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LEVERAGING DIGITAL TRADE GOVERNANCE FOR LOW-CARBON TRANSITION: MECHANISM ANALYSIS AND POLICY OPTIMIZATION UNDER CHINA'S DUAL CARBON TARGETS

HaiHui Wang[1,2*], Yi Hong[1], YunXi You[1], Yue Song[1]
[1]*School of Digital Economics and Management, Wuxi University, Wuxi 214105, Jiangsu, China.*
[2]*Institute of China (Wuxi) Cross-Border Electronic Commerce Comprehensive Pilot Zone, Wuxi University, Wuxi 214105, Jiangsu, China.*
Corresponding Author: HaiHui Wang, Email: wanghh@cwxu.edu.cn

Abstract: The intensifying global climate crisis has necessitated innovative approaches to achieve low-carbon development, with digital trade emerging as a promising pathway due to its energy efficiency and technological advantages. China's Cross-border E-commerce Comprehensive Pilot Zones demonstrate a significant reduction in urban carbon emission intensity, supporting the country's "dual carbon" goals. Empirical analysis of 270 cities (2010-2021) reveals stronger effects in coastal regions, megacities, and service-driven economies. Three key pathways drive this impact: enhanced digital infrastructure, service sector agglomeration, and improved business environments. The findings offer actionable insights for aligning digital trade policies with sustainable urban development.
Keywords: Digital trade; Low-carbon transition; E-commerce; Carbon emissions; Policy evaluation

1 INTRODUCTION

The intensifying global climate crisis has accelerated the search for innovative policy solutions to achieve low-carbon development, with digital trade emerging as a particularly promising avenue due to its inherent energy efficiency and technological advantages. As the world's largest carbon emitter and a rapidly growing digital trade power, China's implementation of its "dual carbon" goals (peaking emissions by 2030 and achieving carbon neutrality by 2060) has created an urgent need to reconcile economic growth with environmental protection through optimized resource allocation and green innovation. Against this backdrop, China established its first Cross-border E-commerce Comprehensive Pilot Zone in 2015 [1], a strategic initiative designed to improve policy frameworks, enhance trade facilitation, and drive industrial upgrading while serving as a crucial testing ground for integrating digital trade expansion with emission reduction objectives. This policy experiment represents a significant effort to harness the potential of digital trade as a dual-force for both economic development and environmental sustainability.

Recent research has highlighted the complex relationship between digital trade and carbon emissions, revealing both promising pathways and potential challenges for environmental sustainability. While Yang et al. identify digital trade as a key driver of emission reduction [2], and Deng et al. demonstrate the significant influence of regional digital development levels on carbon footprints [3], the underlying mechanisms appear multifaceted. Evidence suggests digital trade can yield environmental benefits through optimized supply chains and smart logistics [4], yet may simultaneously increase emissions through expanded logistics volumes, energy-intensive warehousing, and packaging waste [5]. This dual effect appears to follow a nonlinear pattern, with Zhou and Guo documenting an inverted U-shaped relationship where emissions initially rise before declining after reaching a development threshold [6]. Further nuance emerges in the findings of Song et al. [7], who observe that cross-border e-commerce's emission-reduction effects vary significantly by region, city size, and baseline pollution levels, being particularly strong in China's eastern and western regions, large cities, and areas with initially underdeveloped digital infrastructure or lower pollution levels. These findings collectively suggest that the environmental impact of digital trade is contingent on developmental stage, implementation context, and complementary infrastructure.

Regarding transmission mechanisms, Ma et al. assert that digital trade effectively reduces regional carbon emission intensity by promoting scale effects [8], driving technological progress, and optimizing industrial structure. Zhu et al. construct an indicator system to measure regional digital trade development and examine its carbon reduction impact mechanisms and spillover effects from both the enterprise supply side and the resident demand side [9]. Their findings confirm that digital trade effectively promotes regional carbon reduction, with a more substantial effect observed in central and western regions and areas with lower carbon emissions.

Furthermore, regional characteristics, trade openness, and industrial agglomeration also influence the carbon reduction effect of digital trade. Zhou and Guo show that the carbon reduction effect of digital trade is stronger in China's central and western regions than in the eastern region [6], and stronger in inland areas compared to coastal areas. Simultaneously, the carbon reduction effect of digital trade may weaken as trade liberalization increases and carbon emission intensity decreases. Wang et al. further analyze the impact of manufacturing and producer services agglomeration on this effect [10], finding that manufacturing agglomeration may weaken it, whereas producer services agglomeration, the synergistic agglomeration of manufacturing and producer services, and carbon emission trading pilot policies enhance the carbon reduction effect. Additionally, Li et al. [11], using the implementation of the Cross-border E-commerce Comprehensive Pilot Zone policy as a quasi-natural experiment to analyze its impact in Central and Eastern Europe, reveal through mechanism analysis that digital trade holds the potential to indirectly affect urban carbon intensity by influencing green technological innovation, industrial agglomeration, and energy structure optimization.

Despite the rich findings in existing research exploring the relationship between digital trade and carbon emissions, several questions warrant further investigation. Specifically, the impact and mechanisms of cross-border e-commerce—a specific category of digital trade—on carbon emissions remain unclear. The influence of China's policy of establishing Comprehensive Pilot Zones to foster digital trade on the carbon emissions of host cities, along with its underlying mechanisms, is not well understood. Current research provides limited exploration into how such policies reduce carbon emission intensity through optimizing resource allocation, promoting digital infrastructure construction, and fostering green technological innovation. Moreover, the influence of urban characteristics on the carbon reduction effect of digital trade has not been sufficiently examined.

Therefore, investigating the impact of digital trade development on urban carbon emission intensity and its mechanisms holds significant practical relevance. Can developing digital trade effectively promote low-carbon urban transformation? Through what mechanisms does it operate? Does the impact of digital trade development on carbon emissions vary under different urban characteristics? To address these questions, this paper proposes the following hypotheses:

H1: Developing digital trade reduces urban carbon emission intensity.

H2: Digital infrastructure construction, service industry agglomeration, and business environment optimization mediate the relationship through which through which developing digital trade reduces urban carbon emission intensity.

To explore the impact of digital trade development on carbon emission intensity and analyze its mechanisms, we utilize panel data from 270 Chinese cities spanning 2010-2021. Following Udoka, et al. [12], we employ a Difference-in-Differences (DID) approach, treating the establishment of China's Cross-border E-commerce Comprehensive Pilot Zones as a quasi-natural experiment. We further analyze the mediating effects of digital infrastructure, service industry agglomeration, and business environment optimization on the relationship between the Pilot Zones and carbon emission intensity. The empirical results indicate: First, the establishment of Comprehensive Pilot Zones significantly reduces the level of urban carbon emission intensity, a conclusion that remains robust after multiple rigorous tests. Second, the policy effect exhibits significant heterogeneity related to location, population size, and industrial structure characteristics. The effect is most pronounced in eastern coastal regions, megacities (population >5 million), the Yangtze River Delta and Pearl River Delta urban agglomerations, and cities dominated by the tertiary industry. Third, mechanism tests confirm that the establishment of the Comprehensive Pilot Zone policy promotes low-carbon urban development through three pathways: advancing digital infrastructure construction, promoting service industry agglomeration (especially mid-to-low-end services), and optimizing the business environment.

The marginal contributions of this study are threefold: It focuses specifically on the Comprehensive Pilot Zone policy, systematically evaluating the impact of this digital trade policy on low-carbon transition at the city level. By constructing a city-level panel dataset, it deepens empirical research at the micro-level, clarifying the causal effect of the Pilot Zone policy on urban carbon intensity and providing new directions and references for subsequent research, thereby enhancing the understanding of the mechanisms through which emerging economic models contribute to environmental sustainability. It introduces novel mediating variables—digital infrastructure construction index, service industry agglomeration index, and business environment index—offering fresh perspectives on the pathways through which digital trade policies influence urban low-carbon transformation.

2 THEORETICAL MODEL

2.1 Data Sources

The core dataset consists of panel data for 270 Chinese prefecture-level cities spanning the period 2010–2021. Following Wu et al. [13], primary data was sourced from the China City Statistical Yearbook for the respective years. Supplementary data was obtained from prefecture-level city statistical yearbooks, the China Energy Statistical Yearbook, the China Industrial Statistical Yearbook, the China Agriculture Statistical Yearbook, and the China Environment Statistical Yearbook.

2.2 Research Methods

2.2.1 Model specification

The designation of Cross-border E-commerce Comprehensive Pilot Zones (CBECPZs) was granted in multiple batches across different years. To accurately assess the impact of establishing a CBECPZ on urban carbon emission intensity (CEE), this study employs a multi-period Difference-in-Differences (DID) model, drawing on the methodology of Ding, et al. [14]. The specific model is formulated as follows:

$$CEE_{it}=\alpha+\beta_1 CBEC_{it}+\beta_2 Control_{it}+\lambda_i+\mu_t+\epsilon_{it} \tag{1}$$

In the model, i and t denote city and year, respectively; CEE_{it} is the dependent variable, representing urban carbon emission intensity; $CBEC_{it}$ is the core explanatory variable, indicating the treatment status of a pilot city, specifically defined as the interaction term Time × Treat (where Treat identifies the city and Time identifies the policy implementation period); $Control_{it}$ encompasses a vector of control variables, including urbanization rate, industrial structure, population size, and service sector development level; λ_i and μ_t represent city fixed effects and year fixed effects, respectively; and ϵ_{it} is the stochastic error term.

2.3 Variable Definitions

2.3.1 Dependent variable

The dependent variable is Carbon Emission Intensity (CEE). Following Li, K. et al. [15], carbon emission intensity is calculated by dividing total carbon emissions by real GDP (2010 constant prices). This indicator incorporates both economic output and carbon emissions, effectively reflecting the synergy between regional economic growth and environmental protection. Compared to the single metric of total carbon emissions, CEE better reveals the structural emission reduction effects driven by the CBECPZ policy and its role in enhancing the quality of low-carbon economic transformation. This aligns with the policy evaluation needs of balancing development and emission reduction under China's "dual carbon" goals. Total city-level carbon emissions are derived by summing emissions generated from electricity, gas and liquefied petroleum gas consumption, transportation, and thermal energy consumption. The specific calculation method follows the approach of Wu et al. [16].

2.3.2 Core explanatory variable

The core explanatory variable is the CBECPZ establishment interaction term (CBEC). It is constructed as the product of a spatial dummy variable (Treat) indicating the CBECPZ policy implementation and a time dummy variable (Time). Treat identifies cities designated as CBECPZs. It is assigned a value of 1 if the prefecture-level city established a CBECPZ, and 0 otherwise. Time identifies the timing of the CBECPZ establishment. Following the multi-period DID approach, Time is assigned a value of 1 for city i in year t and all subsequent years after the city is designated as a CBECPZ, and 0 otherwise.

2.3.3 Control variable

Control variables are introduced to enhance the accuracy and reliability of the analysis by isolating the effect of the CBECPZ policy from other potential confounding factors that might simultaneously influence carbon emission intensity. This study selects the following control variables:①Economic Development Level (GDP): Measured by real GDP per capita (real GDP divided by the city's year-end population), taken as the natural logarithm. ②Urbanization Level (Urban): Measured by the proportion of the urban population to the total population. ③Government Intervention (Gov): Measured by the proportion of local government fiscal expenditure to GDP. ④Internet Development Level (Inter): Reflecting the state of digital infrastructure, measured by the natural logarithm of the number of internet users in each city. ⑤Infrastructure Level (Infra): Measured by road area per capita.

3 EMPIRICAL ANALYSIS

3.1 Baseline Regression

Table 1 presents the regression results assessing the impact of the Cross-Border E-commerce (CBEC) Pilot Zone policy on urban carbon intensity, with city and year fixed effects controlled. Column (1) reports the estimation results without control variables, while Column (2) incorporates them. The results consistently indicate that the implementation of the CBEC Pilot Zone policy significantly reduces carbon intensity in designated cities.

Table 1 Baseline Regression Result

	(1)	(2)
CBEC	-0.0846* (-3.12)	-0.0475* (-3.80)
GDP		-0.923*** (-18.93)
Urban		0.157 (1.11)
Gov		0.350* (2.13)
Inter		-0.00232 (-0.17)
Infra		0.00155 (1.58)
Cons	0.992* (83.28)	1.636* (5.27)
N	3 240	3218

R-squared	0.225 5	0.7088

Note: *, **,*** indicate significance at the level of 0.1%,1% and 5%, respectively, and the numbers in parentheses are standard errors.

3.2 Robustness Checks

3.2.1 Parallel trend test

The validity of the difference-in-differences (DID) model hinges on the parallel trends assumption. Following Ryan et al. [17], we confirm that the treatment and control groups exhibit similar trends in carbon intensity before the policy implementation. Employing an event-study framework inspired by Derindağ [18], we construct the following specification:

$$CEE_{it} = \theta + \sum_{k \geq -8(+)}^{k \leq 6(+)} k_{Dum}^{it} \beta_k + \mu_i + v_t + \xi_{it} \quad (2)$$

Where, Dum represents a set of dummy variables indicating the event window periods relative to policy implementation, with k = -8(+), -7, -6, ..., 5, 6(+). Using the period immediately preceding the policy implementation as the reference period for the parallel trends test, the results demonstrate that the coefficients for all pre-policy periods are statistically insignificant at the 10% level. This confirms that the parallel trends assumption holds.

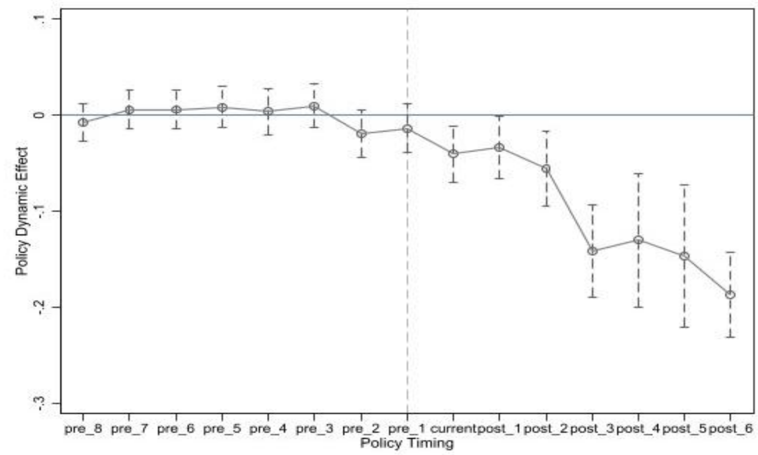


Figure 1 Parallel Trend Test Results

3.2.2 Robustness checks

The benchmark regression results in this paper may be affected by other policy shocks and other conditions, so in order to verify the reliability of the benchmark regression results, robustness tests are carried out from the following aspects:

(1) Placebo Test

To address potential omitted variable bias, we conduct placebo tests by randomly assigning treatment status across 270 cities for 500 iterations. The resulting coefficients form a normal distribution centered around zero, with no statistically significant outliers, confirming the robustness of our baseline estimates. This approach effectively rules out confounding from unobserved time-varying factors.

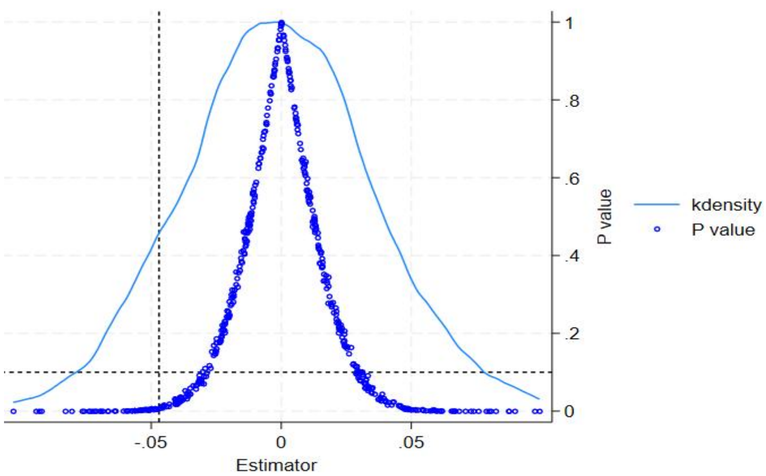


Figure 2 Placebo Test Results

(2) Controlling for Concurrent Policies
To address potential policy confounding during our study period (including "Broadband China," "Low-Carbon City", "Smart City", and "Key Air Control" initiatives), we incorporated these as additional controls in our multi-period DiD specification. The results (Table 2) demonstrate that the CBEC pilot zones maintain statistically significant carbon-reduction effects after accounting for concurrent policies, confirming the robustness of our causal identification. This suggests that while these complementary policies may influence carbon intensity through various channels, their presence does not substantially alter our primary findings regarding the CBEC zones' environmental impact.

