THE IMPACT OF DIGITAL TRANSFORMATION ON WILD COFFEE SUPPLY CHAIN EFFICIENCY: THE MEDIATING ROLE OF PROCESS INNOVATION AND THE MODERATING ROLE OF ENVIRONMENTAL UNCERTAINTY

Hongyang Ni [1*]

Shun-Chen Zhang [2]

Praphaphan Wunsuk [3]

Qifeng Wei [4]

Hongwei Li [5]

[1] Master Candidate in Business Administration, North Chiang Mai University

[2] Lecturer, North Chiang Mai University

[3] Lecturer, North Chiang Mai University

[4] Lecturer, North Chiang Mai University

[5] Lecturer, North Chiang Mai University

[*] **Corresponding Author, E-mail:** hongyangni@northcm.ac.th

Abstract: This study takes digital transformation as the independent variable, the efficiency of the wild coffee supply chain as the dependent variable, process innovation as the mediating variable, and environmental uncertainty as the moderating variable. The core conceptual framework is established through demographic variables such as business scale and production scale. This study proposes the following hypotheses: 1. Digital transformation has a positive impact on the supply chain efficiency of the wild coffee industry. 2. Process innovation is the mediator of the relationship between digital transformation and supply chain efficiency. 3. Environmental uncertainty moderates the relationship between digital transformation and supply chain efficiency. This paper takes the wild coffee industry in Yunnan Province, China as a case study and distributed a total of 400 questionnaires, with 383 valid questionnaires returned.

This study finds that: 1. Digital transformation has a positive impact on the supply chain efficiency of the wild coffee industry; 2. Process innovation partially mediates the relationship between digital transformation and supply chain efficiency; 3. Environmental uncertainty does not significantly moderate the relationship between digital transformation and supply chain efficiency. This study aims to examine the impact of digital transformation on the supply chain efficiency of the wild coffee industry in Yunnan Province, China. By exploring the multifaceted influences of these relationships in depth, it aims to enrich existing knowledge and address how digitalization affects supply chain

operations in a turbulent environment.

Keywords: Digital Transformation, Supply Chain Efficiency, Process Innovation, Environmental Uncertainty

Introduction

The global coffee industry is facing significant challenges due to increasing demand, climate change, and fluctuating market conditions. The wild coffee supply chain, particularly in regions such as Ethiopia, Colombia, and parts of Central America, plays a crucial economic and ecological role. However, the industry continues to grapple with inefficiencies and disruptions, particularly in rural and developing areas. Digital transformation, encompassing technologies such as the Internet of Things (IoT), blockchain, and data analytics, has revolutionized supply chain management by enhancing transparency, efficiency, and operational optimization (Choi, 2020). While digitalization has been widely recognized as a driver of operational efficiency and cost reduction, the wild coffee industry has yet to fully capitalize on its potential. Smallholder farmers and supply chain actors in remote regions face persistent challenges, including resource inefficiencies, supply chain disruptions, and a lack of technological infrastructure (Kassie et al., 2019). Therefore, understanding the role of digital transformation in improving supply chain efficiency is both timely and essential for fostering the sustainability and resilience of the wild coffee sector.

One of the key elements of digital transformation is process innovation, which involves the development and application of new technologies and practices to improve production, processing, and logistics. In the coffee supply chain, innovations such as precision agriculture, automated processing facilities, and digital traceability systems have demonstrated their potential in enhancing efficiency and minimizing waste (Salam et al., 2020). However, despite the importance of process innovation, its role as a mediator in the relationship between digital transformation and supply chain efficiency remains underexplored within the wild coffee sector. Understanding how process innovation enhances the effects of digital transformation can provide valuable insights for stakeholders aiming to leverage technology for improved outcomes.

Another critical factor influencing supply chain efficiency is environmental uncertainty, which refers to unpredictable external factors such as demand fluctuations, price volatility, and climate change. These uncertainties have intensified due to global climate patterns and geopolitical risks, playing a moderating role in the impact of digital transformation on supply chain efficiency (Wagner & Bode, 2020). For instance, extreme weather events, which have become more frequent, significantly affect crop yields and supply chain stability, posing substantial risks to the coffee industry (Lin & Zhang, 2019). Given these challenges, understanding the interaction between environmental uncertainty and digital transformation is essential for developing strategies to mitigate risks and enhance resilience in

the wild coffee industry.

This study aims to investigate the impact of digital transformation on the efficiency of wild coffee supply chains, with a particular focus on the mediating role of process innovation and the moderating role of environmental uncertainty. The findings of this research are significant as they provide empirical insights into how digital technologies can promote more efficient, resilient, and sustainable supply chains in an industry that is vital to millions worldwide. Digital transformation in supply chains is a crucial factor in ensuring operational efficiency, transparency, and sustainability across various industries, including coffee (Angelopoulos & Bendoly, 2023). The wild coffee sector, particularly in China, faces multiple challenges, including climate variability, price fluctuations, logistics inefficiencies, and low production efficiency (Boaventura, Abdalla, & Araújo, 2018). Addressing these issues requires a comprehensive understanding of how digital transformation enhances supply chain efficiency. This study is crucial as it explores the relationship between digital transformation and supply chain efficiency while investigating the mediating role of process innovation and the moderating role of environmental uncertainty. By doing so, it offers valuable insights to industry practitioners, policymakers, and researchers seeking to optimize supply chain operations in the wild coffee sector.

1. Enhancing Supply Chain Efficiency through Digital Transformation

Digital transformation involves the adoption of technologies such as blockchain, IoT, artificial intelligence (AI), and big data analytics, which have significantly altered the operation of supply chains (Thiruchelvam et al., 2020). In the coffee industry, these technologies enable real-time monitoring, predictive analytics, and automated decision-making, ultimately improving efficiency, transparency, and sustainability (Quayson, Bai, & Osei, 2020). By integrating digital technologies into supply chain management, businesses can optimize production and logistics while minimizing inefficiencies that hinder performance.

