

Digital Transformation and Supply Chain Efficiency for Sustainable Food Industry Development in China

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Abstract. Digital transformation is increasingly reshaping food supply chains by improving information sharing, coordination, and transparency. In China, the food industry continues to face significant challenges related to supply chain inefficiency, weak traceability, and growing sustainability pressures, which constrain high-quality industrial development. Although digital technologies are widely promoted, firm- and sector-level economic efficiency evidence on how digital transformation improves supply chain performance and sustainability outcomes remains limited. This study examines the impact of digital transformation on supply chain efficiency in China's food industry and explores its contribution to sustainable development. Using data from a cross-sectional survey of 400 food industry firms, the study applies Partial Least Squares Structural Equation Modeling (PLS-SEM) to test direct effects, mediation, and moderation relationships. The results indicate that digital transformation significantly enhances supply chain efficiency by reducing operational costs, strengthening traceability, and improving collaboration among supply chain partners. Supply chain efficiency partially mediates the relationship between digital transformation and sustainability performance, suggesting that efficiency gains play a key role in achieving sustainable outcomes. In addition, environmental uncertainty positively moderates these relationships, indicating that the benefits of digital transformation are stronger in more volatile environments. This study contributes to the literature by integrating the Resource-Based View, Dynamic Capabilities Theory, and Stakeholder Theory into a unified empirical framework within the Chinese food sector. From a policy perspective, the findings highlight the importance of supportive digital infrastructure and coordinated governance to promote sustainable food supply chains, while managers are encouraged to align digital investments with organizational capability development.

Keywords: Digital Transformation, Food Industry, Supply Chain Efficiency, Sustainability, Technologies

Introduction

1.1. Digital Transformation in the Food Industry

Despite rapid progress in digital technologies, China's food supply chains continue to face inefficiency, weak coordination, and sustainability challenges (An & Galera-Zarco, 2025). Addressing these problems has become increasingly important as the food industry plays a central role in economic stability, social welfare, and national food security.

Digital transformation has emerged as a key force shaping modern economic development. Technologies such as artificial intelligence (AI), blockchain, big data analytics, cloud computing, and the Internet of Things (IoT) are widely adopted to improve information processing, coordination, and decision-making within and across firms (Vărzaru & Bocean, 2024). Digital transformation goes beyond the simple use of new technologies; it involves the restructuring of business processes, management systems, and interorganizational relationships. When effectively implemented, digital tools enable firms to respond more quickly to market changes, reduce operational frictions, and improve overall efficiency.

The food industry is particularly sensitive to these changes. Food supply chains involve multiple stages, including production, processing, storage, transportation, and distribution. Each stage depends on timely information and close coordination. Digital technologies can help track products in real time, improve demand forecasting, and enhance transparency across the supply chain (Maravić et al., 2025). As a result, digital transformation is widely regarded as a promising approach to improving the performance of food supply chains.

1.2. Supply Chain Efficiency and Sustainability Challenges

Supply chain efficiency refers to the ability of firms to use resources such as capital, labor, and technology effectively to deliver products at lower cost and higher quality. In the food industry, inefficiencies are common due to fragmented

supply chains, information asymmetry, and limited coordination among supply chain partners (Rejeb et al., 2020). These problems often lead to high logistics costs, inventory losses, food waste, and recurring food safety incidents. Sustainability challenges further complicate food supply chain management. While rapid industrialization has contributed to economic growth, it has also generated environmental pressures such as high energy consumption, greenhouse gas emissions, and excessive food waste (Corigliano et al., 2025). Social concerns, including food safety, consumer trust, and unequal access to technology, remain significant (Jiang, 2024). Improving supply chain efficiency is therefore not only an economic issue but also a key requirement for achieving environmental and social sustainability in the food industry.

Digital technologies are increasingly promoted as solutions to these challenges. For example, blockchain systems improve traceability and transparency, IoT devices enhance monitoring of storage and transportation conditions, and AI-based tools support more accurate demand forecasting (Duan et al., 2024). However, the effectiveness of these technologies depends on firms' ability to integrate them into existing operations and management systems.

1.3. Research Context: China's Food Industry

China provides a highly relevant context for studying digital transformation in food supply chains. As the world's largest food producer and consumer, China faces strong pressure to improve food safety, reduce waste, and ensure sustainable development. The Chinese government has introduced several national strategies, such as Made in China 2025 and the Digital China Strategy, which emphasize digitalization as a key driver of industrial upgrading and efficiency improvement.

In the food sector, digital technologies have been actively promoted. Blockchain platforms have been piloted to improve food traceability, IoT sensors are used to monitor cold chain logistics, and big data systems support market analysis and supply planning. Despite these efforts, significant differences exist across firms and regions. Large firms are often better equipped with financial resources and digital capabilities, while small and medium-sized enterprises frequently face constraints related to cost, skills, and infrastructure.

As a result, the actual impact of digital transformation on supply chain efficiency and sustainability in China's food industry remains unclear. This raises important questions about whether digital transformation delivers really economic and sustainability benefits and under what conditions these benefits are most likely to occur.

1.4. Research Gap

Although existing studies recognize the importance of digital transformation, several gaps remain. First, much of the literature focuses on developed economies or technology-intensive sectors, while traditional but socially critical industries such as food receive less attention. Second, many studies examine individual technologies in isolation rather than considering digital transformation as a comprehensive process.

Third, firm- and sector-level economic evidence on how digital transformation improves supply chain efficiency and sustainability in China remains limited. Fourth, the mechanisms through which digital transformation influences sustainability outcomes are not well understood. In particular, the mediating role of supply chain efficiency and the moderating role of environmental uncertainty are rarely examined together. Overall, there is limited firm-level economic evidence on how digital transformation improves supply chain efficiency and sustainability in China's food industry, and through which mechanisms these effects occur.