Table 2 Controlling for Other Policy Interventions

Variable	(1)	(2)	(3)	(4)	(5)
CBEC	-0.0438***	-0.0478***	-0.0475***	-0.0480***	-0.0445***
	(-3.61)	(-3.84)	(-3.79)	(-4.01)	(-3.90)
Constant	10.3153*	10.2845***	10.2797***	10.2785*	10.3087*
	(20.58)	(19.99)	(20.06)	(20.00)	(20.52)
Broadband China	Control				Control
Low-carbon City		Control			Control
Smart City			Control		Control
Key Atmospheric Control				Control	Control
Controls	Yes	Yes	Yes	Yes	Yes
N	3206	3206	3218	3218	3206
R-squared	0.7100	0.7091	0.7088	0.7089	0.7101

Note: *, **,*** indicate significance at the level of 0.1%,1% and 5%, respectively, and the numbers in parentheses are standard errors.

3.3 PSM-DID Estimation

This paper adopts the following model to estimate the predicted probability *probit* of each sample city becoming a cross-border e-commerce comprehensive pilot zone, that is, propensity score:

$$probit(treat_i=1)=\alpha+\beta X_i+\varepsilon_i \quad (3)$$

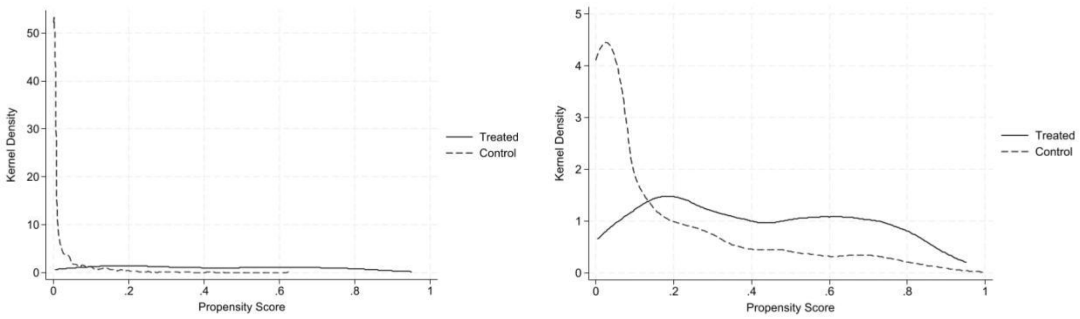
Where, $treat_i$ represents the policy variable for Cross-border E-commerce Comprehensive Pilot Zones: sample cities are assigned a value of 1 if they were designated as Cross-Border E-commerce Comprehensive Pilot Zones during 2010-2021, and 0 otherwise. X_i denotes the matching variables, including real GDP (logarithm), population size (logarithm), urbanization rate, internet user data (logarithm), and infrastructure level.
To ensure robust causal identification, we implement kernel matching (bandwidth=0.20) following established methodologies [19-20]. Balance test results (Table 2) confirm the matching quality: (1) post-matching t-tests reveal no significant mean differences in covariates (all p>0.10); (2) standardized biases decrease for all variables except population size; and (3) the negligible R^2 from the propensity score model indicates successful achievement of conditional randomness in treatment assignment. These diagnostics collectively validate our matching approach and support the conditional independence assumption underlying our analysis.
To satisfy the common support condition critical for propensity score matching [21], we conducted rigorous diagnostic tests. Figure 3 demonstrates that while pre-matching propensity score distributions showed limited overlap between treatment and control groups, post-matching distributions achieved substantial alignment, with only minimal sample loss outside the common support region. This marked improvement in covariate balance ensures our average treatment effect estimates reflect comparable subpopulations, addressing the potential subset effect concern and enhancing the validity of our causal inferences.

Table 3 Covariate Balance Test

Variable	Sample	Mean difference test			Standardization difference test	
		Treated	Untreated	T-test (p-value)	Standardization Differences	Decreasing Amplitude (%)
GDP	Unmatched	10.915	10.238	17.68(0.000)	106.1	99.0
	Matched	10.915	10.922	-0.11(0.909)	-1.1	
Urban	Unmatched	0.7214	0.5363	22.05(0.000)	140.7	99.0

	Matched	0.7214	0.7196	0.1(0.872)	1.4	
Gov	Unmatched	0.1580	0.1998	-7.17 (0.000)	-50.5	74.5
	Matched	0.1580	0.1687	-1.97 (0.049)	-12.8	
Inter	Unmatched	14.791	13.319	28.29(0.000)	190.2	98.9
	Matched	14.791	14.776	0.27 (0.791)	2.0	
Infra	Unmatched	18.909	17.543	3.05 (0.002)	19.0	24.9
	Matched	18.909	17.883	1.60 (0.109)	14.3	
Pseudo R^2	Unmatched				0.423	
	Matched				0.010	

Note: *, **,*** indicate significance at the level of 0.1%,1% and 5%, respectively, and the numbers in parentheses are standard errors.



(a) Before Matching (b) After Matching

Figure 3 Distribution of Propensity Scores Before and After Matching

After confirming that the matched sample satisfies both the conditional independence assumption and the common support condition, the average treatment effect on the treated (ATT) is estimated using the matched sample, following the method of Sun et al. [22]. The results are reported in Table 4. The coefficient is significantly negative, indicating that the CBEC pilot policy significantly reduced carbon intensity in treated cities. This finding is consistent with the baseline regression results, further supporting the robustness of the core conclusion.

Table 4 Average Treatment Effect of CBEC Pilot Policy (ATT Estimation Using Kernel Matching)

	ATT Estimate
	Carbon Intensity
Kernel Matching	-0.2524***(-3.61)
Treated Group Size	302
Control Group Size	2916
Total Sample Size	3218

Note: *, **,*** indicate significance at the level of 0.1%,1% and 5%, respectively, and the numbers in parentheses are standard errors.

3.4 Heterogeneity Analysis

3.4.1 Location heterogeneity

Due to disparities in resources, economy, and industrial structure between China's coastal and inland areas, as well as across eastern, central, western, and northeastern regions and city agglomeration, this study examines the heterogeneous effects of cross-border e-commerce pilot zones. Coastal cities exhibit stronger carbon reduction effects from these policies compared to inland cities, attributed to differences in resource endowments and economic foundations [23-24]. Regionally, the eastern region shows significant policy impacts, while central and western regions see negligible effects, and the northeastern region may even experience increased emissions due to industrial structure and economic factors [25-26]. Among major city clusters, the Pearl River Delta demonstrates notable carbon reduction benefits owing to logistics and industrial transformation advantages, whereas the Beijing-Tianjin-Hebei and Yangtze River Delta regions show no significant impact [27].

Table 5 Location Heterogeneity

	Coastal (1)	Inland (2)	Eastern (3)	Central (4)	Western (5)	Northeastern (6)
Coast×CBEC	-0.0821** (-2.84)					
Inland×CBEC		-0.0145 (-1.20)				
East×CBEC			-0.0765*** (-4.02)			
Mid×CBEC				-0.0029 (-0.17)		
West×CBEC					-0.0204 (-0.95)	
Northeast×CBEC						0.0482 (1.87)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
City Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
N	3218	3218	3218	3218	3218	3218
R-squared	0.4006	0.3984	0.4022	0.4413	0.3974	0.3967

Note: *, **,*** indicate significance at the level of 0.1%,1% and 5%, respectively, and the numbers in parentheses are standard errors.

Table 6 Urban Agglomeration Heterogeneity

	Beijing-Tianjin-Hebei Region (1)	Yangtze (2)	Pearl (3)
BTH×CBEC	-0.0220 (-1.11)		
Yangtz×CBEC		-0.109 (-1.15)	
Pearl×CBEC			-0.2556** (-2.96)
Controls	Yes	Yes	Yes
City Fixed Effects	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes
N	3218	3218	3218
R-squared	0.3973	0.3979	0.4013

Note: *, **,*** indicate significance at the level of 0.1%,1% and 5%, respectively, and the numbers in parentheses are standard errors.

3.4.2 Population size heterogeneity

Cities are classified by population: megacities (permanent population>5 million) and large cities (1-5 million). As shown in Table 7, cross-border e-commerce pilot zones significantly reduce carbon intensity in megacities but not in large cities. Megacities benefit from strong policy coordination, large consumer markets, and efficient logistics integration, which lower energy use and emissions [28]. Their technological innovation capacity and higher consumer environmental awareness also drive low-carbon supply chains [29]. In contrast, large cities lack sufficient scale for optimal resource integration, slowing low-tech adoption and process optimization, leading to weaker policy effects.

Table 7 Population Size Heterogeneity

	Megacities (1)	Large Cities (2)
Large×CBEC	-0.0676*** (-1.09)	
Medium×CBEC		0.00407 (0.27)
Controls	Yes	Yes
City Fixed Effects	Yes	Yes
Year Fixed Effects	Yes	Yes
N	3218	3218

R-squared	0.4064	0.3974

Note: *, **,*** indicate significance at the level of 0.1%,1% and 5%, respectively, and the numbers in parentheses are standard errors.

3.4.3 Industrial structure heterogeneity

Cities are classified as secondary industry-dominant (secondary sector GDP > tertiary sector) or tertiary industry-dominant (tertiary sector GDP > secondary sector). Regression results (Table 8) reveal that cross-border e-commerce pilot zones exert a stronger carbon intensity reduction effect in tertiary industry-dominant cities. This aligns with Ma [30], who highlights the synergy between industrial upgrading and e-commerce pilot policies. Tertiary-driven cities benefit more from institutional and technological innovations in these zones, facilitating structural transformation and emission reductions. Empirical evidence, such as Shanghai pilot zone, further supports this trend, as these initiatives primarily target service-sector optimization.

Table 8 Industrial Structure Heterogeneity

	Secondary industry (1)	Tertiary industry (2)
Second×CBEC	-0.0520 (-1.54)	
Third×CBEC		-0.0356** (-2.91)
Controls	Yes	Yes
City Fixed Effects	Yes	Yes
Year Fixed Effects	Yes	Yes
N	3216	3216
R-squared	0.3981	0.4010

Note: *, **,*** indicate significance at the level of 0.1%,1% and 5%, respectively, and the numbers in parentheses are standard errors.

3.5 Mechanism Analysis

Existing studies confirm that cross-border e-commerce pilot zones significantly reduce carbon intensity by facilitating digital transformation, industrial upgrading, and business environment optimization (Government Policy Documents, Year). However, the underlying mechanisms require systematic empirical examination.

Aligned with policy objectives, we hypothesize three key intermediate pathways:

(1) Digital infrastructure development - Enhancing technological penetration in traditional industries; (2) Service industry agglomeration - Promoting structural transformation toward tertiary sectors; (3) Business environment improvement - Increasing operational efficiency and green practices.

To rigorously test these mechanisms, we employ a Sobel-Goodman mediation analysis using the following model:

$$M_{it}=\beta_0+\beta_3 CBEC_{it}+\gamma X_{it}+\lambda_i+\mu_i+\varepsilon_{it} \tag{4}$$

$$\gamma_{it}=\beta_0+\beta_1 CBEC_{it}+\beta_2 M_{it}+\gamma X_{it}+\lambda_i+\mu_i+\varepsilon_{it} \tag{5}$$

The intermediate variable is replaced by digital infrastructure construction index (Diginf), service industry agglomeration index (Spec) and urban business environment index (Envir), and other variables are the same as those mentioned above.

3.5.1 Digital infrastructure construction

As a key indicator of digital economy development, digital infrastructure reflects hardware investment, technology adoption, and application depth. Following Wang et al. [31], we measure it through six indicators including IT investment and internet penetration. Regression results (Table 9) show that cross-border e-commerce pilot zones significantly improve digital infrastructure, which in turn reduces urban carbon intensity. The mediation test confirms digital infrastructure's crucial role in this relationship. Specifically, pilot zones promote digital technology applications in urban energy management, logistics networks, and industrial collaboration, thereby enhancing energy efficiency and green innovation to lower carbon emissions.

Table 9 Mechanism Analysis: Digital Infrastructure

	(1)
CBEC	-0.4771*** (-8.99)
Diginf	-5.4285*** (-12.23)
Controls	Yes
Con	1.2773*** (62.14)
City Fixed Effects	Yes
Year Fixed Effects	Yes
Sobel-Z	-10.69***

N	3240
R-squared	0.0990

Note: *, **,*** indicate significance at the level of 0.1%,1% and 5%, respectively, and the numbers in parentheses are standard errors.

3.5.2 Agglomeration of services

Following the National Bureau of Statistics (2019) classification and Gu's framework [32-33], we define production services as comprising six sectors: (1) transportation/warehousing/postal services, (2) wholesale/retail trade, (3) leasing/business services (medium-low tier), and (4) information technology, (5) finance, (6) scientific research (high-end tier) [34]. Using Han and Yang's methodology, we calculate the specialization agglomeration index (SAI) as:

$$Spec_{it}=\frac{\sum_{j=1}^{J} S_{ijt}/\sum_{i=1}^{N}\sum_{j=1}^{J} S_{ijt}}{S_{it}/\sum_{i=1}^{N} S_{it}} \tag{6}$$

Among these, S_{ijt} represents the total number of employees in each industry in city i in year t, S_{it} represents the total number of employees in each industry in city i in year t, and N represents the number of cities. The results in Table 6 demonstrate that CBEC pilot zones significantly reduce urban carbon intensity (Spec) by promoting agglomeration of producer services, particularly mid-to-low-end services (Spec_low). This sector's responsiveness stems from e-commerce-driven demand for logistics and warehousing, forcing rapid efficiency gains. In contrast, high-end services (Spec_high) show weaker agglomeration effects due to their dependence on long-term capital and knowledge accumulation. Sobel test confirm this mediating pathway, highlighting service sector agglomeration as a key mechanism linking CBEC policies to emission reductions.

Table 10 Mechanism Analysis: Service Industry Agglomeration

	(1)	(2)	(3)
CBEC	-0.7709*** (-9.53)	-0.7568*** (-9.44)	-0.9015*** (-11.15)
Spec	-0.5780*** (-10.74)		
Spec_low		-0.5540*** (-12.18)	
Spec_high			-0.2702*** (-5.94)
Controls	Yes	Yes	Yes
Con	1.4940*** (34.22)	1.4548*** (40.11)	1.2724*** (32.15)
City Fixed Effects	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes
Sobel-Z	-8.479***	-8.905***	-5.138***
N	2699	2699	2699
R-squared	0.0932	0.1037	0.0666

Note: *, **,*** indicate significance at the level of 0.1%,1% and 5%, respectively, and the numbers in parentheses are standard errors.

3.5.3 Business environment improvement

The development of cross-border e-commerce comprehensive pilot zones has prompted policy innovations targeting reducing operational costs for businesses, enhancing market access, fostering the emergence of new market players, promoting transparent and fair market rules, and creating a favorable business environment. To assess the impact of these pilot zones on the local business environment, this study uses the China City Business Credit Environment Index (Envir) published by the National Information Center as an indicator of urban business conditions. The findings indicate that improvements in the business environment have a significant negative impact on carbon intensity.

Table 11 Mechanism Mechanism Analysis: Business Environment Optimization

	(1)
CBEC	-0.3327*** (-6.67)
lnenvir	-6.3885*** (-22.68)
Controls	Yes
Con	28.2092*** (23.61)
City Fixed Effects	Yes
Year Fixed Effects	Yes

Sobel-Z	-15.06***
N	3231
R-squared	0.1871

Note: *, **,*** indicate significance at the level of 0.1%,1% and 5%, respectively, and the numbers in parentheses are standard errors.

4 CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

This study employs a DID approach with panel data from 270 Chinese cities (2010-2021) to examine the impact of CBEC Pilot Zones on carbon intensity. The results demonstrate that the policy significantly reduces urban carbon emissions, with effects varying by region and city characteristics: the reduction is more pronounced in eastern coastal areas, megacities, the Yangtze/Pearl River Deltas, and service-oriented cities, while being weaker in western regions, smaller cities, and manufacturing-dominated areas. Mechanism analysis reveals three key pathways-digital infrastructure development [35-36], service industry agglomeration (particularly mid-to-low tier services), and business environment optimization-through which the policy achieves its emission reduction effects. These findings provide empirical evidence on how digital trade policies can contribute to environmental sustainability at the urban level.