One of the primary benefits of digital transformation is enhanced operational performance. IoT sensors can continuously monitor soil conditions, weather patterns, and coffee bean quality, ensuring optimal harvesting and processing conditions (Bager & Lambin, 2020). Additionally, automated logistics systems can enhance transportation planning, warehouse management, and inventory control, ultimately reducing operational costs and delivery times (Rauniyar et al., 2023). These improvements are particularly critical for the wild coffee industry, which often faces logistical challenges and inconsistencies in product quality.

Traceability and transparency are also key advantages of digital transformation in coffee supply chains. Blockchain technology ensures that each stage of the supply chain is recorded and verified, making it easier to track ethically sourced products and comply with international regulations (Gligor, Davis-Sramek, & Tan, 2022). As consumer demand for transparency in coffee sourcing and sustainability increases, blockchain applications provide a competitive advantage for companies

seeking to build trust with their customers (Nguyen & Sarker, 2018). Moreover, AI-driven predictive analytics help supply chain managers anticipate disruptions and allocate resources more effectively, minimizing financial risks (Mangla, Kazançoğlu, & Yıldızbaşı, 2022).

2. The Role of Process Innovation in Strengthening the Supply Chain

While digital transformation provides the technological foundation for supply chain improvements, process innovation ensures that these technologies are effectively implemented. Process innovation involves the development and adoption of new methods, workflows, and technologies to enhance production, logistics, and inventory management (Hernandez-Aguilera & Gómez, 2018). In the coffee industry, smart agricultural technologies such as precision farming and AI-driven sorting machines have improved productivity and processing efficiency (Hrustek, 2020). These innovations ensure consistency in coffee quality, reduce waste, and accelerate processing times, benefiting both coffee growers and supply chain stakeholders.

Sustainability is another critical aspect of process innovation in coffee supply chains. Many coffee producers are adopting solar drying systems and water-efficient coffee washing stations to minimize their carbon footprint (Kirchherr, 2021). These innovations align with growing consumer preferences for sustainably sourced coffee, making them a strategic investment for producers seeking to differentiate themselves in the market.

Despite the benefits of process innovation, its adoption is often hindered by organizational readiness and adoption barriers. Many smallholder coffee farmers lack the financial resources and technical expertise required to implement advanced digital solutions (Omol, 2024). Understanding the factors influencing the adoption of process innovation can help policymakers design targeted interventions, such as training programs, subsidies, and infrastructure support, to ensure that digital transformation benefits all stakeholders in the coffee industry.

3. Managing Environmental Uncertainty in Supply Chains

The coffee industry is highly susceptible to environmental uncertainty, including climate change, market price volatility, and regulatory changes (Grabs & Ponte, 2019). These uncertainties affect supply chain stability and necessitate adaptive strategies to ensure long-term sustainability. Digital transformation plays a crucial role in mitigating these risks by providing data-driven insights for proactive decision-making.

Climate change poses one of the greatest threats to the coffee industry. Variations in temperature, rainfall patterns, and extreme weather events disrupt coffee production and affect crop yields (Hofman, Blome, & Schleper, 2020). To address these challenges, coffee producers are increasingly leveraging AI-driven weather forecasting, precision irrigation, and climate-adaptive farming techniques to optimize resource utilization and reduce climate-related risks.

Market fluctuations and price volatility are additional sources of uncertainty in the coffee supply chain. Coffee prices are influenced by global market conditions, speculative trading, and

geopolitical events, making financial planning difficult for producers and exporters (Schroeder, Lampietti, & Elabed, 2021). Digital platforms that provide real-time market data and predictive analytics enable businesses to make informed pricing and inventory decisions, minimizing financial losses.

This study makes several valuable contributions to both academic research and industry practice. First, it fills a significant research gap by extending the literature on digital transformation and supply chain efficiency to the wild coffee industry, a sector that has received limited attention despite its economic and ecological importance. Second, it highlights the mediating role of process innovation, demonstrating that technological adoption alone is insufficient to drive efficiency gains unless accompanied by operational enhancements and workflow improvements. Third, it evaluates the moderating effect of environmental uncertainty, providing insights into how external market and climate conditions shape the effectiveness of digital transformation initiatives.

From a practical perspective, this research offers actionable recommendations for policymakers, supply chain managers, and coffee producers. By identifying the key barriers to digital adoption in wild coffee production, it provides a strategic roadmap for stakeholders to improve digital literacy, infrastructure development, and financial accessibility. Additionally, by emphasizing the role of process innovation, it encourages industry players to integrate digital tools with standardized protocols and agile operational frameworks. Finally, by analyzing environmental uncertainty, the study underscores the need for resilience strategies that complement digital transformation efforts, ensuring long-term stability, sustainability, and competitiveness in the wild coffee supply chain.

In conclusion, this study advances academic knowledge by addressing a critical research gap in digital transformation, process innovation, and supply chain efficiency in the wild coffee industry. By examining how digital technologies interact with process innovation and environmental uncertainty, it provides valuable insights that can inform both academic discourse and industry best practices. As global coffee markets continue evolving, understanding the role of digital transformation in ensuring supply chain resilience will be essential for promoting sustainability, efficiency, and market competitiveness in the wild coffee sector.

Research Objectives

Objective 1: To evaluate the impact of digital transformation on the efficiency of the wild coffee supply chain.

Objective 2: To examine the mediating role of process innovation in the relationship between digital transformation and supply chain efficiency.

Objective 3: To assess the moderating role of environmental uncertainty in shaping the relationship between digital transformation and supply chain efficiency.

Objective 4: To identify key challenges and opportunities for wild coffee producers in adopting

digital technologies to enhance supply chain efficiency.

Literature Review

Digital transformation has emerged as a key enabler of innovation and efficiency across various industries, including supply chain management. The integration of advanced digital technologies such as the Internet of Things (IoT), blockchain, artificial intelligence (AI), big data analytics, and cloud computing allows businesses to streamline operations, improve real-time decision-making, and enhance overall transparency in supply chains (Plekhanov, Franke, & Netland, 2023). These technologies facilitate better traceability, predictive analytics, automation, and data-driven decision-making, leading to improved efficiency and resilience in complex supply networks. In traditional agricultural supply chains, digital transformation has been widely applied to optimize processes such as inventory management, logistics coordination, and demand forecasting.