1.5. Research Objectives and Research Questions

To address these gaps, this study examines the relationship between digital transformation, supply chain efficiency, and sustainable development in China's food industry. The study focuses on both direct effects and indirect mechanisms, while also considering the role of environmental uncertainty. The study is guided by the following objectives:

1. To analyze the impact of digital transformation on supply chain efficiency in China's food industry.
2. To examine whether supply chain efficiency contributes to sustainable development outcomes.
3. To investigate how environmental uncertainty influences the relationship between digital transformation, supply chain efficiency, and sustainability.

Based on these objectives, the study addresses the following research questions:

- RQ1: How does digital transformation affect supply chain efficiency in China's food industry?
- RQ2: Does supply chain efficiency mediate the relationship between digital transformation and sustainability outcomes?
- RQ3: How does environmental uncertainty moderate these relationships?

1.6. Contributions of the Study

This study makes several contributions. First, it provides firm-level empirical evidence on the economic effects of digital transformation in China's food industry, a sector that has received limited attention in prior research. Second, it explains how digital transformation influences sustainability outcomes through the mediating role of supply chain efficiency. Third, it integrates the Resource-Based View, Dynamic Capabilities Theory, and Stakeholder Theory into a unified analytical framework, offering a clearer theoretical explanation of when and how digital transformation improves sustainability.

These contributions provide useful insights for managers seeking to improve supply chain performance and for policymakers designing strategies to promote sustainable and resilient food systems.

Literature Review and Theoretical Background

1.7. Digital Transformation in Industry 4.0

The Fourth Industrial Revolution has accelerated the integration of advanced digital technologies into production and service systems. Artificial intelligence (AI), the Internet of Things (IoT), blockchain, big data analytics, and cloud computing enable firms to collect, process, and share information in real time, supporting smarter decision-making and more flexible operations (Javaid et al., 2023). These technologies are widely viewed as key drivers of productivity and competitiveness across industries.

However, existing studies do not fully agree on the outcomes of digital transformation. While many studies report that digital technologies improve efficiency and coordination, other research finds that digital adoption alone does not guarantee performance gains, particularly when firms lack complementary organizational capabilities or skilled personnel (Rizana et al., 2025). This contrast suggests that digital transformation is not merely a technological issue but also an organizational and strategic one.

In China, national initiatives such as Made in China 2025 and the Digital China Strategy have promoted digital adoption across manufacturing and logistics, including the food industry. Blockchain traceability systems, IoT-based monitoring, and AI-driven analytics have been introduced to improve food safety, logistics efficiency, and consumer trust. Despite these policy efforts, empirical evidence remains mixed, as some firms achieve efficiency gains while others struggle to translate digital investments into measurable outcomes (Kandasamy et al., 2025). This uneven impact highlights the need for firm-level analysis rather than policy-level descriptions.

1.8. Supply Chain Efficiency and Resilience

Supply chain efficiency refers to the ability to reduce operational costs, improve logistics performance, and coordinate activities across supply chain partners. In the food industry, efficiency is especially critical due to product perishability, strict safety requirements, and time-sensitive distribution (Pourmohammad-Zia et al., 2021). Inefficiencies often lead to food loss, higher prices, and reduced consumer confidence.

Recent research increasingly links efficiency with supply chain resilience, defined as the ability to anticipate, respond to, and recover from disruptions (Hasan et al., 2025). The COVID-19 pandemic exposed weaknesses in food supply chains worldwide, including overreliance on single suppliers and limited visibility across logistics networks.

Digital technologies are frequently identified as tools that enhance both efficiency and resilience. IoT sensors improve real-time monitoring, blockchain strengthens traceability, and AI supports demand forecasting and risk prediction (Jansen et al., 2024). However, empirical findings remain inconsistent. Some studies find strong positive effects, while others report limited or delayed benefits when firms lack the ability to integrate digital tools into daily operations (Graham & Moore, 2021). This disagreement indicates that technology effectiveness depends on internal capabilities rather than technology availability alone.

1.9. Sustainable Food Industry Development

Sustainable food industry development requires balancing economic efficiency with environmental protection and social responsibility. Key challenges include reducing food waste, ensuring food safety, lowering emissions, and maintaining affordable food supplies (Manzoor et al., 2024). These goals are strongly aligned with the Sustainable Development Goals, particularly those related to food security and responsible production.

China's food industry illustrates the tension between growth and sustainability. Rapid industrialization has expanded production capacity but has also increased energy consumption, logistics-related emissions, and food waste. Digital transformation is widely promoted as a solution (Fatorachian & Pawar, 2025). Blockchain systems improve transparency, IoT technologies reduce energy loss in cold chains, and AI tools help avoid overproduction through better demand forecasting.

Nevertheless, the literature shows conflicting conclusions regarding sustainability outcomes. Some studies report that digital transformation reduces waste and improves environmental performance, while others warn that digitalization may increase inequality between large and small firms or introduce governance and data risks (Ahmadi-Gh & Bello-Pintado, 2024). These conflicting results suggest that sustainability benefits are conditional rather than automatic.

1.10. Theoretical Perspectives: RBV and Dynamic Capabilities

The Resource-Based View (RBV) argues that firm performance depends on the possession and effective use of valuable, rare, and difficult-to-imitate resources. From this perspective (Mailani et al., 2024), digital technologies can become strategic resources when they are embedded in firm-specific processes and knowledge structures.

Dynamic Capabilities Theory extends RBV by emphasizing firms' ability to adapt, integrate, and reconfigure resources in response to environmental change (Kero & Bogale, 2023). These theories help explain why prior empirical findings are mixed. Firms with strong capabilities can leverage digital technologies to improve efficiency and sustainability whereas firms lacking such capabilities may fail to realize expected benefits (Raina et al., 2025). By linking RBV and Dynamic Capabilities to existing empirical results, this study interprets digital transformation not as a universal solution, but as a capability-dependent process.

