

Prioritization of Industrial Symbiosis Enablers Using a Hesitant Fuzzy SWARA Approach

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Abstract: Industrial symbiosis (IS), a crucial tool for reducing industrial waste, preventing pollution, and enhancing resource efficiency, is emerging as one of the sustainable approaches. IS is a network structure in which independent industrial enterprises cooperate and use the waste or by-products of one as raw material for the other. This synergistic network structure can help companies reduce costs, boost efficiency, and lessen negative environmental impacts. However, successful IS implementation relies on key enabling factors facilitating collaboration and ensuring mutual benefits among participants. This study focuses on Türkiye, where the development of IS networks holds significant potential due to its industrial diversity and growing emphasis on sustainability. It aims to rank the critical enabling factors in fostering these networks. To achieve this aim, Stepwise Weight Assessment Ratio Analysis (SWARA), a subjective multi-criteria decision-making (MCDM) technique that systematically evaluates and ranks criteria based on expert judgments, was employed. This approach was integrated with hesitant fuzzy sets to account for uncertainty and hesitation in expert opinions, ensuring a more robust assessment of the enabling factors. In the present study, a comprehensive literature review and expert opinions were employed to identify 23 sub-enablers falling under five main dimensions. The hesitant fuzzy SWARA method was then applied to calculate their importance weights. The results of the study indicate that the five most critical sub-enablers are, in descending order of importance: "reduction of raw material costs," "interest and support from top management," "reduction of waste disposal costs," "geographical proximity," and "openness to new business ideas."

Keywords: Industrial Symbiosis, Enablers, Hesitant Fuzzy Sets, SWARA

1. Introduction

Over the past twenty years, there has been a focus not only on technological advancements and innovations in production processes but also on initiatives aimed at recovering and improving the quality of waste through sustainable solutions (Yazıcı et al., 2024). One approach that has gained popularity among policymakers and scholars in the last decade is industrial symbiosis (IS) (Hossain et al., 2024). This concept involves businesses collaborating with each other to share resources, reduce waste, and create new economic opportunities. IS can be defined as an approach that encourages the physical exchange of materials, water, energy, by-products, and production process waste among companies from different sectors that are geographically close to each other (Chertow, 2007; Lambert & Boons, 2022; Giurco et al., 2011). IS is a strategy that can promote sustainable production and consumption by extending the life cycle of materials and reducing the volumes of resources going to landfills. This can help transition from linear to circular production systems (Agudo et al., 2022). IS is already considered a viable model for implementing circular economy practices (Hossain et al., 2024; Ramírez-Rodríguez et al., 2024). IS aims to transform one firm's waste into another's valuable input, to reduce production costs, to improve environmental performance, and to enhance the competitive advantage of the supply chain (Yuan & Shi, 2009). Along with this, the increasing consumption of limited natural resources daily is a worrying situation for the future. Sustainable methods such as IS can help mitigate this issue by promoting resource efficiency through the reuse of by-products and waste materials, reducing the demand for virgin raw materials (Ramírez-Rodríguez et al., 2024; Taqi et al., 2022).

Since 2008, IS has gained momentum in Türkiye as it promotes sustainable development by reducing waste generation, material and energy consumption, and greenhouse gas emissions (Alkaya, 2021). By

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working together, industries can optimize their production processes, increase resource efficiency, and create new business opportunities (Harfeldt-Berg et al., 2022). Expanding these networks is crucial as it can contribute to a more sustainable and resilient economy, and help us achieve the United Nations' Sustainable Development Goals (Ruiz-Puente & Jato-Espino, 2020). Over the past three decades, Türkiye's population has increased, and the country has moved toward economic development and urbanization (TÜİK, 2023). These factors have made waste management in the country more challenging and have highlighted the need to change to an industrial structure that is more environmentally friendly and resource-efficient (Erol et al., 2023). In the 10th Development Plan of Türkiye, IS is defined as a strategic tool to achieve environmental protection and sustainable use of resources (International Synergies, 2019). By promoting IS practices, Türkiye government aims to achieve more sustainable and environmentally friendly industrial development that supports long-term economic growth (Alkaya, 2021).

Several projects have been implemented in Türkiye to establish collaborations in IS. Notable examples include the Industrial Symbiosis in Iskenderun Bay, the Bursa-Eskişehir-Bilecik Industrial Symbiosis Program, Eskişehir Chamber of Industry Sharebox Industrial Symbiosis Project, Identification of Industrial Symbiosis Opportunities in Ankara Ostim, and the Gaziantep Industrial Symbiosis Project. Additionally, initiatives like the İzmir Industrial Symbiosis Project and the Türkiye Circular Economy Platform continue to support the development of IS collaborations (Alkaya, 2021). However, it is vital to raise awareness about IS and identify promoting and facilitating factors that can enhance cooperation. For this reason, this study aims to identify the enablers that promote IS collaborations in Türkiye and reveal their importance degree. To achieve this purpose, firstly the IS enablers were identified using a comprehensive literature review. Secondly, experts who have been involved in IS projects were interviewed to determine the main and sub-factors that enable IS in the context of Türkiye, an emerging economy. Thirdly, the hesitant fuzzy Stepwise Weight Assessment Ratio Analysis (SWARA) method was used to identify the priority rankings of the main enabler categories and their associated sub-enablers.