However, despite the growing body of research on digital transformation in various sectors, limited studies have examined its specific impact on the wild coffee industry. Wild coffee, unlike commercially cultivated coffee, is grown in natural forest ecosystems, often by smallholder farmers with limited access to modern technological infrastructure. The unique challenges faced by the wild coffee supply chain, such as climate variability, fluctuating market demand, lack of standardized processing methods, and inadequate infrastructure, make it a compelling area of study. Understanding how digital transformation can address these challenges is crucial to improving the sustainability and competitiveness of wild coffee production.

This chapter provides a comprehensive review of existing literature on digital transformation, process innovation, supply chain efficiency, and environmental uncertainty. It examines how digitalization enhances supply chain operations, the role of process innovation as a key enabler in leveraging digital advancements, and how environmental uncertainties such as climate change and market volatility influence the effectiveness of digital transformation. Furthermore, this review identifies research gaps, particularly in the context of the wild coffee industry, and justifies the need for empirical investigation into the relationships between these variables. By addressing these gaps, the study aims to contribute to both theoretical knowledge and practical applications, offering insights that can benefit coffee producers, supply chain managers, policymakers, and researchers working to optimize supply chain performance through digital transformation.

Digital transformation refers to the strategy and methods used by enterprises to promote their own changes through the use of digital technology. It reflects the combined results of social progress and technological innovation. Digital transformation is the integration of advanced digital technology into supply chain processes to improve operational efficiency and value creation (Plekhanov et al., 2023). The key technologies involved include blockchain for traceability, the Internet of Things for real-time monitoring, artificial intelligence for predictive analysis, and cloud computing for data

management (Feroz, Zo, and Chiravuri, 2021). Together, these technologies improve supply chain visibility, automation and agility.

The coffee industry is increasingly adopting digital solutions to improve supply chain transparency, efficiency and sustainability. The integration of advanced technologies such as blockchain, IoT, AI-driven analytics and cloud platforms enables companies to optimise logistics, improve inventory management, enhance product traceability and ensure ethical sourcing (Feroz et al., 2021). These digital advances have revolutionized commercial coffee production. Companies such as Starbucks, Nestlé and Lavazza use digital tools to achieve end-to-end supply chain visibility and ensure that their coffee products meet quality standards and sustainability commitments.

Supply chain management, as a technical tool formed with the help of advanced science and technology in the process of enterprise development, has included all aspects and processes of the enterprise. Each stage is divided, reshaped and integrated, and finally standardized assessment indicators for the whole process cycle management of the enterprise supply chain are formulated. Supply chain management runs through every link, from the core enterprise to upstream and downstream supply chain enterprises, from raw materials to processing plants to packaging and sales, and finally to consumers. Enterprises organically integrate all aspects, use supply chain management, scientifically shorten the length of the supply chain, reduce the error rate in each link, reduce capital losses and improve efficiency, while also improving the data accuracy and timely validity of each link in the supply chain process, minimizing costs and forming a core market competitiveness to meet customer demands (Sun Guilin, 2009). Most scholars define supply chain management as a new scientific management tool that integrates all links in the supply chain to strengthen cooperation between nodes. The important indicator for measuring supply chain management is supply chain efficiency (Wang Hua et al., 2010). There is not much research literature on supply chain efficiency in China, and some scholars and experts have conducted preliminary explorations. Zheng Shaolian et al. started from the information and decision-making structure of the supply chain, and studied the impact of different decision-making structures on supply chain efficiency under the conditions of information symmetry and asymmetry within the supply chain, respectively. They explored the endogenous nature of supply chain efficiency losses under non-cooperative decision-making structures, and established a cooperation model for two-node enterprises. From this, it can be seen that the supply chain structure affects supply chain efficiency. Chen Jian et al. conducted an in-depth analysis and research on supply chain structure issues, focusing on some optimization models of supply chain structure developed in recent years, and analyzed the main properties of these models. Finally, they discussed the direction of further development of supply chain structure research. Mou Deyi et al. established a model of a two-level inventory system, constructed the objective function of system optimization with the goal of minimizing the total expected cost of system operation, and gave a numerical solution algorithm, solving the joint optimization decision-making problem between two locations (warehouses).

The wild coffee industry plays a crucial role in biodiversity conservation, economic development, and sustainable agriculture, but it faces significant supply chain inefficiencies due to fragmented logistics, inconsistent processing methods, and market access barriers (Davis et al., 2019). Unlike commercial coffee, wild coffee supply chains are largely informal, fragmented, and dependent on natural forest ecosystems, making them vulnerable to climate variability, price volatility, and inefficient logistics (Rhiney, Guido, and Knudson 2021). Improving supply chain efficiency in the wild coffee sector is critical to ensure sustainable production, fair economic returns for farmers, and long-term environmental protection.

The literature on digital transformation and supply chain efficiency focuses more on the upgrading of supply chain management evaluation systems driven by digital technology. Coyle (2019) argues that in the context of the rapid development of the digital economy, digital technology can be used to extend the innovation margin of global enterprises, break down barriers to information asymmetry, and use technological innovation to drive enterprise development as a core capability for enterprise development, thereby achieving the reshaping and upgrading of the global supply chain structure. Cao Xiaoyong and Li Siru (2021) found that the digital economy, as an industry driving force, promotes innovation and upgrading in the service industry, diversified development to meet customer needs, improves efficiency to accurately match and enhance customer satisfaction, and effectively and timely collects data to provide the service industry with timely and effective empirical data support. Zhang Aiqin and Zhang Haichao (2021) found that the integration of enterprise digitalization level construction and artificial intelligence is deepening, and both can help manufacturing enterprises achieve high-quality development from the perspective of technology promotion.