4.2 Policy Implications

Based on our findings, we propose four targeted policy measures:
First, implement regionally differentiated policies that account for developmental disparities. Coastal regions should establish low-carbon e-commerce benchmarks, while inland areas require fiscal support and technical assistance. Megacities need enhanced ecological regulation, service clusters should develop green finance, and industrial bases must accelerate clean energy adoption.
Second, prioritize digital infrastructure investment to address urban digital divides. Strategic upgrades of network capacity and green computing in underdeveloped regions will amplify the carbon-reduction effects of cross-border e-commerce policies.
Third, accelerate the green transition of mid-to-low-end services through fiscal subsidies, green credit products tied to emission performance, and consumer incentives for low-carbon services. This multi-stakeholder approach can improve sector-wide energy efficiency.
Fourth, optimize the e-commerce business environment by streamlining approvals, enhancing policy transparency, and tailoring local interventions. Innovation hubs should focus on low-carbon R&D support, while less-developed cities need foundational business climate improvements.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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VOLATILITY SPILLOVER BETWEEN HUBEI CARBON MARKET AND GREEN FINANCIAL MARKET: EVIDENCE FROM TVP-VAR-DY MODEL

Ying Huang[1*], ZheZhen Wang[2], QiHang Wang[2]
[1]*School of Foreign Languages, Wuhan City Polytechnic, Wuhan 430064, Hubei, China.*
[2]*School of Economics and Management, Wuchang Shouyi University, Wuhan 430064, Hubei, China.*
Corresponding Author: Ying Huang, Email: gracehy_wsyu@163.com

Abstracts: In the context of the global climate crisis and China's dual-carbon target, a Time-Varying Parameter Vector Autoregression-Diebold-Yilmaz (TVP-VAR-DY) model is employed to examine risk spillovers between Hubei carbon and green financial market from January 5th, 2016 to January 6th, 2025. According to the findings, Hubei's carbon-green finance system exhibits moderate and time-varying volatility spillover. Green equities predominantly function as information transmitters, whereas green bonds act as receivers, showing risk concentration within the green stock-bond nexus rather than carbon-finance linkages. Then, exogenous shocks such as trade conflict, the COVID-19 pandemic and carbon policy adjustments amplify cross-market spillover intensity. These findings elucidate risk transmission mechanisms in climate-aligned markets, provide investors with portfolio rebalancing insights and enhance regulators' systemic risk monitoring capabilities.
Keywords: Hubei carbon market; Green bond market; Green stock market; Volatility spillover effects; TVP-VAR-DY model

1 INTRODUCTION

Carbon market and green financial market are key market-based solutions designed to reduce greenhouse gas emissions, operating as complementary mechanisms in facilitating low-carbon economic transitions. As a designated pilot region for both carbon emission trading and green financial innovation in China, Hubei Province presents a critical case for examining the interplay between these two markets. Analysing their intrinsic linkages and spillover effects could not only foster synergistic development through policy interoperability but also inform risk mitigation strategies against cross-market contagion. Current academic investigations mainly concentrate on the following aspects.

1.1 Interdependence between Carbon and Green Financial Markets

Carbon assets exhibit inherent financial attributes, demonstrating time-varying correlations with energy, traditional financial, and commodity markets [1-3]. As green finance matures globally, international studies have focused on the EU Emissions Trading System (ETS), revealing significant bidirectional spillover effects among carbon allowances, green bonds and green stocks, with green financial products serving as effective hedges against carbon price volatility [4-5]. Emerging studies in China suggest time-varying spillovers between domestic carbon markets and green financial instruments [6-7]. Carbon-green bond market linkages surpass those with green equities [8], while short-term risk spillovers dominate long-term interactions [9].

1.2 Policy Synergy in Hubei's Carbon-Green Financial Ecosystem

As China's pioneering carbon market pilot, Hubei Province has institutionalized a distinctive "carbon market–green finance" coupling mechanism. Its tripartite "Carbon Market + Carbon Finance + Inclusive Carbon System" framework leverages innovative instruments like carbon asset pledged loans to amplify green industrial investments, establishing replicable policy templates for regional decarbonization [10]. Academic consensus highlights Hubei's evolving governance model. Lin and Cao conceptualize a "core-dual wings" strategy, positioning the carbon market as the nexus while expanding green bonds and low-carbon industry funds to optimize capital allocation to realize green transformation [11]. Since May 2024, Hubei's "Electricity- Carbon-Finance" tri-market synergy mechanism represents a groundbreaking advancement in carbon finance, enabling cross-market pricing signals and risk-sharing [12].
Current research results have three limitations. First, predominant unilateral analysis of carbon or green financial markets neglect bidirectional interaction mechanisms and coordinated governance strategies. Second, excessive focus on the EU carbon market, overshadows empirical investigations into China's regional pilot systems, particularly Hubei's institutional innovations. Third, static spillover models inadequately capture nonlinear, time-changing interdependencies in emerging markets. Thus, we construct a TVP-VAR-DY model to quantify real-time risk transmission between Hubei carbon market and green financial market by utilizing high-frequency trading data, and explore risk monitoring strategies for both investors and regulators.

2 METHODOLOGY AND DATA

2.1 Construction of TVP-VAR-DY Spillover Index Model

Diebold and Yilmaz introduced the spillover index methodology (DY model), which employs the forecast error variance decomposition (FEVD) within a vector autoregressive (VAR) framework [13-15]. This approach quantifies spillover mechanisms across markets through both static spillover index tables and dynamic spillover index graphs. Compared to traditional spillover analysis methods, the DY framework offers three key advantages. First, it eliminates the dependence of results on subjective selection of VAR lag orders. Second, it quantifies both the intensity and directional pathways of information spillovers among multiple variables, enabling the identification of net spillover transmitters and the roles of different assets in market information transmission. Third, when integrated with a rolling window technique, the model generates a time-varying spillover index, capturing evolving spillover effects in response to market shocks or structural changes.

The construction of a TVP-VAR-DY model can be divided into three steps as follows.

First, construct the VAR model.

Construct the following p-th order VAR model for the returns of N markets.

$$Y_t=\sum_{i=1}^{p} \varphi_i\, Y_{t-i}+\varepsilon_t \tag{1}$$

Where Y_t is the N-dimensional column vector of market returns, φ_i is the N×N dimensional coefficient matrix and ε_t is the N-dimensional column vector of random disturbances, satisfying the basic assumptions of no serial correlation, zero mean, and independent and identical distribution. Σ is the matrix of autoregressive coefficients at time t=1, …, T. Then, the moving average form of VAR(p) is obtained as follows.

$$Y_t=\sum_{i=1}^{\infty} A_i\, \varepsilon_{t-i} \tag{2}$$

$$A_i=\phi_1 A_{i-1}+\phi_2 A_{i-2}+\cdots+\phi_p A_{i-p} \tag{3}$$

where Equation (2) is the moving average form of VAR(p) and A_0 is the N×N unit matrix. When i<0, A_i=0, when i>0, A_i obeys the recursive form of Equation (3).

Second, the generalised variance decomposition is used to deal with the shocks in the predicted residual terms.

In order to make the variance decomposition unaffected by the ordering of variables, the forward H-step FEVD is considered, and the FEVD matrix can be obtained as follows.

$$\theta_{i\leftarrow j}^{H}=\frac{\sigma_{ii}^{-1}\sum_{h=0}^{H}\left(e_i^{'}A_h\Sigma e_j\right)^2}{\sum_{h=0}^{H}\left(e_i^{'}A_h\Sigma A_h e_j\right)} \tag{4}$$

where Equation (4) represents the proportion of forecast error of the ith market return that comes from the jth market return, Σ is the covariance matrix of the error ε vector, and σ_{ii} is the sequence of standard errors of ε. e_i is an N-dimensional selection vector whose ith element is 1, and the rest of the elements are 0. For the variable $\theta_{i\leftarrow j}^{H}$, the sum of the contributions of the other variables to its prediction error variance is not equal to 1. Thus, it is standardized as follows.

$$\bar{\theta}_{i\leftarrow j}^{H}=\frac{\theta_{i\leftarrow j}^{H}}{\sum_{j=1}^{N}\theta_{i\leftarrow j}^{H}} \tag{5}$$

$$\sum_{i,j=1}^{N}\theta_{i\leftarrow j}^{H}=N,\quad \sum_{j=1}^{N}\theta_{i\leftarrow j}^{H}=1 \tag{6}$$

Thus, the pairwise spillover relationship of market I to market j can be obtained under step *H*.

Third, the total connectedness index (TCI), directional connectedness index, net spillover index, and net pairwise directional connectedness (NPDC) are calculated.

The TCI, which represents the contribution of mutual spillovers among N variables to the total forecast error variance, is averaged by summing the off-diagonal elements of the forecast error variance decomposition matrix as follows.

$$\begin{aligned} S^{*}(H)&=100\times\frac{\sum_{i,j=1,i\neq j}^{N}\theta_{ij}^{*\,H}(H)}{\sum_{i,j}^{N}\tilde{\theta}_{ij}^{*\,H}(H)}\\ &=100\times\frac{1}{N}\times\sum_{i,j=1,i\neq j}^{N}\tilde{\theta}_{ij}^{*\,H}(H) \end{aligned} \tag{7}$$

The directional spillover index is decomposed into spill-out index and spill-in index. The spill-out index measures the directional spillover from market i to all other variables, reflecting its outward influence, while the spill-in index quantifies the directional spillover into market i from all other variables, capturing its susceptibility to external shocks. They are as follows.

$$\begin{aligned} S_{to}&=100\times\frac{\sum_{j=1,i\neq j}^{N}\theta_{ij}^{*\,H}(H)}{\sum_{i,j=1}^{N}\tilde{\theta}_{ij}^{*\,H}(H)}\\ &=100\times\frac{1}{N}\times\sum_{j=1,i\neq j}^{N}\tilde{\theta}_{ij}^{*\,H}(H) \end{aligned} \tag{8}$$

$$\begin{aligned} S_{from}&=100\times\frac{\sum_{j=1,i\neq j}^{N}\theta_{ji}^{*\,H}(H)}{\sum_{i,j=1}^{N}\tilde{\theta}_{ji}^{*\,H}(H)}\\ &=100\times\frac{1}{N}\times\sum_{j=1,i\neq j}^{N}\tilde{\theta}_{ji}^{*\,H}(H) \end{aligned} \tag{9}$$

The net spillover index, which measures the size of market's net spillover to all other markets, is as follows.

$$S_{net}=S_{to}-S_{from} \tag{10}$$

The net pairwise directional connectedness (NPDC) is given by:

$$NPDC_{ij}(H)=100\times(\tilde{\theta}_{ji}^{*\ H}(H)-\tilde{\theta}_{ij}^{*\ H}(H)) \tag{11}$$

2.2 Data Selection and Pre-Processing

As the largest and most actively traded pilot carbon market in China, Hubei ETS provides an exemplary case for investigating the interplay between regional carbon market and green financial instruments. This study employs the closing price of Hubei carbon allowance (hbea) as the primary indicator for Hubei carbon market. For analyzing green finance components, it distinguishes between green bonds and green equities markets. While provincial-level price data for green instruments remains limited, this study utilizes two national proxies of China Bond-China Green Bond Wealth Index (gb) and CSI 300 Green Leading Stock Index (gs). This methodological choice aligns with the assumption of uniformity in green financial policies, given that national indices comprehensively encompass major Hubei-based green enterprises and reflect policy coordination effects.

The dataset for each market was sourced from the Wind database, spanning the period from January 5th, 2016 to January 6th, 2025. All variables utilize daily closing prices, with non-synchronous trading days across markets excluded, yielding a total of 2,126 observations. This sample period strategically covers the maturation of Hubei carbon market pilots (2016–2020) and the institutional consolidation following the national carbon market's formal launch (2021–2025). It can comprehensively reflect the market linkage dynamics under "dual-carbon" objectives.

In this paper, we calculate the logarithmic returns for each market using daily closing prices, defined as $r_t = 100 \times \ln(p_{i,t}/p_{i,t-1})$, where p_t denotes the closing price at time t. Table 1 summarizes the descriptive statistics of the market returns.

Table 1 Results of Descriptive Statistics

Yield variable	Mean (%)	Maximum value (%)	Minimum value (%)	Standard deviation	ADF
hbea	0.0262916	11.08045	-19.72102	2.828749	-44.486***
gb	0.0187945	0.8008372	-0.8183246	0.0794773	-29.159***
gs	-0.0044412	10.32083	-10.32339	1.656642	-46.319***

Note: ***, **, * represent statistical significance at the 1%, 5% and 10% level respectively.

First, the mean value of the carbon yield is higher and the standard deviation are larger than other markets, which indicates that Hubei carbon market is characterized by higher yield and high volatility. This volatility pattern highlights the practical significance of studying cross-market spillover effects for carbon market risk management. Second, the green bond market exhibits remarkably low volatility, with its standard deviation approaching zero. This characteristic suggests the green bond has the nature of a hedge asset. Finally, the time series of market yields are found to be stable by Augmented Dickey-Fuller (ADF) test, and can be studied by DY spillover index model for this study.

3 EMPIRICAL ANALYSIS ON MODEL ESTIMATION RESULTS

3.1 Static Time-Domain Spillover Analysis

The TVP-VAR-DY model is used to examine total spillover effects in the static time-domain. Following the Akaike Information Criterion (AIC) and Schwarz Criterion (SC) criteria, the optimal lag order for the autoregressive process is identified as 4, and the Generalized Forecast Error Variance Decomposition (GFEVD) horizon is standardized to 10 periods. Using Equations (7)-(10), total connectedness index (TCI), directional spillover indices (FROM, TO), and net spillover index (NET) are calculated, as shown in Table 2.

The results show a TCI of 4.24% across the integrated system, revealing intricate systemic spillover relationships among Hubei carbon market, green bond market, and green stock market. Directional spillover analysis indicates that Hubei Carbon Emission Allowance (hbea) market receives 1.88% spillovers from external markets, while green bonds (gb) and green stocks (gs) absorb 3.76% and 2.84% respectively. Conversely, these markets transmit spillover effects of 2.06%, 2.52%, and 3.89% to other markets respectively. Significantly, the green stock market emerges as the dominant net transmitter of information flows, primarily driven by their sensitivity to climate policy changes such as subsidies, carbon taxes and to market sentiment fluctuations. It is the first to capture market expectations toward the green economy and transmit signals to other markets. Carbon market exhibits a low-level positive net spillover, where price fluctuations directly impact high-carbon firms' emission costs and profit expectations. Rising carbon prices may force these firms to increase investments in emission reduction or accelerate green technology adoption, thereby influencing both green stock and green bond markets. Green bond market demonstrates a negative net spillover index, functioning mainly as information receivers. This reflects their fixed-income characteristics, pricing mechanisms anchored to traditional bond markets, lower liquidity, and reduced sensitivity to short-term policy and stock market volatility. During risk events, investors often reallocate capital from volatile carbon or equity markets to relatively stable green bonds, resulting in passive spillover reception.

Table 2 Total Static Spillover Indices

Variable	hbea	gb	gs	Directional spillover index (FROM)
hbea	98.12	0.89	0.98	1.88
gb	0.85	96.24	2.90	3.76
gs	1.21	1.63	97.16	2.84
Directional spillover index (TO)	2.06	2.52	3.89	8.47
Net spillover index (NET)	0.19	-1.24	1.05	
Gross connectedness index (TCI)				4.24

3.2 Dynamic Spillover Analysis

Since the static spillover indices fail to capture time-varying interactions, the rolling-window approach with a 200-day window, 10-step forecast horizon reveals evolving spillover dynamics between Hubei carbon market and green financial market. Figures 1 and 2 present the dynamic total spillover index and dynamic net spillover index, respectively.

3.2.1 Dynamic total spillover analysis

Figure 1 illustrates significant time-varying spillover effects between Hubei carbon market and green financial market over the sample period. From 2018 to 2019, heightened systemic risks driven by macroeconomic shocks such as U.S.-China trade tensions, continuous RMB depreciation, and stock market volatility propelled the TCI upward, sustaining it at high levels. In 2020, the outbreak and rapid spread of COVID-19 in Wuhan triggered widespread market panic, amplifying cross-market spillovers and driving the TCI to its peak. In early 2021, the index began to decline, benefiting from China's effective pandemic containment, coupled with economic stabilization and improved investor confidence. In July 2021, the launch of China's national carbon emissions trading market (NCETM) catalyzed low-carbon transition investments. This structural shift intensified carbon-green financial market linkages, driving up the TCI. In January 2024, Chinese Certified Emission Reduction (CCER) was restarted, complementing the carbon pricing mechanism. In April, the State Council formally approved the inclusion of the steel, cement, and aluminium smelting industries into NCETM. In May, implementation of the Interim Regulations on Carbon Emissions Trading bolstered market confidence, diversified participants and financial instruments, and improved cross-market liquidity and price discovery. These reforms accelerated carbon-green financial market integration, elevating spillover levels to new highs. Through the above analysis, it is found that special events such as trade frictions, the COVID-19 pandemic, and intensive implementation of carbon market systems have strengthened the correlation between Hubei carbon market and the green financial market.

