

## Article

# Symbiosis and Empowerment: How Logistics Parks Drive Sustainable Development in Cross-Border Agricultural Supply Chains—A Hybrid Analysis Based on SEM-fsQCA

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## Abstract

Logistics parks are increasingly acting as coordination hubs in cross-border agricultural supply chains (CASCs), yet evidence on how park-enabled governance mechanisms translate into sustainability remains limited. This study examines the drivers of CASC sustainability within the context of logistics parks in Henan, China, and assesses whether the dominant park type conditions these effects. A total of 385 valid questionnaire responses were analyzed using structural equation modeling (SEM) and fuzzy-set qualitative comparative analysis (fsQCA). SEM results show that symbiotic environment cultivation is the strongest predictor of sustainability, while interface mediation efficiency and safety also significantly support cross-border circulation. The moderating role of dominant park type is supported only for the interface and sustainability link. fsQCA further identifies three equifinal configurations leading to high sustainability, indicating that strong environmental cultivation and interface efficiency can compensate for weaker elements under certain combinations. These findings clarify how logistics parks enable economic, environmental, and social value creation in CASCs and provide actionable levers for park management and policy design.

**Keywords:** logistics parks; cross-border agricultural supply chains; sustainable development; multi-method empirical analysis



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## 1. Introduction

Building resilient and low-carbon agri-food supply chains has become a pressing priority as cross-border trade expands and sustainability requirements tighten across logistics and food systems. However, these novel models remain in an exploratory phase, with their maturity and stability requiring further enhancement [1]. Cross-border agricultural supply chains (CASCs) face persistent sustainability challenges because of long chain structures [2], heterogeneous actors [3], operational complexity [4], diverse risks [5], and strong dependence on cold-chain logistics.

Logistics parks increasingly function as coordination hubs in agricultural logistics networks. Supported by geographical advantages, information sharing, resource integration capabilities, and policy support [6], logistics parks can consolidate cold-chain infrastructure and organize multi-actor collaboration. Yet, analytical research explaining

how the integrative governance mechanisms of logistics parks translate into CASC sustainability remains fragmented, limiting both theory development and practical guidance. Against this backdrop, Henan Province, China, is selected as the empirical setting due to its geographic centrality. Bordering six major provinces (Figure 1), it serves as a critical logistics nexus where logistics parks are deeply integrated into cross-border circulation. Currently, Henan hosts four national cold-chain bases and numerous provincial demonstration sites, providing a representative context for analyzing logistics parks as governance nodes within CASCs.



**Figure 1.** Henan Province and surrounding regions.

Existing evidence also leaves an incomplete explanation for logistics parks–dominated CASCs. Studies on logistics parks mainly address conceptualization and quantitative identification [7,8], agglomeration externalities and competitiveness [9], and growth mechanisms [10], while CASCs studies focus on conceptual definitions [11,12], characteristics and elements [13], cultivation and development [14], and challenges and countermeasures [15]. Although sustainability has been discussed in e-commerce platform–dominated CASCs, mechanism-oriented accounts for sustainability under logistics parks–dominated governance remain relatively scarce. Existing studies predominantly employ platform theory, ecosystem theory [16], social exchange theory and transaction cost theory [17], as well as organizational learning theory [18] for analysis, emphasizing digital-centric coordination and single-dimension efficiency. In contrast, logistics park-led models are underpinned by “governance-by-agglomeration,” where physical proximity and shared infrastructure create a symbiotic logic that traditional transaction-based paradigms fail to fully capture. The complexity of these impact pathways determines the necessity of the multi-theoretical framework proposed in this study. To bridge these analytical gaps, this study adopts a multi-theoretical framework tailored to the specific dimensions of our research questions. The selection of these four theories is guided by the necessity to capture the ‘spatial-relational-outcome-context’ nexus of CASCs. Industrial Cluster and Symbiosis theories provide the basis for examining spatial agglomeration and inter-firm coordination; the Triple Bottom Line offers a standardized metric for sustainable performance; and Contingency Theory defines the governance boundaries. This integrated approach ensures that the theoretical framework is a direct logical extension of the identified research needs.

Methodologically, existing research predominantly employs Fuzzy AHP (FAHP) and Fuzzy Type-Operational Preference System (FTOPSIS) [19], alongside Structural Equation Modeling (SEM) [20]. To capture both net effects and equifinal pathways, this study combines SEM with fuzzy-set qualitative comparative analysis (fsQCA). The study contributes by theoretically integrating the key symbiotic mechanism dimensions through which logistics parks, acting as strategic governance hubs, support CASC sustainability. It uniquely

highlights the role of dominant logistics park types as a governance boundary condition, providing complementary evidence from SEM and fsQCA to uncover the complex causality behind sustainability outcomes. Furthermore, it derives actionable governance-relevant implications for synergistically improving economic, environmental, and social performance amidst the dual pressures of global green transformation and trade restructuring.

Accordingly, this study addresses three questions: (1) What are the critical symbiotic dimensions within the logistics park framework that underpin the sustainability of CASCs? (2) How do these symbiotic factors interact within the park's governance structure to influence sustainability outcomes? (3) Through which distinct configurational pathways can different archetypes of logistics parks achieve high-level CASC sustainability? The remainder of this paper is organized as follows: Section 2 reviews relevant literature and establishes the theoretical foundation; Section 3 develops the hypotheses and conceptual model; Section 4 reports SEM results; Section 5 presents fsQCA findings; and Section 6 concludes.

## 2. Literature Review and Theoretical Foundation

### 2.1. Conceptual Definitions

To define “cross-border agricultural product sustainable supply chains led by logistics parks”, this study draws on three related notions. A cross-border agricultural product supply chain is a multi-actor system centered on agricultural products that crosses national borders [13]. It covers production and post-harvest handling, processing, storage, and transportation, cross-border logistics, customs clearance, and overseas distribution, and involves substantial coordination across multiple parties and stages. Sustainable supply chains integrate economic performance with environmental protection and social responsibility, requiring balanced consideration of economic, environmental, and social dimensions over time [21]. Logistics park-led supply chains describe organizational arrangements in which logistics parks, leveraging agglomeration and resource-integration capabilities, assume a leading role in coordinating supply chain operations [22].

Accordingly, this study defines “cross-border agricultural product sustainable supply chains led by logistics parks” as cross-border agricultural product supply chains coordinated by a logistics park as the organizational hub, with sustainability assessed across economic, environmental, and social dimensions.

### 2.2. Literature Review

#### 2.2.1. Research on Logistics Parks

As key carriers of modern logistics systems, logistics parks have garnered extensive academic attention in recent years. Existing research primarily centers on defining the concept of logistics parks, their functional positioning, and competitive advantages. Notteboom et al. [8] define logistics parks from multiple dimensions, including functional characteristics, industrial agglomeration, and spatial planning, emphasizing their role as vital hubs within regional logistics networks. Meanwhile, He et al. [9] further propose that logistics parks significantly reduce logistics costs, enhance regional logistics efficiency, and strengthen industrial competitiveness through industrial agglomeration effects. Additionally, the growth mechanisms of logistics parks have been extensively examined. Fang et al. [10] identified key growth factors, including policy support, infrastructure development, and approaches to fostering industrial ecosystems. However, these studies predominantly focus on theoretical frameworks and practical models for general logistics parks. Research on agricultural product logistics—particularly cross-border agricultural logistics parks—remains notably insufficient, lacking systematic theoretical frameworks and empirical research outcomes.