Process innovation plays a crucial role in improving supply chain performance by introducing new production methods, advanced processing technologies, and logistics optimization to improve operational efficiency and reduce inefficiencies (Belhadi et al., 2024). Unlike product innovation (which focuses on developing new goods and services), process innovation emphasizes workflow improvements to increase productivity, reduce costs, and improve supply chain responsiveness (Wong, Wong, and Boon-itt, 2020).

In the wild coffee industry, process innovation is essential to modernize traditional harvesting, processing, and distribution techniques to ensure better quality control, higher efficiency, and optimized logistics. The adoption of AI-powered coffee sorting can improve the accuracy of bean grading, while automated warehousing solutions can improve inventory management and reduce losses. In addition, blockchain-enabled traceability systems can provide end-to-end visibility to ensure ethical sourcing and quality assurance (Ferreira et al., 2021). In addition, IoT-enabled logistics monitoring enables real-time cargo tracking, reducing delays and improving overall supply chain efficiency. By integrating these technological advancements into their digital transformation efforts, wild coffee producers can maximize efficiency, enhance sustainability, and remain competitive in an increasingly digitalized

global marketplace.

Several studies confirm that process innovation is a key factor in strengthening the relationship between digital transformation and supply chain efficiency (Chen et al., 2019). While digital transformation introduces cutting-edge technologies such as blockchain, artificial intelligence, the Internet of Things and cloud computing, its effectiveness largely depends on how these technologies are integrated with existing supply chain processes. Without sufficient process innovation, digital investments may not lead to tangible improvements, resulting in inefficiencies, low adoption rates and limited return on investment. The application of digital technologies such as artificial intelligence, blockchain and the Internet of Things is increasingly driving innovation in agricultural and supply chain management processes. However, research suggests that the implementation of digital solutions alone is insufficient to improve efficiency – complementary process innovation is essential to fully realise the benefits of digitalisation (Esmaeilian et al., 2020). Environmental uncertainty is the unpredictability and variability of external factors that affect supply chain operations, decision-making and the overall business stability. These uncertainties stem from macroeconomic, regulatory, environmental, and market-driven factors, making it difficult for businesses to plan, predict, and effectively execute supply chain activities (Li, 2022). Environmental uncertainty is particularly pronounced in industries with long production cycles, dependence on natural resources, and exposure to global market fluctuations, such as the coffee industry. In the coffee industry, environmental uncertainty manifests itself in many forms, including climate change, fluctuating consumer demand, regulatory policy changes, and global price fluctuations (Carodenuto, 2021). These factors directly impact coffee production, supply chain costs, and market competitiveness, making it difficult for producers, exporters, and retailers to maintain stable and efficient supply chain operations. Because coffee cultivation is highly sensitive to climate, changes in rainfall patterns, extreme temperatures, and unpredictable weather events can lead to crop failure, unstable yields, and supply chain disruptions (Moat et al., 2021).

Research shows that companies with a high level of digital maturity are better able to cope with these uncertainties through real-time data analysis and AI-driven risk management systems (Wong et al., 2020). AI-driven predictive analytics enable companies to analyze historical data, climate models, and market trends to make proactive decisions. Similarly, IoT tracking systems can monitor supply chain operations in real time, helping companies predict and mitigate disruptions before they escalate (Lagrasta et al., 2021).

This literature review highlights the importance of research related to digital transformation, process innovation, and environmental uncertainty and their impact on supply chain efficiency. However, the wild coffee industry has been largely neglected in existing research. This study fills this gap by examining how digital technologies affect the wild coffee supply chain, the mediating role of process innovation, and the moderating role of environmental uncertainty. By addressing these key issues, this study contributes to both academic research and industry practice by providing insights into

improving supply chain resilience in the wild coffee industry.

Methodology

This study will focus on the wild coffee industry in Yunnan Province, China. The research subjects include individuals and organizations in the wild coffee supply chain. These include wild coffee producers (from small-scale to large-scale operations), supply chain managers, and other stakeholders such as cooperatives, processing plants, logistics companies, and wholesalers involved in the coffee supply chain. It is estimated that the total number of individuals and organizations of relevant stakeholders in the region is about 1,500. We will use a stratified random sampling method to ensure that stakeholders of different business sizes and types are represented.

The sample size used in the study was determined using The Taro Yamane sample size formula (1973), and the sample size was determined using a 95% confidence level and allowable value. The sampling error is 5% or 0.05. The total sample size is 1500. When n = the number of samples used in the study. N = the size of the population, e = the error of the random sample is set to 0.05.

The sample size and calculation formula are as follows:

$$n = \frac{N}{1 + Ne^2}$$
$$n = \frac{1500}{1 + 1500 X 0.05^2}$$
$$n = 315.7$$

In order to increase the accuracy of the research results and the generalizability of the conclusions, a total of 400 questionnaires were distributed in this study, and 383 valid questionnaires were returned, for a recovery rate of 95.8%.

The main data collection instrument for this study is a structured questionnaire designed to measure four key variables: digital transformation, process innovation, environmental uncertainty, and supply chain efficiency. These variables are critical to understanding the relationship between digital transformation and supply chain outcomes in the wild coffee industry.

To ensure the validity and reliability of the questionnaire, we will use established scales from previous studies to design the questionnaire. For digital transformation, the scale by Chong et al. (2020) will be used, which assesses the adoption of key digital technologies in the supply chain such as the Internet of Things, blockchain, and cloud computing. Process innovation will be measured using the scale proposed by Krause et al. (2018), which focuses on the introduction of new processes, methods and technologies in production, processing and logistics. Environmental uncertainty will be assessed using the scale proposed by Li et al. (2019).

The following hypotheses were developed for this study:

Hypothesis 1: Digital transformation has a positive impact on supply chain efficiency in the

wild coffee industry.

Hypothesis 2: Process innovation mediates the relationship between digital transformation and supply chain efficiency.

Hypothesis 3: Environmental uncertainty moderates the relationship between digital transformation and supply chain efficiency.

