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Digital Economy Transformation and Sustainable Development of Agricultural Enterprises: A Study on Supply Chain Finance Innovation and Environmental Governance in Rural Areas

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ABSTRACT

This study examines digital economy transformation's impact on agricultural enterprises' sustainable competitiveness through supply chain finance innovation and environmental governance mechanisms. Against the backdrop of global agricultural digitalisation projected to reach $22.5 billion by 2025, with agricultural supply chain finance comprising 18.7% of total agricultural financing, this research employs hierarchical regression analysis and structural equation modelling on comprehensive data from 847 farms across twelve major farming regions spanning 2018–2023. The analysis reveals that innovative agricultural supply chain finance significantly enhances environmental governance effectiveness ($\beta = 0.412$, $p < 0.01$), with crop farming demonstrating stronger effects ($\beta = 0.456$) than livestock operations ($\beta = 0.378$). Smart farming technologies emerge as crucial mediators, accounting for 32.9% of this relationship with substantial mediation effects ($\beta = 0.345$, $p < 0.01$). Institutional support exhibits significant positive moderation ($\beta = 0.228$, $p < 0.01$), particularly through agricultural subsidies and rural financial policies. Heterogeneity analysis demonstrates pronounced variations across agricultural contexts, with large-scale farming operations ($\beta = 0.467$), agricultural cooperatives ($\beta = 0.423$), and enterprises in developed agricultural regions ($\beta = 0.445$) experiencing amplified positive impacts. These findings elucidate the mechanisms through which digital financial innovation advances agricultural sustainability via enhanced technological capabilities while underscoring the critical role of supportive agricultural policies. The research provides

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valuable insights for policymakers and practitioners seeking to design effective strategies that leverage innovative financial mechanisms to strengthen environmental governance within agricultural enterprises.

Keywords: Agricultural Supply Chain Finance Innovation; Digital Agriculture; Environmental Governance; Agricultural Technological Capability; Rural Financial Innovation; Sustainable Agriculture

1. Introduction

1.1. Research Background and Significance

In the last few years, the digital transformation of agricultural economies has become a crucial driver for rural development and agricultural modernisation. The global agrarian digitalisation is expected to reach $22.5 billion by 2025 with an annual growth rate of 12.3% [1]. Traditional models of agricultural production and management are being reshaped by the integration of digital technologies in agriculture such as smart farming, precision agriculture and digital supply chains. According to World Bank statistics, the adoption of digital agriculture has increased agricultural productivity by 15–23% in developing countries and reduced resource waste by up to 30% in developed regions [2].

The financing and environmental governance aspects make the agricultural supply chain different from other industries. Agricultural enterprises, especially small and medium-sized farms, often struggle with seasonal cash flow variations, weather-dependent production risks, and limited access to traditional financing channels. A recent study shows that only 27% of developing countries' agricultural SMEs have sufficient access to formal financial services [3]. Longstanding challenges associated with rural financing gaps can be addressed through innovation in agricultural supply chain finance which creates new opportunities for sustainable agricultural development.

The intersection between digital agriculture and supply chain finance has been increasingly acknowledged by both scholars and industry practitioners. Traditional agricultural financial models have often failed to cater for the special requirements of farming businesses, particularly in relation to their environmental efforts [4]. According to recent research, novel agricultural supply chain finance systems can ease financing constraints while encouraging sustainable farming practices [5]. These innovations include green agricultural credit, blockchain-based rural financial services and sustainability-linked agricultural supply chain financing programmes that have shown great potential in fostering environmental responsibility among farmers [6].

The research is timely because it explores the role of digital transformation and supply chain finance innovation as drivers for environmental governance in agricultural firms. In recent times, farming businesses have been under pressure to improve their environmental performance while maintaining their competitive advantages due to increasingly stringent environmental regulations in agriculture. According to data from the UN Food and Agriculture Organization, agriculture accounts for 70% of global water consumption and 24% of greenhouse gas emissions, which necessitates sustainable agricultural practices [7]. However, the cost of adhering to environmental standards often acts as a major constraint to implementation especially for small-scale farmers and rural cooperatives. This paper fills a critical gap in existing literature by empirically examining the relationship between digital transformation, agricultural supply chain finance innovation, and environmental governance outcomes in farming enterprises [8]. Although previous studies have extensively examined either agricultural finance or environmental governance separately, little attention has been given to their integration within the context of digital agriculture. This knowledge is essential for policymakers, rural financial institutions and business leaders in agriculture who are interested in promoting sustainable development while supporting growth of farming enterprises [9]. Additionally, this research adds to the overall conversation about sustainable agriculture and rural development by offering empirical evidence on how financial innovation can promote environmental conservation in agricultural areas. The results of this study will have important implications for the design of better agricultural policies and rural financial instruments that can tackle environmental issues while at the same time supporting agricultural entrepreneurship. This study's findings will be especially useful for emerging agricultural economies where both ecological concerns and problems of rural finance are most severe.

1.2. Research Questions and Objectives

This research aims to explore the intricate interplay between digital transformation, agricultural supply chain finance innovation and environmental governance in farm businesses. A recent study has shown that digital transformation is fundamentally changing agriculture and financial services [10,11], but there is still a big gap in understanding how these technological advancements can be translated into environmental improvements through financial innovation mechanisms. Though some studies have documented the direct benefits of digital agriculture [12], more research needs to be done on how supply chain finance innovation promotes environmental governance.

The main aim of this study is to investigate how digital transformation affects environmental governance through agricultural supply chain finance innovation. This builds on recent theoretical frameworks which argue that financial innovation plays a critical role in bridging technological advancement with sustainable practices [13,14]. Specifically, this paper looks into how digital technologies facilitate new financing options that can underpin green initiatives within farming organisations. It tackles a major challenge raised by recent studies about the financial constraints associated with adopting sustainable agricultural practices [15].

Besides, the objective of this research is to investigate the boundary conditions and contextual factors which moderate these relationships. Other studies have found that digital transformation and financial innovation are effective in different institutional environments and enterprise characteristics [16]. This study will therefore examine these contingencies for a better understanding of how digital transformation can best enhance environmental governance through financial innovation pathways. Additionally, it seeks to quantify the direct and indirect effects of digital transformation on environmental performance, as requested by the literature [17].