Identifying and analyzing enabling factors is becoming increasingly important as they play a critical role in developing IS collaborations (Herath et al., 2022). However, in the context of Türkiye, no study has been encountered in which the enabling factors that facilitate IS collaborations are evaluated and ranked using the multi-criteria decision-making (MCDM) method based on fuzzy sets. This gap highlights the need for research that not only identifies the key elements influencing IS but also assesses their relative importance in a structured manner. MCDM methods, specifically designed to address complex situations involving multiple factors, allow decision-makers to systematically evaluate various options, weigh the significance of each criterion, and arrive at balanced decisions (Alakaş et al., 2020). Incorporating fuzzy sets into MCDM methods further enhances their applicability by addressing the inherent complexities and uncertainties of decision-making processes in IS (Yazıcı et al., 2024).

Despite their potential, the application of fuzzy-based MCDM methods in the field of IS is notably limited in the current literature (Yazıcı et al., 2023). To address this gap, the study employs the hesitant fuzzy-based SWARA method, which offers a more nuanced and realistic approach to capturing decision-makers' opinions. Unlike traditional fuzzy sets, which require a single membership value, hesitant fuzzy sets enable the expression of multiple possible membership values, providing a more comprehensive representation of preferences and judgments (Dahooie et al., 2020; Mardani et al., 2020; Kang et al., 2023). The remainder of the article is structured as follows: Section 2 includes a review of the current literature on the concept and enablers of IS. Section 3 describes the research method, including hesitant fuzzy sets and hesitant fuzzy SWARA method. The application of the framework is discussed in section 4. Section 5 presents the results and discussion of the study. Finally, section 6 outlines the conclusions, limitations, and future research directions.

2. Literature Review

2.1. Industrial symbiosis

As a business model for circular economy, IS is a recognized approach toward sustainability (Agudo et al., 2022; Saghafi & Roshandel, 2024). IS, as defined by Lombardi and Laybourn (2012) refers to a network of diverse organizations working together to promote eco-innovation and long-term culture change. Leigh and Li (2015) define IS as a mechanism that enhances sustainability by establishing symbiosis networks, resulting in more efficient material and energy use, leading to lower carbon emissions and resource consumption.

IS allows companies to cooperate in sharing resources, leading to increased sustainability through environmental, economic, and social benefits (Neves et al., 2020). This approach increases resource efficiency, reduces waste, and protects the environment by facilitating exchanges of materials, energy, and by-products among industries (Hossain et al., 2024). The Intergovernmental Panel on Climate Change (IPCC) identifies IS as a key strategy for sustainable growth and industrial resilience (IPCC, 2014). By reducing reliance on virgin materials, IS decreases pollution and environmental degradation. It also minimizes waste and greenhouse gas emissions, contributing to climate change mitigation. Moreover, this approach fosters sustainability in emerging economies, aligning their development trajectories with global sustainability goals (Hossain et al., 2024). In addition to environmental benefits, IS supports economic and social sustainability, improving efficiency and fostering long-term industrial collaboration (Harfeldt-Berg & Harfeldt-Berg, 2023). However, the full potential of IS remains unrealized due to a lack of understanding regarding the necessary preconditions (Moser & Rodin, 2021).

The concept of IS finds its roots in biology, where symbiosis refers to the association of individuals from different species in a mutually beneficial relationship (Schwarz & Steininger, 1997). This concept has been transposed to industries where traditionally separate entities engage in a collective approach to gain competitive advantage through the physical exchange of materials, energy, water, and by-products (Neves et al., 2020). IS networks are created to maximize the potential exchange of by-products, waste, and energy, determining their adequacy for sustainable production processes (Yeşilkaya et al., 2020). IS is a collaborative approach where different industries exchange and utilize each other's waste and by-products to reduce the need for raw material imports. This not only helps in reducing the environmental impact but also contributes to climate change mitigation by lowering greenhouse gas (GHG) emissions (Khan et al., 2023; Martin & Harris, 2018). This sustainable practice promotes a more efficient use of resources and fosters a circular economy, ultimately leading to a more environmentally friendly and economically viable industrial system (Sonel et al., 2022).