To analyze the relationships between the research variables (digital transformation, process innovation, environmental uncertainty, and supply chain efficiency), we will use a combination of statistical methods. These methods include descriptive statistical analysis, regression analysis, mediation analysis, and moderated effect analysis.

Results

This study examines a sample of 383 enterprises operating in the coffee industry, categorized based on business size, geographical distribution, and market access. The sample includes small, medium, and large businesses, with 167 small businesses (43.6%), 152 medium-sized businesses (39.7%), and 64 large businesses (16.7%). Additionally, enterprises are distributed across various regions, with the majority located in Baoshan City (24.8%), followed by Pu'er City (21.1%), Dehong Prefecture (17.8%), Lincang City (16.2%), and Xishuangbanna Prefecture (8.6%). The remaining 11.5% of businesses are scattered across other regions. The sample composition also includes different types of farms: medium-sized farms (38.6%), large farms (27.9%), small farms (27.4%), and wild forest coffee collectors (6.0%). Regarding market access, 100 enterprises (26.1%) have established domestic market access, 98 enterprises (25.6%) have expanded local market access, 72 enterprises (18.8%) operate in global export markets, and 63 enterprises (16.4%) have access to regional export markets. However, 50 enterprises (13.1%) face restricted access to local markets.

Table 1: Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.895[a]	.800	.800	7.12685

a. Predictors: (Constant), Digital Transformation

Table 2: ANOVA [a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	77485.568	1	77485.568	1525.548	.000[b]
	Residual	19351.737	381	50.792		
	Total	96837.305	382			

a. Dependent Variable: Supply Chain Efficiency

b. Predictors: (Constant), Digital Transformation

Table 3: Coefficients [a]

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
1 (Constant)	-7.371	1.968		-3.745	.000
Digital Transformation	1.073	.027	.895	39.058	.000

a. Dependent Variable: Supply Chain Efficiency

In the regression analysis of the impact of digital transformation on supply chain efficiency, the adjusted R-squared is 0.800. Digital transformation (independent variable) can explain 80% of the variation in supply chain efficiency (dependent variable). In the variance test, the F value is 1525.548, and the significance P value is .000b less than 0.01, which means that the regression model is highly significant at the 0.01 level, and the model is usable and meaningful.

After analyzing the coefficients[a], we found that the unstandardized coefficient of digital transformation and supply chain efficiency is 1.073, the standardized coefficient is 0.895, and the P value is 0.000, indicating that there is a positive and significant relationship between digital transformation and supply chain efficiency. That is, enterprises optimize their operating models, improve information sharing and automation management levels through digital transformation, which helps significantly improve supply chain efficiency.

Table 4: Intermediary Analysis

Model	R	R-sq	MSE	F	df1	df2	p-value
Process Innovation (M)	0.928	0.8611	24.6261	2362.7893	1	381	0
Supply Chain Efficiency (Y)	0.9013	0.8124	47.8168	822.5864	2	380	0
Total Effect Model	0.8945	0.8002	50.792	1525.5478	1	381	0

This study uses mediation analysis to explore the impact of digital transformation on supply chain efficiency, with process innovation as the mediating variable. The results are as follows:

First, the impact of digital transformation on process innovation is significant. The regression model R = 0.928, and the square of the coefficient of determination R is 0.8611, indicating that digital transformation can explain 86.11% of the variation in process innovation. The F-value of the regression equation is 2362.7893 ($p < 0.001$), indicating that the impact is highly statistically significant.

Second, in the model that includes process innovation, digital transformation and process innovation jointly predict supply chain efficiency. The R of this model is 0.9013, and the R² is 0.8124, indicating that the two jointly explain 81.24% of the variation in supply chain efficiency. The F value

of the model is 822.5864 (p < 0.001), indicating a high overall fit. Finally, in the total effect model that does not consider the mediating variable of process innovation, the regression result is still significant (R=0.8945, R² =0.8002), that is, the impact of digital transformation on supply chain efficiency alone explains 80.02% of the variance, and the F value is 1525.5478 (p < 0.001), indicating that this direct impact is extremely significant.

Overall, the mediating analysis in this study shows that process innovation partially mediates the impact of digital transformation on supply chain efficiency, that is, digital transformation not only directly improves supply chain efficiency, but also further enhances supply chain performance by promoting process innovation.

Table 5: Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	0.976	0.953	0.953	3.4596	
2	0.976	0.953	0.953	3.45394	1.787

Table 6: ANOVA ª

Model	Regression Sum of Squares	df	Mean Square	F	Sig.
1	92289.146	2	46144.573	3855.392	0
2	92315.955	3	30771.985	2579.446	0

Table 7: Coefficients ª

Model	Variable	Unstandardized B	Std. Error	Beta	t	Sig.	95% CI Lower	95% CI Upper
1	Constant	68.167	0.177		385.61	0	67.82	68.515
1	Digital Transformation	8.126	0.248	0.51	32.748	0	7.638	8.614
2	Constant	68.025	0.2		339.457	0	67.631	68.419
2	Digital Transformation	8.16	0.249	0.513	32.802	0	7.671	8.649
2	Environmental Uncertainty	8.769	0.249	0.551	35.171	0	8.279	9.259

Tables 5, 6 and 7 above show that:

Both digital transformation and environmental uncertainty have a significant positive impact on supply chain efficiency, indicating that when enterprises face an uncertain environment, improving the level of digital transformation can effectively improve supply chain efficiency. The impact of the

interaction term on supply chain efficiency is not significant (p = 0.135), indicating that the interaction between digital transformation and environmental uncertainty may be weak, and the two mainly affect supply chain efficiency independently. The overall model fit is high (R^2 = 0.953), but the introduction of the interaction term did not significantly improve the explanatory power of the model, which indicates that the impact of enterprise digital transformation may directly affect supply chain efficiency without significant differences due to environmental uncertainty.

In summary, the results show that digital transformation and environmental uncertainty are key factors affecting supply chain efficiency, but their interaction is not yet significant. In other words, environmental uncertainty does not significantly moderate the impact of digital transformation on supply chain efficiency.

