grammar errors of the learners.

CONCLUSION AND RECOMMENDATIONS

This study demonstrates that large-scale, corpus-based analysis provides a strong foundation for understanding grammar error in EFL learners' writing. Language learning generates substantial amount of analyzable data, including essays, digital submissions, and classroom writing tasks. Traditionally, such data has been examined through small samples, limiting the totality of findings. A big data-informed approach addresses this limitation by revealing patterns and tendencies that are not visible through only classroom observation.

In the context of EFL teaching, corpus-based analysis enables educator to identify common grammar errors across groups of learners examine their persistence, and relate them to linguistic development and first-language influence. Grammar error should therefore be viewed not as simple deviation, but as reflection of ongoing interlanguage development. It provides a scientific foundation for improving instruction because it allows educators to:

1. Identify common grammar errors across large groups of learners, not just within one classroom.
2. Understands the frequency and distribution of these errors, showing which grammar areas need greater emphasis.
3. Link learner errors to first language influence, proficiency level, or learning environment.
4. Develop evidence- based teaching strategies that target the most frequent and persistent problems.

In short, the basis of big data analysis in English teaching is its ability to transform qualitative observations into quantitative evidence, giving teachers and researchers a clearer, data-driven picture of how students learn, struggle, and improve in using English. Big data when used with empathy and insights, becomes more than just numbers and algorithms. It becomes a bridge between transformation and understanding. Learner errors should not be viewed simply as deviations, but as indicators of ongoing linguistic development and cognitive processing.

As researchers and educators, we must use technology not to standardize learning, but to humanize it. To connect with our student's journeys, recognize their challenges and guide them with compassion and evidence.

Based on the findings, big data analysis helps us understand grammar errors as part of the learning process and provides a strong basis for improving English writing instruction. EFL teachers should **adopt corpus-based and data -informed approaches** to identify and address common grammar errors in writing instruction, educational institutions should support the use of **NLP-assisted and AI -powered feedback tools** as complementary resources to develop writing skills, teacher training programs should emphasize **cross-linguistic awareness** to help educators

better understand learner error patterns, and future research may develop to examine how grammar error patterns evolve over time across proficiency levels.

Overall, when used thoughtfully, large-scale learner data analysis offers a powerful means of supporting more inclusive, effective, and evidence-based EFL writing instruction, contributing directly to **the goals of quality education under SDG 4**.

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Optimization of Employee Mixed Incentive System From the Perspective of Social Sustainable Development

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KEYWORDS

Sustainable development;
Multiple incentives;
Industry 5.0;
Human resource management

ABSTRACT

Under the dual background of the global promotion of the United Nations Sustainable Development Goals (SDGs) and the technological innovation of Industry 5.0, the mixed incentive system for employees of enterprises needs to be adapted to the sustainable development of society. Based on comprehensive research and analysis, this paper preliminarily sorted out the gaps in the research on the synergy effect of incentive mechanism and sustainable development, constructed an employee incentive optimization framework with target docking, multiple incentives, technical support and institutional guarantee, and put forward specific optimization paths. It aims to solve the problems of disconnection between enterprise incentive system and sustainable development and single form, and provide practical reference for improving employee enthusiasm and promoting enterprise to fulfill social responsibility.

INTRODUCTION

The 17 Sustainable Development Goals (SDGs)[1], established by the United Nations in 2015, have become the overarching framework for global development, covering the three basic dimensions of economic growth, environmental resilience and social equity. As the core implementation subject, the human resource management mode of enterprises directly affects the promotion effect of SDGs.

Fu & Zhang (2024) pointed out that the current global SDGs implementation is faced with challenges such as regional imbalance and insufficient enterprise participation, while employee motivation, as the core link of human resource management, generally has problems such as disconnection from sustainable goals and single form, which restricts enterprises' contribution to SDGs [2]. Horvat et al. (2024) emphasized that Industry 5.0 promoted deep complementarity between human capabilities and emerging technologies, providing important technical support for incentivizing institutional innovation [3]. Gechbaia et al. (2024) proved through empirical research that the deep

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integration of human resource management and SDGs needs the support of multiple incentive mechanisms [4].Raman et al. (2024) reveals significant research gaps in collaborative studies of incentive mechanisms and sustainable development, particularly in the integration of digital technologies with human-centric approaches [5]. Therefore, based on the perspective of social sustainable development, constructing an appropriate employee mixed incentive optimization framework has become a key issue to address the dilemma of enterprise sustainable development.