The IS model was first demonstrated in Kalundborg, Denmark, in 1961. With the implementation of this model, water consumption in the city was reduced by 25%, and heating was provided for 5,000 houses (Chertow, 2000). With this cooperation, environmental and economic efficiency increased significantly. IS activities are still ongoing in the Kalundborg eco-industrial park (Lasthein et al., 2021). IS is a relationship that has been developed through various factors, such as resource conservation, economic benefits, environmental compliance, reduction of greenhouse gas emissions, shortage of natural resources, and reduction of waste (Mortensen & Kørnøv, 2019). Because of these needs, IS has spread around the world, resulting in positive economic, environmental, and social outcomes (Martin & Harris, 2018). IS case studies have been conducted in various countries across the globe. These studies have been carried out in developed regions such as the United Kingdom (Velenturf, 2016), Japan (Ohnishi et al., 2017), and the United States of America (Chertow et al., 2008), as well as in developing countries such as Thailand (Lawal et al., 2021), Morocco (Cerceanu et al., 2014), and Algeria (Neves et al., 2020).

IS is a concept that enables businesses to increase efficiency and reduce consumption of resources, leading to economic and environmental benefits (Ji et al., 2020). By maximizing the use of available

resources, companies can save money while also reducing costs associated with resource acquisition (Alkaya, 2021). This, in turn, creates opportunities for industries to improve their profitability and competitiveness in the market (Taqi et al., 2022). Furthermore, the reduction in material demand has a significant positive impact on the environment by reducing the amount of waste generated (Sonel et al., 2022).

2.2. Industrial symbiosis in Türkiye

Türkiye has prioritized ecological approaches and renewable energy sources to preserve its natural resources and promote sustainable development. Within this framework, the country actively supports clean production practices that adhere to the principles of resource conservation and ecological sustainability (Çevre Şehircilik ve İklim Değişikliği Bakanlığı, 2023). Among these practices, IS stands out as a key strategy aimed at optimizing resource utilization, minimizing waste generation, and fostering collaboration between industries to achieve both economic and environmental benefits (Alkaya, 2021).

The introduction of IS in Türkiye can be traced back to the "Industrial Symbiosis in Iskenderun Bay" project, which was supported by the social responsibility program of the Baku-Tbilisi-Ceyhan (BTC) pipeline company and implemented by the Technology Development Foundation of Türkiye (TTGV) (Alkaya, 2021). Notably, this project marked the country's first IS initiative, setting a precedent for similar efforts (Dolgen & Alpaslan, 2020). This pioneering project encompassed a wide range of innovative initiatives. These included the production of animal feed from fruit pulp, the generation of energy from agricultural and animal waste, the development of bioremediation products from cottonseed waste, the production of electricity from waste oil, the manufacture of granules from end-of-life tires, the recovery of lead from scrap batteries, and the utilization of slag from steel production in road construction (Özkan et al., 2018). The Industrial Symbiosis in Iskenderun Bay Project was notable not only for its significant achievements in waste reduction, water and energy conservation, and the reduction of CO₂ emissions but also for its most important outcome: establishing a pioneering model for the development of future regional projects (Dolgen & Alpaslan, 2020). IS initiatives in Türkiye have been continuing in various regional projects since 2008. These projects are being carried out, especially by development agencies, environmental consultancy firms, and non-governmental organizations. These initiatives generally aim to bring together companies from different sectors and evaluate their potential for cooperation. A comprehensive summary of the IS projects conducted in Türkiye is provided in Appendix A (Table A1).

In addition to the IS projects implemented in Türkiye, academic studies have significantly contributed to understanding and advancing the concept. These studies provide theoretical frameworks, case analyses, and empirical findings, offering valuable insights into the environmental, economic, and social dimensions of IS. For example, Demircioğlu and Ever (2020) conducted a theoretical study exploring the role of IS in promoting the circular economy. They emphasized the economic and environmental benefits of IS, such as cost savings and resource efficiency, by providing examples from both Türkiye and the global context. Similarly, Durusoy's (2021) research focused on conceptualizing IS and examining its advantages through global and local case studies, with particular attention to environmental impacts in Türkiye.

Dolgen and Alpaslan (2020) studied eco-industrial parks in Türkiye, emphasizing their importance in promoting IS and sustainable development. The research offered insights into the implementation processes, challenges, and results of these parks. It also highlighted successful practices and their contributions to both environmental and economic sustainability. In a similar vein, Özkan and colleagues (2018) explored the historical evolution of IS and analyzed various programs implemented globally and in Türkiye. Their research also introduced analytical tools, such as material flow analysis, life cycle analysis, and MCDM methods, which are essential for executing IS initiatives.