Discussion

1. The Positive Impact of Digital Transformation on Supply Chain Efficiency

Digital transformation significantly enhances supply chain efficiency, aligning with prior studies in agriculture and agribusiness (Wong, Wong, & Boon-itt, 2020). It involves integrating blockchain, artificial intelligence (AI), and the Internet of Things (IoT) into supply chain management to optimize logistics, reduce costs, and improve transparency. Blockchain technology enhances traceability and accountability, addressing concerns related to product authenticity and ethical sourcing (Zhu, Song, & Hazen, 2018). By creating secure, immutable transaction records, blockchain allows stakeholders to verify product origins, ensuring compliance and reducing fraud (Feroz et al., 2021). This is particularly relevant in boutique coffee markets, where consumers demand high traceability and sustainability assurance.

AI-driven demand forecasting improves efficiency by enhancing production planning and inventory management. Traditional methods rely on historical data, often failing to account for market volatility, climatic shifts, and geopolitical changes (Chen & Tian, 2019). AI models leverage machine learning to analyze vast data sets, improving forecasting accuracy and helping businesses mitigate inventory shortages and overproduction losses. This is particularly valuable in wild coffee production, where supply fluctuates due to seasonal and ecological factors.

IoT-based real-time monitoring improves logistics, warehousing, and transportation efficiencies. Sensors embedded in storage units, transport containers, and processing facilities track temperature, humidity, and location to ensure optimal storage and transportation conditions (Ghobakhloo & Iranmanesh, 2021). This reduces spoilage risks, contamination, and delays, which are prevalent in traditional agricultural supply chains (Flammini et al., 2020).

More broadly, digital transformation enhances supply chain agility, allowing businesses to adapt to market fluctuations, minimize waste, and improve responsiveness (Belhadi et al., 2024). However, smallholder-led industries, such as wild coffee production, face adoption barriers, including

limited technological access, financial constraints, and lack of technical knowledge (Hanelt, Bohnsack, & Marz, 2021). Overcoming these challenges requires investment in digital infrastructure, training programs, and policy incentives to support technology adoption.

In summary, digital transformation plays a crucial role in improving supply chain efficiency, particularly in industries where traceability, demand forecasting, and logistics optimization are essential. As technology advances, wild coffee producers and supply chain managers must prioritize digital integration to remain competitive in an increasingly globalized and technology-driven market.

2. The Mediating Role of Process Innovation

Process innovation acts as a key mediator, reinforcing the relationship between digital transformation and supply chain efficiency. While digital technologies enhance visibility, connectivity, and automation, their impact depends on complementary process innovations to integrate them seamlessly into workflows, supplier networks, and operational processes (Candelo et al., 2018).

For instance, blockchain technology has revolutionized traceability, creating tamper-proof transaction records, origin tracking, and quality certifications. However, its effectiveness relies on standardized data entry, automated compliance verification, and platform interoperability (Zhu, Song, & Hazen, 2018). Without these process improvements, inconsistent manual data entry, supplier coordination delays, and compliance errors can undermine blockchain's ability to streamline operations.

Similarly, IoT enhances logistics tracking, but its full potential is realized only when combined with AI-driven predictive analytics and lean supply chain approaches (Ciccullo et al., 2020). Without automated replenishment systems, demand-driven inventory adjustments, and intelligent logistics planning, IoT may fail to deliver substantial supply chain performance gains.

The wild coffee sector faces unique operational challenges, including fragmented production networks, decentralized operations, and fluctuating yields (Belhadi et al., 2024). Unlike commercial coffee plantations, wild coffee supply chains often lack standardized production practices, quality assurance protocols, and advanced infrastructure. This underscores the need for process innovation to ensure that digital transformation translates into scalable efficiency gains.

For example, automated coffee sorting and grading machines improve quality control, but their success requires standardized classification criteria, calibrated AI algorithms, and worker training programs to ensure consistent implementation. Similarly, AI-powered supply chain forecasting tools enhance demand planning, but their effectiveness is amplified by agile manufacturing principles and flexible logistics scheduling (Flammini et al., 2020).

Moreover, firms with strong dynamic capabilities, including knowledge-sharing, cross-functional collaboration, and continuous process improvement, derive greater benefits from digital transformation (Appio, Frattini, & Petruzzelli, 2021). In contrast, firms that passively adopt digital technologies without corresponding process innovations risk encountering operational bottlenecks, resistance to change, and inefficient digital execution (Wang, Chen, & Benitez-Amado, 2019).

Strategically, digital transformation and process innovation should be viewed as interconnected rather than isolated initiatives. Simply adopting digital technologies without redesigning supply chain processes may result in underutilization of digital assets and misalignment with operational realities (Negri, Cagno, & Colicchia, 2021). Thus, firms aiming for maximum supply chain efficiency in the wild coffee sector must integrate digital transformation with targeted process innovation strategies.

In conclusion, technology adoption alone does not guarantee supply chain efficiency. Instead, firms must develop process innovation capabilities to align digital transformation with real-world operational improvements. The success of blockchain, IoT, AI, and cloud-based logistics solutions depends on how effectively they are integrated into standardized workflows, performance assessment frameworks, and adaptive supply chain management practices. By fostering a culture of continuous innovation and operational agility, firms can fully realize the benefits of digital transformation, achieving long-term supply chain resilience and efficiency.

3. The Moderating Role of Environmental Uncertainty

Contrary to traditional assumptions, this study finds that environmental uncertainty does not significantly moderate the relationship between digital transformation and supply chain efficiency. While previous research suggests that firms in volatile environments rely more on digital transformation for risk mitigation and resilience (Negri, Cagno, & Colicchia, 2021), the current findings indicate that efficiency gains from digital transformation remain stable regardless of external uncertainties.

This suggests that digital transformation investments are inherently resilient, reducing dependence on external stability. Blockchain traceability, AI-driven predictive analytics, and IoT-enabled logistics monitoring help firms streamline operations, improve responsiveness, and ensure supply chain continuity, even in unpredictable environments (Reyes, Visich, & Jaska, 2020).

