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Exploring the Role of Waste Storage in Industrial Symbiosis Networks via a Hybrid Simulation Approach: A Case Study of the Food Industry

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ABSTRACT

Objective: This study investigates how waste storage, waste quality, and market dynamicity influence the economic and environmental performance of industrial symbiosis networks in Iran's food sector.

Methodology: A hybrid simulation approach, combining agent-based modeling and discrete event simulation, is employed to analyze the dynamics of industrial symbiosis networks in the food sector in Iran. This integrated method enables a detailed examination of how waste quality, storage duration, and market dynamicity jointly affect network performance. The model is implemented and simulated using AnyLogic software.

Results: The simulation results demonstrate that effective management of waste storage is essential for improving the economic and environmental performance of industrial symbiosis networks in the food sector. Extending the storage duration allows firms to better align waste supply with demand, which is particularly valuable in volatile markets. However, the benefits of longer storage depend on waste quality: for high-quality waste, additional storage costs are offset by higher exchange values, while for low-quality waste, prolonged storage mainly increases costs and reduces profitability. The study also finds that waste storage strategies can substantially buffer the negative effects of market fluctuations.

Conclusion: This paper advances circular economy research by presenting an analytical framework that integrates agent-based modeling and discrete event simulation to analyze industrial symbiosis networks. The findings suggest that managing storage duration can improve economic and environmental outcomes, while waste storage strategies help firms mitigate the negative impacts of market volatility. These insights can help managers and policymakers improve waste management in Iran's food sector.

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Introduction

Industrial symbiosis (IS), a subfield of industrial ecology (IE), has gained significant attention in recent years as a strategy to advance a circular economy (CE) (Corsini et al., 2024; Foroozanfar et al., 2022). IS involves the collective engagement of enterprises, where waste generated by one firm is utilized as a production input by another. This approach allows waste-producing firms to reduce landfill disposal, while waste-utilizing firms decrease their reliance on primary raw materials (Junge et al., 2023). Consequently, IS implementation can enhance production efficiency, generate competitive advantages, and simultaneously create economic, environmental, and social benefits. These advantages may provide participating companies with a competitive edge over those not engaged in IS, ceteris paribus (Fraccascia, Albino, et al., 2017). Numerous studies have also demonstrated that IS can yield indirect environmental benefits for society, such as reduced CO_2 emissions and lower energy consumption. Therefore, industrial symbiosis is widely recommended by both scholars and policymakers for its potential to improve environmental and economic outcomes (Ashton et al., 2017; Barrau & Glaus, 2023; Huang et al., 2019).

The exchange of waste materials between firms forms what is known as an industrial symbiosis network (ISN), which can develop through two main mechanisms: (i) top-down ISNs, established by a central authority, and (ii) bottom-up, self-organized ISNs (Huang et al., 2019). The current research concentrates on the self-organized ISNs, which naturally emerge from individual IS relationships between independent firms, typically without an initial intention to create a broader network. These networks are categorized as complex adaptive systems, arising from interactions among autonomous agents at the foundational level (Albino et al., 2016; Demartini et al., 2022; Ghali et al., 2017).

While IS facilitates reductions in waste disposal and raw material procurement costs, it introduces two additional operational costs, including waste transportation and treatment (Ayazi et al., 2023). The allocation of these costs among participating firms is crucial, as cost-sharing strategies can significantly influence the feasibility of ISNs. Moreover, various factors, such as geographical location, type, quantity, price, and quality of waste materials, affect the emergence and success of IS (Yazan & Fraccascia, 2020).

To manage mismatches in the timing and quantity of waste exchange in ISNs, waste storage is an essential operational strategy. This involves temporarily storing waste produced by one firm until they can be utilized by another (Wu et al., 2017). Waste storage is particularly useful when the timing or amount of waste generation and consumption do not align, making direct and continuous exchange challenging (Yazan & Fraccascia, 2020). By storing waste for later use, firms are able to accommodate fluctuations in production and demand, enabling the continuation of material exchanges despite temporal or quantitative disparities (Golev et al., 2014).

However, the effectiveness of waste storage is strongly influenced by waste quality, including purity, composition, and contaminant levels. Variations in waste quality, which may arise from differences in production processes or operational practices, can significantly affect the suitability of stored waste for reuse and the associated economic and environmental benefits (Fraccascia, 2019; Golev et al., 2014). Therefore, to comprehensively evaluate the impact of waste storage, it is essential to explicitly consider waste quality, as the interaction between storage strategies and quality attributes determines the overall value and sustainability of ISNs.

The present research aims to investigate the effects of storing waste for specific durations under different levels of waste quality in ISNs, specifically addressing the following research questions:

RQ1: What is the effect of implementing waste storage on the economic and environmental performance of ISNs utilizing food-grade fruit juice waste in Iran?

RQ2: How does waste storage influence the waste exchange ratio among firms participating in ISNs based on food-grade fruit juice waste in Iran?

To address these questions, a cost-benefit analysis model is proposed to evaluate the potential economic advantages of IS relationships under different scenarios from the perspective of enterprise operations. The model is based on the Enterprise Input-Output (EIO) framework and integrates agent-based modeling (ABM) with discrete-event simulation (DES) to simulate the dynamics of ISNs. Simulation is a useful tool for studying complex systems, especially when primary data is limited, enabling researchers to explore system behavior under various scenarios and assess how different variables affect outcomes (Davari et al., 2022; Hatami-Marbini et al., 2020). This approach is particularly valuable in the early design phase, helping to reduce the risk of wasted time and costs through improved decision-making. By analyzing interactions and dynamics, simulation can also enhance system performance and support the development of innovative solutions for adaptive systems (Maleki et al., 2024). In addition, a systematic literature review (SLR) is conducted to provide a comprehensive understanding of existing research on IS, ABM and DES.

By integrating ABM and DES and specifically examining waste storage, this paper aims to provide valuable insights for the effective establishment of IS. The scenarios are simulated in a numerical case study involving an ISN consisting of fruit juice producers and dairy producers. By comparing outcomes under various scenarios, this research quantitatively investigates the impacts of waste storage on the effectiveness of ISNs.

The selection of the food industry in Iran as a case study is based on several key factors, including the significant volume and diversity of waste generated by this sector, its strategic importance to the national economy and the high potential for resource recovery and exchange within its supply chains (Taghizadeh-Yazdi et al., 2021). Additionally, the food industry faces increasing regulatory and environmental pressures to improve waste management practices, making it a relevant and timely context for investigating the effectiveness of IS strategies (Garcia-Garcia et al., 2019; Mirabella et al., 2014; Mohammadi et al., 2022). The availability of data and the presence of existing networks of producers and processors further support its suitability for in-depth analysis using simulation approaches.

The remainder of this research is organized as follows: Section 2 provides a systematic review of the literature, highlighting key research gaps, particularly in the areas of IS and simulation approaches. Section 3 explains the research methodology, detailing simulation models and analytical techniques used to address the research questions. Section 4 presents the main results, offering a comprehensive analysis of the simulation outcomes and their implications for ISNs. In Section 5, the findings are discussed in relation to the existing literature, and directions for future research are suggested.

Literature Background

This section provides a systematic review of the literature related to ISNs. The objective is to identify research gaps relevant to the consideration of waste storage and the integration of advanced simulation methods. Such a review establishes the relevance and novelty of the current research.

To ensure the quality and reliability of the reviewed literature, the Web of Science (WOS) database was chosen as the primary search platform due to its reputation for indexing reputable scholarly journals (Ayazi et al., 2025). The search strategy was designed to align with the research objectives and followed best practices for SLR (Hansen et al., 2019). Specifically, the search was conducted using the terms "industrial symbiosis" AND ("agent based model*" OR ABM OR "multi-agent"), covering articles published between 2009 and July 2025.

As illustrated in Figure 1, the search terms were initially applied across all text fields in the Web of Science (WOS) database, resulting in the identification of 55 records. In the next stage, only journal articles were retained in order to ensure scientific rigor, which reduced the number of records to 46. The search was then further refined to include only those articles where the terms appeared specifically in the title, abstract, author keywords, or keyword plus fields, which helped to improve the relevance and specificity of the results and yielded 44 English-language papers. To guarantee a comprehensive and focused review, a detailed manual screening of the full texts of these 44 papers was conducted, evaluating each article for its alignment with the study's research objectives. This final selection process identified 30 articles as most relevant to the objectives of this study, ensuring a solid foundation for the subsequent analysis and discussion.