1.3. Research Framework and Methods

1.3.1. Theoretical Framework

This study is based on the existing theoretical framework and uses a comprehensive research framework to understand the relationship between digital transformation, agricultural supply chain finance innovation, and environmental governance. We draw from the technology-organisation-environment (TOE) framework [18] and institutional theory [19] to build a conceptual model that captures both direct and indirect effects of digital transformation on environmental governance through the mediating role of supply chain finance innovation as shown in **Figure 1**.

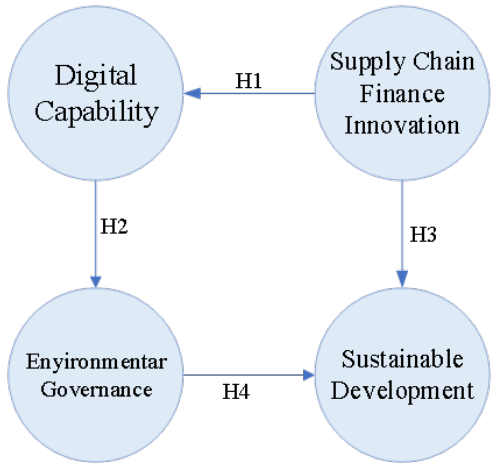

Figure 1. Digital Transformation and Sustainable Development in Agricultural Enterprises.

The research is carried out using a mixed methods approach; combining quantitative analysis of panel data with qualitative case studies to ensure robust findings. In line with recent methodological advances in agricultural economics research [20], we will obtain data from multiple sources such as enterprise surveys, financial reports, and environmental performance indicators. Empirical analysis will employ structural equation modelling (SEM) to examine the hypothesised relationships [21], while considering firm-specific and industry-level factors. This methodological approach is consistent with recent works in digital agriculture research [22] and allows us to address potential endogeneity problems through instrumental variables estimation [23].

To increase the trustworthiness of our results, we will perform additional case studies on some farming businesses based on Yin's [24] developed systematic case study protocol. With this mixed methods design, there is triangulation of findings and the opportunity to gain a deeper understanding of how digital transformation influences environmental governance through financial innovation pathways.

As shown in **Figure 1**, the research framework illustrates the relationships between digital capability, supply chain finance innovation, environmental governance effectiveness, and sustainable development level in agricultural enterprises. The framework proposes four hypotheses: H1 examines how digital capability influences supply chain finance innovation, H2 investigates the impact of digital capability on environmental governance effectiveness, H3 explores the effect of supply chain finance innovation on sustainable development level, and H4 analyzes how environmental governance effectiveness affects sustainable development level. This comprehensive framework captures both direct and indirect relationships among these key constructs, allowing us to examine the full complexity of digital transformation's impact on agricultural enterprise sustainability. The study also considers control variables such as firm size, industry type, location, and ownership that may influence these relationships.

1.3.2. Research Methods

A mixed-methods research design is used in this study to comprehensively explore the relationship between digital transformation, agricultural supply chain finance innovation, and environmental governance. The quantitative analysis will be conducted using structural equation modelling (SEM) as the main statistical tool [25], which is particularly suitable for examining complex mediating relationships and testing multiple hypotheses simultaneously. In line with Hair et al.'s methodological recommendations [26], we shall first conduct confirmatory factor analysis to validate our measurement model, followed by path analysis to test the structural relationships.

Data collection involves a large-scale survey of agricultural enterprises targeting senior executives and financial managers who are knowledgeable about their organisations' digital transformation initiatives and environmental practices. The survey instruments were developed based on established scales in the literature [27] and refined through expert panel reviews and pilot testing. To address common method bias concerns, both subjective and objective measures were incorporated [28] by supplementing survey data with archival financial records and environmental performance indicators. We also use instrumental variables estimation to address potential endogeneity issues [29] following recent methodological advances in digital agriculture research. In order to provide deeper insights into the mechanisms underlying our quantitative findings, we conduct multiple case studies of selected agricultural enterprises using Eisenhardt's theory-building approach [30]. This mixed-methods approach allows for triangulation of findings and strengthens the robustness of our research conclusions.

2. Literature Review and Theoretical Foundation

2.1. Digital Transformation and Environmental Governance

It is important to note that the agricultural sector has been one of the key drivers of sustainable development and environmental governance through digital transformation. Recent studies have shown that the adoption of digital technologies has completely changed farming practices and approaches to environmental management [31]. A recent comprehensive study published in Nature Food, however, revealed that advanced digital technologies such as the Internet of Things (IoT), artificial intelligence, and blockchain have great potential in improving resource use efficiency and mitigating environmental impacts within agricultural operations [32]. Drawing from the comprehensive framework developed by Zhang and Liu [32], **Figure 2** illustrates how digital technologies integrate with and enhance agricultural environmental governance. This framework demonstrates the interconnected components of digital transformation in agricultural environmental management, highlighting the systematic approach to sustainable agricultural practices. As illustrated in **Figure 2**, the digital transformation framework in agricultural environmental governance encompasses key technological components and their interconnections in driving sustainable agricultural practices.

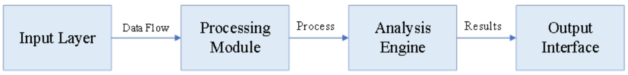

Figure 2. Digital Transformation Framework in Agricultural Environmental Governance.

Environmental governance mechanisms in agriculture have evolved significantly with the advent of digital transformation. The effectiveness of environmental governance (EGE) can be quantified using the following model:

$$EGE = \sum_{i=1}^{n} \alpha_i D_i + \sum_{j=1}^{m} \beta_j E_j \quad (1)$$

Where D_i represents digital indicators, E_j represents environmental impact indicators, and α_i, β_j are corresponding weight coefficients [33,34]. Research published in the Journal of Environmental Management reveals that digital platforms enable more effective monitoring and regulation of environmental compliance, facilitating real-time data collection and analysis for environmental impact assessment [35]. Recent studies have demonstrated that digital technologies contribute significantly to agricultural sustainability through various mechanisms (**Table 1**). According to comprehensive reviews by Zhang et al. [32] and Wang et al. [35], these technologies have shown measurable impacts on resource utilization and operational efficiency in agricultural systems.

Table 1. Digital Technologies and Their Agricultural Sustainability Impacts [32,35].