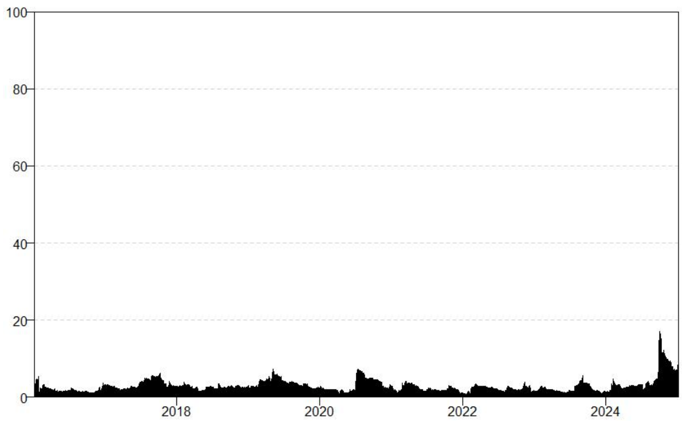

Figure 1 Dynamic Total Connectedness Index

3.2.2 Dynamic net spillover analysis

In Figure 2, during the sample period, the dynamic net spillover indices of Hubei carbon market, green bond and green stock markets exhibited significant time-varying features, fluctuating within a 10% range. First, the absolute value of net spillover index in Hubei carbon market exhibits limited variations, indicating a generally low net spillover level. However, distinct cyclical patterns emerge as compliance deadlines approach. During these periods, trading activity surges, driving a sharp rise in transaction volumes and transforming the carbon market into a net transmitter. The outbreak of COVID-19 pandemic in early 2020 triggered a marked decline in carbon market activity, showing its high sensitivity to external shocks. Second, green bond market function as net recipients of spillover effects, absorbing shocks from interconnected markets, while green stock market act as net transmitter. Both have higher net spillover levels than the carbon market. The spillover fluctuations in green bond and stock market intensified under major events including US-China trade tensions, the COVID-19 pandemic and intensive rollouts of carbon market regulations.

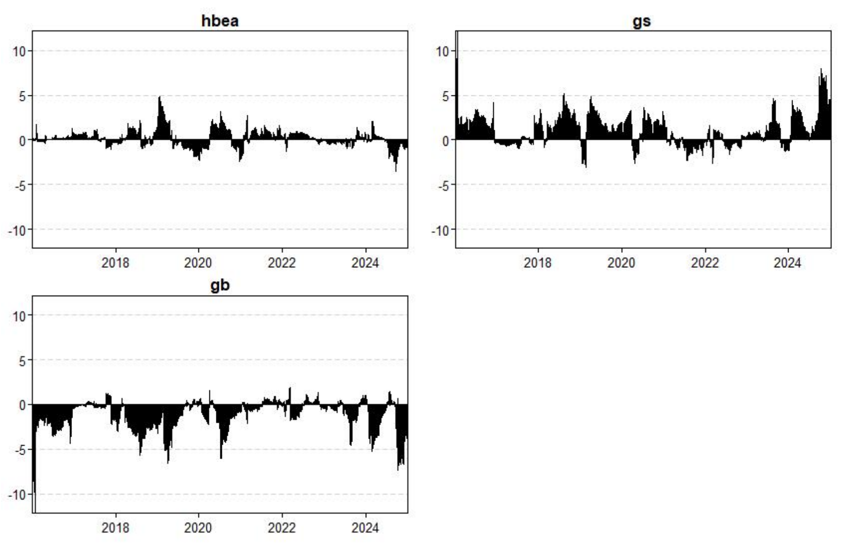

Figure 2 Dynamic Net Spillover Indices of Various Markets

3.3 Volatility Spillover Network Analysis

Understanding spillover network paths enables investors, enterprises and policymakers to better anticipate market fluctuations and optimize decision-making. Based on Equation (11) of the TVP-VAR-DY model, we derive the NPDC indices and employ complex network analysis to construct a spillover network. Figure 3 shows the dynamic NPDC indices across markets, while Figure 4 illustrates the time-domain spillover network for the “carbon-green bond-green stock” system, revealing transmission pathways between markets. The direction and thickness of connecting lines respectively signify spillover directions and intensities. Risk transmission follows a closed-loop spillover pathway of “green stocks → green bonds → carbon market → green stocks”, reflecting a transmission mechanism where the stock market reflects corporate expectations for green technologies, which subsequently affects green bond issuance costs, and ultimately transmits to carbon allowance demand via green financing projects. The green stock market predominantly acts as an information transmitter, while the green bond market serves as a net receiver. The volatility spillover level between the green stock and green bond markets is significantly high, whereas the carbon market exhibits weaker interconnectivity with both green financial markets (Figures 3 and 4). This disparity stems from the nascent stage of the Hubei carbon market, which currently lacks derivative instruments such as carbon futures. Consequently, its price discovery mechanism remains underdeveloped, and its pricing efficiency requires enhancement. Looking ahead, as carbon financial derivatives develop and the green financial system becomes more integrated, the connectedness among Hubei carbon market, green bond and green stock markets is expected to strengthen over time.

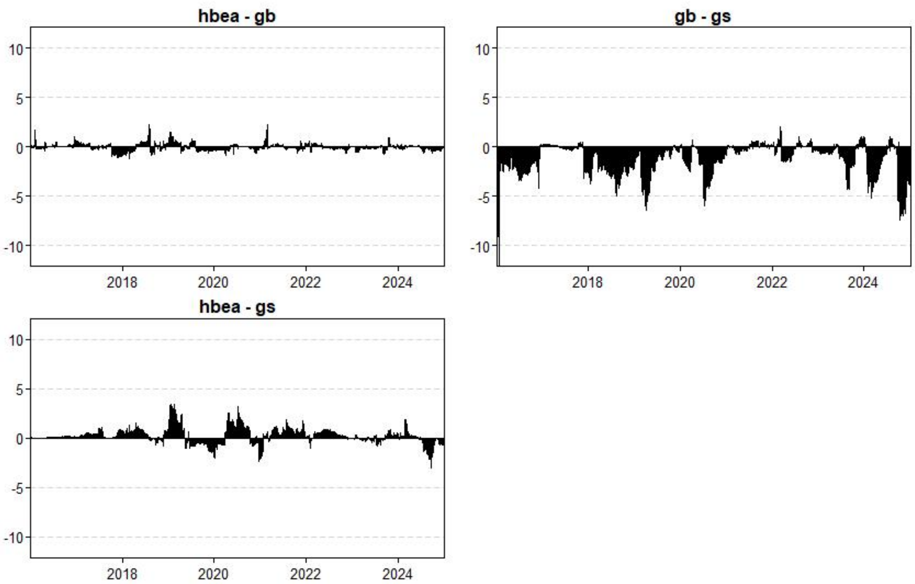

Figure 3 Dynamic NPDC Indices of Various Markets

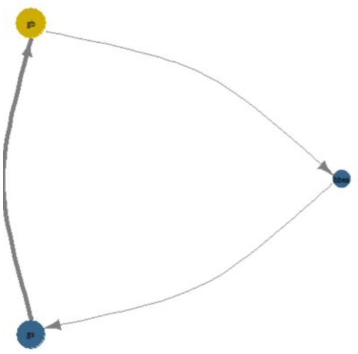

Figure 4 Time-Domain Spillover Network

4 CONCLUSIONS

Based on a TVP-VAR-DY model, this study has examined the dynamic spillover effects between Hubei carbon market and green financial markets. The findings reveal the following conclusions.

First, there is a complex systematic spillover relationship among Hubei carbon market, green bond and green stock markets, with an average total spillover index of 4.24% across the sample period. This indicates moderate but persistent interconnectedness within the "Carbon-Green Bond-Green Stock" system.

Second, both gross and net spillover indices exhibit significant time-varying characteristics. Gross spillover analysis reveals the green stock market predominantly acts as an information transmitter, while the green bond market serves as an information receiver. Net spillover analysis shows the green stock and carbon markets as persistent net spillover transmitters, contrasted with the green bond market as a net receiver. Therefore, investors should adapt portfolio allocations dynamically based on differentiated green asset-carbon market linkages, policy adjustments and external shocks.

Third, external shocks including trade conflicts, the COVID-19 pandemic, and regulatory reforms in carbon market systems substantially amplified cross-market correlations. Therefore, Hubei government should develop cross-market risk warning mechanisms to avoid systemic spillovers and adopt forward-looking policies to reduce market uncertainties. In addition, carbon-linked financial instruments such as carbon futures and carbon options should be innovated to stabilize market expectations under policy shocks.

Finally, the risk contagion follows a closed-loop pathway of "green stocks → green bonds → carbon market → green stocks". Green stocks act as the risk source, while the carbon market serves as a feedback amplifier. Notably, spillover effects concentrate between green bonds and stocks, with weaker direct linkages to the carbon market. As low-carbon transition policies intensify, interconnectivity between carbon market and green finance strengthens. Thus, policy design should prioritize leveraging the differentiated linkages between Hubei carbon market and green financial market to maximize their synergy and complementarity.

COMPETING INTERESTS

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METHODS AND COUNTERMEASURES OF STORAGE AND SAFETY MANAGEMENT FOR HAZARDOUS CHEMICALS IN UNIVERSITIES

ZhongGuo Mu*, HongYu Yang, XueLian Bai, WenBin Dong
Department of Underwater Weapon and Chemical Defense, Dalian Naval Academy, Dalian 116018, Liaoning, China.
Corresponding Author: ZhongGuo Mu, Email: muzhongguo2022@163.com

Abstract: In response to the storage and safety management requirements of hazardous chemicals. It is proposed that in order to avoid safety accidents, universities should start form the construction of storage environment, safety management system, waste disposal, personnel capacity and quality,safety management informatization, and emergency plan formulation to improve the storage,use, and safety management of hazardous chemicals. The methods and countermeasures proposed can provide guidance and reference for universities to achieve the safe use and management of hazardous chemicals. It is of great significance for the construction and development of university laboratories.
Keywords: University; Hazardous chemicals; Storage environment; Safety management;Method and countermeasures

1 INTRODUCTION

In the daily teaching and research work of universities, The hazardous chemicals is often used. Unlike general chemical reagents, hazardous chemicals have characteristics such as toxicity, corrosion, explosion, combustion, and combustion assistance, and their types are diverse and their properties vary greatly[1-2]. Once stored improperly or safety management problems arise, serious accidents can be causedand pose potential hazards to human health, facilities, and the environment. For example, in 2016, three graduate students from a university in Shanghai were involved in an experiment to synthesize graphene oxide. Due to violating safety management principles and operating in violation of regulations, an explosion accident occurred, one graduate student sustained minor injuries and two graduate students sufferded from serious injuries due to accident. These tragic accidents have profoundly revealed the need for unremitting efforts in the storage and safety management of hazardous chemicals. To ensure the maximum reduction of the probability of safety accidents. At present, although universities attach great importance to the storage and safety management of hazardous chemicals, there are still certain problems and deficiencies. To further improve the level of storage and safety management, it is necessary to start from these issues, pursue scientific innovation in stable development, and explore the best methods and countermeasures for the storage and safety management of hazardous chemicals. This article conducts preliminary research on this topic, and the research results can provide theoretical guidance and reference for universities to do a good job in the storage and safety management of hazardous chemicals.

2 PROBLEMS IN STORAGE AND SAFETY MNAGEMENT OF HAZARDOUS CHEMICALS

2.1 The Environment and Equipment do not Meet the Storage Requirements

At present, there is still a certain gap between the construction materials and structural layout of hazardous chemical storage sites in some universities and the requirements of construction standards. The building materials and structural layout are not significantly different from other building facilities. There are deficiencies in explosion prevention, earthquake resistance, waterproofing, and fire prevention capabilities, and the resistance to natural disasters and fire accidents is poor. Once an accident occurs, it is easy to cause serious damage to the storage site, leading to safety accidents; In terms of the construction of safety supporting facilities, although ventilation equipment, air conditioning systems and other ventilation and purification facilities are installed in the storage area, the main way to eliminate toxic and harmful gases in the storage environment is through natural ventilation and local ventilation. There are problems with low ventilation frequency and limited scope of action, making it difficult to ensure the complete evacuation of polluted gases in the storage area. Moreover, most storage facilities do not have a micro overpressure environment, making it difficult to control the potential harm caused by toxic and harmful gases seeping into the external enviroment through gaps in doors and windows. In terms of the configuration of safety monitoring facilities, there is a lack of environmental detection instruments and temperature and humidity control devices. When the concentration of toxic and harmful gases in the storage area exceeds the standard or the temperature (humidity) is too high, warnings cannot be issued, resulting in personnel being unable to realize the existence of potential dangers and increasing safety hazards in accidents.

2.2 High Cost and Untimely Disposal of Hazardous Chemicals Waste

At present, most universities mainly rely on local relevant disposal institutions for waste disposal. This approach not only costs a lot, but also has strict regulations on the processing capacity of disposal institutions, which means that waste hazardous chemicals can only be disposed of by institutions after reaching a certain processing quantity. As a result, waste hazardous chemicals are stored in storage sites for a long time and cannot be processed in a timely and proper manner.

2.3 The ability and quality of management personnel need to be improved

At present, although universities have formulated strict safety management regulations and systems for hazardous chemicals, there are still some problems and shortcomings. Specifically, the existing regulations and systems only emphasize precautions and behavioral rules, and do not emphasize enough on the necessary abilities and qualities of personnel in the management of hazardous chemicals. If this issue is not resolved, it will limit the improvement of the level of chemical hazardous material safety management.

2.4 The Level of Information Management for Hazardous Chemicals Needs to be Further Improved

At present, most universities have invested a lot of material and financial resources in developing information management systems to manage hazardous chemicals. However, the functions of the management system are somewhat limited, only recording data information such as the storage location, quantity, and inbound/outbound status of hazardous chemicals. There are shortcomings in information acquisition, resource sharing, and auxiliary safety management, and the advantages of information technology in safety management have not been fully reflected.

2.5 The Emergency Response Plan for Accidents is not Detailed and Comprehensive Enough

In response to possible incidents and accidents related to hazardous chemicals, universities have developed emergency response plans for accidents. However, in terms of content, most plans are more similar to accident emergency response methods and measures, and fail to strictly develop accident emergency response plans from the aspects of disposal content, organizational responsibilities, personnel strength, task division, disposal resource allocation, and emergency action methods, resulting in deficiencies in the guidance, comprehensiveness, and practicality of the plans.

3 STORAGE AND SAFETY MANAGEMENT STRATEGIES FOR HAZARDOUS CHEMICALS

3.1 Improve the Environmental Construction and Safety Monitoring Level of Storage Facilities

For storage facilities, in terms of material selection, concrete and lightweight steel should be chosen as building structural materials. According to national standards, materials with fire-resistant, explosion-proof, and anti-corrosion properties such as glass magnesium board, fireproof board, silicate board, fiber cement board, and galvanized steel composite fiber cement board should be selected as panel materials[3]. Door, window, and floor materials should meet the requirements of fire prevention, anti-static, and anti-corrosion. Door and window glass should be tempered glass to meet the safety storage requirements of hazardous chemical warehouses. In terms of structural layout, multiple independent rooms should be built to classify and place hazardous chemicals, avoiding as much as possible the influence and reaction of volatile substances caused by the mixing of multiple hazardous materials, which can lead to accidents. Reasonable construction of structural columns and rings should be carried out, and the impact of accidents and explosions should be reduced by scientifically arranging side windows[4]. In terms of air conditioning and ventilation equipment, direct current air conditioning systems should be chosen as much as possible, which have the advantages of not recycling contaminated air in the warehouse, good safety and stability [5]. Comprehensive ventilation systems should be selected as much as possible for ventilation and purification, and micro overpressure regulation and control technology should be introduced to prevent toxic and harmful gases from entering the external environment through door and window gaps and causing harmful pollution.

In terms of security monitoring of storage facilities, infrared alarm devices and multi screen monitoring systems should be installed to timely understand the activities and movements of personnel near the storage site, as well as the storage status of hazardous chemicals, through rigorous and multi-directional automatic monitoring, in order to avoid theft, damage, and accidents. To effectively control the temperature and humidity changes in the storage area and monitor whether the concentration of harmful gases exceeds the standard, automatic temperature monitoring devices and toxic and harmful gas detection devices should be installed. The automatic temperature monitoring device can be interlocked with the air conditioning system for control[6]. When the temperature and humidity in the storage area exceed the standard, the automatic temperature monitoring device will send an indication to the air conditioning system. After receiving the indication, the air conditioning system will automatically adjust the indoor temperature to the specified value; When the air conditioning system encounters abnormal conditions and cannot regulate temperature, the automatic temperature monitoring device will issue an alarm prompt. Considering that universities have winter and summer vacations, there may be situations where personnel are not present. Therefore, the security monitoring system can be linked with the mobile phones of security supervisors, so that in case of any unexpected situations, they can be promptly informed for emergency response.