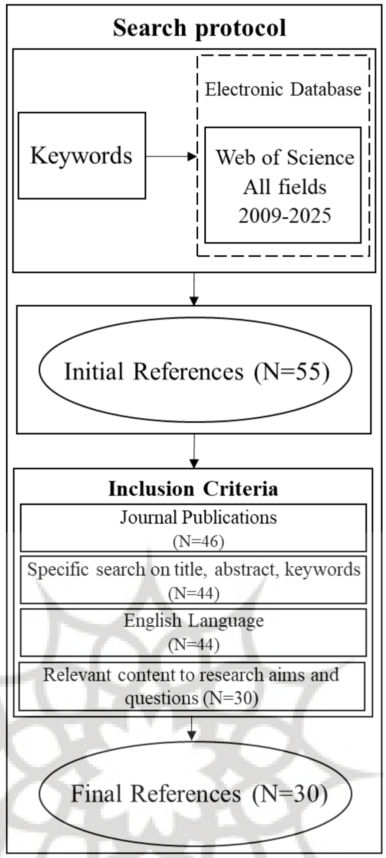

Figure 1. Systematic literature review methodology.

Consequently, 30 articles were chosen for comprehensive review and detailed analysis. Table 1 provides a summary of the findings from this review, allowing for a clear comparison of the main factors investigated across the selected studies. In this table, the "Factor" columns represent the key elements that affect the formation and development of ISNs. "Location" refers to the geographical position of the participating firms, while "Price," "Quality," and "Quantity" specify the respective characteristics of the industrial waste considered in each study. The "Storage" factor indicates whether a waste storage buffering strategy was examined, highlighting the role of storage in managing fluctuations in supply and demand. Together, these factors highlight the main aspects identified in the literature as influencing the establishment and performance of IS collaborations, providing a foundation for further analysis in this research.

Table 1. Overview of reviewed papers.

Scholar(s)	Aim	Method(s)	Factors						Result
			Location	Price	Quality	Quantity	Type	Storage	
(Mollica et al., 2025)	Exploration of the factors motivating companies to join IS online platforms	Agent based simulation	✓	✓	-	✓	✓	-	Subscription drivers and system benefits were identified
(Hua, 2024)	Analysis of the impact of environmental taxation on the performance of ISNs	Agent based simulation	-	-	-	✓	✓	-	Increasing environmental tax was found to increase symbiotic connections
(Anane et al., 2023)	Analyzing how transportation costs affect the feasibility of ISN	Agent based simulation and System dynamic	✓	✓	-	✓	✓	-	Feasibility of symbiosis was increased when transportation costs were lower and distances were shorter
(Walzberg et .al., 2023)	Evaluating the effectiveness of circular economy initiatives using agent-based modeling	Agent based simulation	✓	-	-	✓	✓	-	Six limitations of the circular economy have been identified
(L. Wang et al., 2023)	Evaluating policy effectiveness on China's industrial symbiosis system	Agent based simulation	✓	-	-	✓	✓	-	Increased symbiosis likelihood is demonstrated through the policy influence framework
(Han et al., 2022)	Developing an agent-based model to simulate material flows and IS processes	Agent based simulation	✓	-	-	✓	✓	-	Results in China indicate increased environmental efficiency and IS indicators during the growth phase
(L. Wang et al., 2022)	Examining the efficacy of policy strategies in promoting IS	Agent based simulation	✓	-	-	✓	✓	-	Both subsidy and penalty policies positively impact the implementation of IS

(Lange et al., 2021)	Examining the impact of actor behavior on the robustness of ISN	Agent based simulation	-	-	✓	✓	✓	-	Integrating behavior theory improves network robustness and emphasizes the role of human behavior in IS success
(Ruiz-Puente et al., 2021)	Developing a - model to understand urban-industrial systems	Agent based simulation	-	✓	✓	✓	✓	-	Urban-industrial systems are complex, self-organizing, and nonlinear
(Yu et al., 2021)	Examining IS implementation in the construction industry	Agent based simulation	✓	✓	✓	✓	✓	-	IS dynamics in concrete waste are highlighted, and circular strategies for construction are suggested
(Raimbault et al., 2020)	Introducing a simulation model for IS, with a focus on macro-level understanding	Agent based simulation and Optimization	✓	✓	✓	✓	✓	-	Geographical factors are shown to significantly influence the performance of ISNs
(Yazan et al., 2020)	Examining the negotiation phase of IS relationships	Agent based simulation and Game theory	-	✓	-	-	✓	-	Fair strategies are ultimately learned to be more beneficial in the long term,
(Fraccascia, 2020)	Examining the impact of online platforms on the creation of IS collaborations	Agent based simulation and Game theory	✓	-	-	✓	✓	-	The platform usage threshold for corporate benefits is highlighted
(Yazan & Fraccascia, 2020)	Examining the economic feasibility of IS	Agent based simulation	✓	✓	✓	✓	✓	-	Insights into cost-sharing dynamics influenced by the imbalance of waste supply and demand are found
(Fraccascia et al., 2020)	Examining the - impact of redundancy policy on the economic and environmental outcome of ISNs	Agent based simulation	✓	✓	✓	✓	✓	-	The optimal redundancy policy is affected by waste market dynamics and transaction costs
(Mantese & Amaral, 2018)	Assessment of IS indicators to enhance evaluation and decision making	Agent based simulation	-	✓	✓	✓	✓	-	Indicators were grouped by behavior, and combining them was recommended

(Meng et al., 2018)	Analyzing household solid waste recycling behavior and policy impacts	Agent based simulation	✓	✓	-	✓	✓	-	Resident separation and recycling rates were increased by specific waste charge policies
(Yazan et al., 2018)	Examining the dynamics of fertilizer markets and collaboration between livestock farmers and biogas producers	Agent based simulation	✓	-	✓	✓	✓	-	Economic benefits and price fluctuations were demonstrated by agent-based modeling
(Fraccascia & Yazan, 2018)	Investigating how online platforms impact the effectiveness of ISN	Agent based simulation	✓	-	-	✓	✓	-	Online platforms can improve economic and environmental performance
(Ghali et al., 2017)	Developing a model to examine the effect of social factors on the forming of industrial synergy	Agent based simulation	-	✓	-	-	-	-	Social dynamics and structure affect the creation of synergy
(D. Wang et al., 2017)	Developing a framework to examine the vulnerability of complex ISN	Agent based simulation	✓	-	-	✓	✓	-	system vulnerability is determined with the interaction between economic fluctuations and network structure
(Couto Mantese & Capaldo Amaral, 2017)	Validation of IS indicators	Agent based simulation	-	-	✓	✓	✓	-	The effectiveness of agent-based simulation in enhancing the robustness of IS indicators is emphasized
(Lange et al., 2017)	Developing design rules for implementing interventions in urban symbiotic agriculture networks	Agent based simulation	✓	-	✓	✓	✓	-	Proposing a design science method to bridge theory and practice in urban agricultural symbiosis networks
(Fraccascia, Giannoccaro, et al., 2017)	Examining the effectiveness of taxes and economic subsidies in ISN	Agent based simulation	-	✓	-	✓	✓	-	Both policies positively influence the creation of IS relationships
(Zheng & Jia, 2017)	Examining strategies to	Agent based simulation	-	-	-	-	✓	-	The identification of IS opportunities is influenced by

	promote the emergence of IS								knowledge coordination and relational coordination strategies
(Albino et al., 2016)	Examining the effectiveness of contractual mechanisms in ISN	Agent based simulation	✓	✓	-	✓	✓	-	The establishment of symbiotic relationships is facilitated by the proposed contract scheme
(Chandra-Putra et al., 2015)	Examining how jobs, housing, and environmental factors shape the development of industrial settlements	Agent based simulation	✓	-	-	✓	✓	-	Four classic settlement types; isolated enterprise, company town, economic agglomeration, and balanced city are found
(G. Wang et al., 2014)	Demonstrating a symbiosis analysis method for industrial ecological systems	Agent based simulation	-	✓	-	✓	-	-	System stability and increased symbiosis profit were demonstrated under modeled conditions
(Romero & Ruiz, 2014)	Development of an analytical model for redesigning industrial zones into eco-industrial parks	Agent based simulation and Game theory	-	✓	✓	✓	✓	-	The identification of collaborative strategies is facilitated
(Batten, 2009)	Demonstrating how agent-based simulation can foster IS among firms	Agent based simulation	✓	-	-	-	✓	-	Self-organized and eco-efficient IS has been fostered by agent-based simulation

A systematic review of the selected papers reveals that the role of waste storage has received limited attention. Previous studies (e.g., (Han et al., 2022; Walzberg et al., 2023; L. Wang et al., 2023)) neglect the possibility of temporarily storing waste before it is exchanged, and rarely consider the impact of waste quality on waste storage strategies. By overlooking waste storage strategies and their relationship with waste quality, these studies fail to capture how waste storage can effectively manage temporal mismatches between waste supply and demand, especially under market fluctuations. Furthermore, the explicit consideration of waste quality as a parameter influencing the economic and environmental performance of the ISNs is largely absent (e.g., (Lange et al., 2021; Mantese & Amaral, 2018)). This gap overlooks real-world complexities, where both the duration of waste storage and fluctuations in waste quality, driven by changes in production processes or operational strategies, jointly affect the outcomes of IS.

