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

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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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