One possible explanation is that other resilience strategies, such as supply chain diversification and strategic collaborations, play a greater role in managing uncertainty than digital transformation alone (Ciccullo et al., 2020). This is particularly evident in wild coffee supply chains, where producers often operate in cooperatives, benefiting from shared resources, risk-sharing mechanisms, and collective bargaining power (Flammini et al., 2020).

Additionally, environmental uncertainty may affect supply chain efficiency indirectly through other mediating factors, such as adaptive inventory management, agile production processes, and sustainability initiatives (Wang & Li, 2020). Digital transformation, therefore, functions as a universal efficiency enabler, independent of external business fluctuations.

Furthermore, these findings challenge contingency theory, which argues that the effectiveness of organizational strategies depends on external conditions (Donaldson, 2001). Instead, this study suggests that digital transformation consistently improves supply chain efficiency, irrespective of environmental stability (Feroz et al., 2021).

From a practical perspective, firms should view digital transformation as a long-term

investment rather than a short-term response to external volatility. Rather than passively adopting digital tools to mitigate external shocks, firms should proactively integrate digital transformation into core operations to ensure sustained efficiency, agility, and competitiveness (Belhadi et al., 2024).

In conclusion, environmental uncertainty does not significantly alter the impact of digital transformation on supply chain efficiency. This challenges traditional assumptions about the role of external conditions in shaping digital transformation outcomes. While digital transformation provides strong, independent efficiency gains, firms should also develop additional resilience-building strategies to complement technological advancements. Future research should examine how different types of uncertainty (e.g., regulatory risk vs. climate risk) interact with digital transformation to refine our understanding of this complex relationship.

Conclusions

1. The positive impact .of digital transformation on supply chain efficiency in the wild coffee industry

The results of the study show that digital transformation significantly improves supply chain efficiency. This result is in line with existing literature where technologies such as blockchain, Internet of Things (IoT), big data analytics and artificial intelligence (AI) have been shown to optimize supply chain operations. These technologies facilitate real-time monitoring, predictive analytics, and automation, leading to greater transparency, cost reduction, and operational responsiveness. Blockchain ensures tamper-proof records and improves traceability, thereby reducing fraud and increasing compliance with sustainability standards (Zhu, Song, & Hazen, 2018). IoT sensors can accurately track harvested coffee beans, temperature conditions during storage, and logistics routes to minimize spoilage and inefficiencies (Ghobakhloo & Iranmanesh, 2021). Meanwhile, big data analytics enable companies to predict market fluctuations, optimize inventory, and improve demand forecasting (Feroz et al., 2021).

2. The partial mediating role of process innovation in the relationship between digital transformation and supply chain efficiency.

In addition, the findings suggest that process innovation relationship between digital transformation and supply chain efficiency partially mediates . It was found that the process innovation moderated the relationship between digital transformation and supply chain efficiency to a certain extent, which implies that digital transformation can improve efficiency independently, but when complemented by it is more effective (.process innovation

3. The moderating role of environmental uncertainty.

Contrary to expectations, environmental uncertainty did not significantly moderate the relationship between digital transformation and supply chain efficiency. This contradicts previous research, which argues that technology investments are more critical in highly uncertain environments.

Environmental uncertainties include the following factors: Climatic unpredictability affecting

coffee yields. Market price volatility due to supply and demand imbalances. Regulatory changes affecting export policies. Previous research hypothesized that firms in uncertain environments benefit more from digital transformation because it provides real-time risk assessment, supply chain flexibility, and scenario planning tools (Pero, Gosling, and Purvis, 2020). However, the moderating effect of this study suggests that digital transformation can improve efficiency independent of external fluctuations.

In view of the above results, this study offers the following recommendations:

The adoption of digital transformation is essential for improving supply chain efficiency, transparency, and resource optimization in the wild coffee sector. However, smallholder farmers and supply chain stakeholders face several challenges, including limited access to technology, inadequate digital literacy, and poor infrastructure. Overcoming these barriers requires a combination of financial support, training programs, and infrastructure investments to facilitate digital adoption. One of the main constraints is the high cost of advanced technologies such as IoT sensors, blockchain traceability systems, AI-driven forecasting tools, and cloud-based logistics platforms. Many smallholder farmers lack the capital to invest in these technologies, limiting their ability to optimize production and supply chain processes. To address this, governments, financial institutions, and technology companies should collaborate to provide subsidized loans, financial grants, and incentive programs that make digital tools more affordable and accessible. Public-private partnerships can further support the development of cost-effective and scalable digital solutions tailored to the specific needs of smallholder farmers, ensuring that technological advancements benefit the entire supply chain.

Beyond financial constraints, low levels of digital literacy pose a significant barrier to digital transformation. Even when digital tools such as blockchain-based traceability systems, AI-driven analytics, and mobile logistics platforms are available, farmers and supply chain managers often lack the necessary skills to implement and maintain them effectively. Structured digital literacy training programs, including hands-on workshops, mobile learning platforms, and peer-to-peer knowledge exchange initiatives, are needed to equip farmers, cooperatives, and supply chain stakeholders with the necessary skills to integrate and utilize digital technologies. Additionally, a strong digital infrastructure is crucial for implementing real-time supply chain management technologies. Many rural coffee-growing areas, including those in Yunnan Province, lack stable internet connectivity and cloud computing access, making it difficult to leverage AI-powered logistics, blockchain tracking, and predictive analytics. Expanding broadband connectivity, developing mobile digital tools, and integrating satellite remote sensing technology can enhance climate monitoring, soil health analysis, and yield predictions, improving both productivity and sustainability. A comprehensive strategy that simultaneously addresses financial, educational, and infrastructure barriers will enable smallholder farmers and cooperatives to leverage digital transformation for enhanced supply chain efficiency, market access, and long-term competitiveness.