Another dimension that remains unexplored is the integration of ABM and DES in modeling ISNs. While ABM is effective for capturing decentralized decision making and emergent network structures, it often abstracts away operational details (Albino et al., 2016; Yazan et al., 2018). Conversely, DES excels at modeling operational dynamics such as processing times, production buffering, and stochastic events, but lacks the flexibility to represent strategic behavior, negotiation, and adaptive learning typical of ISNs (Kampa et al., 2017; Sajadi et al., 2010).

This paper pioneers the integration of ABM with DES in the field of ISNs. By adopting this hybrid approach, the study yields enhanced understanding of complex phenomena such as waste storage and stochastic events.

Materials and Methods

A hybrid simulation framework integrating ABM and DES is employed to more realistically describe the dynamics of ISNs in current work. Integrating these two simulation approaches allows the model to simultaneously capture the detailed operational aspects of production and waste management within firms as well as the adaptive, strategic interactions among network participants. By linking DES to ABM, the hybrid model enables a detailed analysis of how the duration of waste storage influences the overall performance of ISNs (Dubiel & Tsimhoni, 2005; Hybinette et al., 2006). The model is developed using Anylogic 8.9.0 Professional, which is a multi-method simulation modeling tool.

Within this framework, the internal production processes of both waste-producing and waste-utilizing firms are modeled using DES. The DES component simulates the temporal flow of production activities, capturing the generation of waste as discrete events within production lines. Each production process is represented as a sequence of events, including raw material input, processing, waste storage, product output, and waste generation (Ebrahimi et al., 2022; Zandieh & Motallebi, 2018). A notable capability of the DES is its support for inventory management of waste, facilitating the individual tracking of each batch by recording production timestamps and storage periods. Waste batches remain in inventory until they are either transferred for IS exchange or reach the end of their viable life and are discarded. This mechanism incorporates realistic constraints regarding the usability and shelf-life of waste, which can significantly influence the feasibility and timing of symbiotic exchanges (Azadeh et al., 2015; Bursi et al., 2015). The DES also allows consideration of waste quality throughout the production process. The quality attribute of waste can be configured to represent different scenarios (e.g., low, medium, or high quality), enabling the investigation of how variations in waste quality affect both economic and environmental outcomes (Fraccascia, 2019).

In ABM, each firm within the industrial symbiosis network is represented as an autonomous agent with its own objectives, behavioral rules, and decision-making processes. This approach enables the model to capture the heterogeneity of firms, such as differences in resources, preferences, operational strategies, and responses to environmental changes, reflecting the diversity found in real-world industrial networks. Within this ABM framework, companies act as agents functioning either as waste producers or waste users, and are modeled according to the EIO approach, whereby materials are transformed into finished goods, with waste generated as a secondary outcome. In the context of IS, the waste produced by one firm can be reused by another as a primary input (Alizadeh Asari et al., 2025; Yu et al., 2021). ABM facilitates the analysis of these diverse interactions, allowing firms to adopt different strategies for waste exchange, storage, and collaboration based on their economic motivations and operational context. Furthermore, ABM can simulate evolutionary processes and adaptive behaviors over time, representing how symbiotic relationships are established, maintained, or dissolved, as well as how firms adapt to regulatory changes or market dynamics (Han et al., 2022; Khatami Firouzabad et al., 2025; Mollica et al., 2025).

At the agent level, the model characterizes the operational behavior of firms involved in waste exchange. Each firm produces a single primary product, and the production quantity is driven by market demand. For simplicity, the model includes only those wastes that can substitute for inputs, and only those inputs that are replaceable by wastes (Fraccascia, 2020).

Assume that there are n(P) waste producers of type P and n(U) waste users of type U situated within a specific geographic region. let firm i represent one of the waste producers, and firm j represent one of the waste users. The quantities of waste produced and inputs required depend on both the output generated and the specific production technologies employed (Fraccascia & Yazan, 2018).

Therefore, the quantity of waste generated by firm i at time t is determined as outlined below.

$$w_i(t) = x_i(t) \cdot W_p \tag{1}$$

where $x_i(t)$ represents the quantity of output produced at time t by firm i, and W_p is a technical coefficient that indicates how much waste is generated per unit of output. In a similar manner, the amount of input requirement of firm j at time t can be calculated as follows.

$$r_j(t) = x_j(t) \cdot R_u \tag{2}$$

Where $x_j(t)$ indicates the quantity of output generated by company j at time t, and R_u is a technical parameter that specifies the amount of the input consumed for each unit of output.

For simplicity, it is also presumed that a company is unable to trade the similar type of waste with multiple firms simultaneously. This reflects actual business practices, as companies typically favor one-to-one IS partnerships (Chopra & Khanna, 2014).

The exchangeable quantity of waste between companies i and j at time t is defined using the following equation, assuming that a unit of waste is capable of substituting for one input unit (Fraccascia, Giannoccaro, et al., 2017).

$$e_{i\to j}(t) = \min\{w_i(t); r_j\} \tag{3}$$

It is assumed that transferring waste from i to j involves no lead time, as IS relations are generally formed between companies located in close proximity (Fraccascia, 2020; Jensen et al., 2011a). At time t, such symbiotic collaborations can generate two main benefits: (1) the reduction of waste disposed of in landfills ($RDC_{i\to j}(t)$), and (2) the decrease in primary inputs purchased from conventional suppliers ($RPC_{j\to i}(t)$). These advantages can be computed as described below.

$$RDC_{i\to j}(t) = udc_i \cdot e_{i\to j}(t) \tag{4}$$
$$RPC_{j\to i}(t) = upc_j \cdot e_{i\to j}(t) \tag{5}$$

where udc_i represents the cost of disposing of a unit of waste, and upc_j indicates the cost of purchasing a unit of input from traditional suppliers.

Arising additional costs from IS, specifically, waste transportation and treatment expenses are represented by $Wtra_{i\to j}(t)$ and $Wtre_{i\to j}(t)$, respectively. Transferring waste from the producer to the user company entails transportation costs. This can be calculated by the following equation.

$$Wtra_{i\to j}(t) = utra_{i\to j} \cdot d_{i\to j} \cdot e_{i\to j}(t) \tag{6}$$

where $utra_{i\to j}$ is defined as unit transportation cost per kilometer between firms i and j, $d_{i\to j}$ is the distance between these firms.

Treatment costs are incurred when waste must be processed before it can be used as an input by another firm (L. Wang et al., 2022). Furthermore, to analyze the effect of waste quality on the performance of the ISN, the processing cost of a unit of waste is modeled as a function of the quality parameter over simulation time. This can be calculated as described below.

$$Wtre_{i\to j}(t) = utre_{i\to j} \cdot e_{i\to j}(t) \tag{7}$$

Where:

$$utre_{i\to j} = utre_{i\to j}^{max} - \left(utre_{i\to j}^{max} - utre_{i\to j}^{min}\right) \cdot \frac{q_i - q_{min}}{q_{max} - q_{min}} \tag{8}$$

Where $Wtre_{i \to j}(t)$ is the waste treatment cost, and $utre_{i \to j}$ is the expense to treat a unit of waste, which is a function of waste quality. It is assumed that this function is linear (Yazan et al., 2016). Also, $utre_{i \to j}^{min}$ and $utre_{i \to j}^{max}$ represent the minimum and maximum processing costs per unit of waste, respectively. In addition, q_i describes the quality of waste produced by firm i, while q_{min} and q_{max} are the minimum and maximum quality values of a unit of waste exchanged.