### 2.2.2. Research on Cross-Border Sustainable Agricultural Supply Chains

As global economic integration deepens, CASCs have become crucial for ensuring global food security and enhancing agricultural trade efficiency. Van Roekel et al. [11] first introduced the CASC concept, emphasizing its transnational, complex, and multi-stakeholder characteristics. Building upon this, Wang et al. [12] further refined CASC structural features, revealing supply chain complexity, diverse risks, and a dynamic nature. In terms of sustainability research, Bernzen et al. [23] and Bubicz et al. [24] explored evaluation frameworks and influencing factors for CASC sustainability across economic, social, and environmental dimensions. Further, Bai and Sarkis [25] proposed leveraging information technology—particularly blockchain—to enhance supply chain operational efficiency and information transparency. Additionally, Abula et al. [13] offered recommendations for cultivating export agricultural supply chains. With respect to CASC infrastructure, logistics parks—serving as critical nodes—exert positive impacts on sustainable development by integrating logistics resources, enhancing operational efficiency, and optimizing supply chain management [6]. However, existing research predominantly remains at the macro-level analysis of supply chains as a whole, with limited in-depth theoretical and empirical studies addressing either the specific role logistics parks play in cross-border agricultural supply chains or how they achieve sustainability. Regarding theoretical frameworks and analytical methods, researchers have employed diverse theories, including supply chain collaboration theory [5], sustainable supply chain management, and stakeholder theory [23]. Relevant analytical approaches, such as grounded theory [26], provide rich methodological tools for CASC research. Nevertheless, explanations of how these factors interact and their underlying influence mechanisms remain insufficient.

### 2.2.3. Research Gaps and Significance of This Study

Existing scholarship on logistics parks and CASCs provides a crucial foundational understanding, yet a systematic review reveals significant theoretical and methodological gaps. Theoretically, current research predominantly relies on isolated perspectives. While studies on CASCs engage with platform and ecosystem theories, they often lack a multi-theoretical integration framework to capture the complexity of “governance-by-agglomeration”. The systematic orchestration of industrial cluster theory, symbiotic systems theory, triple bottom line theory, and contingency theory remains largely unexplored in this field. Methodologically, the prevailing use of singular analytical approaches often overlooks the interplay between linear causality and configurational complexity. Hybrid empirical designs that combine structural equation modeling (SEM) with fuzzy-set qualitative comparative analysis (fsQCA) are lacking, which limits the simultaneous representation of net effects and equifinal configuration mechanisms. Content-wise, research integrating logistics park theory with CASC governance is restricted. There is insufficient exploration of how symbiotic mechanisms and contingency adaptation function within logistics park-dominated ecosystems. This study bridges these analytical gaps, offering a novel framework that theorizes the logistics park as a strategic symbiotic host for agricultural green transformation.

## 2.3. Theoretical Foundation

### 2.3.1. Industrial Cluster Theory

Industrial cluster theory was first proposed by Porter [27] in *The Competitive Advantage of Nations*, explaining how geographic concentration of firms accelerates knowledge and technology diffusion, enhances innovation capabilities, and improves production efficiency, thereby strengthening competitive advantage. Its core lies in geographic proximity, facilitating inter-firm interaction and collaboration, enabling efficient resource sharing, rapid diffusion of knowledge and technology, and continuous collision and integration

of innovative ideas, driving efficiency gains and innovation across the entire cluster [9]. In the agricultural supply chain domain, logistics parks function as strategic nuclei. This agglomeration effect optimizes the allocation of logistics facilities, information resources, and human capital within the cluster [6]. Consequently, industrial cluster theory provides the structural economic justification for our model, identifying spatial integration as a fundamental precursor to symbiotic synergy and guiding the measurement design for resource complementarity among constituent enterprises.

### 2.3.2. Symbiosis Theory

Originating from De Bary's pioneering 1879 biological research [28], symbiosis theory centers on describing interdependent, mutually beneficial survival relationships between different species. Zhang et al. [29] extended this concept to management studies, applying it to analyze mutually beneficial symbiotic relationships formed between organizations based on shared interests. In supply chain management, scholars apply symbiosis theory to study interactions among supply chain participants—including information sharing, resource coordination, and risk sharing—examining how these dynamics enhance overall supply chain stability and operational efficiency under specific environmental influences [30]. Symbiosis theory elucidates inter-firm interaction patterns, such as efficient resource matching between logistics providers and agricultural suppliers, and information sharing between processing and sales enterprises that align production with demand [31]. By extrapolating these biological principles to industrial ecosystems, this theory directly informs the operationalization of the internal interaction mechanisms within our model, providing the evaluative logic for quantifying the efficiency and security of supply chain exchanges.

### 2.3.3. Triple Bottom Line Theory

The Triple Bottom Line theory, proposed by Elkington [32], emphasizes that while pursuing economic gains, enterprises must also balance environmental protection and social responsibility. This multidimensional perspective guides enterprises to identify synergies between long-term interests and social value within uncertain and pressured environments [33]. TBL theory serves as the primary evaluative framework for conceptualizing the research outcomes. It ensures that the model's measurement of sustainability performance is grounded in a balanced integration of economic viability, ecological footprint, and social equity.

### 2.3.4. Contingency Theory

Contingency theory originated in the field of organizational management during the 1960s. Its core premise is that organizational effectiveness depends on the degree of fit between its structure and operational practices and the prevailing environmental conditions [34]. The core elements of contingency theory include environmental variables, organizational characteristics, matching relationships, and performance outcomes [35]. This perspective underscores the necessity of dynamic adaptation, breaking away from the traditional single-causal mindset that "structure determines performance" [36]. Accordingly, contingency theory provides the logical rationale for exploring the moderating factors within our model. It justifies the inclusion of governance archetypes as critical situational drivers, suggesting that the ultimate success of supply chain symbiosis is contingent upon the alignment between park leadership models and operational contexts.

### 2.3.5. Hierarchically Integrated Theoretical Framework

The theoretical architecture of this study synthesizes Industrial Cluster Theory, Symbiosis Theory, Triple Bottom Line (TBL) Theory, and Contingency Theory into a hierarchically integrated framework that links spatial structures, relational mechanisms, sustainabil-

ity goals, and situational boundaries. First, Industrial Cluster Theory specifies the spatial–structural foundation, explaining how agglomeration effects and network externalities create the macro-level conditions under which logistics parks can evolve into organizational platforms. On this basis, Symbiosis Theory serves as the core mechanism, showing how spatial proximity is translated into dynamic interdependence among heterogeneous actors, thereby enabling coordinated value creation and system stability. TBL Theory then provides the evaluative lens by defining sustainability performance across economic, environmental, and social dimensions, ensuring that the effects of the internal mechanisms are assessed against multidimensional criteria. Finally, Contingency Theory introduces boundary conditions by recognizing that these mechanisms are not uniformly effective, but depend on park-specific governance logics and leadership effectiveness. Together, the four perspectives form an explanatory chain from structural preconditions to relational processes, performance outcomes, and contextual adaptation, providing a consistent theoretical basis for the subsequent empirical analysis.

### 3. Research Hypotheses and Model Construction

#### 3.1. Hypothesis Development

##### (1) Compatibility of Symbiotic Unit Quality Parameters

Logistics parks may operate as organizational platforms for sustainable cross-border agricultural business models by attracting suitable participating actors and coordinating their interactions. The qualitative parameters of symbiotic units capture key attributes of participating actors and provide indicators of their intrinsic characteristics [29]. Under park leadership, brand-related governance arrangements can support industrial clustering by concentrating specialized agricultural activities and bringing complementary actors and production factors into the park network [37]. Through shared infrastructure, coordinated services, and digital support, logistics parks can improve the operational conditions of resident cross-border agricultural enterprises. However, excessive similarity among participating units may lead to a “homogeneity trap”, reducing diversity and limiting innovation. When heterogeneous actors display high compatibility in qualitative parameters related to sustainability-oriented management and shared governance expectations, complementarity is more likely to emerge, which may lower coordination costs and strengthen supply chain resilience.