3.2 Disposal of Waste through a Combination of Self Disposal and Specialized Disposal

Chemical hazardous waste has a strong toxic effect. In order to avoid endangering people's health and affecting the environment, it can be disposed of by local institutions authorized by the state. untreated chemical toxins are strictly prohibited from being discarded or dumped [7]. Given that there are strict regulations on the quantity of hazardous chemical waste to be disposed of through professional handling institution, it is recommended to adopt a combination of self disposal and professional handling to handle hazardous chemical waste. Universities can construct small-scale chemical hazardous material disposal facilities to self destruct and dispose of waste materials that are less difficult to dispose of and in smaller quantities. The disposal device should include a reaction chamber and a waste liquid recovery device. After reaction treatment, the waste is converted into non-toxic substances and discharged into the waste liquid recovery device to achieve harmless treatment of the waste. To ensure the safety of disposal, relevant operating procedures and safety disposal plans should be formulated. The disposal personnel should adopt strict protection and operate according to the regulations. Once an accident occurs, it should be immediately disposed of according to the plan, thus achieving the maximum avoidance of accidents. For some difficult to dispose of and large quantities of waste, it should be sealed and stored. When it meets the requirements of outsourcing disposal, it should be handed over to the outsourcing unit for disposal. By combining self destruction with specialized agency destruction, not only can hazardous chemical waste be disposed of in a timely manner, reducing safety hazards, but it can also save a significant amount of disposal costs. Effectively solve the problem of difficult disposal of hazardous chemical waste.

3.3 Strict Safety Management, Improving the Professional Ability and Quality of Management Personnel

According to the principle of "understanding in place, leadership in place, system in place, and responsibility in place", strengthen the safety management of hazardous chemicals, and ensure that there are rules to follow and regulations to be followed. Establish a regular inspection system to conduct regular checks on the types, quantities, and storage status of hazardous chemicals, in order to promptly identify storage issues and safety hazards and prevent accidents from occurring before they occur; Strengthen the safety management of experimental personnel, requiring them to be familiar with the properties, characteristics, and emergency response methods of storing hazardous chemicals, proficient in the operation methods and regulations of various experimental instruments and equipment, and strictly follow the reaction conditions for experimental operations to prevent accidents caused by illegal operations[8]. Strengthen safety inspections of chemical hazardous material warehouses. For chemical hazardous materials with unstable properties and easy decomposition and deterioration, dedicated personnel should be arranged to conduct regular performance inspections and keep relevant records. Intensify training efforts for management personnel to enhance their abilities and qualities. By inviting experts to give lectures and regular training, the business ability and quality of management personnel can be improved, and the possibility of chemical hazardous material accidents caused by human factors can be minimized to the greatest extent possible.

3.4 Strengthen the Design of Information Security Management and Promote Information Exchange and Sharing

Currently The chemical hazardous materials management software used in universities basically meets the daily management requirements in terms of data processing, but there is still significant room for improvement in assistant decision-making management. We should strengthen information technology design, upgrade and transform existing chemical hazardous material management software, and improve its auxiliary decision-making function. It can be achieved by adding knowledge of chemical hazard management and emergency response database modules. Through these modules, not only can knowledge about the physical and chemical properties, toxic characteristics, and protective measures of hazardous chemicals be obtained, but also relevant regulations and standards for chemical hazard safety management can be learned, and the principles and methods for handling typical chemical hazard accidents can be understood. Through upgrading and transformation, the safety management system is linked with the temperature control device, toxic and harmful substance detection device, and monitoring alarm device of the storage site. Personnel can always understand the temperature (humidity) changes, whether the concentration of toxic and harmful substances exceeds the standard, and whether there are any abnormal situations in the storage site through the safety management system. Thus, the implementation of a safety management system not only records the types, quantities, and storage conditions of hazardous chemicals, but also provides information support for personnel to assist in safety management, achieving the goal of fully utilizing information technology to manage hazardous chemicals. Strengthen information exchange and sharing between universities and relevant local institutions in the management of chemical hazardous materials safety. Through information exchange, learn from each other's strengths and weaknesses, draw on experience, and provide reference and guidance for further improving the level of safety management.

3.5 Improve the Scientific, Practical, and Comprehensive Nature of Emergency Response Plans

To improve the scientific, practical, and comprehensive nature of emergency response plans. Based on the types of hazardous chemicals stored, the possible types and characteristics of accidents should be analyzed, and an emergency response plan should be developed from the aspects of formulation basis, organizational structure, division of responsibilities, disposal guarantee, and emergency response procedures and methods. In terms of organizational structure and division of responsibilities, in addition to the unit at the same level, it is also necessary to clarify the higher-level leadership department and organizational structure to ensure that in the event of an accident, the unit at the same level can quickly report the situation to the higher-level department and complete emergency response under its leadership; In terms of disposal support, the types and quantities of various disposal equipment such as protection, firefighting, decontamination, and first aid should be clearly defined; In terms of emergency response methods and procedures, the timing, principles, procedures, and measures should be clearly defined to ensure the scientific and rational nature of the contingency plan. After the completion of the contingency plan, relevant departments and experts in the field must be hired to conduct a strict review, confirm its reasonableness, and make modifications and improvements before it can be used to guide emergency response to chemical hazardous material accidents. It is necessary to conduct an effectiveness test on the emergency response plan to ensure its practicality and reliability. It can be combined with the plan to organize personnel for accident emergency response training and drills. Through training and drills, potential problems and deficiencies in the actual application of the plan can be identified, and the plan can be adjusted and improved to ensure that the emergency plan can scientifically and efficiently guide the emergency response of chemical hazardous material accidents.

4 CONCLUSION

As the top priority in safety management, universities must make great efforts to do a good job in the storage and safety management of hazardous chemicals. Only by constantly thinking about the construction of conditions and strengthening management and disposal, and constantly improving and innovating, can the probability of accidents be minimized. To this end, the following methods and countermeasures can be adopted:

a. In terms of storage condition construction, ensure that the building materials have strong explosion-proof and seismic resistance, and that the panel, door, window, and floor materials meet the standards of fire prevention, corrosion resistance, and anti-static. Use DC air conditioning systems and micro overpressure technology to achieve comprehensive ventilation purification and pollutant leakage; By closely monitoring multiple parties, theft incidents and accidents can be avoided. Through automatic temperature and humidity control devices linked to the air conditioning system, abnormal problems can be avoided;

b. By combining self disposal with specialized disposal, the disposal of hazardous chemical waste can save disposal costs and avoid the accumulation of large amounts of waste, which may cause safety issues;

c. Implement safety management for hazardous chemicals based on the four in place principle, implement a regular inspection system, strengthen the safety management of laboratory personnel, and enhance the safety inspection of hazardous chemicals with poor stability. By teaching with experts and conducting regular training, we aim to enhance the abilities and qualities of management personnel;

d. Strengthen the auxiliary decision-making function of the information security management system, and achieve information linkage between the security management system and the temperature control and detection devices in the storage area. Strengthen information exchange and sharing among universities and between universities and relevant local departments;

e. Improve the scientific nature , practicality, and comprehensiveness of emergency response plans. Once the plan is formulated, it must be reviewed by experts and tested for effectiveness through drills before it can be used to guide emergency response to chemical hazardous material accidents.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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SUSTAINABILITY ANALYSIS OF DATA-DRIVEN AGRICULTURAL ECOLOGICAL ECONOMIC SYSTEMS: A CASE STUDY OF NORTHERN ANHUI

Xue Wu[1*], GuoWei Xu[2]
[1]Business School, Suzhou University, Suzhou 234000, Anhui, China.
[2]School of Environment and Surveying Engineering, Suzhou University, Suzhou 234000, Anhui, China.
Corresponding Author: Xue Wu, Email: snowu@ahszu.edu.cn

Abstract: The agro-eco-economic system (AEES) is a fundamental system underpinning human survival. To improve the evaluation of regional AEES performance, this study proposes an emergy-based framework for assessing sustainable development and constructs a corresponding evaluation index system. Applying this framework, we analyzed AEES data from the Northern Anhui from 2014 to 2023. Key findings reveal: The average total emergy input was 6.04×10^{22} solar emjoules (sej), while the average total emergy output was 5.08×10^{23} sej. The average emergy self-sufficiency ratio (ESR) and net emergy yield ratio (EYR) were 0.13 and 9.72, respectively, showing no significant temporal trend over the decade. The emergy investment ratio (EIR) and environmental loading ratio (ELR) exhibited a declining trend post-2017, indicating substantial yet gradually decreasing environmental pressure on the AEES. The average emergy sustainability index (ESI) was 1.15, with a moderate upward trend observed over the past five years, suggesting developing sustainability potential. Based on these results, the study provides targeted decision-making insights and management implications for advancing high-quality agricultural development in Northern Anhui. This research holds significant theoretical and practical relevance for sustainable AEES management.
Keywords: Data-driven; Emergy; Agricultural eco-economic system; Sustainaxbility; Northern Anhui

1 INTRODUCTION

In 1987, the World Commission on Environment and Development, in its report "Our Common Future," first articulated the concept of sustainable development. Today, eliminating hunger, achieving food security and improved nutrition, and promoting sustainable agriculture are among the United Nations' 17 Sustainable Development Goals. Therefore, the sustainable development of the AEES is both an effective pathway to solving hunger and an important integral component of global sustainable development.

To better understand AEES sustainability, scholars have employed diverse methods and tools for assessment [1-4]. However, a key issue with these evaluation methods is the difficulty in unifying indicator selection. The root cause is the inability to convert economic, material, and energy flows into a unified standard. The emergence of emergy analysis has changed this situation. Furthermore, emergy analysis allows for the quantification and comparison of energy flows across different systems. Emergy, pioneered by the renowned ecologist Odum, posits that all energy on Earth originates from solar energy. Therefore, inputs and outputs (materials or energy) of the AEES can be uniformly converted into solar emergy based on specific ratios, measured in solar emjoules (sej) [5]. Emergy analysis uses emergy as a baseline, converting different types of otherwise incomparable energy within a system into a common standard for measurement and analysis, enabling the quantitative analysis of AEES sustainability. Currently, emergy analysis is widely applied in the sustainability evaluation of ecological economic systems [6-8]. Research on emergy analysis applications in agricultural ecosystem sustainability primarily focuses on two main areas: comparing sustainability across different AEES [9] and studying regional AEES sustainability [10-11].

This study takes the AEES of Northern Anhui as its object and employs emergy analysis for quantitative evaluation. It constructs a sustainable development evaluation index system for the Northern Anhui AEES. By collating and calculating basic AEES data for Northern Anhui from 2014 to 2023, it evaluates the sustainable development capacity of the region's AEES.

2 RESEARCH METHODS AND INDEX SYSTEM

2.1 Research Methods

The AEES is an organic whole. To scientifically and comprehensively evaluate its operational status and development characteristics, selected evaluation indicators should possess relative independence. This paper divides the AEES energy flow into Total Emergy Used (Input, E) and Total Emergy Yield (Output, Y). System input emergy is categorized by source into Renewable Environmental Resource Input (R), Non-renewable Environmental Resource Input (N), Renewable Organic Emergy Input (T), and Non-renewable Industrial Auxiliary Emergy Input (F). System output emergy is categorized by agricultural sector into crop farming, animal husbandry, forestry, and fishery.

According to the emergy calculation method, the emergy values for the input and output items are calculated separately using the following formula:

$$B_i = \sum_i O_i E_i Tr_i \qquad i = 1, \ldots, n \tag{1}$$

Where B_i is the solar emergy of the i-th input or output item, O_i is the actual collected data for the i-th item, E_i is the energy conversion coefficient for the i-th item, and Tr_i is the solar transformity for the i-th item. After calculation using Formula 1, the emergy units for all input and output items are unified into solar emjoules (sej).

2.2 Index System

To understand the operational status of the regional AEES, this paper, from the perspectives of resources, environment, economy, and sustainability, and drawing on relevant literature, introduces five evaluation indicators: Emergy Self-Sufficiency Ratio (ESR), Emergy Investment Ratio (EIR), Net Emergy Yield Ratio (EYR), Environmental Loading Ratio (ELR), and Emergy Sustainability Index (ESI). This establishes the regional AEES emergy evaluation index system.

Emergy Self-Sufficiency Ratio (ESR) evaluates the system's self-sufficiency (Formula 2). A higher value generally indicates a greater contribution of natural resources to the system's inputs and stronger self-sufficiency. Renewable resources include solar radiation, wind energy, rain potential energy, and rain chemical energy. As wind, rain potential, and rain chemical energy ultimately derive from solar energy, the maximum value among renewable resources is used as the system's renewable resource emergy input.

$$ESR = (R + N) / E \tag{2}$$

Environmental Loading Ratio (ELR) characterizes the magnitude of environmental pressure borne by the AEES (see Formula 3). A higher ELR value indicates more non-renewable resource inputs (e.g., fertilizers, pesticides), leading to excessive dependence on artificial resources, significant environmental pressure, and hindering sustainable AEES development.

$$ELR = (F + N) / R \tag{3}$$

Emergy Investment Ratio (EIR) is the ratio of the sum of non-renewable industrial auxiliary emergy (F) and organic emergy (T) to the natural environmental input emergy (R + N). This indicator measures the development level of the AEES and its resource and environmental pressure. A higher EIR value indicates a higher level of economic development but also greater environmental pressure (see Formula 4).

$$EIR = (F + T) / (R + N) \tag{4}$$

Net Emergy Yield Ratio (EYR) is the ratio of output emergy (Y) to the sum of non-renewable industrial auxiliary emergy (F) and organic emergy (T) inputs (see Formula 5). This index reflects the system's sustainability. A higher value indicates higher efficiency, stronger sustainability, and higher price competitiveness of agricultural products.

$$EYR = Y / (F + T) \tag{5}$$

Emergy Sustainability Index (ESI) was proposed by Italian scientist Ulgiati and American ecologist Brown in 1997 (Formula 6) [12]. A region with a high EYR and a low ELR has a high ESI, indicating good sustainability; conversely, it indicates unsustainability. An ESI between 1 and 10 suggests the system is vigorous with development potential. ESI > 10 indicates weak ecosystem sustainability, while ESI < 1 indicates a consumer-oriented economic system.

$$ESI = EYR / ELR \tag{6}$$

Based on the above emergy indicators, the regional AEES emergy evaluation index system is constructed, as shown in Table 1.

Table 1 Sustainability Evaluation Index System for the Agricultural Ecological Economic System in Northern Anhui

Index Category	Expression	Indicator Description
Basic Indicators		
Renewable Natural Resources	R	Renewable resources from nature, e.g., solar, wind, rain energy
Non-renewable Natural Resources	N	Non-renewable resources from nature, e.g., topsoil loss
Non-renewable Industrial Auxiliary Emergy	F	Non-renewable industrial products in input emergy, e.g., fertilizer, pesticide, diesel, etc.
Organic Emergy	T	Organic emergy input to the system, including labor, seeds, organic fertilizer, etc.
Total Input Emergy	E=R+N+F+T	Sum of all input emergy items
Total Output Emergy	Y	Total emergy output of the system
Sustainability Indicators		
Emergy Self-Sufficiency Ratio (ESR)	ESR = (R + N) / E	Natural resource endowment and contribution to AEES development
Environmental Loading Ratio (ELR)	ELR = (F + N) / R	Pressure on the environment
Emergy Investment Ratio (EIR)	EIR = (F + T) / (R + N)	Level of regional agricultural economic development and environmental pressure
Net Emergy Yield Ratio (EYR)	EYR = Y / (F + T)	Ecosystem operational efficiency
Emergy Sustainability Index (ESI)	ESI = EYR / ELR	Sustainable development capacity of the regional agricultural ecosystem

3 SUSTAINABILITY EVALUATION OF THE AGRICULTURAL ECOLOGICAL ECONOMIC SYSTEM IN NORTHERN ANHUI

3.1 Study Area Overview

Northern Anhui Province is located in the northern part of Anhui, encompassing six prefecture-level cities: Bengbu, Fuyang, Bozhou, Suzhou, Huaibei, and Huainan. It features a warm-temperate semi-humid monsoon climate with distinct seasons, moderate temperatures, and average annual precipitation of 845mm. Annual solar radiation ranges from 5200 to 5400 MJ/m², with 2303.1 sunshine hours annually. In 2023, the grain sown area in Northern Anhui was 4123.72 thousand hectares, accounting for 56.22% of Anhui Province's total. The total grain output reached 40.5075 million tons, representing 54.96% of the provincial total. The permanent population was 26.47 million (43.24% of Anhui), with a rural population of 12.906 million (54.78% of Anhui's rural population). The gross output value of agriculture, forestry, animal husbandry, and fishery was 296.7 billion yuan, constituting 47.48% of Anhui's total. Northern Anhui is a crucial agricultural region in Anhui Province. To enhance its agricultural sustainability and promote high-quality development, this study selects Northern Anhui as the research area.