By varying waste quality across different scenarios, the model enables a detailed analysis of how fluctuations in waste quality affect processing costs, waste acceptance rates, and subsequently the overall economic performance of the symbiosis network.

Furthermore, waste storage costs are incurred when industrial waste needs to be kept in storage facilities for a period of time before it is reused, or disposed of. This can be calculated as follows.

$$Wst_{i \to j}(t) = ust_{i \to j} \cdot WSD \cdot e_{i \to j}(t) \quad (9)$$

Where $ust_{i \to j}$ denotes the daily storage cost per unit of waste and WSD is the number of storage days for storing each unit of waste.

To clarify these interactions, Figure 2 illustrates the physical flows between two generic firms forming an IS relationship, along with the monetary flows between these firms and the external environment.

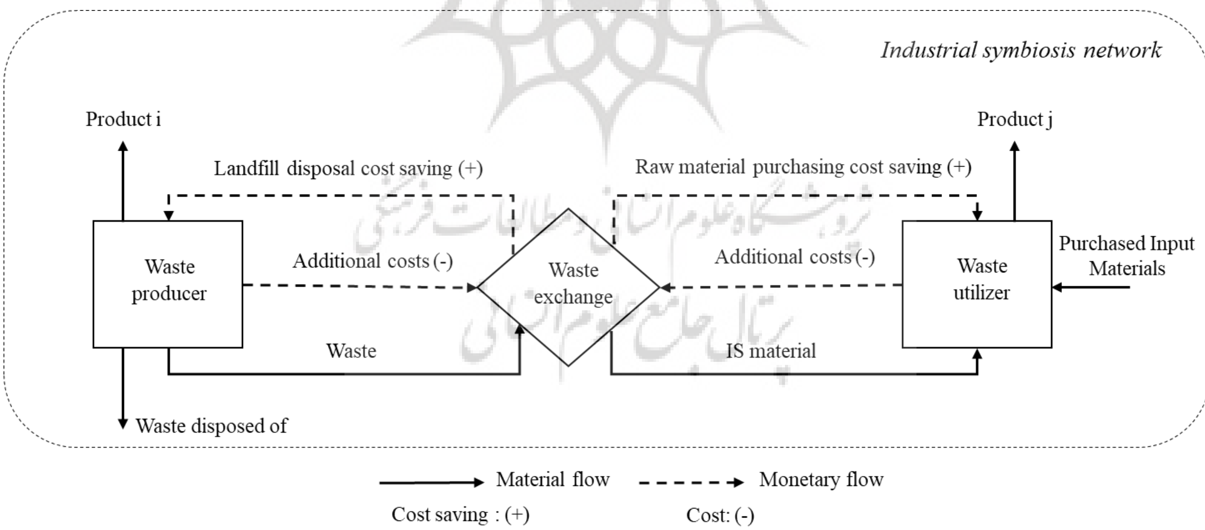

Figure 2. Physical and monetary flows between two firms and the external environment

Building on agent interactions, different contractual arrangements may affect how costs are shared between firms involved in waste exchange. According to the (Fraccascia, 2020), five distinct contractual clauses can govern the allocation of costs in waste exchange transactions between firms

i and j. These terms are captured by the parameter $\alpha_{i\rightarrow j}$, which specifies the proportion of transportation and treatment costs paid by firm i (see Table 2).

Table 2. Various contract terms that company can employ for waste exchange.

Case	Cost sharing + monetary flow between firms
$\alpha_{i\rightarrow j} < 0$	Firm j pays additional costs +firm j purchase the waste from firm i
$\alpha_{i\rightarrow j} = 0$	Firm j pays additional cost + the waste is exchanged free of charge
$0 < \alpha_{i\rightarrow j} < 1$	Additional costs are shared between firms + the waste is exchanged free of charge
$\alpha_{i\rightarrow j} = 1$	Firm i pays additional cost + the waste is exchanged free of charge
$\alpha_{i\rightarrow j} > 1$	Firm i pays additional costs +firm i pays compensation to firm j

The economic benefit (EB) that companies i and j would obtain through symbiotic collaboration at time t is obtained using the equations provided below.

$$\mathrm{EB}_{i\rightarrow j}(\mathrm{t}) = RDC_{i\rightarrow j}(t) - \alpha_{i\rightarrow j}(\mathrm{t}) \cdot [Wtra_{i\rightarrow j}(t) + Wtre_{i\rightarrow j}(t) + Wst_{i\rightarrow j}(t)] \quad (10)$$

$$\mathrm{EB}_{j\rightarrow i}(\mathrm{t}) = RPC_{j\rightarrow i}(t) - [1 - \alpha_{i\rightarrow j}(\mathrm{t})] \cdot [Wtra_{i\rightarrow j}(t) + Wtre_{i\rightarrow j}(t) + Wst_{i\rightarrow j}(t)] \quad (11)$$

The greater this economic benefit, the more likely a firm is to participate in the industrial relationship, ceteris paribus. A fitness function, $\mathrm{F}_{i\rightarrow j}(\mathrm{t})$ (or $\mathrm{F}_{j\rightarrow i}(\mathrm{t})$), is described to quantify the willingness of firm i (j) to engage in symbiotic cooperation with firm j (i). The value of the fitness function is determined by calculating the ratio of each enterprise's economic benefits obtained through IS to the costs associated with non-cooperation (Yazan & Fraccascia, 2020).

$$\mathrm{F}_{i\rightarrow j}(\mathrm{t}) = \frac{RDC_{i\rightarrow j}(t) - \alpha_{i\rightarrow j}(\mathrm{t}) \cdot [Wtra_{i\rightarrow j}(t) + Wtre_{i\rightarrow j}(t) + Wst_{i\rightarrow j}(t)]}{udc_i \cdot w_i(t)} \quad (12)$$

$$\mathrm{F}_{j\rightarrow i}(\mathrm{t}) = \frac{RPC_{j\rightarrow i}(t) - [1 - \alpha_{i\rightarrow j}(\mathrm{t})] \cdot [Wtra_{i\rightarrow j}(t) + Wtre_{i\rightarrow j}(t) + Wst_{i\rightarrow j}(t)]}{upc_j \cdot r_j(t)} \quad (13)$$

Firm i (or j) is assumed to collaborate with firm j (or i) only if the fitness value of their symbiotic relationship is at least equal to a predetermined threshold, T_i (T_j). Collaboration will only take place when this fitness value meets or exceeds the required threshold. This threshold reflects each firm's inclination to adopt the symbiotic approach: a higher threshold requires greater economic benefits to incentivize cooperation.

Based on the model dynamics, each firm is capable of performing the following activities: (1) searching for a new IS cooperator with whom to attempt forming a partnership; (2) initiating a new

IS collaboration; and (3) assessing a current IS collaboration to decide whether to continue or terminate it.

In this context, all firms are considered potential candidates for symbiotic partnerships. When selecting a partner, it is assumed that a given firm i attempts to create a symbiotic collaboration with firm j based on a certain probability, denoted as $P(i \rightarrow j)$. This probability is influenced by the geographic distance between the two firms; specifically, the likelihood of firm j being selected as a potential partner increases as its proximity to firm i decreases (Jensen et al., 2011b).

Suppose firms i and j were not collaborating at time $t-1$. As they attempt to form an IS partnership at time t, each firm computes its own fitness value using Eqs. (12) and (13), and the parameter $\alpha_{i \rightarrow j}(t)$ is assigned randomly, as shown in Table 2. If both conditions $F_{i \rightarrow j}(t) \geq T_i$ and $F_{j \rightarrow i}(t) \geq T_j$ are satisfied simultaneously, a symbiotic collaboration between i and j is established; otherwise, it does not form (Fraccascia, Giannoccaro, et al., 2017).

The employed hybrid model is depicted in Figure 3, where at each simulation step, the DES layer models the discrete event sequence of each firm's production line and provides updated data on the quantity of waste produced to the ABM layer. The interaction between the layers enables agents to dynamically respond to changes in waste availability driven by the operational events simulated in the DES layer.