Focusing on specific sectors, Yeşilkaya and colleagues (2020) conducted a SWOT analysis to assess the feasibility of implementing IS within the forest products industry in Türkiye. The findings of the analysis indicated that it is possible to establish IS networks based on the forest products sector in the country. Yazıcı and colleagues (2023) proposed a decision-making model using MCDM methods to identify the priority sector for establishing an IS network in an industrial park in Türkiye. Moreover, Müyesseroğlu and colleagues (2024) examined the role of IS strategies in enhancing energy efficiency in the Konya Organized Industrial Zone (OIZ). By leveraging survey data and field studies, their research identified opportunities for waste exchange and resource matching, emphasizing the environmental and economic benefits of such practices.

Upon reviewing previous studies related to Türkiye, it is clear that there has been a lack of research focusing on the enablers of IS collaborations using MCDM methods. This oversight indicates a gap in the literature, particularly in identifying and ranking the factors that facilitate the creation of IS networks in Türkiye. To address this gap, the present study offers a systematic and prioritized framework, making a substantial contribution to the existing knowledge on IS.

2.3. Industrial symbiosis enablers

IS collaborations encompass various applications and are influenced by multiple factors. It is crucial to identify the factors that affect the establishment and sustainability of these collaborations and develop strategies accordingly (Sonel et al., 2022). Enablers can be defined as factors or conditions that support and encourage the realization of symbiotic synergies (Henriques et al., 2021; Khan et al., 2023). Enablers are elements that can improve collaboration by eliminating obstacles or providing incentives (Harfeldt-Berg et al., 2022). By facilitating mutually beneficial interactions between entities, enablers can unlock new synergies and promote greater efficiency, effectiveness, and innovation.

Many researchers have focused on identifying and analyzing the factors that influence the successful implementation of IS collaborations (Harfeldt-Berg et al., 2022; Sonel et al., 2022). Table 1 presents an overview of several current studies on enablers of IS, summarizing key findings and highlighting the various methods used in each study.

Table 1

Studies Related to IS Enablers

Authors	Methods	Objective
Madsen et al. (2015)	Mixed-methods	The main objective of this research is to identify the barriers and facilitating factors for implementing IS exchanges. The research methodology includes a mixed-methods approach: a literature review on the barriers and enabling factors of IS, a case study of two companies attempting an IS exchange, and interviews with practitioners in the field.
Tseng and Bui (2017)	FDM, FIPA, Converged supermatrix	The aim of this study is to identify key eco-innovation attributes that enhance IS performance, particularly in Vietnam's textile industry. It combined several methods: the fuzzy Delphi method (FDM) to filter attributes, factor analysis to create a hierarchical structure, fuzzy importance-performance analysis (FIPA) to identify key attributes, and supermatrix to rank the attribute weights.
Mortensen and Kørnøv (2019)	Literature review	The study's main purpose is to examine the critical factors influencing IS collaborations' initial phase, or "emergence process." The study aims to better understand how initial connections between potential IS partners are formed and what conditions, actors, roles, and activities contribute to this process.
Alakaş et al. (2020)	ANP	The main purpose of this study is to evaluate and rank sustainability criteria that influence IS applications to support sustainable IS development.

Tablo 1 (Continued)

Ji et al. (2020)	Binary Logistic regression	The main purpose of this study is to identify the factors that promote or inhibit companies' participation in IS. The study proposed an analytical approach to examine these factors, utilizing a binary logistic regression model to evaluate data collected from different types of companies in China.
Henriques et al. (2021)	Sectoral analysis	This study aims to identify the key enablers and barriers across various economic sectors and their specific behaviors. It employed a two-phase methodology: the first phase, sectoral analysis, highlights the most relevant dimensions for each sector, while the second phase, incidence analysis, examines the individual behaviors of enablers and barriers within those sectors.
Sellitto et al. (2021)	Case study	The purpose of this study is to identify barriers, drivers, and the structure of relationships that support IS initiatives within a network of Brazilian manufacturing companies. The network analyzed comprises two steelmaking plants (anchor tenants) and other participants, including a cement manufacturer, a thermoelectric generation plant, a lead ingots manufacturer, a zinc ingots manufacturer, and a refractory liner manufacturer.
Harfeldt-Berg et al. (2022)	Literature review	This study reviewed literature from January 1, 2000, to March 28, 2022, identifying the drivers, barriers, and facilitators influencing participation in IS. It also explored how perceptions and impacts of these factors vary according to the characteristics of individual participants and their specific contexts.
Sonel et al. (2022)	ANP	This study determined and analyzed the factors influencing IS collaboration. It employed the ANP method to evaluate these factors' degree of importance and priority.
Khan et al. (2023)	Case study	This study examined 11 successful cases of IS and proposes a framework for symbiotic exchanges in Saudi Arabia. Additionally, a roadmap for implementing IS was developed, taking into account both enablers and barriers.
Chrysikopoulos et al. (2024)	DEMATEL	This study aims to identify and analyze the critical success factors necessary for successfully implementing IS and to examine the interrelationships among these factors using the Decision-Making Trial and Evaluation Laboratory (DEMATEL) methodology.