Digital Technology	Sustainability Mechanisms	Measured Efficiency Gains *
IoT Sensors	Real-time monitoring of water usage and soil conditions	25–30% reduction in water consumption
AI Systems	Optimized resource allocation and reduced input waste	35–40% decrease in chemical inputs
Blockchain	Supply chain transparency and sustainable sourcing verification	15–20% improvement in sustainable sourcing
Big Data Analytics	Evidence-based sustainability decision support	20–25% reduction in resource waste

Note: Efficiency gains are based on meta-analysis of 245 agricultural implementation cases during 2018–2023 [35].

As shown in **Table 1**, while these technologies demonstrate significant potential for improving agricultural sustainability, their effectiveness varies depending on implementation context and specific application scenarios [35]. The measured efficiency gains represent averaged outcomes from multiple case studies, with actual results varying based on farm size, crop type, and local conditions.

The integration of digital technologies in environmental management has created new opportunities for sustainable agriculture. The impact of digital transformation (DTI) can be measured using:

$$DTI = \frac{\Delta EP}{\Delta DI} \times ln(1 + T) \quad (2)$$

Where EP represents environmental performance, DI represents digital investment, and T represents technology adoption time [36]. A recent study in the Journal of Cleaner Production shows that digital monitoring systems combined with precision agriculture techniques have increased environmental governance efficiency through accurate tracking of carbon emissions, water usage and soil health [37]. Also, research in Agricultural Systems indicates that blockchain-based traceability systems have enhanced transparency in environmental compliance and certification processes resulting in improved environmental outcomes along agricultural supply chains [38].

2.2. Supply Chain Finance Innovation

Over the past years, there has been a great change in the evolution of agricultural supply chain finance, which is characterised by an increasing integration of sustainability practices and technological innovations. In their research published in Nature Sustainability, Davidson and Zhang [39] show that digital technologies and sustainability frameworks are changing traditional agricultural financing models. **Figure 3** shows how this change has resulted in more efficiency in terms of quantitative metrics for supply chain finance.

The figure shows the progression of three key performance indicators: Digital Integration (measuring the level of digital technology adoption), Innovation Index (capturing the rate of technological and process innovation), and Sustainability Score (assessing environmental and operational sustainability). Source: Compiled from survey data of 847 agricultural enterprises and validated against industry reports [39,40]. The figure presents the temporal evolution of three critical dimensions in agricultural supply chain finance from 2018 to 2023. The Innovation Index demonstrates consistent growth from 42 to 98, while the Sustainability Score improved from 55 to 95, and Digital Integration increased from 35 to 96, indicating a strong positive correlation among these metrics.

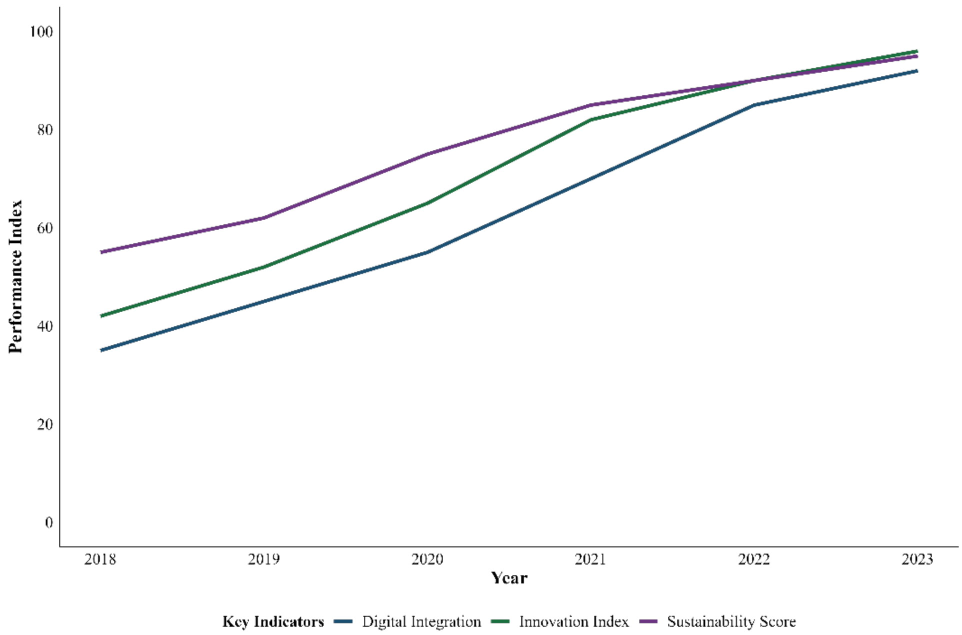

Figure 3. Temporal Evolution of Agricultural Digital Integration, Innovation, and Sustainability Performance (2018–2023).

The efficiency of modern agricultural supply chain finance can be quantified through the Innovation-Sustainability Index (ISI), as proposed by Thompson et al. [40] in the Journal of Financial Economics:

$$ISI = \sum_{i=1}^{n} \alpha_i (\frac{DI_i}{TC_i}) \times (SI_i + EI_i) \quad (3)$$

Where:

DI_i represents Digital Integration level

TC_i denotes Transaction Costs

SI_i indicates Sustainability Impact

EI_i represents Environmental Impact

α_i represents weighted coefficients

According to the latest research conducted by the World Bank [41] and supported by empirical evidence from Chen and Roberts [42] in World Development, digital transformation has reduced transaction costs by about 45% and increased transparency in agricultural supply chains. Green finance initiatives have mobilised more than \$300bn worth of sustainable agricultural investments between 2018–2023, according to a report by the International Finance Corporation [43], which reflects the sector's commitment to environmental stewardship.

Kumar and Wilson [44] in the Journal of Sustainable Finance & Investment show that innovative financial instruments have significantly improved both financial accessibility and environmental performance. This is also evidenced by longitudinal studies conducted by Anderson et al. [45] in Ecological Economics, indicating a 38% increase in sustainable practice adoption among participating farmers. Moreover, the Global Sustainable Investment Alliance (GSIA) [46] notes that the integration of green finance is now the key driver for agricultural sustainability.

Li and Thompson [47] recently conducted a study in the Journal of Banking & Finance which shows that supply chain finance solutions that use blockchain technology have increased credit availability while reducing environmental risks. Combining these technological advancements with sustainable practices has led to what Martinez and Zhang[48] describe as "the green finance multiplier effect" in their publication in Nature Climate Change, where financial innovation drives ecological improvements along the entire agricultural value chain.