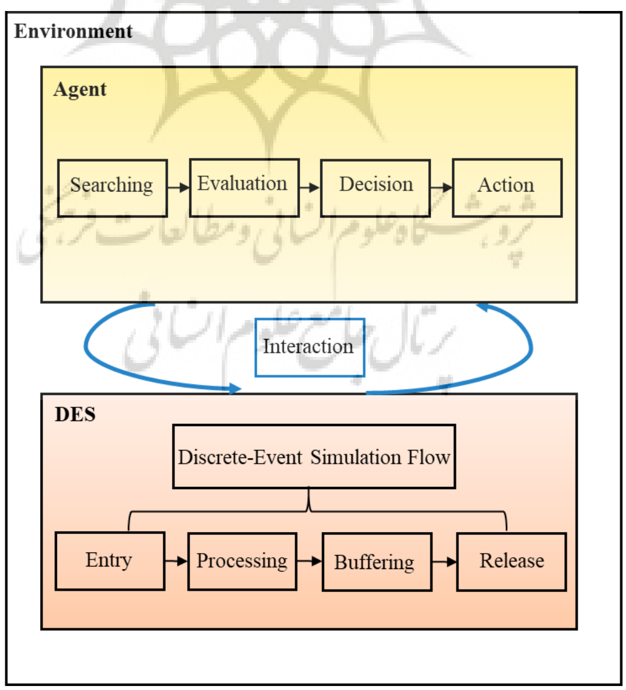

Figure 3. Agent-based and discrete-event simulation framewor

To run simulation, data adapted from fruit juice producers and dairy producers in Iran are utilized (Iran Dairy Industries Society, 2024; Iran Soft Drink Producers Association, 2024). The model considers two categories of firms located in a given geographical area: fruit juice producers, which act as waste generators, and dairy producers, which serve as waste users. To streamline the analysis, it is presumed that every firm runs a single production process, and the resulting output is the principal product sold. Fruit juice producers generate waste by-products during production, which can be utilized as alternative inputs by dairy producers, after completing a treatment process. Thus, IS relationships can be established between fruit juice producers and dairy producers.

The present study considers 100 fruit juice producers and 100 dairy producers, each randomly distributed within a square geographical area with a 200 km side in Iran (Euclidean distances among companies are considered). The locations of all firms are explicitly mapped using a Geographic Information System (GIS). At the beginning of the simulation, each fruit juice producer tries to establish symbiotic partnerships with dairy producers. The simulation is conducted and monitored over 250 days to observe the formation and evolution of IS partnerships. Each scenario is replicated 20 times. The findings reflect the average values obtained from all replications.

Each company experiences stochastic demand for its primary product over time, represented by a normal distribution with mean μ and standard deviation σ. It is presumed that $= x$, and σ is uniformly distributed within the range of 10% to 30% of μ. The numerical values for average product demand, waste production and input requirement technical coefficient, disposal costs for fruit residuals, input purchasing costs, as well as expenses related to waste transportation, treatment and storage, are based on empirical case studies and summarized in Table 3.

Table 3. Physical and monetary data used in the numerical example.

	Fruit Juice Producers	Dairy Producer
Average amount of output produced (x)	$300 \frac{\text{t}}{\text{day}}$	$50 \frac{\text{t}}{\text{day}}$
Waste production technical coefficient (W)	$0.2 \frac{\text{t fruit residuals}}{\text{t fruit}}$	-
Waste disposal cost	$20{,}000{,}000 \frac{\text{IRR}}{\text{t fruit residuals}}$	-
Input requirement technical coefficient (R)	-	$1.2 \frac{\text{t feed}}{\text{t dairy}}$
Input purchase cost	-	$80{,}000{,}000 \frac{\text{IRR}}{\text{t feed}}$
Waste transportation cost	$800{,}000 \frac{\text{IRR}}{\text{t fruit residuals}\cdot\text{Km}}$	
Minimum waste treatment cost	$10{,}000{,}000 \frac{\text{IRR}}{\text{t fruit residuals}}$	
Maximum waste treatment cost	$60{,}000{,}000 \frac{\text{IRR}}{\text{t fruit residuals}}$	
Daily storage cost	$1{,}200{,}000 \frac{\text{IRR}}{\text{t fruit residuals}}$	

To account for the unique characteristics of individual firms, each waste producer and waste user is assigned a threshold value that is uniformly distributed between 10% and 15%, reflecting varying tendencies to participate in IS relationships. Waste quality, modeled as an input parameter with values uniformly distributed between 40% and 46% of the nutritional value of standard feeds (such as corn or soybean meal), is evaluated to determine its influence on network performance. Additionally, the duration of waste storage is considered as a decision variable, with simulations conducted separately for three fixed periods: 1 day, 5 days, and 10 days. The maximum storage duration is considered based on the expiration period of this type of waste, which is 10 days. Throughout this storage period, within the expiration period and under appropriate storage conditions designed to maintain quality, the quality of waste does not change significantly, according to empirical evidence and real operational data.

The simulation scenarios systematically vary three key factors: market dynamicity, waste quality, and storage duration, to assess their effects on economic and environmental outcomes. Market dynamicity is represented by the coefficient of variation (σ/μ) of final customer demand, indicating the level of demand fluctuations. For waste quality, three scenarios are considered, in which all firms are assigned either low, medium, or high quality values, representing uniform quality levels across the network. Each scenario is analyzed and compared to evaluate its impact on the performance of the ISN. The simulation thus explores three distinct values for market dynamicity, three levels of waste quality, and three storage durations.

Three indicators are defined to assess the performance of the ISN: the economic performance indicator (ECOP), the environmental performance indicator (ENVP) and the waste exchange ratio (WER).

The economic performance indicator (ECOP) is calculated as the ratio of the economic benefits generated through the IS procedure (ECOB) to the production costs (PC) incurred by the participating firms over the entire simulation period.

$$ECOP = \frac{\sum_t ECOB(t)}{\sum_t PC(t)} \tag{14}$$

Where:

$$ECOB(t) = \sum_i \sum_j \{[udc_i(t) + upc_j(t) - utra_{i\to j}(t) \cdot d_{i\to j} - utre_{i\to j}(t) - ust_{i\to j}(t) \cdot WSD] \cdot e_{i\to j}(t)\} \tag{15}$$

$$PC(t) = \sum_i udc_i(t) \cdot w_i(t) + \sum_i upc_j(t) \cdot r_j(t) \tag{16}$$

ECOP takes values from 0 to 1 and represents the proportion of production cost savings achieved through IS. For example, an ECOP value of 0.3 indicates that IS has led to a 30% reduction in production costs for firms participating in the network.

The ENVP is calculated as the proportion of the total amount of waste not disposed of in the landfill and primary inputs saved to the total waste generated and primary inputs required throughout the entire simulation time. The coefficient “2” in the numerator of equation (17) reflects that each exchanged unit of waste simultaneously (1) avoids landfill disposal and (2) eliminates the need for inputs from conventional suppliers at the recipient firm. In this way, both key environmental benefits of waste exchange are captured (Fraccascia & Yazan, 2018).

$$ENVP = \frac{\sum_{t=1}^{20}[2\sum_{i=1}^{100}\sum_{j=1}^{100} e_{i\to j}(t)]}{\sum_{t=1}^{20}[\sum_{i=1}^{100} w_i(t) + \sum_{j=1}^{100} r_j(t)]} \quad (17)$$

ENVP ranges from 0 to 1 and indicates the extent to which material flows into and out of the ISN are reduced compared to a scenario without symbiotic relationships. For example, ENVP=0.2 indicates that industrial symbiosis is decreasing waste flows from the ISN and input flows to the ISN by 20% compared to a scenario without IS. A higher ENVP value reflects greater environmental sustainability, assuming all other factors remain constant.

The WER is calculated as the amount of waste transferred (i.e., not disposed of due to IS practices) divided by the total amount of waste produced (Fraccascia, 2020).

$$WER = \frac{\sum_{t=1}^{20}[\sum_{i=1}^{100}\sum_{j=1}^{100} e_{i\to j}(t)]}{\sum_{t=1}^{20}\sum_{i=1}^{100} w_i(t)} \quad (18)$$

This ratio ranges from zero, when no waste is exchanged within the IS network, to one, when all produced waste is recovered through IS.

Results

This section presents the simulation results for all scenarios. The economic and environmental performance of fruit waste-based IS exchanges are described in the Table 4 and

Table **5**, respectively. The validation process for the simulation model is outlined in the Appendix A.