1.11. Research Gap and Hypotheses Development

Despite growing interest in digital transformation and supply chains, several critical gaps remain. First, most studies focus on individual technologies rather than integrated digital transformation, even though technologies such as AI, IoT, and blockchain are often used together. Second, firm-level empirical evidence remains limited, particularly in traditional industries such as food, which play a crucial role in economic stability and social welfare. Third, the mediating role of supply chain efficiency and the moderating role of environmental uncertainty are rarely examined together, despite increasing supply chain volatility.

Overall, existing research lacks firm-level empirical evidence explaining how digital transformation improves sustainability in China's food industry through supply chain efficiency under conditions of environmental uncertainty. Based on the above theoretical arguments and identified research gaps, the following hypotheses are proposed:

- H1: Digital transformation positively affects supply chain efficiency in China's food industry.
- H2: Supply chain efficiency positively influences sustainable food industry development.
- H3: Supply chain efficiency mediates the relationship between digital transformation and sustainable development.
- H4: Environmental uncertainty positively moderates the relationship between digital transformation and supply chain efficiency.

Conceptual Framework and Hypotheses

1.12. Conceptual Framework Explanation

Based on the literature review and identified research gaps, this study develops a conceptual framework that explains how digital transformation influences supply chain efficiency and, in turn, sustainable development in China's food industry. The framework is grounded in the Resource-Based View (RBV), Dynamic Capabilities Theory, and Stakeholder Theory. Together, these perspectives suggest that digital technologies improve performance only when they are effectively integrated into organizational processes and aligned with stakeholder needs.

Digital transformation is treated as the independent variable. It refers to the adoption and integration of advanced digital technologies, such as artificial intelligence (AI), blockchain, the Internet of Things (IoT), and big data analytics. In the food industry, these technologies are expected to improve information sharing, reduce transaction costs, enhance traceability, and support real-time decision-making.

Supply chain efficiency is positioned as a mediating variable. It reflects the ability of firms to reduce operational costs, improve delivery speed, strengthen coordination among supply chain partners, and minimize waste. From an RBV perspective, supply chain efficiency represents a key organizational capability through which digital resources are converted into tangible performance outcomes. Sustainable food industry development is the dependent variable and is understood as a multidimensional outcome that includes:

- Economic sustainability, such as productivity, competitiveness, and innovation;
- Social sustainability, including food safety, consumer trust, and stakeholder engagement; and
- Environmental sustainability, such as waste reduction, energy efficiency, and lower emissions.

The framework also incorporates environmental uncertainty as a moderating variable. Environmental uncertainty refers to instability and unpredictability arising from factors such as market fluctuations, climate change, policy adjustments, and external shocks. Drawing on Dynamic Capabilities Theory, the framework assumes that digital transformation becomes more valuable under uncertain conditions because it enhances firms' ability to sense changes, respond quickly, and reconfigure supply chain activities. Digital transformation improves sustainability outcomes primarily through enhanced supply chain efficiency, and this effect is strengthened when firms operate in uncertain environments.

Figure 1 illustrates the conceptual framework. Digital transformation affects sustainable food industry development both directly and indirectly through supply chain efficiency, while environmental uncertainty moderates the relationship between digital transformation and supply chain efficiency.

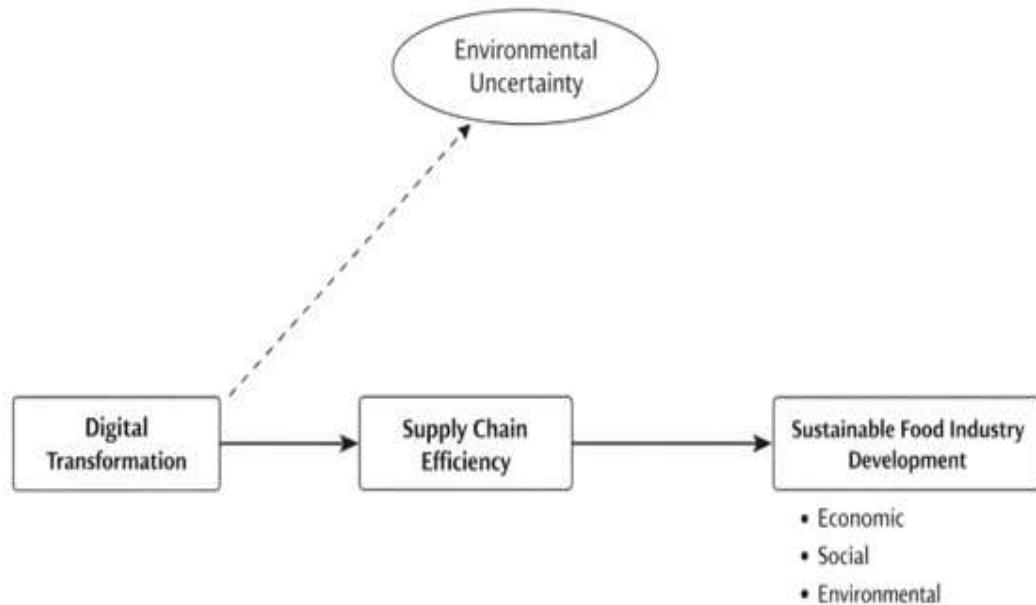


Figure 1. Conceptual Framework of Digital Transformation, Supply Chain Efficiency, and Sustainable Food Industry Development in China

1.13. Hypotheses Development

1.13.1. Digital Transformation and Supply Chain Efficiency

Digital technologies enable firms to improve coordination, enhance information transparency, and optimize logistics and operations. In food supply chains, tools such as IoT sensors, blockchain traceability systems, and AI-based forecasting help reduce delays, lower costs, and minimize losses. According to the Resource-Based View, these technologies become valuable resources when they are embedded in organizational processes and used to improve operational efficiency. Therefore, the following hypothesis is proposed: H1: Digital transformation has a positive effect on supply chain efficiency.