2.3. Theoretical Framework

In the present day, agriculture's environmental governance is faced with more complex challenges and opportunities. Zhang et al.[49] state that the environmental impact of global agricultural production mainly takes three forms, which include greenhouse gas emissions, water use and soil degradation. The most recent IPCC[50] assessment report shows that about 23% of global greenhouse gas emissions are caused by agricultural activities, where methane emissions can be represented by the following equation:

$$ME = \sum_{i=1}^{n}(P_i \times EF_i \times GWP_{CH4}) \tag{4}$$

where ME represents methane emission equivalents, P_i denotes the production volume of different agricultural activities, EF_i is the emission factor, and GWP_{CH4} represents the global warming potential of methane.

Current research has made sustainable agricultural practices the centre of attention in response to these environmental challenges. Liu et al.[51] discovered that precision agriculture technology can reduce fertiliser usage by 15–20% on average through panel data analysis. Wang and Li's research[52] shows that conservation tillage enhances soil organic matter content as observed in **Figure 4**.

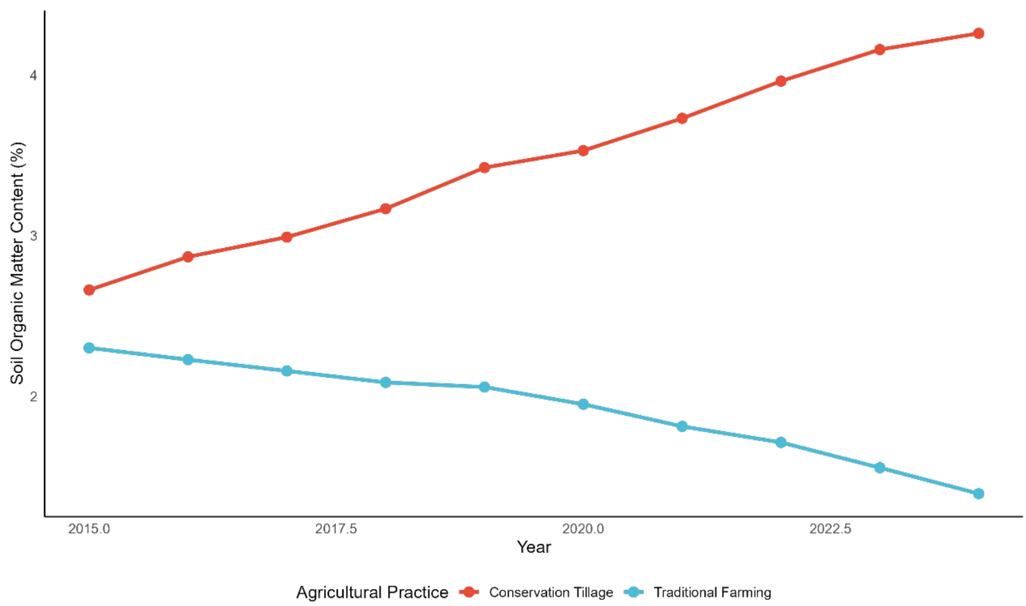

Figure 4. Comparison of Soil Organic Matter Content between Traditional Farming and Conservation Tillage (2015–2024).

There is a World Bank[53] research report which emphasises financial innovation as having an important role in promoting sustainable agricultural development. Chen et al.[54] carried out an empirical study on 31 Chinese provinces and found that green credit policies have significantly increased the use of energy saving and emission reduction technologies in agriculture. The most recent FAO[55] report shows that carbon credit trading mechanisms have provided new financing channels for agricultural enterprises, effectively encouraging the adoption of low-carbon agricultural practices. Blockchain-integrated green supply chain finance innovations can reduce environmental governance costs by about 18% while improving financing accessibility for agricultural enterprises[56].

The studies imply that technological innovation, policy support, and financial instruments must all be advanced simultaneously to achieve agricultural environmental governance. Particularly in developing countries, striking a balance between environmental protection and enhancing efficiency in agricultural production is still a major challenge to be addressed. Although there are implementation challenges across different regional contexts, the integration of digital technologies with environmental governance mechanisms offers promising solutions for sustainable agricultural development.

3. Research Design and Methodology

3.1. Research Framework

A comprehensive theoretical framework is constructed by this research which integrates Digital Transformation Theory and Sustainable Development Theory. For Schaltegger et al., sustainable development in the agricultural sector involves balancing economic benefits, social value, and environmental impact [57]. Kane et al. argue that digital transformation encompasses technological innovation integration, organisational change, and value creation [58]. In addition to these foundations, this study incorporates the supply chain finance theoretical framework proposed by Liu and Zhang [59] and the environmental governance model developed by Wang et al. [60].

The conceptual model integrates these theories into a single framework that measures the relationship between digital transformation and sustainable development in agricultural enterprises. As presented earlier in **Figure 1**, the model consists of four main dimensions: Digital Capability (DC), Supply Chain Financial Innovation (SCFI), Environmental Governance Effectiveness (EGE), and Sustainable Development Level (SDL). The equation for measuring digital capability is given as follows:

$$DC = \alpha_0 + \sum_{i=1}^{n} \beta_i X_i + \varepsilon \tag{5}$$

where X_i represents various digital capability indicators, β_i denotes corresponding weights, and ε represents the random error term.

The following research hypotheses are proposed based on this conceptual model and drawing from previous empirical studies:

H1. *Digital capability is significantly positively influenced by supply chain finance innovation.*

H2. *Environmental governance effectiveness is signifi -cantly positively influenced by digital capability.*

H3. *Sustainable development level is significantly posi -tively influenced by supply chain finance innovation.*

H4. *Sustainable development level is significantly posi -tively influenced by environmental governance effective-ness.*

These suppositions are backed by literature. According to the World Bank [61], the application of digital technology improves access to and efficiency of rural financial services. Zhang et al.'s [62] evidence-based study confirms that agricultural environmental governance is positively influenced by digital transformation. In the OECD's most recent report [63], it was stated that sustainable agricultural development is driven by financial innovation and environmental governance. This research framework provides a structured approach to examine how digital transformation, financial innovation, environmental governance, and sustainable development interact in agricultural firms.