Table 4. Economic performance for fruit waste-based IS exchanges.

Waste Storage Duration	Waste Quality	Waste Market Dynamicity		
		0.1	0.2	0.3
WSD=1	Low	0.154	0.168	0.189
	Medium	0.211	0.219	0.232
	High	0.253	0.257	0.262
WSD =5	Low	0.284	0.2835	0.282
	Medium	0.374	0.377	0.379
	High	0.391	0.402	0.406
WSD =10	Low	0.232	0.232	0.232
	Medium	0.392	0.395	0.394
	High	0.476	0.474	0.477

Table 5. Environmental performance for fruit waste-based IS exchanges.

Waste Storage Duration	Waste Quality	Waste Market Dynamicity		
		0.1	0.2	0.3
WSD =1	Low	0.023	0.026	0.032
	Medium	0.163	0.161	0.156
	High	0.311	0.309	0.304
WSD =5	Low	0.124	0.1234	0.121
	Medium	0.25	0.25	0.251
	High	0.338	0.337	0.337
WSD =10	Low	0.104	0.1	0.1
	Medium	0.273	0.273	0.274
	High	0.365	0.36	0.36

A prominent trend observed is that increasing waste storage duration (WSD) from a very short period ($WSD = 1$) to a moderate one ($WSD = 5$) substantially improves economic benefit across all levels of waste quality and market dynamicity. For example, with low-quality waste at low market dynamicity (0.1), economic benefit nearly doubles, from 0.154 at ($WSD = 1$) to 0.284 at ($WSD = 5$), an 84.4% increase. This rise is similarly evident at higher dynamicity (e.g., at dynamicity 0.3, 0.189 to 0.282, or +49.2%). Comparable or greater gains are achieved for medium and high-quality waste: for medium quality at dynamicity 0.1, economic benefit rises from 0.211 ($WSD = 1$) to 0.374 ($WSD = 5$), a +77.25% increase; for high quality, from 0.253 to 0.391 (+54.5%).

However, the effect of WSD is not linear and depends on waste quality. For low-quality waste, increasing storage duration beyond ($WSD = 5$) (i.e., to $WSD = 10$) actually results in a decline in economic benefit: at dynamicity 0.1, benefit drops from 0.284 ($WSD = 5$) to 0.232 ($WSD = 10$), a decrease of 18.3%. This pattern is consistent across higher market dynamicity and reflects the fact that, for low-quality waste, the daily storage cost quickly erodes the potential benefit of having a longer matching period. In other words, when waste quality is low, the likelihood of successfully forming symbiotic relationships is limited, the waste is less attractive to potential partners, so even with longer WSD, the opportunity for exchange does not increase proportionally, while the cost accumulates steadily. This directly reduces not only the economic benefit for individual firms, but also the overall number of symbiotic relationships formed in the network, as fewer firms find it worthwhile to participate.

In contrast, for medium and especially high-quality waste, longer storage durations continue to yield increasing or at least stable benefits. For instance, for high quality waste at dynamicity 0.1, economic benefit increases from 0.391 ($WSD = 5$) to 0.476 ($WSD = 10$), a 21.7% increase. This demonstrates that, when waste quality is high, the value and demand for the waste are sufficient to generate additional symbiotic matches during the longer storage window. Here, the positive impact of higher quality outweighs the negative impact of storage cost. For example, at ($WSD = 10$) and high quality, the economic benefit is more than double that of (WSD = 1) and low quality (0.476 vs. 0.154, a 209% increase). This means that, as quality increases, not only does each storage day become more productive in terms of matching, but the likelihood and sustainability of symbiotic relationships also increase, leading to a denser and more robust ISN.

At every WSD and market condition, waste quality emerges as the important driver of economic benefit. For instance, at (WSD = 5) and dynamicity 0.1, moving from low to medium quality increases economic benefit by 31.7% (from 0.284 to 0.374), and from medium to high quality by an additional 4.5% (0.374 to 0.391). This pattern holds for all storage durations and dynamicity levels, confirming that higher quality waste not only increases the magnitude of benefit but also intensifies the effectiveness of other strategies like storage buffering.

Moreover, the buffering effect provided by the duration of waste storage acts as a shock absorber against market fluctuations. For example, at (WSD = 1) and low quality, economic benefit actually increases with market dynamicity, rising from 0.154 to 0.189 as dynamicity goes from 0.1 to 0.3 (+22.7%). At (WSD = 5), this effect is almost neutral (0.284 to 0.282, just -0.7% for low quality; for high quality, 0.391 to 0.406, +3.8%). These findings indicate that WSD, particularly when combined with higher quality, can almost completely mitigate the negative effects of market volatility and, in some cases, even turn them into a slight advantage by enabling more flexible matching.

A similar but not identical pattern is observed for environmental benefit. At short WSD (WSD = 1), environmental benefit is generally low, especially for low quality waste (e.g., 0.023 at dynamicity 0.1). As WSD increases to (WSD = 5), environmental benefit rises sharply for all qualities, most dramatically for low quality waste (from 0.023 to 0.124, a 439% increase). For medium and high quality, the benefit grows by over 50% and 8%, respectively, under the same conditions. However, excessive WSD (WSD = 10) does not necessarily result in additional environmental benefits. For low quality waste, environmental benefit decreases (from 0.124 at WSD = 5 to 0.104 at WSD = 10, -16.1%), again due to the cost of holding waste outweighing the likelihood of successful exchange. For medium and high quality, environmental benefit continues to increase or remains steady (medium: 0.25 to 0.273, +9.2%; high: 0.338 to 0.365, +8%). This indicates that higher quality waste is more likely to find compatible users within the network, making longer storage durations more advantageous by supporting more frequent and effective exchanges. This suggests that, as with economic benefit, higher quality waste justifies the extra storage cost, supporting more symbiotic relationships and reducing total disposal volumes in the network.

In line with the economic indicator results, increasing waste market dynamicity from 0.1 to 0.3 does not lead to a significant decrease in the environmental performance index across different storage durations and quality levels, highlighting the stabilizing effect of the WSD. For example, at a short WSD (WSD = 1), the environmental index for low quality waste even increases from 0.023 to 0.032, while for medium and high quality, it remains relatively stable (medium: 0.163 to 0.156; high: 0.311 to 0.304). At medium WSD (WSD = 5) and long WSD (WSD = 10), the indices show minimal variation regardless of market dynamicity. As an instance, for high-quality waste, the index at (WSD = 10) stays almost constant (0.365 at 0.1, 0.36 at 0.3).

In addition, Figure 4 visually illustrates the average effect, calculated on all the simulated scenarios, of the investigated WSD.

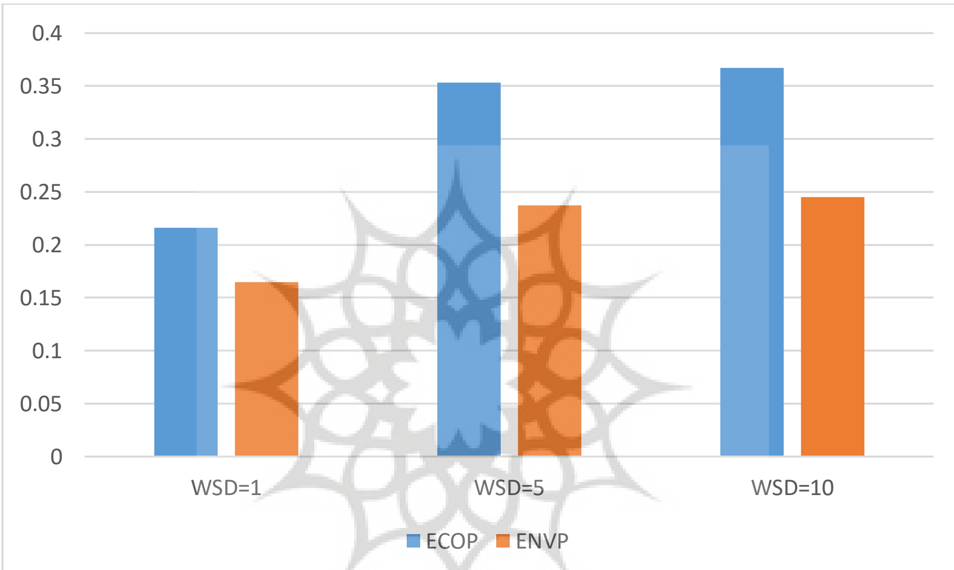

Figure 4. Average values of economic and environmental performance for fruit waste-based IS exchanges

The chart reveals that both economic and environmental performance improve as the WSD increases from 1 to 5 days. Specifically, ECOP rises from about 0.216 at (WSD = 1) to 0.353 at (WSD = 5), while ENVP increases from 0.165 to 0.237. This suggests that allowing for moderate WSD enables the network to operate more efficiently and sustainably, by providing more flexibility for matching waste producers with suitable consumers.