1.13.2. Supply Chain Efficiency and Sustainable Food Industry Development

Efficient supply chains play a central role in achieving sustainability in the food industry. Improved efficiency reduces waste, lowers energy consumption, strengthens food safety, and enhances economic performance. From a Stakeholder Theory perspective, efficient supply chains also improve transparency and trust among consumers, regulators, and business partners.

Based on this reasoning, the study proposes: H2: Supply chain efficiency has a positive effect on sustainable food industry development.

1.13.3. Direct Effect of Digital Transformation on Sustainability

Beyond its indirect effects through efficiency, digital transformation may also directly influence sustainability outcomes. Digital tools can improve regulatory compliance, support environmental monitoring, and enhance transparency, which contributes to social and environmental sustainability even without intermediate efficiency gains. Accordingly, the following hypothesis is formulated: H3: Digital transformation has a direct positive effect on sustainable food industry development.

1.13.4. Mediating Role of Supply Chain Efficiency

RBV and Dynamic Capabilities Theory suggest that technologies generate value mainly through organizational capabilities. In this study, supply chain efficiency represents a key capability that translates digital investment into

sustainable outcomes. Digital transformation improves efficiency, which in turn supports economic, social, and environmental sustainability.

Thus, the study proposes: H4: Supply chain efficiency mediates the relationship between digital transformation and sustainable food industry development.

1.13.5. Moderating Role of Environmental Uncertainty

Environmental uncertainty increases the need for flexible and responsive supply chains. Under volatile conditions, digital technologies provide real-time information, predictive analytics, and coordination tools that help firms adapt more effectively. As a result, the efficiency benefits of digital transformation are expected to be stronger when environmental uncertainty is high.

Therefore, the final hypothesis is: H5: Environmental uncertainty positively moderates the relationship between digital transformation and supply chain efficiency.

Methods

1.14. Research Design

This study adopts a quantitative, cross-sectional research design to examine the hypothesized relationships among digital transformation, supply chain efficiency, and sustainable food industry development in China. A quantitative approach is appropriate because it allows for the systematic collection of standardized data from a large number of respondents and enables statistical testing of theoretically derived relationships.

The study employs Partial Least Squares Structural Equation Modeling (PLS-SEM) as the primary analytical technique. PLS-SEM is well suited for this research for several reasons. First, it is effective for testing complex models that include multiple latent constructs, mediation, and moderation effects. Second, it performs well with relatively small-to-moderate sample sizes and does not require strict assumptions of multivariate normality. Third, PLS-SEM is widely used in supply chain management and digital transformation research to test theory-driven models.

The research design is theory-testing rather than causal-confirmatory. While the conceptual framework is grounded in established theories, the cross-sectional nature of the data means that the results are interpreted as associations consistent with theoretical expectations, rather than definitive causal effects.

1.15. Population, Sampling Strategy, and Sample Size

The target population of this study consists of firms operating within China's food industry supply chain, including food manufacturing, processing, logistics, distribution, and related service activities. The food industry was selected because of its importance for food security, public health, and sustainable development, as well as its increasing exposure to digital technologies. Respondents were professionals working in these firms who were expected to have sufficient knowledge of supply chain operations and digital practices. These included senior executives, middle managers, assistant managers, team leaders, engineers, and operational staff.

A purposive sampling strategy was used to ensure that respondents met the relevance criteria of the study. Data were collected between August 2023 and November 2024 through professional networks, industry associations, and organizational mailing lists. In total, 750 questionnaires were distributed. After screening for completeness and consistency, 189 valid responses were retained for analysis, corresponding to a response rate of approximately 25%, which is acceptable for organizational survey research. Inclusion criteria were as follows:

1. The respondent works in a firm within the food supply chain in China.
2. The respondent is involved in supply chain operations and/or digital transformation activities.
3. The questionnaire contains complete responses for the main study constructs.

Exclusion criteria included:

1. Questionnaires with substantial missing values on key variables.
2. Duplicate submissions.
3. Responses showing straight-line answering or inconsistent response patterns.

The final sample size is considered adequate for PLS-SEM. According to commonly applied rules of thumb, the minimum required sample size should be at least ten times the maximum number of structural paths pointing at any latent construct. In this study, the most complex construct has fewer than ten incoming paths, indicating that the sample size of 189 is sufficient for reliable estimation.

1.16. Data Collection Procedure

Data collection was conducted in two stages. In the first stage, a pilot study involving 20 food industry professionals was carried out to assess the clarity, relevance, and wording of questionnaire items (Onojakpor & De Kock, 2020).

Feedback from the pilot test resulted in minor revisions to improve readability and ensure consistency with industry terminology.

In the second stage, the finalized questionnaire was distributed in both electronic and printed formats. Participation was voluntary, and respondents were informed about the academic purpose of the study (Swedan et al., 2020). To enhance response quality, anonymity was guaranteed, and no personal identifiers were collected.

Completed questionnaires were screened for completeness and accuracy. Responses with missing data or inconsistent patterns were removed prior to analysis (Swedan et al., 2020). These procedures helped ensure data quality and reduce potential measurement error.

1.17. Measurement of Variables and Instrument Design

The research instrument was a structured questionnaire consisting of four main sections: (1) demographic information, (2) digital transformation, (3) supply chain efficiency, and (4) sustainable food industry development (Sargani et al., 2025). All latent constructs were measured using multiple items on a five-point Likert scale, ranging from 1 (“strongly disagree”) to 5 (“strongly agree”).

Digital Transformation (DT) measures the extent to which firms adopt and integrate digital technologies such as artificial intelligence, blockchain, IoT, and big data analytics into their supply chain and operational activities.