**H1.** *Compatibility of qualitative parameters among symbiotic units positively influences the sustainable development of logistics park-dominated cross-border agricultural supply chains.*

##### (2) Operational Mechanisms of Symbiotic Models

Logistics parks may function as organizational hubs in sustainable business models by coordinating resource allocation and inter-firm collaboration. Their strengths in talent concentration, infrastructure provision, and platform-based information integration are associated with the agglomeration and resource-consolidation effects of logistics industry clusters [7,38]. Through formalized governance arrangements within the park, interdependence and complementarity among resident enterprises can facilitate joint operations and shared services relative to fully independent firm activities. However, more complex collaborative arrangements may also increase coordination costs and generate procedural inertia, which can weaken the expected efficiency benefits. Park-led collaboration may also be linked to greater supply chain responsiveness to environmental change by enabling coordination across upstream and downstream actors. Information sharing and joint coordination mechanisms can reinforce inter-firm trust and improve the perceived credibility of shared information, thereby supporting coordination among supply chain participants [39].

**H2.** *The effective operation of symbiotic models positively promotes the sustainable development of logistics park-led cross-border agricultural supply chains.*

(3) Efficiency and Security of Symbiotic Interface Mediation

Logistics parks can integrate physical and digital interfaces that support cross-border flows, and the effectiveness of these interfaces influences the timeliness and reliability of related business activities. Cross-border e-commerce relies on digital platforms to enable border-spanning transactions and is often associated with higher communication and transaction efficiency in cross-border agricultural supply chains [7]. In addition, logistics parks can mitigate in-transit losses of agricultural products through coordinated services and enabling infrastructure, such as facilitation for customs procedures and smart cold-chain systems. However, interface management may involve a “security–efficiency trade-off”, whereby faster circulation can increase compliance risks or weaken product traceability. As an intermediary for the movement of products, information, and funds, the efficiency and security of symbiotic interfaces can be strengthened through park-level governance and standardization, helping to address loss and uncertainty arising from complex cross-border processes.

**H3.** *The mediating efficiency and security of symbiotic interfaces positively promote the sustainable development of logistics park-dominated cross-border agricultural supply chains.*

(4) Building Symbiotic Environments

Logistics parks can mediate the implementation of macro-level policy instruments and translate them into operational practices at the firm level. Sound management practices and regulatory frameworks are important drivers for advancing sustainable supply chain management [40]. By improving the local business environment and coordinating support services, logistics parks may reduce the exposure of agricultural supply chains to internal and external disruptions. In particular, park-based platforms can facilitate access to financial services provided by governments or financial institutions, helping cross-border agricultural enterprises address liquidity constraints and financing frictions. At the same time, excessive reliance on policy support may lead to institutional over-dependence and weaken firms’ market-based autonomy. Overall, a stable symbiotic environment supported by park governance can provide institutional conditions and economic incentives that are conducive to the green transformation of business models.

**H4.** *The construction of a symbiotic environment positively impacts the sustainable development of logistics park-dominated cross-border agricultural supply chains.*

(5) The Regulatory Role of Logistics Park-Dominated Models

Logistics parks, as spatial forms of industrial clustering, are typically planned and operated in alignment with regional economic development priorities. Zeng [41] classifies industrial parks into three dominant types: government-led, enterprise-led, and government–enterprise collaborative. Government-led parks are characterized by public-sector coordination in infrastructure provision and investment attraction, whereas enterprise-led parks rely more on firms’ capital capacity and brand influence to mobilize clustered entry. Collaborative parks combine governmental coordination with leading enterprises’ market-oriented capabilities. As these dominant types influence how resources are mobilized and coordination is organized within parks, the governance authority embedded in each type is likely to condition the effectiveness of park-led mechanisms. This consideration is particularly relevant in Henan, where logistics parks play an important role in supporting

cross-border agricultural supply chains. Accordingly, this study treats the dominant type of logistics park as a moderating condition.

**H5.** *The dominant type of logistics park moderates the relationship between symbiotic unit parameter compatibility and the sustainable development of logistics park-dominated cross-border agricultural supply chains.*

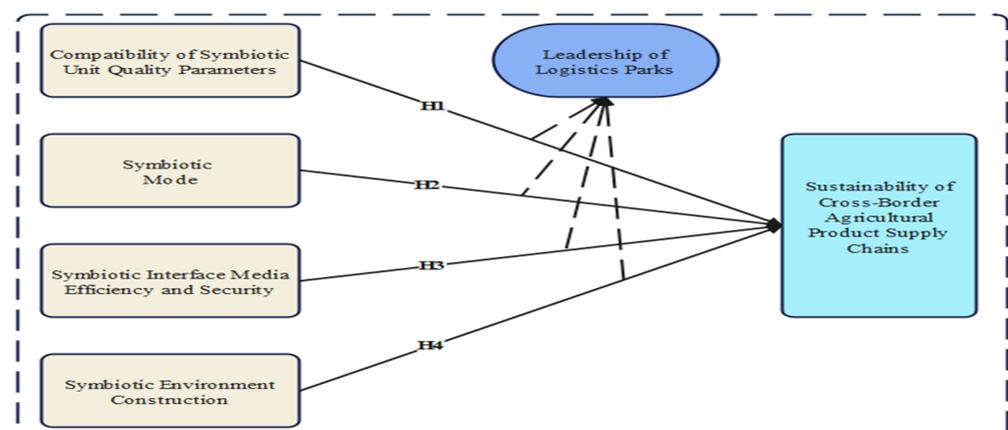
**H6.** *The dominant type of logistics park moderates the relationship between symbiotic mode operation and the sustainable development of logistics park-dominated cross-border agricultural product supply chains.*

**H7.** *The dominant type of logistics park moderates the relationship between the efficiency and security of symbiotic interface mediation and the sustainable development of logistics park-dominated cross-border agricultural supply chains.*

**H8.** *The dominant type of logistics park moderates the relationship between symbiotic environment construction and the sustainable development of logistics park-dominated cross-border agricultural supply chains.*

### 3.2. Model Construction

Building on the proposed theory and hypotheses, this study develops a conceptual model to examine sustainability in logistics park-dominated cross-border agricultural supply chains in Henan Province (Figure 2). The model links four symbiotic dimensions—symbiotic unit compatibility (SU), symbiotic mode operation (SM), symbiotic interface efficiency and safety (SI), and symbiotic environment cultivation (SE)—to triple-bottom-line sustainability performance. SU reflects partner fit and resource complementarity, SM captures coordinated routines and joint operations, SI concerns interface efficiency and risk control (e.g., information exchange, cold-chain logistics, and traceability), and SE represents enabling infrastructure, institutional arrangements, and support services. Together, these dimensions form a complementary mechanism system through which logistics parks can enhance coordination and resource utilization, thereby improving economic, environmental, and social outcomes. To account for governance heterogeneity, the dominant type of logistics park is specified as a contingency-based boundary condition that moderates the effects of SU, SM, SI, and SE on sustainability. PLS-SEM is employed to estimate net effects and moderation patterns.



**Figure 2.** SEM Research Model Diagram.

## 4. Empirical Analysis

### 4.1. Structural Equation Modeling Analysis

#### 4.1.1. Questionnaire Design and Data Collection

During questionnaire design, each indicator was measured on a five-point Likert scale (1 = “Not at all important/Disagree” and 5 = “Very important/Agree”). This design facilitates the collection of quantitative data with high reliability.