3.2 Data Sources and Calculation Results

The relevant agricultural basic data used in this paper mainly come from the Anhui Statistical Yearbook(2015-2024) compiled by the Anhui Provincial Bureau of Statistics, supplemented by the author's field surveys. Field survey items mainly included organic fertilizer application, seed usage, and labor input. Climate data (temperature, precipitation, sunshine) for Northern Anhui were obtained from the Meteorological Data Center of the National Meteorological Information Center. Energy conversion coefficients and emergy transformities primarily came from relevant literature [13-15]. The calculation method and process refer to the literature [15]. Based on the AEES emergy flow data for Northern Anhui and Formula 1, 35 input and output items that significantly impact the calculation results were retained. The calculation results are shown in Table 2 and Table 3.

Table 2 Emergy Input Analysis of the Agricultural Ecological Economic System in Northern Anhui (2014-2023) (sej)

	Project	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
	Renewable Resource Input (R)(×10^{21})	5.19	5.61	5.19	5.36	6.06	4.26	5.48	6.60	5.25	5.52
1	Solar Energy(×10^{19})	5.27	5.79	5.79	5.79	5.93	6.01	5.78	5.88	5.98	6.00
2	Wind Energy(×10^{20})	7.62	8.34	8.34	8.34	8.60	8.76	8.33	8.52	8.71	8.75
3	Rainwater Chemical Energy(×10^{21})	5.19	5.61	5.19	5.36	6.06	4.26	5.48	6.60	5.25	5.52
4	Rainwater Potential Energy(×10^{20})	7.83	8.47	7.83	8.08	9.14	6.43	8.27	9.95	7.91	8.32
	Non-renewable Resource Input (N) (×10^{21})	2.31	2.50	2.31	2.39	2.70	1.90	2.44	2.94	2.34	2.46
5	Topsoil Loss(×10^{21})	2.31	2.50	2.31	2.39	2.70	1.90	2.44	2.94	2.34	2.46
	Non-renewable Industrial Auxiliary Input (F)(×10^{22})	4.58	4.67	4.74	4.79	4.86	4.92	4.95	3.92	3.89	3.56
6	N Fertilizer(×10^{21})	7.06	7.07	7.04	7.00	6.95	6.95	6.83	6.69	6.41	5.29
7	P Fertilizer(×10^{21})	8.45	8.43	8.40	8.30	8.30	8.37	8.26	8.05	7.70	4.26
8	K Fertilizer(×10^{20})	7.78	7.94	8.00	8.06	8.24	8.29	8.30	8.20	7.89	7.10
9	Compound Fertilizer(×10^{21})	2.50	2.68	2.79	2.91	2.97	3.08	3.17	3.19	3.10	4.20
10	Pesticides(×10^{20})	1.40	1.37	1.34	1.37	1.40	1.40	1.35	1.32	1.26	9.95
11	Agricultural Film(×10^{15})	3.46	3.45	3.60	3.69	3.96	4.01	4.01	4.03	3.73	3.19
12	Agricultural Machinery(×10^{22})	2.66	2.73	2.79	2.84	2.91	2.95	2.99	1.99	2.04	2.08
13	Electricity(×10^{20})	2.78	2.93	3.20	3.40	3.53	3.61	3.50	3.44	3.52	2.89
14	Fuel Oil(×10^{17})	1.99	1.97	1.84	1.92	1.94	1.92	1.93	1.44	1.48	1.43
	Organic Emergy Input (T)(×10^{21})	8.03	7.95	7.82	7.75	7.63	7.59	7.50	7.48	7.41	7.40
15	Organic Fertilizer(×10^{20})	2.59	2.55	2.57	2.57	2.61	2.62	2.61	2.60	2.60	2.58
16	Labor(×10^{21})	7.77	7.69	7.56	7.49	7.37	7.33	7.23	7.22	7.15	7.14
17	Seeds(×10^{17})	6.30	6.52	6.99	7.19	7.49	7.46	7.53	7.90	8.00	7.73
	Total Input Emergy (E)(×10^{22})	6.13	6.28	6.27	6.34	6.50	6.30	6.49	5.62	5.39	5.10

Table 3 Emergy Output Analysis of the Agricultural Ecological Economic System in Northern Anhui (2014-2023) (sej)

	Project	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
	Crop Farming(×10^{22})	6.80	6.85	7.21	7.13	7.14	7.14	7.03	6.55	6.61	6.51
1	Wheat(×10^{21})	6.91	6.94	7.22	7.59	7.90	8.04	8.26	8.24	8.38	8.08
2	Rice(×10^{20})	4.41	4.14	4.56	3.75	4.40	4.00	4.01	4.01	3.90	4.11
3	Corn (Maize)(×10^{22})	1.34	1.42	1.55	1.58	1.64	1.62	1.62	1.73	1.73	1.65
4	Beans (Legumes)(×10^{21})	2.08	1.90	1.94	1.67	1.53	1.63	1.32	1.37	1.43	1.94
5	Tubers (Potatoes)(×10^{19})	1.64	2.03	2.14	2.36	2.38	2.06	2.08	3.17	3.61	3.98

6	Peanuts($\times 10^{21}$)	4.76	4.64	4.46	4.37	4.47	4.14	4.03	4.03	4.05	3.86
7	Cotton($\times 10^{21}$)	11.4	10.7	12.2	10.5	8.46	7.74	6.34	4.69	4.71	4.69
8	Vegetables($\times 10^{21}$)	2.76	2.90	3.04	3.17	3.25	3.35	3.38	3.39	3.41	3.47
9	Fruits & Melons($\times 10^{22}$)	2.62	2.68	2.72	2.78	2.90	3.00	3.04	2.61	2.64	2.61
	Livestock Products($\times 10^{23}$)	4.48	4.36	4.26	4.35	4.38	4.49	4.39	4.11	4.14	3.95
10	Pork($\times 10^{22}$)	5.49	5.49	5.34	5.61	5.74	6.09	5.95	5.74	6.31	6.20
11	Beef($\times 10^{21}$)	8.52	8.95	8.40	8.52	8.06	8.07	8.20	8.37	8.57	8.71
12	Mutton (Sheep/Goat)($\times 10^{21}$)	8.17	8.49	8.29	8.38	8.49	8.87	9.25	9.46	8.78	8.90
13	Poultry Eggs($\times 10^{22}$)	6.08	5.85	5.87	5.93	6.00	6.30	6.50	6.77	6.57	6.47
14	Dairy (Milk)($\times 10^{22}$)	6.55	6.38	6.63	6.80	6.61	7.04	6.83	6.34	6.60	6.65
15	Other Meats($\times 10^{22}$)	3.09	2.85	3.00	3.37	3.43	3.48	3.43	3.46	3.40	3.34
16	Wool($\times 10^{23}$)	2.19	2.13	2.01	2.01	2.04	2.03	1.95	1.70	1.68	1.51
	Forestry($\times 10^{19}$)	4.96	6.09	6.09	6.38	7.23	7.70	6.87	7.03	6.72	7.46
17	Forest Products($\times 10^{19}$)	4.96	6.09	6.09	6.38	7.23	7.70	6.87	7.03	6.72	7.46
	Fishery($\times 10^{21}$)	9.01	9.63	10.1	10.6	11.0	10.6	10.7	11.2	7.06	6.56
18	Aquatic Products($\times 10^{21}$)	9.01	9.63	10.1	10.6	11.0	10.6	10.7	11.2	7.06	6.56
	Total Output Emergy (Y)**($\times 10^{23}$)**	5.25	5.14	5.09	5.17	5.21	5.31	5.20	4.87	4.87	4.67

Based on the relevant emergy data in Tables 2 and 3 and the calculation methods, and using the emergy evaluation index system constructed in Part 2, the indicator values for the AEES in Northern Anhui from 2014 to 2023 were calculated, as shown in Table 4.

Table 4 Sustainability Indicator Values for the Agricultural Ecological Economic System in Northern Anhui (2014-2023)

	Project	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
Basic Indicators	R($\times 10^{21}$sej)	5.19	5.61	5.19	5.36	6.06	4.26	5.48	6.60	5.25	5.52
	N($\times 10^{21}$sej)	2.31	2.50	2.31	2.39	2.70	1.90	2.44	2.94	2.34	2.46
	F($\times 10^{22}$sej)	4.58	4.67	4.74	4.79	4.86	4.92	4.95	3.92	3.89	3.56
	T($\times 10^{21}$sej)	8.03	7.95	7.82	7.75	7.63	7.59	7.50	7.48	7.41	7.40
	E($\times 10^{22}$sej)	6.13	6.28	6.27	6.34	6.50	6.30	6.49	5.62	5.39	5.10
	Y($\times 10^{23}$sej)	5.25	5.14	5.09	5.17	5.21	5.31	5.20	4.87	4.87	4.67
Sustainability Indicators	ESR	0.12	0.13	0.12	0.12	0.13	0.10	0.12	0.17	0.14	0.16
	EIR	7.17	6.74	7.35	7.18	6.42	9.22	7.19	4.89	6.10	5.39
	EYR	9.76	9.40	9.22	9.28	9.26	9.35	9.13	10.5	10.5	10.9
	ELR	9.26	8.77	9.56	9.39	8.46	12.0	9.47	6.38	7.86	6.90
	ESI	1.05	1.07	0.96	0.99	1.09	0.78	0.96	1.64	1.34	1.57

3.3 Results and Analysis

3.3.1 Basic indicator analysis

From 2014 to 2023, the average renewable resource emergy input into the AEES in Northern Anhui was 5.45×10^{21} sej, remaining relatively stable. Variations were primarily caused by changes in rainwater chemical energy due to annual precipitation fluctuations. The input of non-renewable industrial auxiliary emergy (F) increased from 4.58×10^{22} sej in 2014 to 4.95×10^{22} sej in 2020 (see Fig. 1). After 2020, F input gradually decreased. The reduction in industrial auxiliary energy input helps decrease fertilizer and pesticide residues, improve the AEES environment, and enhance farmers' quality of life. Since 2014, the organic emergy input (T) showed a significant declining trend. This is mainly due to migrant workers typically returning only during busy farming seasons and their farming practices increasingly relying on mechanization. Additionally, the number of large livestock decreased from 962,000 head in 2014 to 786,000 head in 2023, contributing to the reduction in organic emergy input.

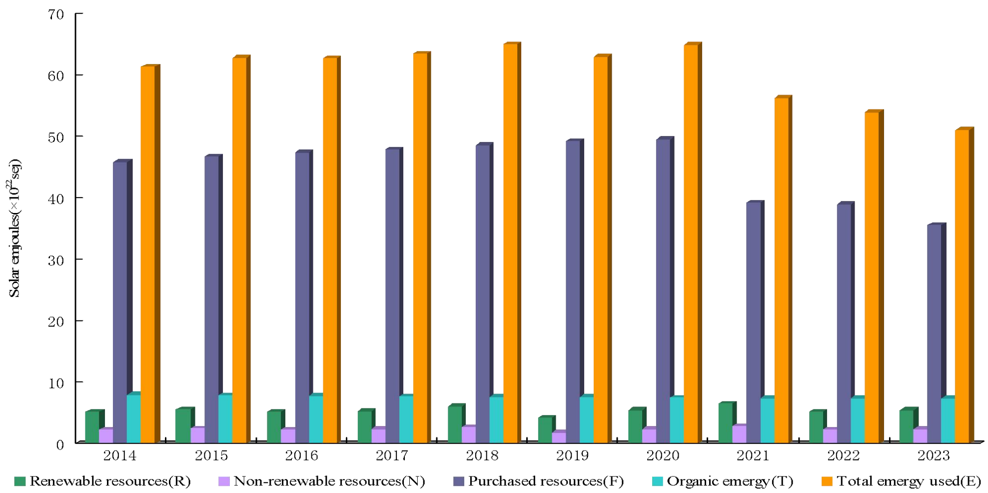

Figure 1 Emergy Inputs of the Agricultural Ecological Economic System in Northern Anhui Region (2014-2023)

The average total emergy input (E) for the Northern Anhui AEES from 2014 to 2023 was 6.04×10^{22} sej. Renewable resources (R), non-renewable resources (N), non-renewable industrial auxiliary emergy (F), and organic emergy (T) accounted for 9.03%, 4.02%, 74.28%, and 12.67% of the total input, respectively (see Table 2, Fig. 2). Over the past decade, fertilizers and pesticides accounted for 30.74% of the total input emergy, indicating they still dominate industrial emergy input in Northern Anhui, exerting significant pressure on the soil and water environment.

The average total emergy output (Y) from 2014 to 2023 was 5.08×10^{23} sej. The lowest output was in 2023 (4.67×10^{23} sej), and the highest was in 2020 (5.31×10^{23} sej). Output fluctuated noticeably from 2015 to 2020 but showed a declining trend after 2020, decreasing from 5.31×10^{23} sej in 2020 to 4.67×10^{23} sej in 2023 (see Table 3). Among the output sectors, livestock products contributed the most emergy, followed by crop farming. The average outputs were 4.29×10^{23} sej for livestock and 6.90×10^{22} sej for crops, accounting for 84.50% and 13.58% of total output, respectively. This indicates that agricultural output in Northern Anhui is still dominated by animal husbandry and crop farming. Due to forests being primarily ecological reserves and limited freshwater areas, forestry and fishery outputs were minor, together accounting for only 1.91% of total output emergy.

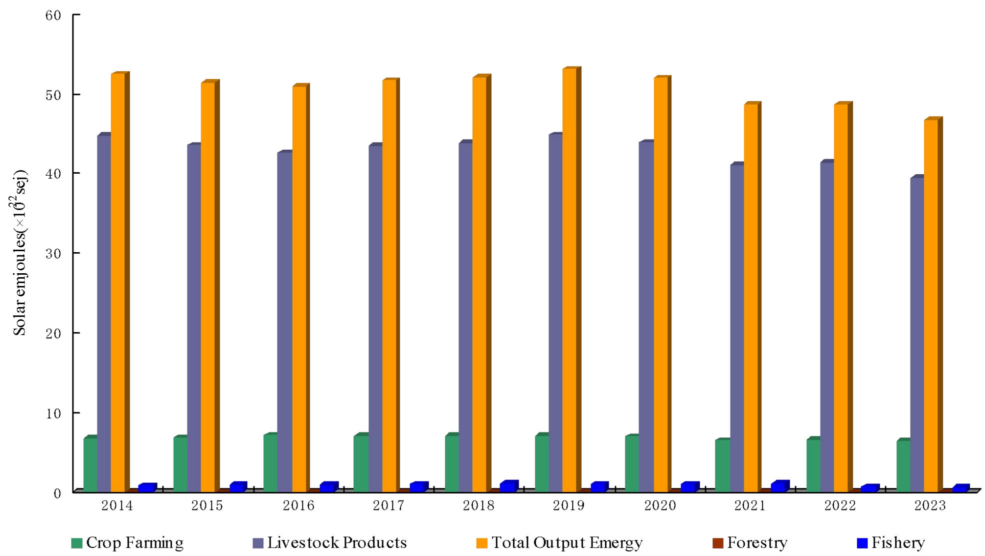

Figure 2 Major Output Emergy of the Agricultural Ecological Economic System in Northern Anhui (2014-2023)

3.3.2 Sustainability indicator analysis

Based on the emergy data analysis results, this study analyzes and evaluates the AEES in Northern Anhui from four dimensions: resources, environment, economy, and sustainability indicators.

(1) Emergy Self-Sufficiency Ratio (ESR)

Since 2014, the ESR of the Northern Anhui AEES ranged from a maximum of 0.17 to a minimum of 0.10, showing little change over the decade (see Fig. 3a). This reflects the relative stability of renewable natural resource input (R), non-renewable natural resource input (N), and total input emergy (E). It also indicates that the proportion of natural resource input within the total input is small, showing relatively low dependence on natural resources, high dependence on industrial inputs, and a relatively high level of agricultural intensification.