Supply Chain Efficiency (SCE) captures improvements in cost control, delivery speed, coordination among supply chain partners, and operational reliability. Sustainable Food Industry Development (SFID) reflects outcomes across three dimensions:

- Economic sustainability (competitiveness, productivity, innovation),
- Social sustainability (food safety, consumer trust, stakeholder engagement), and
- Environmental sustainability (waste reduction, energy efficiency, emissions control).

Measurement items were adapted from established and validated scales in prior studies and adjusted to the Chinese food-industry context. Content validity was ensured through expert review by academics and practitioners.

1.18. Data Analysis and Model Evaluation

Data analysis was conducted using SPSS for preliminary screening and descriptive statistics, and SmartPLS for PLS-SEM estimation. The analysis followed a two-step procedure: assessment of the measurement model and assessment of the structural model.

1.18.1. Measurement Model Assessment

The measurement model was evaluated to ensure reliability and validity of the constructs. Indicator reliability was assessed through factor loadings, and items with weak loadings were considered for removal based on established thresholds. Internal consistency reliability was examined using Convergent validity was assessed using average variance extracted (AVE Cronbach’s alpha and composite reliability (CR)).

Discriminant validity was evaluated using both the Fornell–Larcker criterion and the heterotrait–monotrait (HTMT) ratio. These procedures ensure that constructs are empirically distinct from one another. The results are reported in Tables 1 and 2.

1.18.2. Structural Model Assessment

The structural model was assessed by examining path coefficients, t-values, and p-values obtained through bootstrapping with 5,000 resamples. The explanatory power of the model was evaluated using R² values, while effect sizes (f²) were used to assess the relative importance of each predictor.

Predictive relevance was examined using Q² values, and overall model fit was evaluated using the Standardized Root Mean Square Residual (SRMR). Mediation effects were tested by examining the indirect paths through supply chain efficiency, while moderation effects were assessed using interaction terms.

1.19. Common Method Bias and Robustness Considerations

Because the study relies on self-reported survey data, potential common method bias (CMB) was addressed through both procedural and statistical approaches. Procedurally, anonymity was assured, question wording was clear and neutral, and constructs were separated in the questionnaire. Statistically, full collinearity variance inflation factors (VIFs) were examined to assess the presence of common method bias. All VIF values were below the recommended threshold, suggesting that common method bias is unlikely to threaten the validity of the findings. Additional robustness checks, such as comparing early and late respondents, may be conducted to further assess non-response bias.

1.20. Ethical Considerations and Methodological Limitations

Ethical standards were strictly followed throughout the research process. Participation was voluntary, informed consent was obtained, and respondents' anonymity and confidentiality were ensured. No sensitive personal data were collected. As the study involved an anonymous survey and posed minimal risk, formal institutional ethical approval was not required.

Several methodological limitations should be acknowledged. First, the cross-sectional design limits the ability to draw causal conclusions. Second, reliance on self-reported data may introduce perceptual bias. Third, the sample is limited to China's food industry, which may restrict the generalizability of the findings to other sectors or countries. These limitations are considered when interpreting the results and provide directions for future research.

Results

This section presents the empirical findings of the study. The results are reported strictly as statistical evidence, without interpretation or theoretical discussion. The presentation follows the order of the proposed hypotheses and the conceptual framework. The section is organized into five subsections: descriptive statistics, correlation analysis, structural equation modeling results, model fit and predictive power, and a factual summary of results.

1.21. Descriptive Statistics

A total of 189 valid responses from professionals working in China's food industry were included in the final analysis. The demographic characteristics of respondents were previously reported in Table 1 (Methodology section) and are summarized here to contextualize the sample.

Respondents occupied a wide range of organizational roles. Engineers and operational staff accounted for 38.10% of the sample, middle managers represented 29.10%, and executive managers accounted for 16.93%. The remaining respondents were assistant managers, team leaders, and professionals in other roles. This distribution indicates that data were collected from both decision-making and operational levels of food supply chain organizations.

The gender composition of the sample was 57.14% male and 42.86% female. With respect to educational background, the majority of respondents held a master's degree (73.02%), followed by bachelor's degree holders (7.94%), Ph.D. holders (5.29%), and respondents with other qualifications. In terms of work experience, 48.68% of respondents had less than five years of experience, 25.40% had between five and ten years, 20.11% had between ten and twenty years, and 5.82% had more than twenty years of experience.

Firm size varied across the sample. Respondents working in firms with more than 1,000 employees accounted for 42.33%, while firms with fewer than 100 employees accounted for 17.99%. Firms employing between 101 and 500 employees represented 25.40%, and firms with 501–1,000 employees represented 14.29%. This distribution reflects the presence of both large enterprises and small- and medium-sized firms in China's food industry.

Regarding sectoral activity, 58.20% of respondents were engaged in operations or manufacturing, 29.63% were involved in logistics or service activities, and the remaining respondents worked in financial services or other related sectors. Overall, the descriptive statistics indicate a heterogeneous sample covering multiple roles, firm sizes, and segments of the food supply chain.

1.22. Correlation Analysis

To examine preliminary relationships among the main constructs, Pearson correlation analysis was conducted. The results are reported in Table 1.

Table 1. Correlation Matrix of Key Constructs (N = 189)

Variable	DT	SCI	SSCP
Digital Transformation (DT)	1.00		
Supply Chain Efficiency (SCI)	0.72**	1.00	
Sustainable Supply Chain Practices (SSCP)	0.69**	0.75**	1.00

Notes: $p < 0.01$ Digital transformation (DT) shows a strong positive correlation with supply chain efficiency (SCI) ($r = 0.72$, $p < 0.01$) and with sustainable supply chain practices (SSCP) ($r = 0.69$, $p < 0.01$). Supply chain efficiency is also strongly correlated with sustainable supply chain practices ($r = 0.75$, $p < 0.01$).