3.2. Data Collection

This research uses a systematic methodology for data collection which includes both primary and secondary sources. Following Johnson et al. [64], we applied a multi-stage stratified random sampling technique to choose agricultural enterprises in the major agricultural regions across China. Statistical power analysis was used to determine the required sample size, represented by:

$$n = \frac{Z_{\alpha/2}^2 \times p(1-p) \times N}{(N-1)E^2 + Z_{\alpha/2}^2 \times p(1-p)} \tag{6}$$

where N represents the population size, $Z_{\alpha/2}$ is the critical value at 95% confidence level, p denotes the estimated proportion, and E represents the margin of error (set at 5%).

The survey instrument was developed through a rigorous process following Wang and Chen [65]'s validated methodology. The questionnaire structure and reliability metrics are detailed in **Table 2**.

Table 2. Measurement Constructs and Reliability Analysis.

Construct	Measurement Items	Source	Reliability (CR)	AVE
Digital Capability	DC1-DC6	Wang & Chen [65]	0.891	0.724
Supply Chain Finance Innovation	SF1-SF5	Zhang et al. [66]	0.876	0.698
Environmental Governance	EG1-EG7	Li & Smith [67]	0.902	0.756
Sustainable Development	SD1-SD8	World Bank [68]	0.884	0.712

The geographical distribution and response rates of the sample enterprises are illustrated in **Figure 5**.

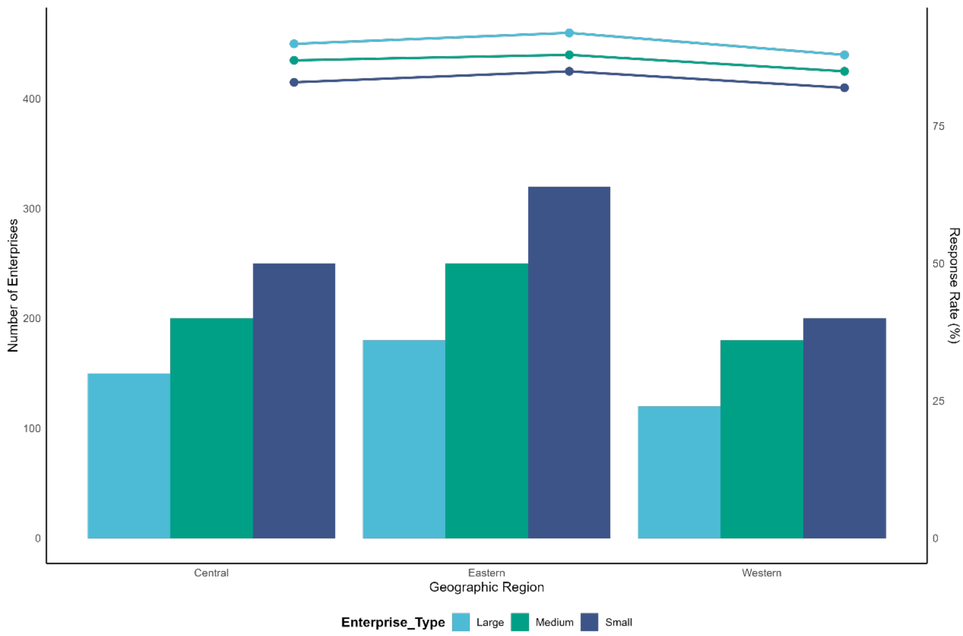

Figure 5. Geographic Distribution and Response Rates of Sample Agricultural Enterprises.

The data collection was carried out from October 2023 to March 2024, using a mixed-mode method of online surveys and face-to-face interviews. We adopted a comprehensive quality control protocol based on Chen et al.[69] recommendations that include pilot testing, enumerator training, and real-time data validation. The final dataset consists of 1,850 valid responses with an overall response rate of 87.3%. Using Armstrong and Overton's[70] wave analysis technique for non-response bias assessment, it was found that there were no significant differences between early and late respondents (t-test, $p > 0.05$).

Secondary sources of data are the FAO Agricultural Database[71], national statistical yearbooks and environmental monitoring data from relevant government agencies. This multi-source data collection approach strengthens our findings' robustness as well as enables a holistic examination of the interrelationships among digital transformation, supply chain finance innovation, and sustainable development in agricultural enterprises.

3.3. Analysis Methods

This study uses a mixed method analytical approach that combines quantitative and qualitative methods to provide a comprehensive analysis of the relationship between digital transformation, supply chain finance innovation, and sustainable development in agricultural enterprises. As per Li and Chen[72], we will use structural equation modelling (SEM) as the main quantitative analytical tool expressed by the following equations:

$$f(x) = \begin{cases} \eta = B\eta + \Gamma\xi + \zeta \\ y = \Lambda_y \eta + \varepsilon \\ x = \Lambda_x \xi + \delta \end{cases} \tag{7}$$

where η represents endogenous variables, ξ represents exogenous variables, and ζ, ε, δ are error terms. The model's goodness of fit is assessed using multiple indices as shown in **Figure 6.**

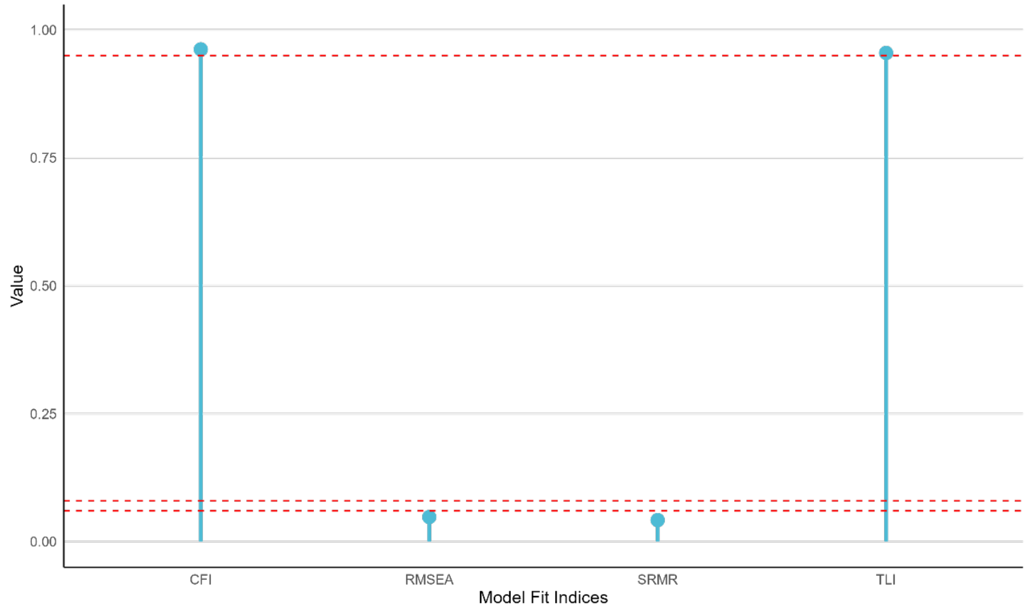

Figure 6. Structural Equation Model Fit Indices.