Process innovation plays a crucial role in maximizing the benefits of digital transformation by

ensuring that new technologies are effectively integrated into supply chain operations. While digital tools such as blockchain, AI, and IoT can enhance transparency and efficiency, their full potential can only be realized when accompanied by innovative process improvements that streamline production, logistics, and quality management. One of the most effective ways to enhance process innovation is through supply chain automation. Many wild coffee producers still rely on manual sorting, quality control, and logistics management, leading to inefficiencies and inconsistent product quality. Automating these processes through AI-driven quality control, predictive maintenance, and robotic sorting technologies can significantly enhance productivity. AI-powered defect detection systems can analyze coffee beans more accurately and efficiently than manual inspectors, ensuring higher-quality output. Similarly, predictive maintenance using IoT sensors can monitor machine performance in processing facilities, reducing unexpected breakdowns and minimizing downtime. Automated tracking systems also improve real-time inventory visibility, optimize transportation routes, and minimize logistics delays, further enhancing supply chain efficiency.

In addition to automation, standardizing digital processes is essential for seamless data integration and blockchain traceability. One of the key challenges in supply chain digitization is the lack of uniform data entry protocols and inconsistent quality control mechanisms among different stakeholders. Without standardized procedures, blockchain tracking systems may contain inaccurate or incomplete data, weakening their effectiveness. To address this, industry stakeholders must establish common digital reporting frameworks and quality assurance standards to ensure that coffee producers, processors, exporters, and retailers operate within a unified digital ecosystem. Implementing smart contracts on blockchain networks can further simplify compliance verification, automate supplier payments, and ensure that all transactions adhere to predefined quality and traceability requirements. Additionally, adopting lean and agile supply chain management practices can help reduce operational waste and improve responsiveness to fluctuating market demands. Lean supply chain management focuses on minimizing inefficiencies, eliminating redundant processes, and optimizing resource allocation, making it particularly beneficial for wild coffee producers facing volatile demand. Agile supply chain practices allow organizations to quickly adapt to changing consumer preferences, supply disruptions, and regulatory changes. For instance, AI-driven demand forecasting and dynamic inventory optimization enable supply chain managers to align production schedules with market needs, reducing excess inventory and lowering warehousing costs. Flexible supply chain networks that diversify sourcing and distribution channels also enhance resilience against external shocks, such as climate change and trade restrictions. By investing in automation, standardization, and lean supply chain strategies, wild coffee producers can streamline operations, improve quality consistency, and increase overall efficiency, allowing them to compete effectively in a global coffee market that increasingly prioritizes sustainability, efficiency, and traceability.

Environmental uncertainty poses a significant challenge to supply chain stability, particularly

for agriculture-dependent industries such as wild coffee production. Climate change, market price volatility, and regulatory shifts can disrupt supply chains, making it difficult for small-scale coffee growers and exporters to maintain stable yields and incomes. To mitigate these risks, stakeholders must adopt climate-adaptive farming practices, expand market access, and strengthen regulatory and policy frameworks to enhance long-term supply chain resilience. One of the most critical strategies for mitigating climate-related disruptions is promoting farming practices adapted to climate change. Given that wild coffee cultivation is highly dependent on stable weather patterns, changes in rainfall distribution, temperature extremes, and soil degradation can severely impact coffee yields. To address these challenges, coffee producers should adopt drought-resistant coffee varieties that can withstand fluctuating precipitation levels and rising temperatures. Additionally, integrating agroforestry systems—where coffee is grown alongside native shade trees—can help conserve biodiversity, reduce soil erosion, and enhance carbon sequestration, thereby improving farm resilience. Regenerative agricultural techniques such as organic composting, soil amendments, and diversified crop rotations can further improve soil health and long-term productivity. By scaling up these climate-smart agricultural practices, coffee growers can reduce their vulnerability to climate shocks and maintain stable supply chain operations.

Beyond climate concerns, market instability remains a major risk affecting the efficiency of wild coffee supply chains. Price volatility in global coffee markets often exposes smallholder producers to economic vulnerability, particularly when they rely on traditional commodity trading mechanisms. To reduce dependence on fluctuating market conditions, coffee producers should expand market access by establishing direct trade relationships, obtaining specialty coffee certifications, and utilizing digital marketplaces. Direct trade partnerships with roasters, boutique coffee retailers, and cooperatives provide greater pricing transparency, better profit margins, and long-term buyer commitments. Additionally, obtaining certifications such as Fair Trade, Rainforest Alliance, and organic labeling enables farmers to command higher prices, attract ethical buyers, and access niche markets with stable demand. Digital transformation further supports market expansion by enabling e-commerce platforms, blockchain-based traceability systems, and digital payment solutions that allow producers to connect with international buyers and optimize pricing strategies.

Lastly, strengthening regulatory and policy frameworks is essential to ensuring financial stability, trade incentives, and institutional support for wild coffee producers. Many smallholder farmers struggle with unstable pricing mechanisms, limited access to credit, and a lack of government-backed risk mitigation programs. To address these issues, governments should establish price stabilization funds to protect farmers from extreme market fluctuations by guaranteeing minimum price thresholds. Additionally, fair trade incentives such as tax credits for sustainably certified coffee producers and financial subsidies for climate-resilient agriculture initiatives can help offset the costs of sustainable coffee production. Expanding access to digital finance—including mobile banking, blockchain-based

smart contracts, and microfinance solutions—can ensure timely payments, facilitate access to trade finance, and support long-term agricultural investments. By implementing climate adaptation strategies, expanding market access, and strengthening policy frameworks, wild coffee supply chains can become more resilient to environmental uncertainty and market volatility. These measures will not only improve financial and production stability but also contribute to long-term sustainability and competitiveness in the global coffee industry.

In conclusion, enhancing supply chain efficiency in the wild coffee sector requires a holistic approach that integrates digital transformation, process innovation, and environmental adaptation. By investing in digital tools, automation, and sustainable farming techniques, stakeholders can build a resilient, efficient, and competitive wild coffee industry that is well-positioned to navigate evolving market and environmental challenges.

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