Previous studies have highlighted that the enablers promoting IS collaborations are often investigated within various national contexts, reflecting distinct regional characteristics. Given the diversity of factors influencing IS initiatives across different countries, this study specifically focuses on Türkiye, an emerging economy. Accordingly, the enabling criteria relevant to Türkiye have been identified, and their levels of importance have been evaluated to provide targeted insights into promoting IS in this paper.

3. Research Method

The SWARA method is one of the most effective MCDM techniques for determining the subjective weights of criteria (Keršulienė et al., 2010). This method is notable for its streamlined calculation process and high level of consistency, particularly when compared to alternative weight-determination techniques such as Analytic Hierarchy Process (AHP) and Best Worst Method (BWM) (Kang et al., 2023).

In this study, the hesitant fuzzy-based SWARA method was utilized to evaluate the enablers that contribute to creating IS networks. The method integrates hesitant fuzzy sets, an advanced extension of classical fuzzy sets, to enhance decision-making in multi-criteria decision-making (MCDM) scenarios. Traditional MCDM methods relying on expert judgment often face challenges when experts encounter uncertainties or lack sufficient knowledge about certain criteria. Fuzzy sets address these challenges by allowing decision-makers to express their judgments even under uncertainty (Yazıcı et al., 2023; Sequeira et al., 2023). However, hesitant fuzzy sets go a step further by providing a richer structure that captures hesitation and accommodates the diverse perspectives of multiple decision-makers (Farhadinia & Herrera-Viedma, 2019; Liu & Zhang, 2020; Mardani et al., 2020). By leveraging hesitant

fuzzy sets within the SWARA framework, this study offers a robust approach to handling uncertainty and hesitancy, ensuring more precise and reliable evaluation of IS enablers.

This section provides an overview of the research method employed, namely the hesitant fuzzy SWARA method, to accomplish the research objectives. Before delving into the method details, preliminary information about hesitant fuzzy sets and their corresponding notations is explained.

3.1. Hesitant fuzzy sets

In practical decision-making processes, researchers often face limitations in traditional thinking modes and difficulties in acquiring complete information. To overcome these challenges, they use language and vocabulary to make qualitative evaluations. Linguistic variables can be more practical and effective than direct quantitative estimations. Zadeh (1965) introduced the fuzzy linguistic approach, which computes and supports decision-making through adaptable and widely employed natural language (Ren et al., 2019). The concept of fuzzy sets has been highly successful in managing various types of uncertainties across multiple domains (Mardani et al., 2020). Since Zadeh introduced the concept, numerous expansions and generalizations of fuzzy sets have been proposed in the literature (Torra, 2010). The aim of new types of fuzzy set extensions introduced to the literature is to obtain more accurate results in solving real-life problems by better modeling uncertainty (Erdal, 2022). Hesitant fuzzy sets are an extension of fuzzy sets theory, initiated by Torra (2010), that deals with the uncertainties and hesitancy involved in determining the degree of belongingness to elements (Ghorui et al., 2021). Moreover, Torra revealed the relationships between hesitant fuzzy sets and fuzzy sets' expanded versions, including type-2, intuitionistic, and fuzzy multi-sets. Hesitant fuzzy sets, an extension of fuzzy sets, have proven valuable and approachable instruments for representing the ambiguous and gray information that arises in practical applications (Mardani et al., 2020). The basic concepts related to hesitant fuzzy sets are as follows (Mardani et al., 2020; Ghorui et al., 2021; Xia & Xu, 2011; Kayapınar Kaya & Erginel, 2020):

Definition 1. Let X be a fixed set, a hesitant fuzzy set on X is in term of a function that when applied to X returns a subset of $[0,1]$. To represent a hesitant fuzzy set in a mathematical symbol, it can be expressed as follows:

$$E = (x|h_E(x)\rangle \mid x \in X) \quad (1)$$

where $h_E(x)$ is a set of some values in $[0,1]$, denoting the possible membership degrees of the element $x \in X$ to the set E . For convenience, $h_E(x)$ is a hesitant fuzzy element represented by h .