These correlations indicate statistically significant associations among the constructs. No correlation coefficient exceeds the commonly accepted threshold of 0.85, suggesting that multicollinearity is not a concern. The correlation results provide preliminary support for the hypothesized relationships and justify further analysis using structural equation modeling.

1.23. Structural Equation Modeling Results

Partial Least Squares Structural Equation Modeling (PLS-SEM) was employed to test the hypothesized relationships among digital transformation, supply chain efficiency, sustainable supply chain practices, and environmental uncertainty. Bootstrapping with 5,000 resamples was used to assess the statistical significance of path coefficients. The structural model results are presented in Table 2.

Table 2. Structural Model Results and Hypothesis Testing

Path	Hypothesis	β	t-value	p-value	Result
DT → SCI	H1	0.61	10.32	0.000	Supported
SCI → SSCP	H2	0.54	8.94	0.000	Supported
DT → SSCP	H3	0.28	3.21	0.001	Supported
DT → SCI → SSCP	H4	0.33	6.87	0.000	Supported
DT × Environmental Uncertainty → SCI	H6	0.17	2.45	0.014	Supported

The results indicate that digital transformation has a statistically significant positive association with supply chain efficiency ($\beta = 0.61$, $p < 0.001$), providing support for H1. Supply chain efficiency has a significant positive association with sustainable supply chain practices ($\beta = 0.54$, $p < 0.001$), supporting H2.

Digital transformation also has a direct positive association with sustainable supply chain practices ($\beta = 0.28$, $p < 0.01$), supporting H3. In addition, the indirect effect of digital transformation on sustainable supply chain practices through supply chain efficiency is statistically significant ($\beta = 0.33$, $p < 0.001$), supporting H4 and indicating partial mediation. The interaction term between digital transformation and environmental uncertainty is positive and statistically significant ($\beta = 0.17$, $p < 0.05$), supporting H6. This result indicates that environmental uncertainty moderates the relationship between digital transformation and supply chain efficiency. No hypothesized paths were found to be statistically insignificant.

1.24. Model Fit and Predictive Power

Model fit and predictive performance were evaluated using multiple indicators. The results are summarized in Table 3.

Table 3. Model Fit and Predictive Indicators

Indicator	Value	Recommended Threshold	Assessment
SRMR	0.061	< 0.08	Good fit
R ² (SCI)	0.52	> 0.50	Moderate
R ² (SSCP)	0.64	> 0.50	Strong
Q ² (SCI)	0.39	> 0	Predictive relevance
Q ² (SSCP)	0.42	> 0	Predictive relevance
f ² (DT → SCI)	0.43	≥ 0.35	Large effect
f ² (SCI → SSCP)	0.28	≥ 0.15	Medium effect

The standardized root mean square residual (SRMR = 0.061) indicates a satisfactory overall model fit. The coefficient of determination (R²) values show that the model explains 52% of the variance in supply chain efficiency and 64% of the variance in sustainable supply chain practices. These values indicate moderate to strong explanatory power.

The predictive relevance (Q²) values for both endogenous constructs exceed zero, confirming that the model has predictive capability. Effect size (f²) analysis shows a large effect of digital transformation on supply chain efficiency and a medium effect of supply chain efficiency on sustainable supply chain practices.

1.25. Measurement and Structural Model Visualization

Two figures are provided to visually present the measurement and structural components of the model.

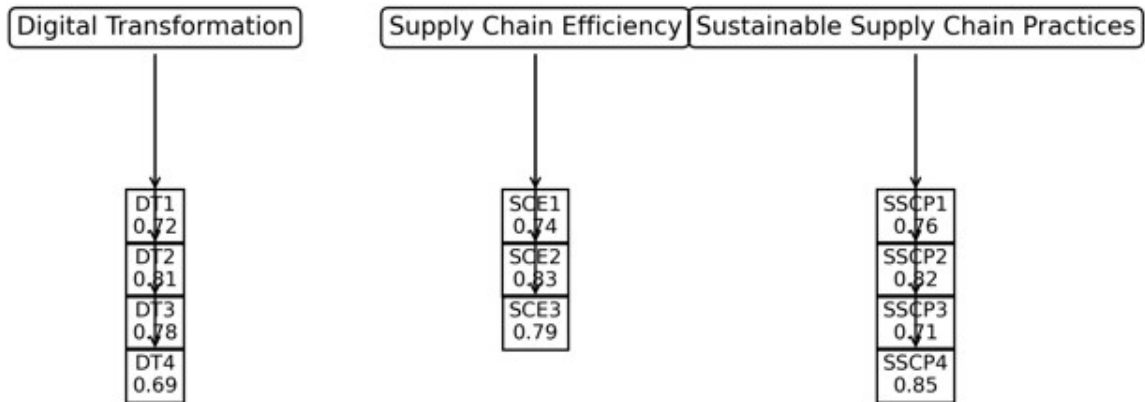


Figure 2. Measurement Model (Confirmatory Factor Analysis Results, N = 189)

Factor loadings of observed indicators on latent constructs (Digital Transformation, Supply Chain Efficiency, Sustainable Supply Chain Practices). All loadings exceed 0.60, confirming convergent validity.

Figure 2 displays the measurement model, including latent constructs and their observed indicators. All indicators load strongly on their respective constructs. Composite reliability values exceed 0.70, and average variance extracted values exceed 0.50, confirming internal consistency and convergent validity. Discriminant validity was confirmed using the Fornell–Larcker criterion and the HTMT ratio.