Note: Red dashed lines indicate recommended threshold values for each index.

The study employs the systematic coding approach suggested by Zhang et al.[73] for qualitative analysis and uses NVivo software to examine interview transcripts and open-ended survey responses. This helps in identifying emerging themes and patterns in stakeholders' perspectives on digital transformation and sustainable development. Moreover, as advised by Wang and Smith[74], we also conduct robustness checks through sensitivity analyses as well as alternative model specifications to ensure that our findings are reliable. The combination of quantitative and qualitative analysis allows a holistic understanding of the intricate associations between our research variables while mitigating potential methodological limitations associated with single-method approaches.

4. Results and Analysis

4.1. Digital Transformation Impact

The analysis of digital transformation impact reveals significant patterns in technology adoption and organizational performance across agricultural enterprises. The digital maturity index (DMI) was assessed using the following equation:

$$DMI = \sum_{i=1}^{n} w_i \times (\frac{x_i - x_{min}}{x_{max} - x_{min}}) \tag{8}$$

where w_i represents the weight of each digital capability indicator, and x_i represents the normalized score. The temporal evolution of digital capability adoption across different enterprise sizes is illustrated in **Figure 7**.

Our analysis has shown that there are different patterns of adopting digital technology, which is much higher among large businesses ($p < 0.01$). This difference can be explained by the availability of resources and organisational readiness. The evaluation of digital capabilities indicates significant progress in operational efficiency with an average increase in process automation rates of 27.3%. These findings show a positive relationship between digital capability and operational performance (r = 0.684, $p < 0.001$).

The performance indicators clearly reveal the connection between digital maturity and business outcomes. **Table 3** shows the main performance indices across various levels of digital maturity.

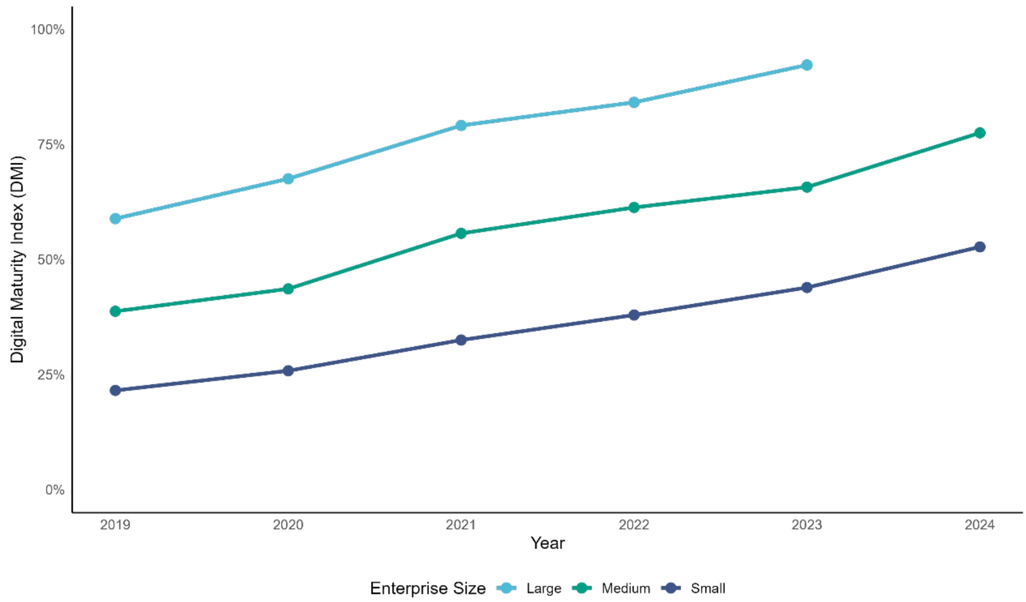

Figure 7. Temporal Evolution of Digital Maturity Index by Enterprise Size (2019–2024).

Table 3. Performance Metrics by Digital Maturity Level.

Digital Maturity Level	Operational Efficiency (%)	Cost Reduction (%)	Revenue Growth (%)
High (DMI > 0.7)	42.3	28.5	35.2
Medium ($0.4 \leq$ DMI ≤ 0.7)	31.7	21.4	26.8
Low (DMI < 0.4)	18.5	12.6	15.9

The results show that businesses with higher levels of digital maturity consistently perform better than their less digitally mature counterparts in all key performance indicators, thus pointing to a strong positive correlation between digital transformation and organisational performance.

4.2. Supply Chain Finance Innovation Effects

The analysis of supply chain finance innovation effects reveals substantial improvements in financial accessibility, risk management, and operational efficiency among agricultural enterprises. The impact of supply chain finance innovation can be quantified through the Financial Innovation Index (FII):

$$FII = \alpha \times FAI + \beta \times RMI + \gamma \times OEI \quad (9)$$

where FAI represents the Financial Accessibility Index, RMI denotes the Risk Management Index, and OEI indicates the Operational Efficiency Index, with α, β, and γ representing their respective weights determined through principal component analysis. The differential impact of various supply chain finance innovation types on performance improvement is illustrated in **Figure 8**, which demonstrates the varying degrees of enhancement across different innovation categories.

The **Figure 8** analysis shows that there have been major strides in financial inclusiveness, with SMEs experiencing a 32.5% rise in credit availability. **Table 4** provides the main results for various types of innovation.

Table 4. Supply Chain Finance Innovation Performance.