When WSD is further increased from 5 to 10 days, both performance measures show only a slight additional improvement (ECOP to 0.367, ENVP to about 0.245). This indicates diminishing returns for very long WSD, most of the benefit is captured with moderate storage, and extending it further provides minimal extra advantage.

Let us consider waste exchange ratio as another performance measure. Figure 5 provides a comparison of waste exchange efficiency across varying WSD and waste quality levels under a steady market dynamicity of 0.2. Each chart illustrates the proportion of waste successfully reused through IS (green segment) versus waste disposed (red segment), with both segments shown as percentages. The green percentage directly reflects the waste exchange ratio.

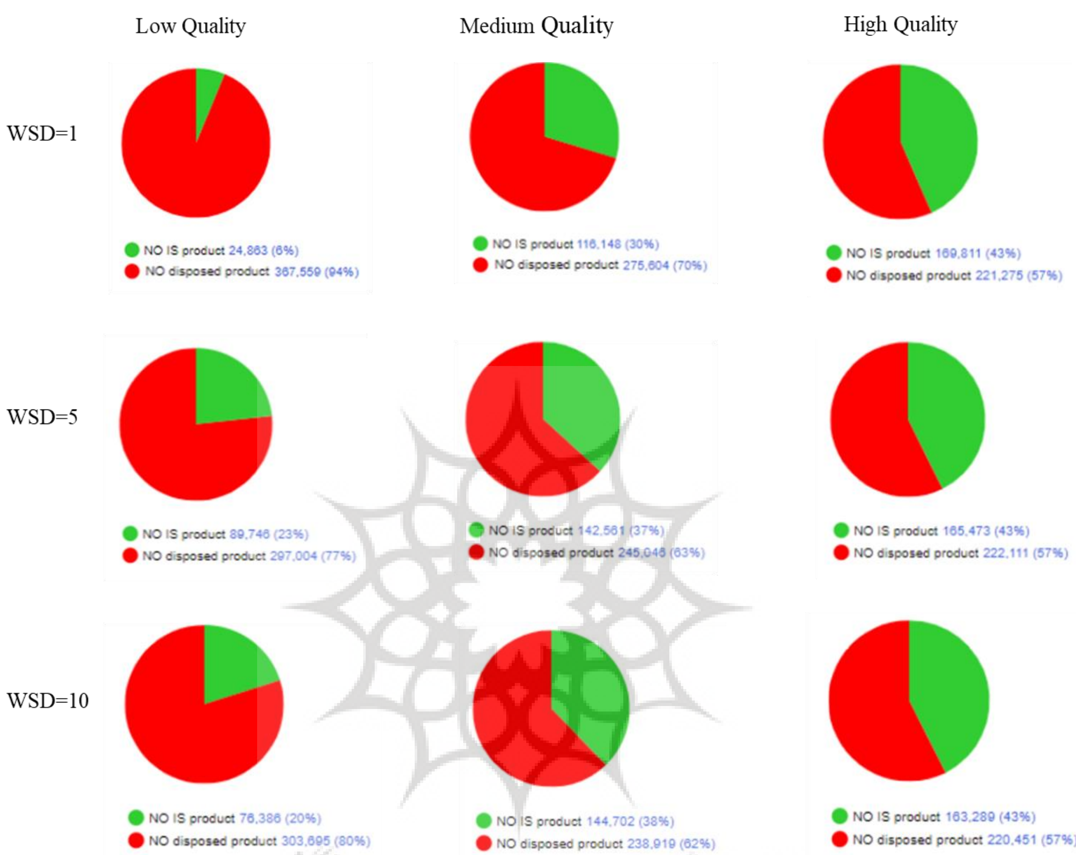

Figure 5. Average values of waste exchange ratio of fruit waste-based IS exchanges.

As illustrated in Figure 5, for low-quality waste, increasing WSD from 1 to 5 days leads to some improvement in reuse, with WER rising from 6% to 23%, but extending storage further to 10 days actually reduces reuse to 20%, likely due to rising storage costs. In the case of medium-quality waste, longer storage consistently enhances WER, increasing from 30% at 1 day to 38% at 10 days, with most of the benefit achieved by 5 days. For high-quality waste, the WER remains stable at 43% across all storage durations.

Conclusion

This paper begins with a systematic literature review to map the landscape of agent-based simulation, discrete event simulation, and their application in ISNs. The adopted SLR identifies key research trends and critical factors influencing the success of IS, thereby providing a solid foundation for the simulation model developed herein.

Building on these insights, a simulation-based methodology is developed to assess the combined effects of waste storage period, waste quality, and market dynamicity on economic and environmental performance indicators within the context of IS in Iran's food sector. The model integrates both ABM and DES paradigms to capture the complex interactions among 100 waste supplier and 100 waste user firms, along with the operational processes involved in waste exchange. Scenario variables and parameters i.e. WSD, quality, and market dynamicity, are systematically varied to evaluate their individual and interactive impacts on network outcomes.

The findings reveal that effective management of waste storage period and quality plays a decisive role in shaping both economic and environmental outcomes. Higher waste quality facilitates more efficient resource recovery and reuse, which results in greater economic gains and reduced environmental impacts. While extending storage duration offers firms greater flexibility to match supply with demand, each extra day of storage incurs a cost that must be weighed against the potential benefits. For higher quality waste, these costs are often justified, but for low-quality waste, prolonged storage may result in diminishing returns.

Interestingly, the effect of market dynamicity departs from what has been widely reported in the literature, where increased dynamicity, reflecting more frequent mismatches between supply and demand, typically erodes both economic benefit and the number of symbiotic links (Fraccascia, Giannoccaro, et al., 2017; Fraccascia & Yazan, 2018). In the current study, the waste storage policy proves effective in mitigating the negative impacts of supply and demand fluctuations. By allowing waste to be stored for some days, the network is able to absorb temporary mismatches in the market, preventing sharp declines in both economic and environmental performance indices. This buffering effect helps stabilize outcomes, ensuring that firms can maintain higher levels of benefit even under volatile market conditions.

From a managerial perspective, the findings suggest that managers should adopt a flexible and context-sensitive approach when determining storage duration and capacity, taking into account the expiration characteristics and quality of the waste. Rather than relying on fixed storage periods, managers are encouraged to regularly assess the trade-off between the benefits of extended storage, such as increased opportunities for exchange and market buffering, and the associated costs, including storage expenses. By monitoring waste quality and market conditions, managers can make informed decisions about when to release or retain waste, thus optimizing both economic and environmental outcomes. Establishing protocols for routine quality checks, investing in sorting and processing technologies, and training staff to recognize optimal handling strategies will further enhance the effectiveness of ISNs.

In practice, under a given level of market dynamicity, shorter or moderate storage durations within the expiration period are most appropriate for low-quality waste, as extending storage to the maximum expiration period does not improve and may even reduce performance. For medium-quality waste, adopting a moderate or maximum storage duration within the expiration window yields the best results. For high-quality waste, extending storage up to the maximum expiration period is recommended, since performance continues to improve with longer storage durations. Ultimately, tailoring waste storage policies within ISNs to the specific operational context and waste characteristics will enable firms to maximize resource recovery, minimize unnecessary disposal, and maintain resilient performance under market fluctuations.

This research contributes methodologically by bridging ABM and DES approaches in IS, particularly in resource-constrained settings such as developing countries. The hybrid simulation enables more nuanced and actionable insights, supporting better network design, investment evaluation, and risk management. Policymakers can also use these findings to design effective regulations and incentives for waste storage improvement and IS promotion.