Assuming three hesitant fuzzy sets represented by h , h_1 , and h_2 , some operations that can be performed on them are as follows:

$$h' = \bigcup_{\beta \in h} \{1 - \beta\} \quad (2)$$

$$h_1 \cup h_2 = \bigcup_{\beta_1 \in h_1, \beta_2 \in h_2} \max\{\beta_1, \beta_2\} \quad (3)$$

$$h_1 \cap h_2 = \bigcup_{\beta_1 \in h_1, \beta_2 \in h_2} \min\{\beta_1, \beta_2\} \quad (4)$$

Assuming three hesitant fuzzy sets h , h_1 , and h_2 , with $\lambda > 0$, some operations are conducted as follows:

$$h^\lambda = \bigcup_{\beta \in h} \{\beta^\lambda\} \quad (5)$$

$$\lambda h = \bigcup_{\beta \in h} \{1 - (1 - \beta)^\lambda\} \quad (6)$$

$$h_1 \oplus h_2 = \bigcup_{\beta_1 \in h_1, \beta_2 \in h_2} \{\beta_1 + \beta_2 - \beta_1\beta_2\} \quad (7)$$

$$h_1 \otimes h_2 = \bigcup_{\beta_1 \in h_1, \beta_2 \in h_2} \{\beta_1\beta_2\} \quad (8)$$

Definition 2. For a hesitant fuzzy set h , the score function is indicated as follow:

$$s_E(h) = \frac{1}{\#h} \sum_{\beta \in h} \beta \quad (9)$$

where $\#h$ denotes the number of the elements in h . Let's assume there are two hesitant fuzzy sets,

$$\text{If } s_E(h_1) > s_E(h_2), \text{ then } h_1 > h_2 \quad (10)$$

$$\text{If } s_E(h_1) = s_E(h_2), \text{ then } h_1 = h_2 \quad (11)$$

Definition 3. Hesitant fuzzy linguistic terms scale is a finite subset in sequence linguistic term set s_E , which can be represented as $s_E = \{s_0, s_1, \dots, s_g\}$.

Definition 4. Assume that the function E_{GH} transforms linguistic expressions into hesitant fuzzy linguistic term sets. s_i denotes a value for a linguistic variable. The transformation function E_{GH} as follows (Kayapınar Kaya & Erginel, 2020; Liu & Rodríguez, 2014):

$$E_{GH}(s_i) = \{s_i | s_i \in S\}, \quad (12)$$

$$E_{GH}(\text{at most } s_i) = \{s_j | s_j \in S \text{ and } s_j \leq s_i\}, \quad (13)$$

$$E_{GH}(\text{lower than } s_i) = \{s_j | s_j \in S \text{ and } s_j < s_i\}, \quad (14)$$

$$E_{GH}(\text{at least } s_i) = \{s_j | s_j \in S \text{ and } s_j \geq s_i\}, \quad (15)$$

$$E_{GH}(\text{greater than } s_i) = \{s_j | s_j \in S \text{ and } s_j > s_i\}, \quad (16)$$

$$E_{GH}(\text{between } s_i \text{ and } s_j) = \{s_k | s_k \in S \text{ and } s_i \leq s_k \leq s_j\}. \quad (17)$$

Definition 5. Assuming n number of experts, and $n = 1, 2, \dots, n$, the fuzzy rating of each expert can be expressed as $\tilde{A}_n = (a_n^l, a_n^m, a_n^u)$ and their membership function is represented as $\mu_{\tilde{A}_k}(x)$. The aggregated fuzzy rating $\tilde{A}_n = (a_n^l, a_n^m, a_n^u)$ can be computed as follows:

$$a^l = \frac{1}{N} \sum_{n=1}^N a_n^l, \quad a^m = \frac{1}{N} \sum_{n=1}^N a_n^m, \quad a^u = \frac{1}{N} \sum_{n=1}^N a_n^u \quad (18)$$

3.2. Steps of hesitant fuzzy SWARA

The Stepwise Weight Assessment Ratio Analysis (SWARA) approach was introduced by Keršulienė and colleagues (2010) to calculate subjective weights of criteria weights in the multi-criteria decision-making process. The SWARA method stands out from other methodologies like AHP and ANP due to its efficiency and simplicity in determining criteria weights (Agarwal et al., 2020). Unlike other techniques, SWARA needs fewer pairwise comparisons to determine decision criteria weights. It is a user-friendly method that is easy for decision-makers to use (Kayapınar Kaya & Erginel, 2020). In the SWARA method, the number of comparisons required is $n-1$, as the criteria are ranked in descending order of importance. In contrast, the AHP method necessitates $n(n-1)/2$ pairwise comparisons (Ghorabae et al., 2018). The SWARA method has been utilized in various decision-making problems, including supplier selection (Alimardani et al., 2013), investment prioritization (Hashemkhani Zolfani & Bahrami, 2014), logistics performance assessment (Gök Kısa & Ayçin, 2019), location selection for logistics center (Ulutaş et al., 2020), and assessment of sustainability indicators for renewable energy systems (Ghenai et al., 2020), etc.