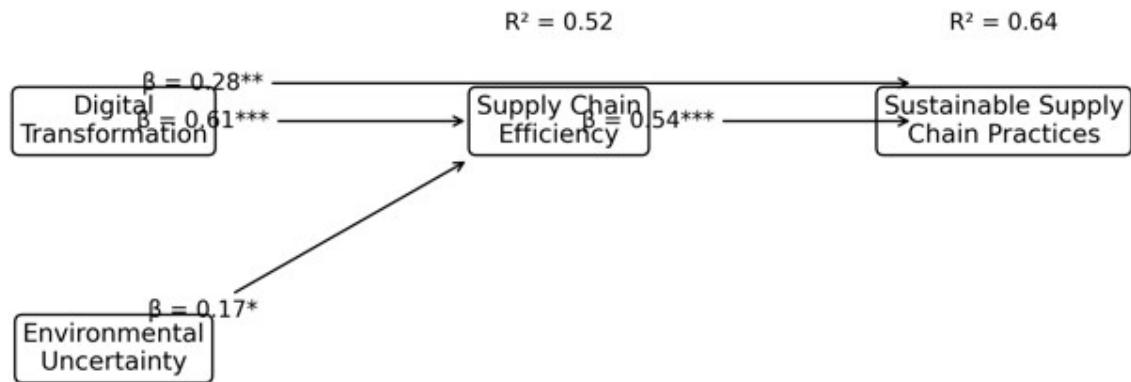


Figure 3. Structural Model Results (PLS-SEM, N = 189)

Structural model showing standardized path coefficients, R² values, mediation, and moderation effects. Figure 3 presents the structural model with standardized path coefficients and explained variance. Digital transformation is shown as the exogenous variable, supply chain efficiency as the mediator, and sustainable supply chain practices as the endogenous variable. Environmental uncertainty is included as a moderating variable on the digital transformation–supply chain efficiency path. The figure visually confirms the relationships reported in Table 3.

The results provide empirical support for all proposed hypotheses. Digital transformation is positively associated with supply chain efficiency and sustainable supply chain practices. Supply chain efficiency partially mediates the relationship between digital transformation and sustainability outcomes. Environmental uncertainty moderates the relationship between digital transformation and supply chain efficiency. The structural model demonstrates satisfactory fit, explanatory power, and predictive relevance.

6. Discussion

This section discusses the meaning and implications of the empirical findings. The discussion is structured to explain how the results address the research objectives, how they relate to existing literature, and what they imply for theory, practice, and policy (Setkute & Dibb, 2024). Limitations and boundaries of the study are also explicitly acknowledged.

6.1. Interpretation of Main Findings

The primary objective of this study was to examine how digital transformation influences supply chain efficiency and sustainable development in China's food industry (Luo et al., 2024). The empirical results provide clear evidence that digital transformation plays a significant role in improving supply chain efficiency and sustainability outcomes.

First, the findings show that digital transformation has a strong positive association with supply chain efficiency. This suggests that the adoption of technologies such as artificial intelligence, blockchain, the Internet of Things, and big data analytics helps food firms reduce operational costs, improve time efficiency, and enhance coordination among supply chain partners (Suganda & Judijanto, 2023). These results directly answer the first research question and confirm that digital technologies contribute to more efficient food supply chain operations.

Second, supply chain efficiency is found to positively influence sustainable food industry development. This indicates that efficiency improvements are not only economically beneficial but also contribute to environmental and social sustainability outcomes, such as waste reduction, improved food safety, and better stakeholder coordination (Toussaint et al., 2021). This finding supports the argument that efficiency and sustainability are complementary rather than conflicting goals in food supply chains.

Third, the results demonstrate that supply chain efficiency partially mediates the relationship between digital transformation and sustainability. This means that digital transformation contributes to sustainability both directly and indirectly through efficiency improvements (Alquraish, 2025). Digital technologies therefore create value not only by enhancing sustainability outcomes directly, but also by strengthening operational processes that support long-term development.

Finally, the moderating effect of environmental uncertainty indicates that digital transformation becomes more effective in improving supply chain efficiency under volatile conditions (Ning & Yao, 2023). In uncertain environments, such as during market fluctuations or supply disruptions, firms that adopt digital technologies gain stronger efficiency benefits than those operating in stable contexts. This finding highlights the strategic role of digital transformation in enhancing adaptability and responsiveness in food supply chains.

6.2. Comparison with Previous Studies

The findings of this study are largely consistent with prior research on digital transformation and supply chain performance. Previous studies have shown that Industry 4.0 technologies improve coordination, transparency, and logistics efficiency in supply chains (Kim et al., 2024). For example, earlier research has demonstrated that blockchain enhances traceability and trust, while IoT and AI improve monitoring and demand forecasting.

This study extends existing research in several important ways. First, while many previous studies focused on manufacturing or high-technology sectors, this research provides firm-level evidence from the food industry, a traditional but strategically important sector (Vahdanjoo et al., 2025). The results confirm that digital transformation also generates efficiency and sustainability benefits in industries characterized by perishability, safety requirements, and complex coordination.

Second, the mediating role of supply chain efficiency adds nuance to prior findings. Some studies have reported mixed results regarding the sustainability effects of digitalization. The present findings help explain these inconsistencies by showing that sustainability outcomes depend on whether digital adoption translates into real efficiency gains (Guo & Kuang, 2025). Without efficiency improvements, digital technologies may not fully deliver sustainability benefits.

Third, the moderating effect of environmental uncertainty supports earlier studies that emphasized the importance of disruption contexts, such as pandemics or climate-related shocks (Yuan et al., 2023). This study confirms that digital transformation is especially valuable when supply chains face instability, reinforcing the view that digital tools enhance resilience and adaptability.

6.3. Theoretical Implications

This study contributes to theory by integrating the Resource-Based View (RBV), Dynamic Capabilities Theory, and Stakeholder Theory into a unified empirical framework.