1.Theoretical Framework and Model Construction

1.1.Core Theoretical Basis

① SDGs orientation theory: SDGs emphasize the coordinated development of economy, society and environment, and provide multiple value guidance for the setting of incentive goals [6].

② Industry 5.0 technology enabling theory: Industry 5.0, which emphasizes human-centric manufacturing and collaboration between humans and machines, provides new opportunities for incentive system innovation. The integration of artificial intelligence, big data and other technologies provide the possibility for the precision of incentives, which can realize the intelligentization of employee needs identification, contribution quantification and scheme optimization [7]. Syncframe (2025) also pointed out in its Industry 5.0 guidelines that the core of Industry 5.0 lies in the synergy between humans and machines, which provides a fundamental direction for the technological transformation of incentive mechanisms [8].

③ Multi-dimensional incentive theory: The integration of material and non-material, short-term and long-term incentives can better meet the multiple needs of employees and stimulate behaviors related to sustainable development [9].

1.2.Optimization Framework Model

Based on the above theoretical basis and current enterprise needs for aligning incentive systems with sustainable development goals, this paper constructs an employee hybrid incentive optimization framework integrating target docking, multiple incentives, technical assistance and institutional guarantee. Core tasks and specific measures of each dimension are shown in Figure 1:

Framework dimension	Core Task	Concrete measure
Docking of targets	To achieve the alignment between enterprise incentive goals and the SDGs.	The sustainable development goals are translated into specific incentive indicators that employees can understand and implement, such as green innovation contribution awards, environmental protection performance scores, and social responsibility participation indicators.
Multiple incentives	To meet the multi-level and diverse needs of employees.	The combined incentive mode of material incentive and non-material incentive, short-term incentive and long-term incentive is constructed to take into account the material return and spiritual needs of employees, immediate incentive and long-term development
Technical assistance	To enhance the accuracy and fairness of incentives.	Big data technology is used to analyze the job characteristics and demand preferences of employees, and AI model is used to quantify the contribution of employees to sustainable development, so as to avoid single incentive.
Institutional guarantee	Break down the barriers and ensure that the incentives are implemented and effective.	Embed the incentive mechanism into the whole process of human resource management such as recruitment, training, assessment and promotion, integrate internal resources and external cooperation forces, and establish a long-term implementation mechanism.

Fig.1.Core Contents of the Employee Mixed Incentive Optimization Framework

Source: This framework is based on SDGS-oriented theory, Industry 5.0 technology enabling theory and multi-dimensional incentive theory, combined with relevant research [6][7][9].

Through the integration of goal, form and technology, the optimization framework not only ensures that the incentive mechanism is consistent with the sustainable development goals, but also improves the identity of employees and the efficiency of system operation.

1.3.Framework Implementation Guidelines

To ensure the effective implementation of the employee mixed incentive optimization framework, several key guidelines should be followed. First, the framework should be adapted to the specific context of each enterprise, considering industry characteristics, organizational culture, and employee demographics. Işık et al. (2024) found in their study of SDGs in the United States that policy effects vary due to differences in economic structure and social environment, indicating that incentive system design must be contextually appropriate [10]. Second, stakeholder engagement is crucial, including leadership commitment, employee participation, and external partnerships with sustainability organizations. Third, a phased implementation approach is recommended, starting with pilot programs in specific departments before full-scale deployment. Finally, continuous monitoring and evaluation mechanisms should be established to track the effectiveness of the incentive system and make necessary adjustments based on performance metrics and feedback. The specific flow chart is shown in Figure 2:

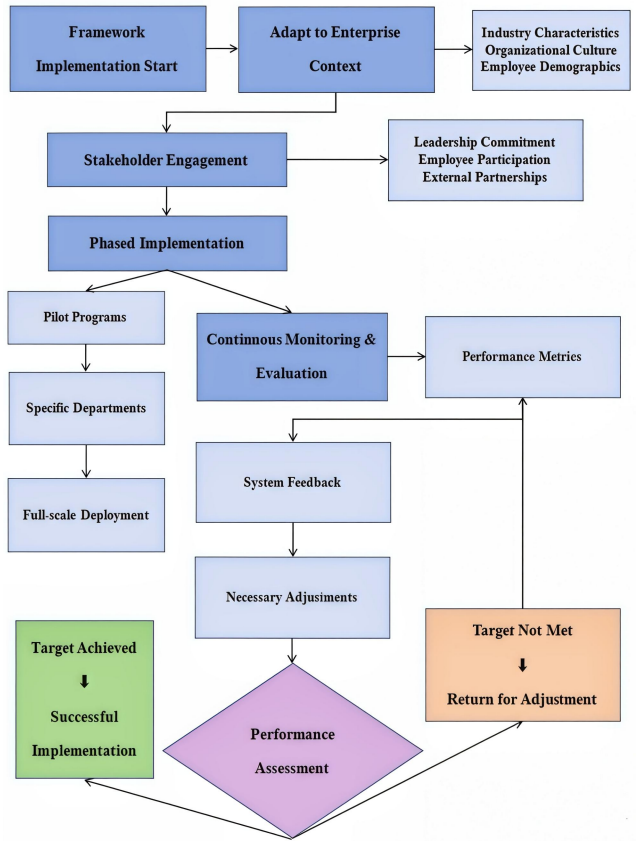


Fig.2. Framework Implementation Guidelines Flowchart

2.Analysis and Discussion

2.1.Shortcomings of the Sustainable Development Adaptation of the Current Incentive System

From the perspective of current practice, the current corporate incentive system has obvious deficiencies in the process of adapting to the SDGs. There are four dilemmas in the enterprise incentive system when connecting with the sustainable development goals (SDGs).

1) Misaligned objectives, where incentive targets diverge from sustainable development goals, prioritising short-term financial performance over long-term sustainability metrics. This leads management to prioritise quarterly profits in decision-making while adopting a cautious wait-and-see approach towards investments in long-term initiatives such as green R&D and social impact programmes [2].

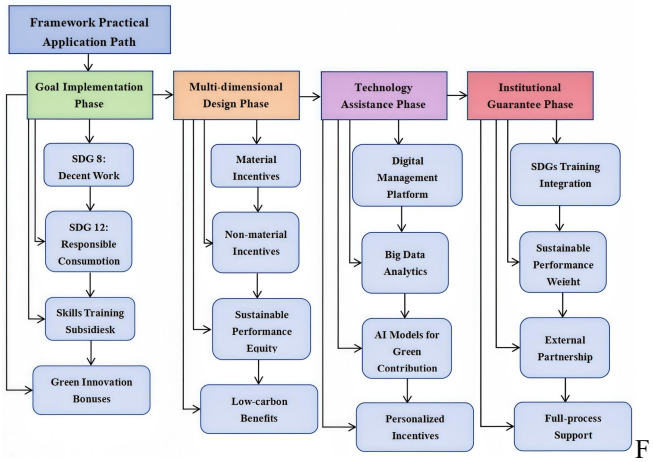
2) Structural uniformity, with excessive reliance on remuneration and bonuses. Incentives such as training and recognition awards remain superficial. Employees often focus solely on metrics directly linked to bonuses to secure rewards, neglecting sustainability requirements. Non-financial incentives lack systematic design and effective implementation, failing to foster intrinsic commitment and active participation towards sustainability goals [4].

3) Lack of technology, failure to achieve data-driven precise incentive with the help of Industry 5.0, enterprise HRIS and production, supply chain and community impact data are not connected, resulting in the lack of real-time and accurate data support when evaluating employees' sustainable contribution, and delayed reward decision. It missed the best opportunity to strengthen employees' green behavior in a timely manner [3].