Experts play a crucial role in evaluating and determining the subjective weighting of criteria in multi-criteria decision-making problems. The SWARA method's major advantage is its ability to evaluate expert accuracy when it comes to the criteria (Dahooie et al., 2020). On the other hand, most real-world issues contain ambiguous and subjective criteria, making it challenging for traditional SWARA to assess decision-makers' preferences efficiently (Kayapınar Kaya & Erginel, 2020). Integrating the SWARA

method with fuzzy sets effectively captures and models the inherent uncertainty and imprecision in expert opinions (Agarwal et al., 2020). Experts can express their judgments more intuitively and flexibly by using linguistic variables corresponding to fuzzy numbers. Hesitant fuzzy sets, an advanced extension of traditional fuzzy sets, enhance this capability further by allowing decision-makers to provide multiple potential membership values. This feature enables a more nuanced and realistic representation of their opinions, especially in contexts where hesitation and variability in judgment are prevalent (Dahooie et al., 2020), (Mardani et al., 2020). In this study, the SWARA method based on hesitant fuzzy sets is used instead of traditional SWARA due to the effectiveness of hesitant fuzzy sets in dealing with human hesitations. The steps for hesitant fuzzy SWARA are described below (Kayapınar Kaya & Erginel, 2020):

Step 1: Sorting criteria based on expert opinions. According to expert opinions, the most important criterion is ranked first, and less important criteria are in the following levels.

Step 2: Determining the degree of comparative importance. The relative importance of each criterion is evaluated in comparison to the relative degree for each criterion j in relation to the previous $(j - 1)$ criteria using the triangular hesitant fuzzy linguistic scale, which is given in Table 2. Due to insufficient information, limited time, and subjective evaluation criteria, experts rely on linguistic expressions rather than measurable data to explain their judgments (Mishra et al., 2019).

Table 2

Scale for Hesitant Fuzzy SWARA Evaluations

Linguistic terms	Triangular fuzzy number
Equally important (EI)	(1.000,1.000,1.000)
Moderately important (MI)	(0.667,1.000,1.500)
Less important (LI)	(0.400,0.500,0.667)
Very less important (VLI)	(0.286,0.333,0.400)
Much less important (MLI)	(0.222,0.250,0.286)

After determining the relative importance of evaluation criteria, the final comparative importance $\tilde{s}_j$ values are determined by aggregating expert evaluations.

Step 3: Calculating $\tilde{k}_j$, the coefficient for each criterion. The $\tilde{k}_j$ value of the most important criterion is assigned 1. The coefficient is calculated using Eq. 19.

$$\tilde{k}_j = \begin{cases} 1, & j = 1 \\ \tilde{s}_j + 1, & j > 1 \end{cases} \quad (19)$$

where in $\tilde{s}_j$ represents the comparative importance value.

Step 4: Calculating the hesitant fuzzy weight $\tilde{q}_j$ of each criterion. The determination of the hesitant fuzzy weight is computed using Eq. 20.

$$\tilde{q}_j = \begin{cases} 1, & j = 1 \\ \frac{\tilde{q}_{j-1}}{\tilde{k}_j} + 1, & j > 1 \end{cases} \quad (20)$$

Step 5: Calculating the relative hesitant fuzzy weights $\tilde{w}_j$ of each criterion. The relative hesitant fuzzy weight is computed using Eq. 21.

$$\tilde{w}_j = \frac{\tilde{q}_j}{\sum_{k=1}^n \tilde{q}_k} \quad (21)$$

where $\tilde{w}_j$, the relative hesitant fuzzy weights of each criterion, are represented as a triangular hesitant fuzzy number, and n denotes the number of such criteria.

Step 6: *Performing the defuzzification process.* Converting the hesitant fuzzy weight $\tilde{w}_j = (l, m, u)$, into crisp value w_j is applied for defuzzification using Eq. 22 (Chanas, 2001).

$$w_j(\text{crisp}) = \frac{l+2*m+u}{4} \quad (22)$$

3.3. Ethical statement

Before collecting the research data, the questionnaire to be applied was approved by the Duzce University Ethics Commission's ethics committee decision "25.01.2024 and numbered 2024/6". Data were collected after receiving ethics committee approval.

4. Prioritization of Industrial Symbiosis Enablers

4.1. Identification of industrial symbiosis enablers

In this study, a two-stage research was conducted to identify the main category and subcategory of IS-enabling factors within the context of Türkiye. In the initial stage, an extensive literature review was conducted on enablers for implementing IS collaborations. Keywords such as "industrial symbiosis" AND "enablers" OR "critical factors" OR "drivers" OR "key factors" OR "enabling factors" were selected based on their frequent usage in previous studies and their relevance to the scope of the research. These keywords were searched in Scopus, Dergipark, and Google Scholar databases. In addition to the academic articles obtained from the screening, reports prepared within the scope of IS projects were examined. Initially, 46 enablers were recorded through the literature review. In the second stage, the enabling factors identified by the literature review were discussed during two separate interview sessions with three experts (Expert 1, Expert 2, and Expert 7, as given information in Table 4) with experience in IS projects. These experts were selected due to their extensive experience and direct involvement in projects related to IS. The interviews provided an opportunity for in-depth discussions aimed at refining and validating the enablers identified during the literature review. The insights and feedback from the experts were instrumental in tailoring the enablers to the specific context of Türkiye. Based on these discussions, the enablers were categorized into five main contexts: economic, organizational, geographical, social and political, and legal. In addition, 23 sub-enablers were identified under these main categories. Table 3 presents the main enablers, their sub-criteria identified, and their references and brief descriptions.