The sampling strategy for this study was structured as a tripartite stakeholder ecosystem to ensure both operational depth and ecological validity. First, practitioners directly engaged in cross-border agricultural trade and management within logistics parks provided empirical insights into internal operational dimensions. Second, academic researchers contributed theoretical validation for the structural symbiotic mechanisms. Third, consumer groups were purposefully integrated as external evaluators of the system’s “outputs”. This inclusion is theoretically grounded in the Triple Bottom Line (TBL) theory, which posits that the sustainability of logistics park-led CASCs—particularly social performance regarding food safety and responsibility—must be validated by end-market stakeholders. This tripartite synthesis balances internal technical expertise with external perception, capturing the complete feedback loop of the logistics park-led ecosystem. Prior to formal questionnaire distribution, the research team conducted a pre-survey (50 distributed, 45 valid responses collected). Based on feedback, item wording and logical sequencing were revised to enhance the questionnaire’s scientific rigor and operational feasibility. Following expert pre-testing and feedback-driven refinements, the final indicator system shown in Table 1 was established to guide actual data collection.

**Table 1.** Key Factors Influencing the Sustainability of Cross-Border Agricultural Supply Chains Dominated by Logistics Parks.

Variable	Question Number	Observed Variable	Variable Source
Symbiosis Unit Quality Parameter Compatibility	SU1	Degree of Compliance with the Ten Principles of the Global Compact by Tenant Enterprises	Rasche [42]
	SU2	Green Transition and Governance Capability of Tenant Enterprises	Wan et al. [43]
	SU3	Degree of Industrial Agglomeration	Chen et al. [44]
	SU4	Degree of Branding Development in Industrial Clusters	Crombie [45]
	SU5	Value-Added Level of Exported Agricultural Products	Bas et al. [46]
	SU6	Symbiosis Unit Sustainability Awareness	Li et al. [47]
	SU7	Overall Development Potential of the Park	Park et al. [48]
Symbiosis Model Operation	SM1	Degree of Resource Aggregation and Integration in the Park	He et al. [9]
	SM2	Collaboration Level Between Leading and Supporting Enterprises Within the Park	Inkpen et al. [49]
	SM3	Overall open innovation capability of the park	Tao et al. [50]
	SM4	Supply Chain Collaboration Capability	Li et al. [51]
	SM5	Agility of Supply Chain in Responding to Environmental Changes	Gligor [52]
	SM6	Supply Chain Resilience to Adverse Conditions	Davis et al. [53]
	SM7	Integrity of Agricultural Product Quality Certification and Traceability Systems	Hoorfar et al. [54]
	SM8	Market Trading Mechanism Improvement	Yu et al. [55]

Table 1. Cont.

Variable	Question Number	Observed Variable	Variable Source
Efficiency and Security of Symbiotic Interface Media	SI1	Cross-border Agricultural Product Circulation Efficiency and Safety	Teng [56]
	SI2	Level of New Infrastructure Development	Dai and Yang [57]
	SI3	Cross-border E-commerce Platform Development Level	Wang et al. [12]
	SI4	Cross-Border Trade Facilitation Level	Moyo [58]
	SI5	Supply Chain Information Technology Level	Vanpoucke et al. [59]
	SI6	Supply Chain Information Data Sharing Level	Sahoo et al. [60]
Symbiotic Environment Creation	SE1	Supply Chain Information Transparency and Disclosure	Wang et al. [26]
	SE2	Cultivating Risk Prevention Awareness and Response Capabilities in Symbiotic Systems	Chertow [30]
	SE3	Intellectual Elements of Symbiotic Systems	Yao [61]
	SE4	Innovation and Application of Sustainable Business Models for Parks and Enterprises	Evers et al. [62]
	SE5	Degree of Trade Digital Transformation	Zhou et al. [63]
	SE6	Financial Policy Support for Logistics and Supply Chain	Ma et al. [64]
Logistics Park Dominant Type	DT1	Strategic orientation dominance	Zeng [41]
	DT2	Resource allocation control	
	DT3	Operational rule-making leadership	
Sustainability of Cross-Border Agricultural Supply Chains in Logistics Parks with Dominant Models	SCS11	Level of Economic Benefit Increase in Symbiotic Units	Lu et al. [65]
	SCS12	Level of Economic and Energy Consumption Cost Reduction in Symbiotic Units	Malak-Rawlikowska et al. [66]
	SCS13	Agricultural Productivity and Farmer Income Levels	Mishra and Dey [15]
	SCS14	Growth Capacity of Industrial Parks	Wang et al. [67]
	SCS21	Intensity of Resource Conservation in Symbiotic Systems	Chertow et al. [68]
	SCS22	Ecological Priority and Green Low-Carbon Level of Symbiotic Systems	Nogueira [69]
	SCS31	Social Responsibility Implementation in Symbiotic Units	Novitasari et al. [70]
	SCS32	Level of Stakeholder Welfare and Rights Protection	Bubicz et al. [24]
	SCS33	Reliability of Food Safety Assurance and Quality Traceability	Hoorfar et al. [54]
	SCS41	Resilience of Supply Chains to Environmental and Operational Shocks	Davis et al. [53]
	SCS42	Competitiveness of Industrial Parks	Wang et al. [67]

#### 4.1.2. Descriptive Statistical Analysis

To ensure data quality and adequate coverage of the target context, the research team adopted a phased, multi-channel sampling strategy. Potential respondents were first identified and screened via expert interviews, industry associations, and liaison contacts at logistics parks to enhance relevance to cross-border agricultural supply chains. Subsequently, surveys were administered through a combination of online questionnaires and on-site visits to enterprises and institutions located in logistics parks in Henan Province,

followed by strict validity screening. This process yielded 385 valid questionnaires. Because the structural model was estimated using partial least squares structural equation modeling (PLS-SEM), sample adequacy was evaluated using established PLS-SEM rules of thumb. In particular, the “10-times rule” indicates that the minimum sample size should exceed ten times the largest number of indicators used to measure a construct and the maximum number of structural paths pointing to any endogenous construct; the effective sample size ( $n = 385$ ) satisfies this criterion and supports stable estimation [71]. In the final sample, practitioners directly engaged in cross-border agricultural supply chains accounted for 57.66%, followed by university researchers (27.02%) and consumers (15.32%). Organizational characteristics were reported for practitioner-linked enterprises, among which firms with more than 100 employees accounted for 60%. Respondents’ experience ranged from less than one year to more than five years. Overall, the sample composition aligns with the study’s multi-stakeholder design and is suitable for the subsequent empirical analyses.

#### 4.1.3. Reliability and Validity Analysis

To further assess the reflective measurement specification, a Confirmatory Tetrad Analysis (CTA-PLS) was conducted [72,73]. To keep the procedure parsimonious, a four-indicator set was used for each construct (SU1–SU4, SM1–SM4, SI1–SI4, and SE1–SE4), yielding two non-redundant tetrads per construct under the  $k(k - 3)/2$  rule ( $k = 4$ ). Reflective specification is supported when the bias-corrected 95% confidence interval includes zero and  $p > 0.05$ . As reported in Table 2, all assessed tetrads met these criteria ( $p = 0.298$ – $0.815$ ), supporting the reflective specification.

**Table 2.** Results of Confirmatory Tetrad Analysis.

Construct	Model-Implied Tetrad (Non-Redundant)	Tetrad Value	95% CI (Lower)	95% CI (Upper)	<i>p</i> -Value	Result
SU	T1: SU1, SU2, SU3, SU4	0.022	−0.118	0.162	0.612	Reflective
	T2: SU1, SU3, SU2, SU4	−0.015	−0.145	0.115	0.524	Reflective
SM	T1: SM1, SM2, SM3, SM4	−0.009	−0.095	0.077	0.742	Reflective
	T2: SM1, SM3, SM2, SM4	0.034	−0.062	0.130	0.418	Reflective
SI	T1: SI1, SI2, SI3, SI4	0.011	−0.102	0.124	0.815	Reflective
	T2: SI1, SI3, SI2, SI4	−0.028	−0.144	0.088	0.531	Reflective
SE	T1: SE1, SE2, SE3, SE4	−0.035	−0.172	0.102	0.324	Reflective
	T2: SE1, SE3, SE2, SE4	0.019	−0.085	0.123	0.482	Reflective

SU denotes symbiosis unit parameter compatibility; SM denotes symbiosis mode operation; SI denotes symbiosis interface mediation efficiency and security; SE denotes symbiosis environment creation.