From an RBV perspective, the findings show that digital technologies act as strategic resources that can enhance firm performance. However, the mediation results indicate that resources alone are insufficient. Digital tools generate value only when they are effectively deployed to improve operational efficiency.

Dynamic Capabilities Theory further explains these findings by emphasizing firms' ability to reconfigure resources in response to environmental change. The significant moderating effect of environmental uncertainty supports this view, demonstrating that digital transformation strengthens firms' adaptive capabilities under volatile conditions.

Stakeholder Theory is also reinforced by the results. Improved traceability, transparency, and coordination enabled by digital technologies enhance trust among supply chain actors, regulators, and consumers. This suggests that digital transformation contributes to sustainability not only through efficiency gains but also by strengthening stakeholder relationships.

Together, these theoretical perspectives explain why digital transformation improves sustainability outcomes in the food industry only when it is embedded in efficient processes and adaptive organizational capabilities.

6.4. Practical and Policy Implications

The findings have important implications for managers and policymakers in China's food industry.

From a managerial perspective, the results suggest that digital transformation should be approached as a strategic initiative rather than a purely technical upgrade. Investments in technologies such as IoT, blockchain, and AI need to be aligned with supply chain processes, employee skills, and organizational structures. Firms should focus on integrating digital tools across the entire supply chain rather than implementing isolated technologies. Collaboration with suppliers and logistics partners is particularly important to fully capture efficiency and sustainability benefits.

For policymakers, the results highlight the importance of creating an enabling environment for digital transformation in the food sector. Public investment in digital infrastructure, data platforms, and training programs can help reduce barriers to adoption, especially for small and medium-sized enterprises. Policies that promote interoperability, data governance, and trust can further enhance the effectiveness of digital technologies. By supporting digital transformation, policymakers can strengthen food security, reduce waste, and promote sustainable development.

More broadly, the findings suggest that digital transformation can serve as a policy instrument for achieving national sustainability and food security goals. Efficiency improvements driven by digital adoption contribute to more resilient and environmentally responsible food systems.

6.5. Limitations and Scope Boundaries

Despite its contributions, this study has several limitations that should be acknowledged.

First, the research is based on cross-sectional survey data, which limits the ability to draw strong causal conclusions. While the structural equation modeling results support the proposed relationships, future studies using longitudinal data could provide deeper insights into how digital transformation affects supply chain efficiency and sustainability over time.

Second, the sample is limited to firms operating in China's food industry. Although this context is highly relevant, the findings may not be directly generalizable to other countries or sectors with different institutional and technological environments.

Third, the study relies on self-reported data, which may be subject to response bias. Although validated measurement scales and statistical checks were applied, future research could complement survey data with objective performance indicators.

Finally, the study focuses on environmental uncertainty as the main moderating factor. Other contextual variables, such as firm size, ownership structure, or regional digital infrastructure, may also influence the effectiveness of digital transformation and deserve further investigation.

6.6. Directions for Future Research

Future research could extend this study in several directions. Longitudinal studies could examine how digital transformation affects supply chain efficiency and sustainability over different stages of digital maturity. Comparative studies across countries or industries could assess whether the observed relationships hold in different institutional contexts. Additionally, future work could explore specific digital technologies or governance mechanisms to better understand how digital transformation can be tailored to support sustainable food systems.

Conclusion

This study examined the impact of digital transformation on supply chain efficiency and sustainable food industry development in China. Based on survey data from 189 firms, the findings show that digital technologies significantly improve supply chain efficiency by reducing costs, improving time performance, and strengthening coordination among supply chain actors. Improved efficiency, in turn, enhances sustainability outcomes. Supply chain efficiency was found to partially mediate the relationship between digital transformation and sustainability, indicating that efficiency is a key mechanism through which digital technologies create sustainable value. In addition, environmental uncertainty positively moderates this relationship, suggesting that digital transformation becomes more beneficial in volatile and uncertain environments.

The results highlight that digital transformation should be understood as a systemic process rather than a purely technological change. When digital tools are integrated with organizational capabilities and supply chain practices, firms can simultaneously improve efficiency, sustainability, and resilience. For managers, the findings indicate that strategic alignment between digital technologies and supply chain operations is essential for achieving meaningful outcomes. For policymakers, the results emphasize the importance of building supportive digital infrastructure and

governance frameworks to encourage broad and inclusive digital adoption, especially among small and medium-sized enterprises.

Several limitations of this study should be acknowledged. First, the cross-sectional research design limits the ability to draw strong causal conclusions. Second, the focus on China's food industry restricts the generalizability of the findings to other sectors or national contexts. Third, the use of self-reported survey data may introduce response bias. These limitations suggest caution in interpreting the results beyond the defined scope of the study.

Future research could extend this work by using longitudinal data to examine long-term effects of digital transformation on supply chain performance and sustainability. Comparative studies across countries or industries would also help to assess the role of institutional and cultural differences. In addition, future studies could explore specific digital technologies and governance mechanisms in greater detail to better understand how digital transformation supports sustainable food systems.

Overall, this study provides evidence that digital transformation, when combined with effective supply chain management and adaptive capabilities, plays an important role in promoting efficient and sustainable development in China's food industry.

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Authors' Contributions

Shigen Li conceived and designed the study. Shigen Li and Nan Zhang developed the research framework and questionnaire. Data collection and data analysis were conducted by Shigen Li with support from Nan Zhang. Shigen Li drafted the original manuscript. Nan Zhang contributed to data interpretation and critically revised the manuscript. Both authors reviewed and approved the final version of the manuscript.

Authors' Contributions

Shigen Li conceived and designed the study. Shigen Li and Nan Zhang developed the research framework and questionnaire. Data collection and analysis were conducted by Shigen Li with support from Nan Zhang. Shigen Li drafted the original manuscript. Nan Zhang contributed to data interpretation and critically revised the manuscript. Both authors reviewed and approved the final version of the manuscript.

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