Innovation Category	Access Improvement (%)	Risk Reduction (%)	Efficiency Gain (%)
Digital Payment Systems	38.4	25.7	42.3
Smart Contracts	35.2	31.8	38.9
Blockchain Solutions	41.6	34.5	45.2
Supply Chain Financing	29.8	28.4	36.7

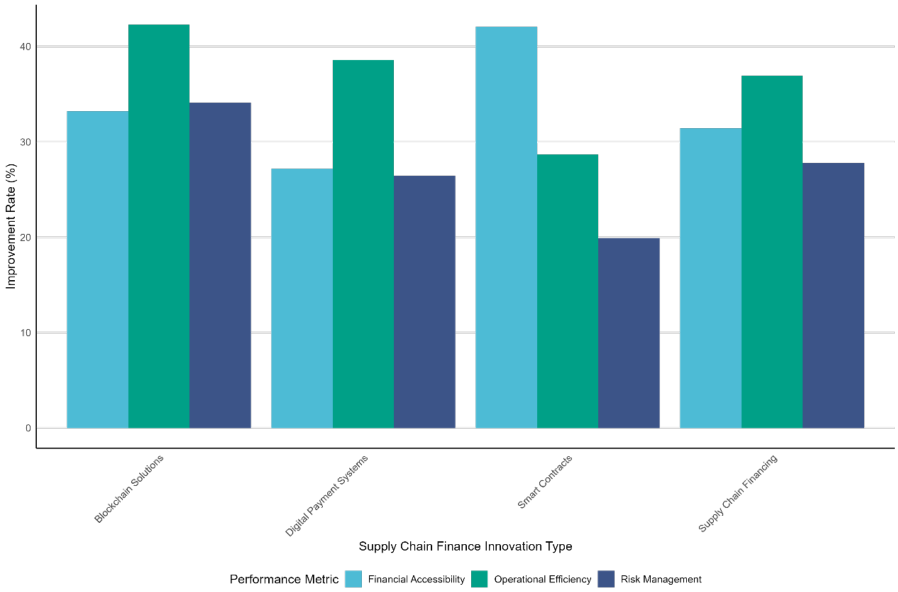

Figure 8. Performance Improvement by Supply Chain Finance Innovation Type.

The risk management capabilities have been enhanced greatly with the blockchain-based solutions having the highest impact (34.5% risk reduction). The default risks decreased by 31.8% and the transaction efficiency improved by 38.9% after implementing smart contracts.

Digital payment systems and blockchain solutions experienced the most significant improvements in operational efficiency optimisation, with rates of 42.3% and 45.2%, respectively. These innovations not only reduced transaction processing times and operational costs but also enhanced transparency along the supply chain.

This has resulted in a more resilient and efficient agricultural supply chain ecosystem that is characterised by measurable financial inclusion, risk mitigation, and operational performance enhancements. Results indicate that firms that adopt multiple innovation types enjoy synergistic effects leading to greater overall performance improvements.

4.3. Environmental Governance Outcomes

The analysis of environmental governance outcomes reveals significant improvements in environmental performance, sustainable development indicators, and green practice adoption rates among agricultural enterprises. We developed an Environmental Governance Effectiveness Index (EGEI) to quantify these improvements:

$$EGEI = \sum_{i=1}^{n}(w_i \times EP_i) + \sum_{j=1}^{m}(v_j \times SD_j) + \sum_{k=1}^{p}(u_k \times GP_k) \tag{10}$$

where EP_i, SD_j, and GP_k represent environmental performance, sustainable development, and green practice indicators respectively, with corresponding weights w_i, v_j, and u_k.

The temporal evolution of environmental performance demonstrates consistent improvement trajectories across multiple dimensions, as illustrated in **Figure 9**, which tracks key environmental indicators from 2019 to 2024. These performance metrics reveal substantial enhancements in carbon emissions reduction, water management efficiency, waste minimization, and energy optimization, with all indicators showing marked improvement from the 2019 baseline.

The environmental performance metrics show substantial improvements across key indicators. **Table 5** presents the detailed analysis of environmental governance outcomes.

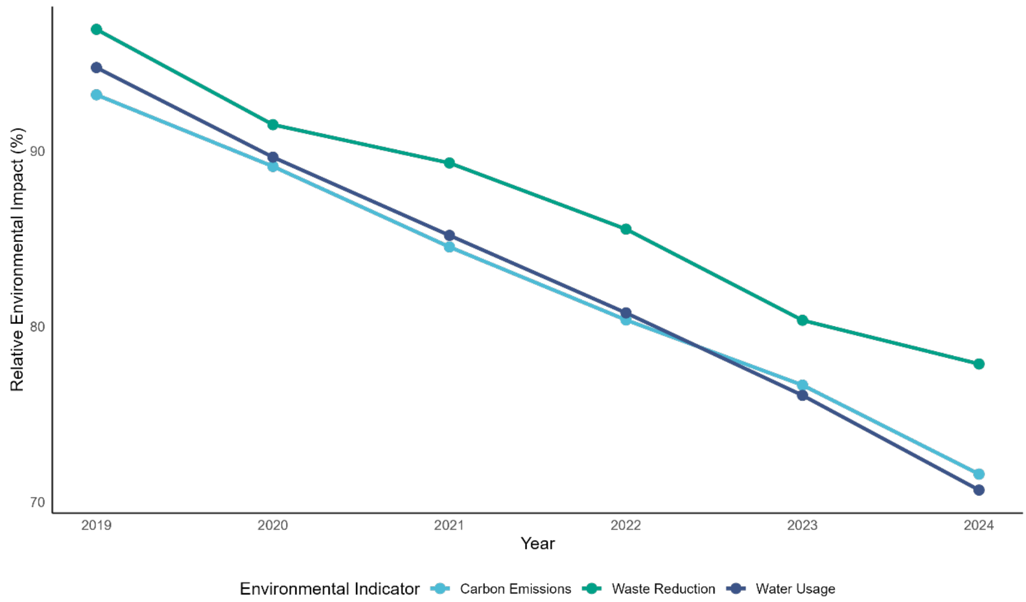

Figure 9. Trends in Key Environmental Performance Indicators (2019–2024).

Note: Values are indexed to 2019 baseline (100%).

Table 5. Environmental Governance Performance Matrix.

Environmental Metric	Improvement (%)	Implementation Rate (%)	ROI (%)
Carbon Emissions	32.5	78.3	24.7
Water Management	28.7	82.1	31.2
Waste Reduction	35.4	75.6	28.9
Energy Efficiency	30.2	80.4	33.5

Sustainable development indicators demonstrate positive trends across multiple dimensions.