Scale quality was assessed using reliability and validity tests. As shown in Table 3, all Cronbach’s alpha values exceed 0.80, satisfying the  $\alpha \geq 0.70$  criterion [74]. Composite reliability (CR) values exceed 0.80, indicating strong internal consistency [75]. All outer loadings exceed 0.70, and all AVE values are at least 0.60, supporting convergent validity [74,76]. Regarding multicollinearity checks, as shown in Table 4, all items in this study exhibited VIF values below 3 and close to 1, indicating no significant multicollinearity issues among the items [74].

Discriminant validity was evaluated using the Fornell-Larcker criterion. As presented in Table 4, the square root of the AVE for each construct (diagonal elements in bold) is consistently higher than its correlation coefficients with other latent variables, confirming that each construct is empirically distinct.

**Table 3.** Reliability and Validity Data.

Latent Variable	Items	Loadings	Cronbach's Alpha	CR	AVE	VIF
Symbiosis Unit Parameter Compatibility	SU1	0.828	0.922	0.937	0.681	2.365
	SU2	0.843				2.524
	SU3	0.824				2.390
	SU4	0.825				2.411
	SU5	0.818				2.286
	SU6	0.824				2.385
	SU7	0.815				2.234
Symbiosis Mode Operation	SM1	0.803	0.925	0.938	0.655	2.323
	SM2	0.792				2.362
	SM3	0.831				2.455
	SM4	0.805				2.339
	SM5	0.800				2.143
	SM6	0.803				2.219
	SM7	0.82				2.474
	SM8	0.816				2.361
Cohesive Interface Medium Efficiency and Safety	SI1	0.800	0.894	0.919	0.654	2.065
	SI2	0.812				2.026
	SI3	0.786				1.930
	SI4	0.824				2.270
	SI5	0.818				2.100
	SI6	0.813				2.154
Symbiosis Environment Creation	SE1	0.803	0.888	0.914	0.640	2.098
	SE2	0.813				2.139
	SE3	0.796				1.907
	SE4	0.810				2.043
	SE5	0.774				1.834
	SE6	0.804				2.016
Park Dominant Type	DT1	0.871	0.856	0.912	0.776	1.956
	DT2	0.888				2.299
	DT3	0.884				2.222
Sustainable Cross-Border Agricultural Supply Chain Dominated by Logistics Parks	SCS11	0.814	0.948	0.955	0.660	2.639
	SCS12	0.821				2.600
	SCS13	0.820				2.558
	SCS14	0.801				2.359
	SCS21	0.796				2.319
	SCS22	0.827				2.677
	SCS31	0.821				2.614
	SCS32	0.801				2.490
	SCS33	0.800				2.393
	SCS41	0.811				2.516
	SCS42	0.822				2.666

CR denotes composite reliability; AVE denotes average variance extracted; VIF denotes variance inflation factor; DT denotes dominant type of logistics park; SCS denotes sustainability of dominant cross-border agricultural supply chain in logistics parks.

Finally, as shown in Table 5, the structural equation model constructed in this study indicates acceptable fit. The coefficient of determination is  $R^2 = 0.416$  (adjusted  $R^2 = 0.402$ ), suggesting meaningful explanatory power for the dependent variable. The Standardized Root Mean Square Residual (SRMR) is 0.040, which is well below commonly used cutoffs (e.g., 0.10) proposed by Hu and Bentler [77]. The Normed Fit Index (NFI) is 0.885, which is close to the conventional reference value ( $\approx 0.90$ ) suggested by Bentler and Bonett [78]. The Root Mean Square Theta (RMS Theta) is 0.108 and below commonly referenced thresholds

(e.g., 0.12). Additional discrepancy measures ( $d_{ULS} = 2.893$ ;  $d_G = 1.261$ ) and the chi-square value (1160.208) are reported in Table 5 [79]. Collectively, these indices support an adequate model fit for the SEM.

**Table 4.** Discriminant Validity Test Results.

	SU	SM	SI	SE	DT	SCS
SU	0.825					
SM	0.449	0.809				
SI	0.440	0.428	0.809			
SE	0.361	0.415	0.429	0.800		
DT	0.408	0.420	0.432	0.426	0.881	
SCS	0.441	0.432	0.446	0.488	0.454	0.812

**Table 5.** Model Fit Tests.

Fit Indices	Saturated Model	Estimated Model
SRMR <sup>1</sup>	0.040	0.040
$d_{ULS}$ <sup>2</sup>	2.786	2.893
$d_G$ <sup>3</sup>	1.166	1.261
Chi-square ( $\chi^2$ )	1160.208	1160.208
NFI <sup>4</sup>	0.885	0.885
RMS Theta <sup>5</sup>	- <sup>6</sup>	0.108
$R^2$ <sup>7</sup>	-	0.416
Adjusted $R^2$	-	0.402

<sup>1</sup> Standardized Root Mean Square Residual; <sup>2</sup> model difference test statistics; <sup>3</sup> model difference test statistics; <sup>4</sup> Normative Fit Index; <sup>5</sup> Residual Mean Square Theta; <sup>6</sup> indicates the indicator is not applicable in the corresponding model; <sup>7</sup> Determination Coefficient.

#### 4.1.4. Hypothesis Testing

To capture the multi-faceted nature of park governance, Park Dominant Type (DT) is operationalized both as a latent construct for interaction testing and as a grouping variable for Multi-Group Analysis (MGA). Following the heterogeneity testing procedure proposed by Henseler et al. [72] This study further explores the differential mechanisms of park-dominant types using SmartPLS 4.0's Multi-Group Analysis (MGA). First, the 385 samples were grouped by dominant type into three categories: government-dominant (132), enterprise-dominant (144), and government-enterprise cooperative (109). Second, MICOM replacement tests confirmed measurement invariance across groups (composite invariance  $p > 0.05$ , scalar invariance  $p > 0.05$ ). Finally, PLS-MGA nonparametric tests compared path coefficient differences between groups. Results indicate that government-led parks demonstrate optimal performance in fostering symbiotic environments ( $\beta = 0.338$  vs. 0.241,  $p = 0.018$ ), enterprise-led parks exhibit significant advantages in mediating symbiotic interfaces ( $\beta = 0.221$  vs. 0.165,  $p = 0.031$ ), while government-enterprise collaboration parks show relative strengths in operating symbiotic models. This finding suggests that parks of different dominant types should select differentiated symbiosis paths based on resource endowments and institutional environments, further validating the applicability of contingency theory in cross-border agricultural supply chain governance.

In the path analysis of the structural equation model, we conducted hypothesis testing for the core variables of the study (as shown in Table 6). Results indicate that the absolute values of the T-statistics for all four paths exceed 1.96, while corresponding  $p$ -values are below 0.001 or 0.05. This confirms the statistical significance of these paths' influence effects. Empirical results validate that partner compatibility, operational modes, interface security, and environment cultivation collectively drive CASC sustainability, providing full support

for Hypotheses H1–H4. Further examination of path coefficients reveals that the path coefficient for symbiotic environment cultivation is significantly larger than those of the other three independent variables, highlighting its pivotal role in advancing supply chain sustainability.