For future research, it is recommended to adopt a dynamic modeling approach for waste quality in cases where significant changes may occur in quality due to different waste types or storage conditions. In such situations, advanced tracking solutions, such as blockchain technology, can be employed to accurately monitor and manage quality variations. Moreover, integrating system dynamics approaches with ABM and DES could provide a more comprehensive understanding of the complex interactions over time. Such hybrid modeling would allow researchers to capture feedback loops, long-term trends, and adaptive behaviors within the ISN, leading to deeper insights into system robustness and resilience. Future studies are also encouraged to account for lead time in waste transportation and exchange processes, as these logistical aspects may influence network efficiency. Furthermore, evaluating the capital expenditures required for establishing or equipping storage facilities would provide a more comprehensive economic assessment and support informed decision-making regarding infrastructure investments. It is important to note that this study has primarily focused on the food sector in Iran, which may limit the generalizability of the results to other industries or regions. Therefore, future research could broaden the scope by investigating ISNs in other sectors such as manufacturing, energy, or pharmaceuticals. Researchers are called to advance the model by addressing these noted suggestions.

Data Availability Statement

Data available on request from the authors.

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Ethical considerations

The authors avoided data fabrication, falsification, and plagiarism, and any form of misconduct.

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Conflict of interest

The authors declare no conflict of interest.

Appendix A

The model is validated using four steps: (1) micro-face, (2) macro-face, (3) input, and (4) output validation (Bianchi et al., 2008; Fraccascia, 2020; Mollica et al., 2025).

Micro-face validation confirmed that the model's mechanisms and agent behaviors are consistent with established literature and real-world practices, such as firms' willingness to cooperate, which depends on the economic benefit of IS and the costs of non-cooperation. In addition, agent behaviors were systematically traced throughout the simulation to verify that their interactions strictly followed the defined rules, ensuring that all agent activities and decisions aligned with the intended logic of the model.

The macro-face validation criteria are satisfied, as the model's dynamics described in the methodology section are consistent with real-world behavior. For instance, firms initiate an industrial symbiosis relationship only if their willingness exceeds a certain threshold, ensuring that cooperation occurs only when the expected benefits justify participation, an approach that reflects actual decision-making in industrial settings.

Input validation was performed by setting fixed model parameters (see Table 3), based on real data from industry sources (Iran Dairy Industries Society, 2024; Iran Soft Drink Producers Association, 2024). Furthermore, we conduct sensitivity analysis using the dataset detailed in Table 3 to ensure that the simulation outcomes are not dependent on the specific parameter values selected. In this analysis, the economic parameters udc, upc, and $utrac$ are individually varied by increasing and decreasing each by 10 percent, while all other variables were held constant. The results for economic performance under each parameter adjustment are presented in Tables Table **6** to Table **11**. The findings are consistent with those reported in the main manuscript. Most importantly, the observed patterns on which the study's conclusions are based remained stable throughout the analysis. These results demonstrate that the model performs logically and maintains stable behavior under varying conditions, further supporting the robustness of our approach.

Table 6. Sensitivity analysis of economic performance for fruit waste-based IS exchanges (low udc).

Waste Storage Duration	Waste Quality	Waste Market Dynamicity		
		0.1	0.2	0.3
WSD=1	Low	0.147	0.168	0.191
	Medium	0.208	0.219	0.23
	High	0.252	0.259	0.258
WSD =5	Low	0.281	0.278	0.276
	Medium	0.42	0.415	0.411
	High	0.479	0.492	0.492
WSD =10	Low	0.22	0.219	0.22
	Medium	0.409	0.402	0.399
	High	0.535	0.526	0.532

Table 7. Sensitivity analysis of economic performance for fruit waste-based IS exchanges (high udc).

Waste Storage Duration	Waste Quality	Waste Market Dynamicity		
		0.1	0.2	0.3
WSD=1	Low	0.161	0.167	0.192
	Medium	0.218	0.224	0.233
	High	0.257	0.263	0.27
WSD =5	Low	0.297	0.296	0.296
	Medium	0.422	0.422	0.416
	High	0.489	0.477	0.509
WSD =10	Low	0.238	0.238	0.237
	Medium	0.41	0.408	0.407
	High	0.534	0.527	0.519

Table 8. Sensitivity analysis of economic performance for fruit waste-based IS exchanges (low upc)

Waste Storage Duration	Waste Quality	Waste Market Dynamicity		
		0.1	0.2	0.3
WSD=1	Low	0.143	0.161	0.182
	Medium	0.207	0.218	0.228
	High	0.26	0.266	0.273
WSD =5	Low	0.247	0.246	0.246
	Medium	0.407	0.404	0.405
	High	0.486	0.478	0.486
WSD =10	Low	0.172	0.177	0.178
	Medium	0.382	0.382	0.38
	High	0.512	0.512	0.508

Table 9. Sensitivity analysis of economic performance for fruit waste-based IS exchanges (high upc)

Waste Storage Duration	Waste Quality	Waste Market Dynamicity		
		0.1	0.2	0.3
WSD=1	Low	0.161	0.173	0.199
	Medium	0.213	0.225	0.231
	High	0.258	0.259	0.263
WSD =5	Low	0.322	0.319	0.32
	Medium	0.43	0.424	0.42
	High	0.494	0.495	0.495
WSD =10	Low	0.274	0.275	0.272
	Medium	0.422	0.416	0.426
	High	0.523	0.527	0.54

Table 10. Sensitivity analysis of economic performance for fruit waste-based IS exchanges (low $utra$)

Waste Storage Duration	Waste Quality	Waste Market Dynamicity		
		0.1	0.2	0.3
WSD=1	Low	0.154	0.169	0.187
	Medium	0.213	0.221	0.231
	High	0.259	0.261	0.266
WSD =5	Low	0.289	0.293	0.288
	Medium	0.411	0.416	0.417
	High	0.502	0.486	0.494
WSD =10	Low	0.229	0.229	0.228
	Medium	0.403	0.413	0.412
	High	0.537	0.529	0.528

Table 11. Sensitivity analysis of economic performance for fruit waste-based IS exchanges (high $utra$)

Waste Storage Duration	Waste Quality	Waste Market Dynamicity		
		0.1	0.2	0.3
WSD=1	Low	0.153	0.163	0.188
	Medium	0.213	0.22	0.23
	High	0.258	0.261	0.268
WSD =5	Low	0.289	0.282	0.284
	Medium	0.416	0.415	0.413
	High	0.49	0.495	0.485
WSD =10	Low	0.23	0.229	0.231
	Medium	0.405	0.409	0.405
	High	0.534	0.53	0.523

To further support the model validation process, we also perform statistical comparisons between the simulated scenarios (Ockerman & Goldsman, 1999; Reynolds et al., 1981). Specifically, two-sample t-test is used to assess whether the differences in mean economic performance between scenarios with short and long waste storage duration (WSD = 1 versus WSD = 10 under market dynamicity of 0.1) are statistically significant across different levels of waste quality. The results of this test, summarized in Table Table **12**, show that in all cases the differences are statistically significant at the 95% confidence level ($p < 0.05$). These findings indicate that the scenario comparisons are conducted effectively and that the model can consistently capture the impact of changes in waste storage duration across various quality levels.

Table 12. T-test analysis of economic performance for fruit waste-based IS exchanges

Quality Level	Group 1 Mean (SD)	Group 2 Mean (SD)	t Statistic	p-value	Significant (α=0.05)
Low	0.154 (0.0021)	0.232 (0.0011)	-80.95	<0.001	Yes
Medium	0.211 (0.0016)	0.392 (0.0039)	-103.73	<0.001	Yes
High	0.253 (0.0020)	0.476 (0.0057)	-90.57	<0.001	Yes

Note: Group 1 = (WSD = 1); Group 2 = (WSD = 10); SD = Standard Deviation; Significant = $p < 0.05$ (two-tailed).

Ultimately, the criteria of output validation are satisfied, as the simulation results closely align with both the expected behaviors of agents and established findings in the literature. For example, the model shows that appropriate management of waste storage duration within industrial symbiosis networks can enhance overall network performance, which is consistent with theoretical and empirical studies. Furthermore, higher waste quality enables more effective resource recovery and reuse, leading to increased economic gains and lower environmental impacts, in line with the findings of related research (Fraccascia, 2019). In addition, during our visit to a firm participating in an industrial symbiosis network, discussions with the company's experts confirmed that the patterns and trends observed in our simulation closely align with real-world practices and experiences within the network. This alignment provides further assurance regarding the relevance and practical applicability of our simulation outcomes.

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