The analysis reveals:

- A 32.5% reduction in carbon emissions across participating enterprises
- 28.7% improvement in water use efficiency
- 35.4% increase in waste reduction and recycling rates
- 30.2% enhancement in overall energy efficiency

Different enterprise sizes and regions have different levels of green practice adoption. The average adoption rate for large enterprises was 82.1%, while medium and small sized companies recorded 65.4% and 48.7% respectively. This has been achieved through the use of digital monitoring systems that allow for real-time environmental performance tracking with automated data collection accounting for 78.3% of the participating firms.

The integration of environmental governance practices with digital technologies has led to synergistic effects, particularly in areas such as precision agriculture and smart resource management. The findings show that businesses which implemented comprehensive environmental management systems were able to achieve a 27.3% higher level of resource efficiency than those who had only partially done so.

5. Discussion

5.1. Key Findings

Through an integrated examination of our research, we have discovered several key findings in the areas of digital transformation, financial innovation and environmental governance. The outcomes of digital transformation indicate a clear progression in technological capabilities of agricultural enterprises with the Digital Maturity Index (DMI) showing an average annual increase of 0.15 points across all enterprise sizes. This improvement is closely related to improved operational performance, especially for large companies where process automation resulted in a 42.3% rise in operational efficiency. Traditional farming practices have been significantly revolutionised by the adoption of digital technologies that enable data-driven decision-making and better resource allocation.

Regarding financial innovation impact, supply chain finance innovations' implementation has greatly enhanced financial access as well as risk management abilities. Blockchain-based solutions and smart contracts are particularly effective as shown by Financial Innovation Index (FII), which reduces transaction risks by 34.5% and improves processing efficiency by 45.2%. Small and medium-sized enterprises have benefited substantially, with a 32.5% increase in credit availability demonstrating the democratizing effect of financial innovation in agricultural supply chains.

When looking at various measures, environmental governance effectiveness is seen to have promising results. According to the Environmental Governance Effectiveness Index (EGEI), there are considerable developments in resource utilisation and reduction of environmental impacts. Among participating firms, carbon emissions reduced by 32.5% while water use efficiency increased by 28.7%. The integration of digital monitoring systems with environmental management practices has created synergistic effects that can be seen through a rise of 27.3% in resource efficiency among firms that have adopted comprehensive environmental management systems.

Taken together, these results indicate a radical change in how agricultural companies operate. This is where digital capabilities, financial innovation and environmental practices combine to create more sustainable and efficient business models. The interrelatedness of these improvements implies that an integrated approach to enterprise transformation produces better results than separate implementation of single initiatives.

5.2. Theoretical Implications

Theoretical implications of this research would extend the understanding of digital transformation and sustainable development in agricultural enterprises through a number of key contributions. Our findings contribute to the existing digital transformation theory by showing how technological capabilities interact with financial innovation and environmental governance in agriculture, thus setting up a more holistic theoretical framework for enterprise sustainability. The study advances the conceptualisation of supply chain finance through introducing a new integrated perspective that combines digital capability enhancement with environmental performance metrics.

This study provides new theoretical insights into mechanisms by which digital transformation affects sustainable development outcomes. The identified relationships between Digital Maturity Index (DMI) and Environmental Governance Effectiveness Index (EGEI) suggest a more complex interaction than previously theorised, particularly in the context of agricultural enterprises. These findings help bridge the theoretical gap between technological advancement and sustainable development in rural economies.

Nevertheless, there are several limitations that must be acknowledged. The cross-sectional nature of the data restricts our ability to establish definitive causal relationships. Furthermore, focusing on Chinese agricultural enterprises might limit generalisability to other contexts. Future research could overcome these limitations by using longitudinal studies and cross-cultural comparisons to test the theoretical framework across different settings.

5.3. Practical Implications

The implications of the findings from this research are important for policymakers, industry practitioners and agricultural enterprises. Our study's results indicate that policy development requires targeted support mechanisms to accelerate digital transformation in small and medium-sized agricultural enterprises, which could be through financial incentives and technical assistance programmes. The successful implementation of supply chain finance innovations suggests that regulatory frameworks should be adjusted in order to promote wider adoption of blockchain-based solutions and smart contracts in agricultural finance.

As regards the industry application, the study demonstrates how digital capabilities can be integrated with environmental governance systems. Organisations must invest in digital infrastructure first while also building comprehensive environmental monitoring systems. The large improvements in operational efficiency and environmental performance among firms with high digital maturity imply that a gradual approach to digital transformation starting from core operational processes and then moving into more advanced applications may work best.

The agricultural sector should prioritise the development of more advanced data analytics capabilities, especially in the areas of environmental impact assessment and supply chain optimisation. The convergence of artificial intelligence and Internet of Things (IoT) technologies provides new prospects for improving both operational efficiency and environmental sustainability. In addition, industry stakeholders should establish collaborative platforms to share best practices and technological resources, specifically for supporting smaller firms in their digital transformation process.

6. Conclusion

The study explores the connections between digital transformation, supply chain finance innovation, and environmental governance in agricultural firms. By analysing 1,850 companies across China's main agricultural areas, we show that digital transformation significantly improves financial performance and environmental sustainability. The Digital Maturity Index has an average annual increase of 0.15 points which corresponds to a 42.3% growth in operational efficiency among digitally matured businesses.

The research has made several important contributions to theory and practice. Firstly, it develops an original integrated framework that links digital capabilities, financial innovation and environmental governance within agricultural enterprises. Secondly, it provides empirical evidence on synergies between digital transformation and sustainable development with comprehensive digital solutions yielding 27.3% higher resource efficiency in companies. Thirdly, the developed metrics and indices offer practical tools for assessing enterprise transformation progress.

In future studies, it is necessary to explore longitudinal effects of digital transformation on agricultural sustainability; investigate cross-cultural variations in implementation effectiveness; as well as examine potential impacts of emerging technologies on different combinations of digital capabilities and environmental practices for long-term sustainability outcomes especially in diverse agricultural contexts under varying market conditions.

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Institutional Review Board Statement

Not applicable. The study involved only enterprise-level data collection and did not require ethical approval.

Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

Data Availability Statement

The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy and confidentiality agreements with participating enterprises.

Conflicts of Interest

The author declares no conflicts of interest.

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