(2) Emergy Investment Ratio (EIR)

The average EIR from 2014 to 2023 was 6.76. The highest value was 9.22 in 2016, and the lowest was 4.89 in 2021. After 2016, it showed a declining trend (see Fig. 3b). This indicates high inputs of non-renewable industrial auxiliary emergy (F) and organic emergy (T), meaning a large proportion of purchased emergy input, imposing a certain degree of resource and environmental pressure on AEES sustainable development.

(3) Net Emergy Yield Ratio (EYR)

The average EYR was 9.72. The highest value was 10.86 in 2023, and the lowest was 9.13 in 2020. There was little change from 2014 to 2020, but values increased steadily after 2020 (see Fig. 3c). This indicates high efficiency in converting input emergy within the Northern Anhui AEES, good overall functionality of the agricultural ecosystem, and relatively good sustainability.

(4) Environmental Loading Ratio (ELR)

The ELR fluctuated significantly from 2014 to 2023 and remained at a relatively high level, averaging 8.80. The highest was 11.99 in 2016, and the lowest was 6.90 in 2023 (see Fig. 3c). This indicates that the development of the AEES in Northern Anhui is subject to high environmental pressure, adversely affecting its sustainable development.

(5) Emergy Sustainability Index (ESI)

The average ESI from 2014 to 2023 was 1.15. The highest value was 1.64 in 2021, and the lowest was 0.78 in 2019 (see Fig. 3d). The ESI showed little change from 2014 to 2018 but exhibited a clear upward trend after 2019, increasing from 0.78 in 2019 to 1.57 in 2023. This suggests that the Northern Anhui agricultural ecosystem possesses strong sustainable development potential, showing an increasing trend.

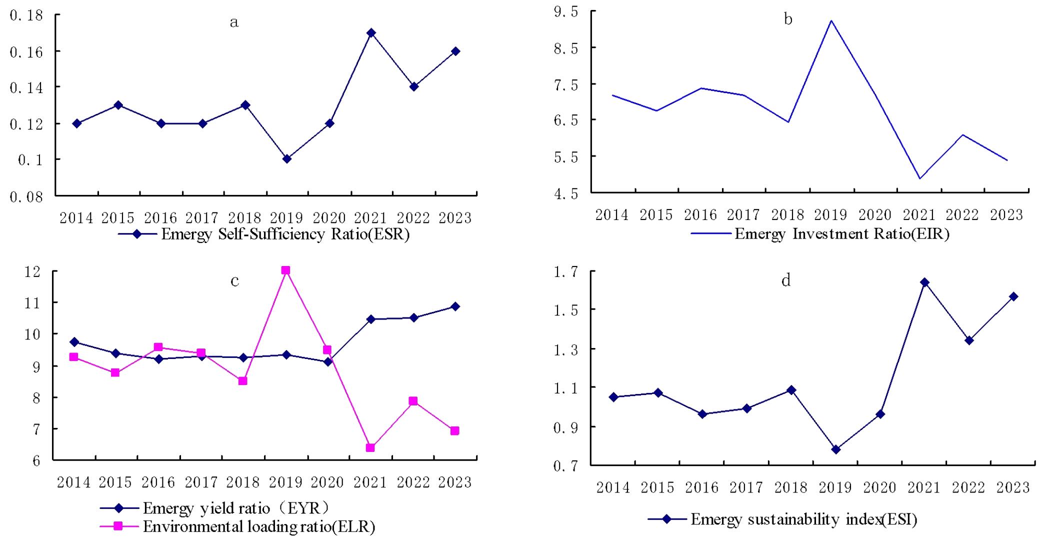

Figure 3 Sustainability Indices of the Agricultural Ecological Economic System in Northern Anhui (2014-2023)

3.4 Management Implications

Based on the quantitative evaluation and research findings, promoting sustainable development of the AEES in Northern Anhui requires multi-faceted solutions. This study proposes the following recommendations:

3.4.1 Reduce non-renewable resource input

Within the AEES inputs of Northern Anhui, non-renewable resources (N) are consumptive and environmentally damaging. Topsoil loss is a major component of N inputs. Therefore, vigorous efforts are needed to prevent soil erosion and soil pollution.

3.4.2 Improve the utilization efficiency of non-renewable purchased resources

Non-renewable purchased resources (F) hold a unique position. While they are artificial inputs, they are also crucial for agricultural production. Thus, reliance on technological advancement is essential to improve the utilization efficiency of F resources, thereby reducing the required input volume. For example, precise measurement of soil nutrient content can enable targeted fertilizer application. Simultaneously, increasing organic fertilizer input and promoting straw return to fields can help reduce chemical fertilizer usage.

3.4.3 Develop ecological agriculture

Encourage the development of ecological planting and breeding, strengthen the certification and management of green food and organic agricultural products. Promote ecological circular agriculture, enhance the resource utilization of livestock and poultry manure, advance comprehensive utilization of crop straw, and strengthen the control of agricultural plastic film pollution. Reinforce the protection and improvement of cultivated land quality and advance the comprehensive management of degraded farmland. Given water scarcity in Northern Anhui, vigorously promote agricultural water conservation and adopt efficient water-saving technologies. Implement healthy aquaculture practices. Conduct actions to reduce pesticide and herbicide usage while enhancing their efficacy.

4 CONCLUSIONS AND DISCUSSION

With the reduction and outflow of rural labor, farming practices have shifted towards efficiency-driven methods, leading to persistently high application rates of fertilizers, pesticides, herbicides, and mechanized farming. This has resulted in increased non-point source pollution and high energy consumption. A critical challenge is how to increase AEES output while reducing its environmental footprint and creating highly sustainable systems under certain input levels. Evaluating regional AEES sustainability and proposing targeted improvement measures are fundamental for transforming agricultural ecosystem development modes and enhancing the quality and efficiency of agricultural development.

This study deepens the understanding of agricultural ecosystem inputs and outputs from an emergy perspective. It establishes a unified measurement model and proposes an evaluation framework integrating economic, environmental, and social benefits. This research provides valuable insights for regional AEES sustainable development, offers theoretical and methodological support for high-quality agricultural development, and furnishes policymakers with effective solutions.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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THE MECHANISM AND PATHWAYS OF INDUSTRIAL SYMBIOSIS NETWORKS EMPOWERING CIRCULAR SUPPLY CHAINS

LingYan Sun
Silk Road Economic Belt Core Area Industrial High-quality Development Research Center, Business School, Xinjiang Normal University, Xinjiang 830054, Urumqi, China.
Corresponding Email: linda.1sunny@163.com

Abstract: The industrial symbiosis network drives the construction and upgrading of circular supply chains through resource collaboration and value reconstruction. This study systematically analyzes the intrinsic mechanisms by which industrial symbiosis empowers circular supply chains, including economic drivers, environmental momentum, risk resistance capabilities, and policy empowerment, thereby enriching the dynamic evolution theory of industrial symbiosis. It also interprets the challenges and contradictions encountered during the process of establishing industrial symbiosis networks and circular supply chains through real-world case studies. Based on the promotion of industrial symbiosis networks for the transformation and upgrading of circular supply chains, it proposes feasible pathways for achieving sustainable economic development.
Keywords: Industrial symbiosis; Circular supply chain; Blockchain

1 INTRODUCTION

With the increasing pressure on global resources and the environment， and the growing strictness of environmental regulations, the global sustainable development plan is deepening. The traditional linear economic model, which goes from resource utilization to waste generation in a single direction, can no longer meet the demands of today's economic development. Thus, the circular supply chain model has emerged [1]. As an innovative model for achieving sustainable development, the core concept of the circular supply chain is to achieve the recycling and reuse of resources through the integration and collaboration of enterprises, thereby enhancing the operational efficiency of the industrial chain and reducing environmental resource costs and waste [2]. In the operation of traditional supply chains, problems such as material shortages, information opacity, difficulties in returning and recycling goods, risk transmission, and severe environmental pollution constantly arise. By adopting circular strategies, such as the recycling and reuse of waste, and the sharing of information and data, enterprises at different links can cooperate closely to form a self-circulating network that shares value, effectively solving these problems. Moreover, the smart contract mechanism and blockchain traceability system of the circular supply chain can effectively alleviate information silos and trust crises. In the traditional supply chain cycle, there are serious information silos and trust crises among enterprises. However, the transparent and shared ledger constructed by blockchain technology can complete the full traceability of resources. Furthermore, with the wide application of smart contracts, enterprises can achieve full-process management through automatically executed electronic contracts, enabling precise resource allocation. This not only improves the efficiency of resource matching but also reduces resource consumption and environmental impact, achieving a dynamic balance of shared environmental risks and economic benefits [3].
However, circular supply chains encounter numerous difficulties and challenges in promoting sustainable development. Firstly, the policy and regulatory framework is incomplete, fragmented and short-term. Information silos and technological bottlenecks among enterprises, as well as high costs of circular transformation, pose constraints. Moreover, the reorganization of transportation and recycling logistics is not well established. The performance degradation of recycled materials and the hidden environmental costs during the processing stage result in insufficient fundamental driving force for supply chain circularity. The feasibility of circular supply chains in promoting sustainable development remains challenging.
The construction of industrial symbiosis networks offers an opportunity to address the bottleneck problems in the circular supply chain. As an important form of realizing a circular economy, industrial symbiosis networks introduce new supplier-buyer relationships, entrusting the by-products and waste from one enterprise to other enterprises for processing and utilization, and forming collaborative relationships among unrelated enterprises. Through cross-industry resource coordination and spatial organizational cooperation, it provides a systematic solution to the sustainability development contradictions of the circular supply chain. Firstly, the physical space agglomeration created by industrial symbiosis networks can effectively achieve the goal of shortening the logistics cycle through the establishment of industrial parks, solving the logistics reorganization problem in traditional supply chains. Moreover, the cross-enterprise collaborative contractual relationships formed by industrial symbiosis, along with the geographical proximity and long-term cooperative relationships, break down the trust barriers. Through cooperation among cross-industry enterprises to explore technological systems and expand technological feasibility at multiple levels, avoiding reliance on a single

technology, it breaks down technological barriers and bottlenecks, constituting the core driving mechanism at the technological level of the circular supply chain. At the same time, industrial symbiosis networks form a policy innovation carrier, allowing for the piloting of new governance tools and reducing the cost of policy trial and error.

However, the current policy framework still faces dual challenges of a lack of systematic support and a structural absence of incentive mechanisms in promoting the coordinated evolution of industrial symbiotic networks and circular supply chain systems. It urgently needs to achieve breakthroughs through collaborative innovation of theory and practice. In this context, deeply deconstructing the enabling mechanism of industrial symbiotic networks for the circular supply chain system has become a core issue for promoting the green transformation of regional economies. This paper focuses on analyzing the main problems at three levels. First, this study aims to clarify the internal mechanism by which industrial symbiotic networks empower the construction of circular supply chains; second, this paper interprets the dilemmas and contradictions in the process of building industrial symbiotic networks and circular supply chains through practical cases; finally, it proposes a feasibility path analysis for promoting the transformation and upgrading of circular supply chains by industrial symbiotic networks and achieving sustainable economic development.

This paper conducts an interdisciplinary study on industrial symbiosis and circular supply chains, proposing a mechanism and path for industrial symbiosis to empower circular supply chains. It expands the related research on circular economy and supply chain management. Moreover, this study reveals that the economic consequences of the industrial symbiosis network are economic drive, environmental momentum, risk resistance capability, and policy empowerment. It improves the dynamic evolution theory of industrial symbiosis. The path proposed by this study for industrial symbiosis network to empower circular supply chains and shape them provides a basis for the design of symbiosis networks and the transformation and upgrading of circular supply chains.

2 RESEARCH REVIEW

2.1 Industry Symbiosis Level

The core function of the industrial symbiosis concept is to achieve waste recycling, promote economic green growth and rapidly enhance resource efficiency. It is regarded as the core driving force of the industrial ecosystem. It uses innovative collaborative logic to reverse the high energy consumption and high pollution of traditional industries into "value sources". Through the sharing of waste materials and the construction of common facilities among enterprises, it realizes the core concept of turning waste into treasure. This has attracted great attention from scholars and the government. Regarding the industrial symbiosis theory, Renner first proposed the term "industrial symbiosis" in his work on industrial location, to describe the organic interactive relationship between different industries. Later, Frosch et al. combined the industrial ecology theory framework and systematically summarized the practical experience of Kallenborg in Denmark, further expanding the related concepts and theoretical frameworks [4-5]. On this basis, researchers in the industrial field and the environmental science field have continuously deepened related research. Some scholars believe that industrial symbiosis is essentially a collaboration model among enterprises, through the exchange of raw materials, energy, resources or by-products, not only deepening enterprise cooperation, but also achieving the goals of improving resource utilization efficiency and reducing environmental pollution. Sokka et al. believe that the foundation of industrial symbiosis is the enterprise relationship formed by the exchange of by-products among enterprises[6], but they place more emphasis on the cooperative relationship between enterprises, and the material exchange is based on the cooperation between enterprises. Chertow's research shows that the formation of the enterprise cooperation emphasized by industrial symbiosis is based on geographical proximity [7]. Enterprise collaboration is mainly aimed at material and energy exchange, infrastructure sharing, service exchange and sharing, etc. Subsequently, Mirata et al. further extended the meaning of "exchange" in their research [8]. They proposed that industrial symbiosis is essentially a long-term symbiotic relationship formed among enterprise entities within a region, and its symbiotic interaction not only covers the exchange of materials and energy, but also goes deeper to the sharing of knowledge, human resources and technical resources. This multi-level exchange ultimately collaboratively achieves the win-win benefits of improving environmental performance and enhancing competitive advantages.

2.2 Circular Supply Chain Aspect

As an important branch of green supply chain management, the core practice path of circular supply chain management lies in establishing an reverse logistics system. The core concept is to recycle waste, process the recyclable parts for regeneration and reintroduce them into the production process, thereby maximizing the resource value of scrapped products and ultimately achieving the goals of reducing environmental pollution and ecological protection. Circular supply chain management emphasizes closed-loop supply chain management, with its core idea being that after the product reaches the end of its lifespan, it is recycled and reused, returning to the same product category. However, Gunasekara et al. further expanded the concept of circular supply chain [9]. Circular supply chain management includes open-loop recycling and closed-loop supply chain management. The open-loop supply chain refers to the situation where waste does not return to the original manufacturer or the same product supply chain, but enters other industries, other products, or other supply chains. By promoting cross-chain cooperation among original supply chain members and external enterprises or departments, it can optimize the waste recycling process, maximize its resource value, and ultimately achieve efficient utilization of waste resources. For example, recycled plastic through the closed-loop recycling model can be transformed into recycled plastic with quality close to the original material, and returned to the original supply chain for reuse; when the recycled materials are processed into new products, if their performance declines and they cannot be used for the original purpose, that is, the so-called open recycling model, they can be converted into recycled fibers and applied to supply chains in different industries. Therefore, circular supply chain not only includes the traditional supply chain's forward logistics from suppliers to manufacturers to customers, but also covers the process from customers to other parts of the supply chain to achieve the recycling and reuse of resources. Regarding the research on the operation management of circular supply chain, Shankar et al. focused on the maximum marginal contribution under different closed-loop supply chain designs [10]; some scholars focused on the application of digital technologies such as blockchain in circular supply chains [11].

2.3 Review of Research on Industrial Symbiosis and Industrial Chain/Supply Chain

At the industrial chain level, regarding the research on industrial symbiosis and the transformation and upgrading of industrial chains, most of the related studies focus on the physical attributes and technical feasibility of exchanged resources. Dong et al. constructed a practical case of industrial symbiosis chain from domestic waste to fuel [12], and this study carefully evaluated the feasibility of using unclassified urban waste as a substitute fuel for coal in the Pingliang Industrial Park Power Plant.

Based on the relevant research at the levels of industrial symbiosis and supply chain operation management, Bansal et al. argued that industrial symbiosis chains are a special form of supply chains [13], which laid the foundation for subsequent research. Scholars' supplementary exploration gradually formed a multi-level research framework: Domenech et al. studied the goals of industrial symbiosis chains from the strategic and tactical dimensions [14], Babazadeh et al. focused on the design of symbiosis chains [15]; Herczeg et al. focused on organizational structure research [16]; and the operational dimension focused on the quantification and quality control of by-products/wastes and low-carbon operation strategies [17-18]. Ventura Vet al. emphasized that through blockchain technology to achieve closed-loop information flow management of industrial symbiosis networks [19], it can promote supply chain participants to establish stable collaborative relationships, thereby converting industrial waste into renewable resources and promoting the sustainable development of the circular supply chain model.