**Table 6.** Hypothesis Testing Results.

No.	Hypothesis	Standardized Path Coefficient	Standard Deviation	<i>t</i> -Value	<i>p</i> -Value	Test Result
1	H1	0.194	0.051	3.796	0.000	Support
2	H2	0.154	0.054	2.870	0.004	Support
3	H3	0.175	0.050	3.477	0.001	Support
4	H4	0.279	0.047	5.935	0.000	Support

To examine the moderating effect, this study employs SmartPLS 4.0 software and follows a standardized interaction effect analysis process: first, evaluating the direct influence of each independent variable on the dependent variable; then introducing the dominant type of logistics park as a moderator variable, constructing an interaction term to test its moderating role in the path relationship; finally, determining the significance of the moderating effect by analyzing the regression coefficients, *t*-values, and *p*-values of the interaction path [80].

This study treats the dominant type of logistics park as a key moderator, hypothesizing that it moderates the relationship between symbiotic unit parameter compatibility, symbiotic mode operation, symbiotic interface mediation efficiency and security, and symbiotic environment cultivation, on the one hand, and the sustainable development of cross-border agricultural supply chains dominated by logistics parks, on the other. According to the test results in Table 7, the *t*-value for park dominant type in the relationship between symbiotic interface mediation efficiency and security and supply chain sustainability reached 2.888, with a *p*-value less than 0.05. This indicates that the moderation path is significant, validating Hypothesis H7: the park dominant type exerts a positive moderating effect on the relationship between symbiotic interface mediation efficiency and security, and the sustainability of cross-border agricultural supply chains dominated by logistics parks

**Table 7.** Path Analysis of Moderating Variables.

Path	Hypothesis	Path Coefficient	<i>t</i> -Value	<i>p</i> -Value	Hypothesis Result
DT × SU→SCS	H5	0.075	1.426	0.154	Not supported
DT × SM→SCS	H6	0.059	1.043	0.297	Not supported
DT × SI→SCS	H7	0.130	2.888	0.004	Support
DT × SE→SCS	H8	0.011	0.237	0.812	Not supported

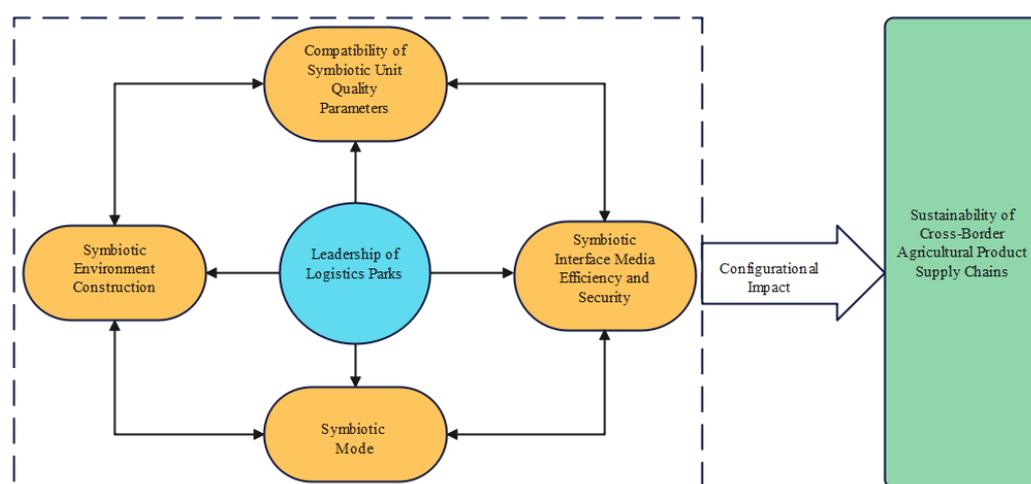
The regression results for H5, H6, and H8 all yielded *p*-values greater than 0.05, failing to reach statistical significance. This indicates that the dominant type of logistics park does not exhibit a significant moderating effect on the relationship between symbiotic unit compatibility, symbiotic mode operation, symbiotic environment creation, and the sustainability of cross-border agricultural supply chains. This finding profoundly reveals the essential characteristics of logistics parks as “symbiosis architects” and “enabling hubs”: First, symbiotic driving forces demonstrate structural stability transcending organizational attributes. Sarkis et al. [81] argue through institutional theory that when specific industries (e.g., cross-border cold chain) face extreme external pressures, organizations exhibit “institutional homogenization,” leading to high convergence in management practices among entities of different ownership structures or dominant types. Within the high-risk,

high-standard domain of cross-border agricultural supply chains, the underlying logic driving sustainable development remains remarkably consistent regardless of whether parks are led by governments, enterprises, or public private partnerships. This demonstrates that “symbiosis” has become an axiomatic pathway for parks to empower supply chain sustainability, with its efficacy remaining stable regardless of micro-level ownership. Second, the “enabling” function exhibits high universality and standardization. To meet stringent quality traceability and cold chain compliance requirements in cross-border trade, all park types must provide standardized enabling services. This functional “rigidity” diminishes marginal differences arising from dominant types. Research by Kauppi [82] further confirms that in operational management practices, the intensity of external regulatory environments and industry benchmarks often neutralizes the impact of organizational characteristics (such as ownership structures) on performance. Zhu and Sarkis [83] similarly note that within green supply chain contexts, institutional pressures exert stronger moderating effects than organizational dominance characteristics, mitigating governance behavior differences across diverse organizational settings. In summary, this lack of significance does not negate the importance of dominance. Rather, it demonstrates that within the context of this study, the “enabling” function of logistics parks has been internalized as a fundamental prerequisite for the operation of symbiotic systems. This allows the system to drive the sustainable transformation of cross-border agricultural supply chains in a “structurally stable” manner.

#### 4.2. Fuzzy Set Qualitative Comparative Analysis

##### 4.2.1. Variable Selection and Calibration

Fuzzy Set Qualitative Comparative Analysis (fsQCA) is suitable for analyzing complex causal relationships, demonstrating significant advantages in studying the influencing factors of sustainable development in logistics park-dominated cross-border agricultural supply chains [84]. fsQCA effectively identifies and explains interactions and combined effects among various influencing factors (as shown in Figure 3). Its capacity lies in its ability to examine conditional interactions, enabling researchers to identify multiple plausible causal pathways. Previous studies have confirmed that integrating such diverse methodologies significantly enhances scientific understanding of complex phenomena. This research employs a combined SEM and fsQCA approach to validate theoretical model hypotheses and conduct an in-depth exploration of different factor combinations influencing the sustainability of logistics park-dominated cross-border agricultural supply chains.



**Figure 3.** fsQCA Research Model Diagram.

### 4.2.2. Necessary Condition Analysis

Necessity condition analysis is the primary step in fsQCA, aiming to identify conditions that are associated with the sustainability of dominant cross-border agricultural supply chains in logistics parks [85]. Analysis was conducted using fsQCA 4.0 software. Following calibration standards proposed by Veríssimo, non-membership thresholds were set at 5%, membership thresholds at 95%, and cross-membership thresholds at 50% (as shown in Table 8) [86,87]. This ensures model path reproducibility and theoretical grounding, supporting analytical rigor and result reliability.

**Table 8.** Calibration Anchors for Conditions and Outcome.

Variables	Full Non-Membership (5%)	Crossover Point (50%)	Full Membership (95%)
SU	2.15	3.55	4.80
SM	2.10	3.45	4.75
SI	2.25	3.60	4.85
SE	2.35	3.70	4.90
SCS	2.20	3.65	4.85

According to the analysis criteria, a consistency level exceeding the 0.9 threshold is required for a condition to be considered necessary [85]. However, as shown in Table 9, none of the considered antecedent conditions reached the 0.9 consistency threshold, indicating that no single condition constitutes a necessary requirement for supply chain sustainability. Therefore, this study will further explore combinations of multiple antecedent variables to identify sufficient conditions for ensuring the sustainability of logistics park-dominated cross-border agricultural supply chains.