4) Weak coordination, where incentive mechanisms are disconnected from HR processes and fail to integrate external resources. Lack of synergy between modules hinders the effective internalisation and transmission of green expertise and sustainable practices. Furthermore, collaborations with external stakeholders such as suppliers, universities, and communities cannot generate synergistic momentum for sustainable development due to absent incentives, thereby increasing supply chain compliance risks and operational costs [5].

2.2.Practical Application Path of the Framework

The framework's practical application proceeds hierarchically across goals, design, technology, and systems，As shown in Figure 3:



ig.3. Four-Phase Implementation Framework

• Goal Implementation Phase

For goal implementation, translate UN SDGs such as SDG 8 (Decent Work) and SDG 12 (Responsible Consumption) into

perceptible, actionable employee incentive indicators (such as skills training subsidies, green innovation bonuses) to align with global sustainability agendas [1].

• Multi-dimensional Design Phase

For multi-dimensional design, expand material incentives with sustainable performance equity and low-carbon benefits, and link non-material incentives (like sustainable contribution certification) to promotion to meet diverse employee needs and guide sustainable behaviors [9].

• Technology Assistance Phase

For technology assistance, to build a digital management platform, use big data to analyze employees' work needs and preferences, use artificial intelligence model to quantify green contribution, avoid single incentive measures, so as to improve accuracy [7].

• Institutional Guarantee Phase

For institutional guarantees, integrate SDGs-related content into training, weight sustainable contributions heavily in performance evaluations, and collaborate with external public welfare organizations to provide full-process support [6].

2.3.Framework Values and Limitations

The core value of the framework is to realize the dual adaptation of incentive system, SDGs and industry 5.0 technology, and balance enterprise efficiency and social value [2]. Specifically, the framework must integrate incentives, SDGs and technology into a closed-loop system, ensuring that green practices, social impact and business outcomes are simultaneously considered in decision-making. This approach addresses capital markets' demand for ESG traceability while providing employees with immediate, visible proof of personal contribution. Consequently, it transforms the traditional trade-off between efficiency and responsibility into synergistic gains. However, in the implementation process, there are significant differences between the process industry and the digital service industry in terms of emission benchmarks, resource density and stakeholder needs, which may distort business decisions if the uniform weight standard is directly applied. The edge computing, iot devices and data governance platforms required by Industry 5.0 require high initial investment for smes and are difficult to replicate the deployment path of large enterprises in the short term. Small and medium-sized enterprises face greater cost pressure when adopting new technologies [11][12].Future research needs to design low-cost, modularizable and subscription-based technology solutions to lower the adoption threshold for smes. The dynamic weight adjustment mechanism based on annual review is established to allow enterprises to flexibly revise the index weight according to policy changes and their own development stages, so as to ensure the operability and sustainability of the framework in multiple situations.

2.4.Future Research Directions

Future research should undertake longitudinal studies to assess the long-term effectiveness of sustainability-oriented incentive mechanisms and their impact on employee behaviour and organisational performance. Cross-cultural research should examine how differing national and cultural contexts influence the framework's implementation outcomes. Empirical validation through case studies and field experiments would provide stronger evidence for the framework's practical value. Integrating blockchain technology to enhance transparency and employing gamification design to boost employee engagement represent areas warranting deeper future exploration. Finally, the cost-benefit analysis study on the implementation of Industry 5.0 technology incentive system for smes will provide valuable reference for practitioners.

Conclusion

Social sustainable development requires enterprises to break through the limitations of traditional incentive models and build a new employee incentive system that is compatible with sustainable development goals. The four integrated optimization frameworks of goal docking, multiple incentives, technical assistance and institutional guarantee proposed in this paper provide realistic incentive optimization ideas for enterprises. Through the implementation of this framework, enterprises can realize the deep integration of employee incentives and SDGs, effectively stimulate employees' behaviors related to sustainable development, and improve the accuracy and efficiency of incentives with the help of Industry 5.0 technology, so as to promote the transformation of human resource management mode from efficiency oriented to sustainable value oriented.

In the future, enterprises need to refine the index design based on their own reality, strengthen cross-department

collaboration and technology application adaptation, promote the transformation of incentive system from efficiency-oriented to sustainable value-oriented, and contribute to the comprehensive realization of SDGs.

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