In conclusion, the current research on industrial symbiosis and circular supply chains still needs to be further deepened. Firstly, there is a lack of theoretical guidance for practice. Although the research framework for unilateral industrial symbiosis and single circular supply chains has gradually formed, there is still a lack of research on industrial symbiosis enabling circular supply chains, and no effective practical transformation mechanism has been established. Thus, theoretical innovation is difficult to be transformed into practical guidance paths for the construction of circular supply chains. Secondly, there is a lack of analysis of the difficulties in the coupling process of industrial symbiosis and circular supply chains. Most of the existing case studies mostly remain at the level of verifying the theoretical framework of circular supply chains and have not conducted detailed analysis of the three obstacles of logical conflicts, imbalance in benefit distribution, and information silos in the practical process, resulting in an incomplete feasibility assessment system. Finally, there is a lack of comprehensive discussions on the institutional and policy dimensions. The consideration of the economic system and policy background of developing countries is insufficient, which may weaken the applicability of the theory in transitional economies. Due to the differences in institutions, even the same circular technologies may have completely different implementation effects, indicating that the development of any theory must strengthen contextual analysis.

3 THE ENABLING MECHANISM OF INDUSTRIAL SYMBIOSIS NETWORK FOR BUILDING CIRCULAR SUPPLY CHAINS

Although the collaborative cooperation among various links of the circular supply chain has received extensive attention from both the academic community and the industrial sector, the construction of the circular supply chain is a complex network system involving multiple levels and entities. Moreover, during the upgrading process of the circular supply chain, the positive and reverse interweaving of material flow, capital flow, and information flow are involved, and these inherent contradictions and difficulties have led to certain constraints in the construction of the circular supply chain. Therefore, the construction of the industrial symbiosis network becomes a catalyst for the construction of the circular supply chain.

3.1 Concept of Industrial Symbiosis and Circular Supply Chain

The core connotation of the industrial symbiosis theory encompasses three aspects: Firstly, it is reflected at the material flow level, where the closed nature is realized through the industrial symbiosis network formed among enterprises, enabling the recycling and sharing of resources, reducing reliance on external inputs and minimizing the output of harmful substances, thereby achieving the transformation from the linear economy of obtaining resources, manufacturing products, and disposing of them to the circular economy; at the organizational level, through a networked governance structure, industrial symbiosis is jointly managed, forming a stable cooperative model based on reciprocal relationships among enterprises, alleviating trust crises and information isolation; at the spatial distribution level, the emphasis is more on the cluster effect, reducing circular logistics costs and transaction costs through geographical concentration [19].

Circular supply chain management essentially represents the intersection of traditional supply chain theory and the concept of circular economy. Its core elements involve the multi-level integration of technical elements, organizational structure elements, and value networks. The technical elements facilitate the improvement of the efficiency of material resource transformation, including clean production technologies and reverse logistics infrastructure. These technical elements collectively form the foundation of the circular supply chain. The organizational structure refers to the systematic reconfiguration of internal organizational functions, cross-enterprise collaboration mechanisms, and external partnerships within an enterprise to achieve closed-loop resource flow. The core lies in breaking down the traditional linear supply chain barriers of enterprises to build a collaborative network that suits the circular model. The value network dimension is the essential characteristic that distinguishes the circular supply chain from the traditional model. It aims to maximize the value of resources and reconfigures the traditional supply chain into a dynamic circular ecological supply chain system through the participation of multiple parties. Therefore, by integrating the characteristics of industrial symbiosis and the core goals of the circular supply chain, the theory of industrial symbiosis has unique advantages in shaping the core elements of the circular supply chain. Firstly, its material flow analysis framework can evaluate the environmental benefits of the circular supply chain; the network governance theory can provide guarantees for the design of organizational structures, while the principles of spatial economics act as a catalyst for the value network [19]. Table 1 compares the core contents of industrial symbiosis and circular supply chains.

Table 1 Core Contents of Industrial Symbiosis and Circular Supply Chains

aspect	Industrial Symbiosis	Circular Supply Chain
Definition Focus	Covers the value creation process of product design and R&D, production and processing, sales, and after-sales service	Focuses on the comprehensive management of logistics, information flow, and capital flow
Key Concerns	Vertical collaboration and value-added processes within the industry	Efficient circulation and resource allocation through coordinating multi-party relationships
Linkage Advantages	Promotes industrial agglomeration effects and enhances risk resistance	Enables information sharing between upstream and downstream, and optimizes procurement and inventory management

3.2 Kinetic Energy of Industrial Symbiosis Environment and Construction of Circular Supply Chain

Industrial symbiosis is regarded as an important approach to promoting sustainable development and building a circular society, and is the ultimate and most important system innovation tool for achieving green economic growth [7]. Based on the existing research results and practical cases, this paper believes that the benefits of enabling the transformation and upgrading of the circular supply chain through industrial symbiosis networks can be divided into four levels: economic drive, environmental kinetic energy, anti-risk ability, and policy empowerment. In the environmental kinetic energy level, industrial symbiosis utilizes the industrial partnerships within the region to transform by-products and waste into material flows and resource recycling. Through cross-enterprise and cross-industry resource collaboration, it breaks the vicious cycle of traditional industries' "high consumption - high emissions" from the source. This process provides stable input of renewable resources for the circular supply chain and promotes its upgrading. Moreover, the symbiosis network builds a waste resourceization potential assessment model to identify cross-industry value conversion paths, and uses dynamic pricing mechanisms to achieve the optimal allocation of by-products.

The environmental benefits of industrial symbiosis emphasize the protection of the ecological environment and the transformation and upgrading of the circular supply chain by improving the efficiency of resource comprehensive utilization, reducing the use of non-renewable resources and pollutant emissions. Traditional supply chains focus on meeting customer demands, and enterprises, in pursuit of market share and profits, will prioritize responding to customer preferences. However, customers often pay more attention to product prices and convenience rather than environmental attributes. To quickly meet market demands, enterprises tend to expand production scale and shorten product life cycles, resulting in excessive resource extraction, high energy consumption and increased waste, thereby exacerbating environmental pressure. One of the goals of the circular supply chain is to achieve closed-loop utilization of resources. In other words, it is to realize the closed-loop circulation of resources and material flows through various methods within the supply chain system, to achieve the maximum value of resource recovery and reuse. Industrial symbiosis, through the collaborative cooperation among supply chain enterprises, transforms the circular model in the traditional linear supply chain, that is, from resource-production-waste to closed-loop network resource-production-reutilization, thereby reducing environmental impacts at multiple stages [8]. This economic consequence directly reflects the low cost nature of the circular supply chain, that is, achieving the goal of saving resource consumption and optimizing business processes.

3.3 Industrial Symbiosis Economy Driving and Circular Supply Chain Construction

The economic driving force of the industrial symbiosis network is to reduce the initial resource input cost in production activities, strengthen cooperation among enterprises to achieve the goals of pollution control and reduction of waste management costs, and thereby realize the circular economy model of waste recycling and reuse. Moreover, industrial symbiosis generates additional revenue for enterprises by maximizing the value of waste materials, enhances the feasibility of recycling and remanufacturing stages in circular supply chains, and improves business sustainability[13]. The economic driving force of industrial symbiosis is a process combining cost savings and value upgrading. It transforms waste in the linear economy into alternative raw materials and energy, directly reducing raw material costs；at the same time, it relies on the value utilization of waste and service model innovation to enhance the economic resilience of the system [20]. The structural upgrading transformation of resource costs formed by it empowers the formation and upgrading of the circular supply chain, breaks through the traditional bottleneck where recycled resources are more expensive than primary resources， and improves the feasibility of the circular supply chain.

3.4 The Risk-Resilience Capacity of Industrial Synergy and the Construction of Circular Supply Chains

The risk-resilience capacity of industrial synergy is achieved by reconfiguring the underlying logic of value creation and enhancing the resilience of the circular supply chain. Firstly, through the construction of inter-enterprise cooperative relationships within the industrial synergy network, technology sharing is facilitated, and customer relationships are restructured through a closed-loop service model. In the energy flow aspect, through the centralized functional systems of industrial parks, the industrial synergy network can achieve resource sharing among enterprises and the development of green products, thereby achieving a low-carbon circular economy. In the information flow aspect, through the digital sharing platform constructed by the symbiotic network, real-time data sharing and supervision can be realized, reducing supply chain risks. For example, the application of blockchain technology has built an immutable traceability system, through a third-party certification mechanism and credit evaluation model, effectively reducing transaction uncertainty [19]. Under the mode of industrial synergy network enabling supply chain management, traditional supply chains gradually evolve into cluster-based supply chain strategic alliance symbiotic systems. The contact methods between enterprises within the alliance, between the supply chain, and between the symbiotic system and the surrounding environment have scenarios of resource exchange and utilization, sharing of energy, real-time information exchange, and symbiotic circulation. For instance, in the Kalenburg Eco-Industrial Park, the by-products such as fly ash and gypsum generated during the flue gas treatment process in coal-fired power generation can be reused by cement and gypsum board manufacturers, enabling producers near the factory to achieve low-cost and efficient utilization of raw materials without the need for long-distance purchases, saving a significant amount of logistics costs and promoting the transformation and upgrading of the circular supply chain [20].

3.5 Policy Empowerment for Industrial Synergy and Construction of Circular Supply Chain

The industrial synergy network enhances market driving force through policy empowerment, thereby indirectly promoting the construction of a circular supply chain. Its core concept requires breaking through traditional enterprise boundaries and expanding a new situation that encompasses the upstream and downstream of the industrial chain, including manufacturers, suppliers, and recyclers. At the same time, government research institutions provide policy support and technological innovation to promote the construction of energy networks and waste treatment facilities, providing a strong guarantee for the development of the circular supply chain.

4 THE CONTRADICTIONS AND CHALLENGES OF THE INDUSTRIAL SYMBIOSIS NETWORK IN ENABLING CIRCULAR SUPPLY CHAINS

Although the intra-industry symbiosis network provides enabling forms such as technological innovation, ecological space-vehicle construction, and policy experimentation fields for the shaping and upgrading of circular supply chains, and offers key enabling support for the shaping and upgrading of circular supply chains, the two still face deep-seated and systemic dilemmas in the process of collaborative evolution.

First, there are challenges in value distribution during the process of shaping the circular supply chain through industrial symbiosis. The ecological benefits generated by the recycling of resources in the circular supply chain often cannot be fairly distributed among different links [21]. The theoretical logic of value realization in the industrial symbiosis network is that ecological benefits automatically transform into common gains. However, in practice, ecological value is difficult to be precisely measured, and the core enterprises still hold monopolistic pricing power and rule-making power, ultimately leading to unfair distribution of ecological benefits. For example, a recycling enterprise uses a certain waste as the raw material for a new product of the downstream enterprise, but the green brand value generated by this new product for the downstream enterprise cannot be quantified for the upstream enterprise, resulting in an uneven distribution of benefits. Long-term imbalance in value distribution will inevitably cause the industrial symbiosis to lose its symbiotic mechanism and motivation.

Second, the industrial symbiosis network has the potential for risk contagion. Due to the significant differences in the risk-resistance capabilities of enterprises within the industrial symbiosis network, the symbiotic network formed by the interconnections among enterprises will intensify the force of risk transmission. Specifically, when some enterprises encounter operational crises or financial chain disruptions, the supply risks caused by these events will be transmitted along the supply chain to their symbiotic partners, resulting in the transfer and spread of risks. This will prevent more enterprises from conducting normal production activities, leading to the collapse of the entire symbiotic network system.

Thirdly, the empowerment of circular supply chains by industrial symbiosis networks faces issues such as technical challenges and difficulties in policy compatibility. At the technical level, the data platform of industrial symbiosis networks and the circular supply chain have a data island effect, causing the disruption of the transmission of material flow and information flow across scales [21]. At the level of institutional compatibility, the industrial symbiosis network theory lacks feasibility effect assessment models and early policy trial-and-error tests when guiding the construction of circular supply chains in practice. Due to the different economic backgrounds and institutional foundations in different regions, the feasibility of industrial symbiosis network empowerment of circular supply chains tends to be theoretical and lacks supporting basic institutional support. When developing countries draw on the experience of developed countries in industrial symbiosis, they often fail to use policy tools due to the imperfect market mechanism, exposing the limitations of theoretical context adaptability [22].

5 ANALYSIS OF THE PATHWAY OF ENABLING CIRCULAR SUPPLY CHAINS THROUGH INDUSTRIAL SYNERGY NETWORKS

As the direct driving force for shaping and upgrading circular supply chains, industrial synergy networks involve complex mechanisms in their enabling process. Meanwhile, they face multiple challenges and difficulties in practice. To address these real-world problems, the academic community is focusing on exploring new paths. The core objective is to focus on three dimensions: how to enhance the enabling effect of industrial synergy networks? How to improve the efficiency of resource recycling throughout the entire chain? And can potential systemic risks be effectively mitigated, thereby achieving efficient and stable operation of the circular economy model?

From the perspectives of addressing information asymmetry and optimizing the mechanism of benefit distribution, the extensive application of digital technology has provided a new opportunity to solve this problem. On one hand, the immutable data chain constructed by blockchain technology enables precise traceability of resources from the source of production, to the final consumption, and to the ultimate recycling, providing a way for data visualization. On the other hand, smart contracts, by reconfiguring the logical basis and technical execution path of value distribution, offer a systematic solution to the issue of unfair benefit distribution. For example, by setting monitoring thresholds for key indicators such as the purity of recycled plastic, once the transaction meets the conditions, the smart contract can automatically trigger the preset benefit distribution rules, significantly alleviating the problem of unfair distribution caused by information asymmetry or execution deviations [3]. The application of digital technology provides strong support for building a fair and efficient collaborative ecosystem for circular supply chains.

In terms of enhancing system resilience, digital technologies have become a key pillar for strengthening the risk-resistance capabilities of industrial symbiotic networks and supply chains. The comprehensive application of technologies such as blockchain, the Internet of Things, and big data analysis enables real-time and comprehensive data monitoring of the entities within the symbiotic network and each link of the supply chain. This comprehensive data visualization not only helps prevent the risk contagion effect caused by excessive symbiotic dependence but also enables rapid response in the event of a risk incident. When some symbiotic enterprises encounter shocks and face the risk of supply disruption, the intelligent scheduling system based on real-time data updates can quickly identify and introduce alternative enterprises to intervene, effectively preventing the breakdown of the supply chain. Therefore, the application of digital technologies significantly enhances the system's risk early warning capability and emergency response efficiency. It provides precise data visualization and monitoring, prompting enterprises to maintain necessary collaboration while moderately adjusting the dependence relationships between symbiotic network and supply chain node enterprises, thereby overall improving the adaptability of the symbiotic network and the resilience of the circular supply chain [23]. Moreover, with the analytical capabilities of big data and cloud computing, enterprises can achieve real-time monitoring and risk assessment of the supply chain throughout the process. On one hand, based on real-time data sharing, they gradually achieve dynamic adjustment of production plans and logistics strategies, effectively reducing inventory accumulation and resource waste, thereby continuously enhancing their operational resilience. On the other hand, advanced data visualization tools can issue warnings when initial signs of an emergency appear and intelligently recommend alternative solutions, achieving global optimization of the supply chain and risk resistance capabilities.

Finally, it must be recognized that the policy environment is indispensable in catalyzing the enabling effect of the industrial symbiosis network. Although the industrial symbiosis network has promoted the structural upgrading of the circular supply chain from multiple aspects such as technology and collaboration models, it is equally important to highly value the strong policy support and clear industrial guidance, which are the key external conditions for ensuring the standardized and orderly transformation of this process. In practical operations, particular attention should be paid to the differences in policy environments among different regions, and a hierarchical and categorized refined management system should be constructed. At the same time, flexible and efficient policy response and feedback channels should be established. By conducting regular policy research and actively collecting enterprise feedback, the perception and adaptation speed of enterprises to policy changes can be effectively enhanced, ensuring that policies truly benefit enterprises and jointly creating a institutional environment that supports the sustainable development of the circular supply chain. Table 2 describes the characteristics, implementation paths and intermediate goals of industrial symbiosis and circular supply chains.

Table 2 Industrial Symbiosis Empowers the Shaping of Circular Supply Chains

Category	Content
Characteristics of Industrial Symbiosis and Circular supply chains	Industrial symbiosis focuses on vertical value integration; supply chains focus on multi-node collaboration of information flow, logistics, and capital flow; linkage relies on digital information sharing, collaborative planning, and risk sharing
Mediating Path	Networked, intelligent, platform-based, and innovation-driven; core technologies include cloud computing, big data, the Internet of Things, and artificial intelligence; emphasis on the status of digital resources as production factors and the construction of digital infrastructure
Ultimate Goal	Sustained economic growth, efficient utilization of resources and the environment, and improvement of social welfare; emphasis on the integration of green supply chain management and circular economy concepts

COMPETING INTERESTS

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