**Table 9.** Necessity Analysis of Sustainability in Logistics Park-Dominated Cross-Border Agricultural Supply Chains.

Prerequisite Condition	Sustainability of Logistics Park-Led Cross-Border Agricultural Supply Chains		Prerequisite Condition	Sustainability of Logistics Park-Led Cross-Border Agricultural Supply Chains	
	Consistency	Coverage		Consistency	Coverage
High Symbiosis Unit Quality Parameter Compatibility	0.743951	0.722143	Low Symbiosis Unit Quality Parameter Compatibility	0.489392	0.509764
High Symbiosis Mode Operation	0.736124	0.736708	Low Symbiosis Mode Operation	0.497999	0.502507
High Symbiosis Interface Medium Efficiency and Security	0.738973	0.722009	Low Symbiosis Interface Medium Efficiency and Security	0.501871	0.519136
High Symbiotic Environment Creation	0.754724	0.744930	Low Symbiotic Environment Creation	0.490198	0.501692
High Logistics Park Dominant Type	0.726608	0.733058	Low Logistics Park Dominant Type	0.493817	0.494293

### 4.2.3. Fuzzy Set Analysis

Sufficiency analysis was conducted via a truth table with minimum case frequency = 2, consistency threshold = 0.80, and PRI consistency  $\geq 0.70$  [85,88]. According to the fsQCA analysis results (as shown in Table 10), three paths were effectively identified, indicating that three configurations can lead to highly sustainable outcomes in dominant cross-border agricultural supply chains within logistics parks. Among these high-sustainability outcome configurations, the overall solution consistency reached approximately 0.884, exceeding

the 0.75 threshold. The coverage rate of 0.566 indicates that these three causal condition combinations explain 56.6% of the cases, indicating substantial explanatory coverage.

**Table 10.** fsQCA Analysis Results.

Predictor Variables	Sustainability of Logistics Park-Dominated Cross-Border Agricultural Supply Chains		
	Configuration 1	Configuration 2	Configuration 3
Symbiosis Unit Quality Parameter Compatibility	● <sup>1</sup>	● <sup>2</sup>	○ <sup>3</sup>
Symbiosis Mode Operation	●	●	●
Symbiosis Interface Medium Efficiency and Security	●	○	●
Symbiotic Environment Creation	○	●	●
Park Dominant Type	●	●	●
Consistency	0.899252	0.903608	0.912356
Original Coverage	0.492230	0.478154	0.486895
Unique Coverage	0.0469903	0.0329141	0.0416555
Overall Consistency		0.884847	
Overall Coverage		0.566799	

<sup>1</sup> indicates core condition present; <sup>2</sup> indicates peripheral condition present; <sup>3</sup> indicates condition absent.

The fsQCA analysis reveals that the sustainability of logistics park-dominated cross-border agricultural supply chains is a multidimensional phenomenon requiring comprehensive evaluation from multiple perspectives. Configuration 1 (Full-Element Collaborative Integration Pathway) indicates that symbiotic unit parameter compatibility, symbiotic mode operation, symbiotic interface mediation efficiency and security, and the logistics park dominant type are core conditions for achieving high sustainability. This configuration (consistency = 0.899, coverage = 0.492) reflects an “all-element synergistic” logic and is highly congruent with government-enterprise collaboration logistics parks, where institutional frameworks and market-driven resource allocation converge to drive systemic performance.

Analysis of Configuration 2 (Environmental-Institutional Empowerment Pathway) reveals that, beyond the three core conditions—symbiotic operation, symbiotic environment creation, and dominant park type—the compatibility of symbiotic unit quality parameters also significantly impacts sustainability. With a consistency of 0.903 and coverage of 0.478, this pathway demonstrates a strong configurational affinity with government-led logistics parks. This alignment validates earlier SEM-MGA findings that government leadership excels in cultivating symbiotic environments, effectively compensating for marginal interface efficiencies through robust policy support.

Analysis of Configuration 3 (Operation-Efficiency Leadership Path) highlights the importance of symbiosis model operation, efficiency, and safety of interface media, and the logistics park dominant type, while unit compatibility serves as a marginal condition. Its consistency (0.912) is the highest among the three configurations, underscoring its congruence with enterprise-led logistics parks that leverage superior agility in smart infrastructure and digital platforms to maintain resilience.

In synthesis, while symbiotic mode operation and the logistics park dominant type serve as universal core conditions across all pathways, this study uncovers three distinct configuration trajectories that steer CASCs toward high sustainability under varying governance contexts. Specifically, Configuration 1 represents an ideal-type synergy for collaborative governance, requiring the simultaneous high-level alignment of all system components. In contrast, Configuration 2 and Configuration 3 offer unique “compensatory”

mechanisms adapted to different logistics parks. The former demonstrates how robust institutional environments can lead to high sustainability by compensating for marginal operational efficiencies in government-led parks, while the latter illustrates how superior technical efficiency can bypass unit compatibility constraints in enterprise-led parks. This diversity of configurations reinforces Contingency Theory, suggesting that high sustainability is not achieved through a singular, universal driver, but rather through the strategic alignment of specific symbiotic elements with the inherent organizational characteristics of the logistics parks.

#### 4.3. Robustness Analysis

##### 4.3.1. Robustness Analysis of SEM Results

To ensure the empirical results are not skewed by the diverse expertise levels of the respondents, a sub-sample sensitivity analysis was first conducted. While the inclusion of consumers is essential for capturing market-end TBL outcomes, a “professional benchmark” sub-sample (practitioners and researchers,  $n = 326$ ) was used to re-estimate the structural model to ensure that the technical assessment of logistics governance was not skewed. As shown in Table 11, the path coefficients ( $\beta$ ) and T-statistics for H1 through H4 in the professional sub-sample are highly congruent with the full-sample estimations ( $n = 385$ ). Specifically, “symbiotic environment cultivation” (H4) consistently emerged as the most dominant driver in both models. This cross-group parameter stability confirms that the multi-stakeholder framework is robust and that consumer data provides a supplementary validation rather than a source of systematic bias.

**Table 11.** Robustness Analysis.

Hypothesis	Path	Full Sample ( $N = 385$ )		Professional Sub-Sample ( $N = 326$ )		Result
		Path Coeff. ( $\beta$ )	$t$ -Value	Path Coeff. ( $\beta$ )	$t$ -Value	
H1	SU $\rightarrow$ SCS	0.194 ***	3.796	0.198 ***	3.842	Robust
H2	SM $\rightarrow$ SCS	0.154 **	2.870	0.157 **	2.915	Robust
H3	SI $\rightarrow$ SCS	0.175 **	3.477	0.179 **	3.521	Robust
H4	SE $\rightarrow$ SCS	0.279 ***	5.935	0.282 ***	6.014	Robust

\*\*\*  $p < 0.001$ ; \*\*  $p < 0.01$ .

##### 4.3.2. Robustness Analysis of fsQCA Results

Building on the data stability confirmed above, this study adopts the consistency threshold adjustment method proposed by Schneider and Wagemann [88]. Specifically, we raised the consistency threshold for high sustainability outcomes in logistics park-dominated cross-border agricultural supply chains from the default value of 0.80 to 0.85. Analysis confirmed that the identified condition configuration is reliable and the results are robust. Furthermore, the output configurations, core conditions, and boundary conditions remained unchanged, further validating the stability and reliability of the findings.

## 5. Discussion

The leading role of logistics parks in Henan Province demonstrates how centralized governance nodes can catalyze CASC sustainability amidst shifting global and regional integration patterns. It reveals the influence pathways of symbiotic mechanism elements on supply chain sustainability and identifies pathways to high sustainability from a multi-configuration perspective. The findings not only enrich the theoretical framework of CASCs but also provide significant implications for logistics park development strategies and policy design.

SEM analysis indicates that fostering a symbiotic environment exerts the most significant influence on CASC sustainability. This suggests that under adequate external conditions—including policy support, financial services, digital transformation, and information transparency—the synergistic potential of parks and their tenant enterprises can be effectively unleashed, propelling the entire supply chain system toward efficient, stable, and green evolution [40]. This validates the core tenet of contingency theory: the effectiveness of supply chain mechanisms depends on their dynamic adaptability to external environments.

Applying fsQCA, this study identifies three distinct configurational pathways leading to high sustainability performance. Symbiotic mode operation and park-dominant types emerge as core conditions across all pathways, supporting symbiosis theory's proposition of "diverse symbiotic structures," in which mutually beneficial cooperation enables resource sharing and capability complementarity, thereby improving system performance [31]. Dominant entities further shape the orderly functioning of symbiotic networks through institutional design and resource allocation. Notably, symbiotic interface efficiency appears as only a marginal condition in some pathways, reflecting uneven infrastructure development within parks; when information connectivity, cold chain capacity, or trade facilitation is inadequate, the park's integrative function is constrained—consistent with the "weakest link effect" discussed in the triple bottom line literature [32,66]. The importance of symbiotic unit compatibility also varies across configurations, underscoring the situational dependency emphasized by contingency theory [89]. Overall, these results indicate that there is no single "optimal model" for CASC sustainability; instead, logistics parks should select governance- and context-matched pathways and operationalize them to deliver triple-bottom-line value. Specifically, under the full-element synergy pathway, parks can institutionalize shared rules and joint routines and standardize traceability/quality-control interfaces to reduce losses and improve reliability (economic), cut waste and emissions via coordinated cold-chain operations (ecological), and strengthen food safety assurance and inclusive participation (social). Under the environmental–institutional empowerment pathway, especially in government-led parks, priority should be given to green infrastructure, institutional arrangements, and shared service platforms (e.g., compliance/certification and facilitation services) to lower coordination and compliance barriers while accelerating green upgrading and inclusive outcomes. Under the operation–efficiency pathway, more typical of enterprise-led parks, smart infrastructure and digital platforms can be leveraged to redesign processes and strengthen interface efficiency and risk control, improving delivery performance while reducing losses and carbon footprints and enhancing product safety and accountability.

Theoretically, this study contributes to concept development and theory integration. By defining "logistics park-led cross-border agricultural sustainable supply chains", it clarifies logistics parks as governance hubs that enable symbiotic mechanisms supporting sustainability-oriented business models. It further proposes an "Aggregation–Synergy–Balance–Adaptation" framework that connects industrial cluster theory and symbiosis theory in a cross-border agricultural setting, addressing the limits of single-theory explanations [9]. In addition, embedding the triple bottom line perspective provides a consistent basis for evaluating outcomes across economic, environmental, and social dimensions and extends related work on green value chains [69]. Methodologically, although Govindan et al. [90] Reviewing major theoretical foundations in sustainable supply chain research, integrated applications of these perspectives in cross-border agricultural contexts remain limited. This study combines SEM and fsQCA to capture both net effects and configurational pathways. While SEM estimates average relationships among symbiotic drivers, fsQCA identifies equifinal configurations and reveals compensatory patterns, showing that

a strong symbiotic environment and the dominant park type can offset weaker interface conditions in some pathways. These results highlight the conjunctural and contingent nature of sustainability drivers in logistics park-led CASCs.

From a practical standpoint, this study positions logistics parks as governance platforms that enable institutional coordination, resource integration, and platform development in cross-border agricultural supply chains. It offers actionable guidance at multiple levels. Firms should embed in the park's symbiotic network and enhance sustainability capabilities through quality certification, information sharing, and risk-sharing arrangements [91], while adjusting collaboration to the park's dominant model. Park operators should strengthen rule-setting, information integration, and credit building to coordinate symbiotic mechanisms and improve ecosystem resilience. Habib [92], based on Ethiopia's coffee industry, highlights policy support, technology application, and social responsibility as key drivers of sustainable supply chain management, consistent with the triple bottom line and contingency logic adopted here. Together, these recommendations target information asymmetry, cold-chain bottlenecks, and fragmented governance, providing a practical pathway for sustainability upgrading in logistics park-led CASCs.

In summary, this study provides empirical insights into the evolution of novel business models in cross-border agricultural supply chains. Unlike traditional linear models focused on single enterprises, the new model emphasizes multi-stakeholder collaboration, platform sharing, and green transformation under park leadership. Symbiotic models and park-led mechanisms transition these business models from experimental phases to structural stability. Through infrastructure integration, information sharing, and resource reallocation, logistics parks create an institutional environment that enhances adaptability and sustainability in high-risk settings. This study advances our understanding of sustainability mechanisms in logistics park-led CASCs, highlighting the need for a holistic approach that integrates structural, process, and environmental factors, while dynamically adjusting resource allocation to build resilient, green, and sustainable cross-border agricultural supply chains.

## 6. Conclusions and Future Outlook

### 6.1. Conclusions

Our findings generate a strategic governance matrix that bridges theoretical symbiosis with actionable policy frameworks for logistics park-led CASCs. The empirical results confirm a significant positive correlation between the four symbiotic dimensions and the sustainability of logistics park-led CASCs. While unit compatibility, operational modes, and interface security are essential, symbiotic environment cultivation demonstrates a particularly pronounced influence, acting as the systemic foundation for sustainability. This finding suggests that in the complex landscape of cross-border trade, top-down environmental empowerment and policy-driven infrastructure are more decisive in driving green transformation than individual firm-level coordination alone. Three takeaways sharpen the contribution. First, high sustainability is reached through multiple viable configurations of symbiotic elements rather than a single best practice, extending symbiosis theory from pairwise cooperation to system-level governance in CASCs. Second, dominant logistics park types act as a governance boundary condition that determines which configurations are feasible, consistent with a contingency view of sustainability governance. Third, environment cultivation functions as the foundational lever, while mode operation and interface efficiency and safety serve as conversion mechanisms that translate enabling conditions into economic, ecological, and social value.

These insights point to differentiated policy priorities. Collaborative parks should institutionalize shared rules and joint routines and standardize information exchange,

cold chain protocols, and traceability and quality control arrangements. Government-led parks should prioritize green infrastructure and enabling public services, including compliance support, certification assistance, and trade facilitation platforms. Enterprise-led parks should leverage smart infrastructure and digital platforms to strengthen operational coordination, real-time monitoring, and disruption response.

The conclusions are most applicable to settings where logistics parks serve as governance hubs and where cold chain and trade facilitation conditions are comparable. Future research can further specify boundary conditions by testing the identified configurations across broader regions and park types.

### 6.2. Future Research Directions

While this study elucidates the role of logistics parks in fostering CASC sustainability, several avenues remain for further scholarly inquiry. First, future research should deepen the exploration of hidden transmission mechanisms within symbiotic systems. Investigating how social relational factors and digital cognitive capabilities mediate the impact of symbiosis will provide a more nuanced understanding of value co-creation. Second, scholars should expand the spatiotemporal scope of current findings. Longitudinal studies and cross-regional comparisons are essential to validate the generalizability of the identified configuration pathways across diverse institutional contexts. Finally, there is a clear need to incorporate product-specific heterogeneity. Analyzing how the varying logistics requirements of different agricultural categories dictate symbiotic efficiency will allow for the development of more granular and targeted supply chain governance strategies.

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