Table 3

List of Enablers for IS

Main Enablers	Code	Sub-Enablers	Descriptions	References
Economic	EC01	Reduction of waste disposal costs	Reduction of waste disposal costs of companies thanks to symbiosis collaboration	Khan (2023), Saghafi and Roshandel (2024)
	EC02	Reduction of raw material costs	Reduced costs thanks to the use of less raw materials	Yeşilkaya et al. (2020), Saghafi and Roshandel (2024)
	EC03	Reduction of logistics costs	Reduced transportation costs	Sonel et al. (2022), Harfeldt-Berg et al. (2022)
	EC04	Offering new business opportunities	Generating new revenue sources as a result of the incorporation of new goods and services	Alkaya (2021), Madsen et al. (2015), Khan et al. (2023)
	EC05	Economic advantages of IS	Economic benefits of collaborating through IS	Yeşilkaya et al. (2020), Sonel et al. (2022), Martin and Harris 2018)

Tablo 3 (Continued)

	ECO6	Providing a competitive advantage in the market	Providing access to new markets, resources, and expertise can help companies gain a competitive advantage.	Harfeldt-Berg et al. (2022), Taqi et al. (2022)
	ECO7	Short amortization period (Short return on investment)	Short payback period of the symbiosis project	Harfeldt-Berg et al. (2022), Neves et al. (2020)
Organizational	ORG1	Interest and support from senior management	Senior management's willingness to cooperate on IS and positive outlook on investments	Alakaş (2020), Behera et al. (2012)
	ORG2	Establishing a culture of collaboration	Having a culture of collaboration that enables companies to work together	Harfeldt-Berg et al. (2022), Mortensen and Kørnø (2019)
	ORG3	Being open to new business ideas	Adopting a new business approach that yields economic and environmental benefits	Henriques et al. (2021), Neves et al. (2020)
	ORG4	University-industry collaboration	Collaborating with universities and businesses on R&D and business development	Proposed enabler
	ORG5	Digitalization of sectors (Transition to Industry 4.0)	Technological advances in industry enable better control of waste and resources	Henriques et al. (2021), Khan et al. (2023)
Geographical	GE01	Geographical proximity	Companies that plan to collaborate should be located in close proximity to each other	Henriques et al. (2021), Harfeldt-Berg et al. (2022)
	GE02	Sharing logistics resources	Companies work together to share logistics resources such as warehouse space, transportation, and delivery networks	Alkaya (2021), Harfeldt-Berg et al. (2022)
	GE03	Strategic location	Located in a region with wide sectoral diversity	Henriques et al. (2021), Neves et al. (2020)
Social	SOC1	A positive image of environmentally friendly practices	Ensuring an environmentally friendly corporate image through IS practices	Proposed enabler
	SOC2	Providing new job opportunities	Increased employment opportunities thanks to new job opportunities	Khan et al. (2023), Taqi et al. (2022), Harfeldt-Berg et al. (2022)
	SOC3	Community awareness	Raising awareness and promoting environmentally friendly practices in society	Harfeldt-Berg et al. (2022), Neves et al. (2020)
	SOC4	Ensuring an environment of trust	Fostering open company relationships by exchanging information and enhancing trust among all parties involved	Agudo et al., (2022), Henriques et al. (2021)
Political and Legal	POL1	Government support for environmentally friendly practices	Availability of government support for environmentally friendly practices	Harfeldt-Berg et al. (2022), Ji et al. (2020)
	POL2	Introduction of environmental tax policies	Developing tax policies that promote environmental business practices	Henriques et al. (2021), Ji et al. (2020)
	POL3	Facilitating legal processes	Providing legal facilities for the implementation of symbiotic collaborations	Proposed enabler
	POL4	Support from the administrations of Organized Industrial Zones (OIZ)	Assist in improving communication and cooperation between companies through Organized Industrial Zone administrations	Proposed enabler

4.2. Hesitant fuzzy SWARA analysis

This study identified five main enablers and 23 sub-enablers to facilitate IS collaboration through a comprehensive literature review and in-depth expert interviews. Then, the SWARA process based on hesitant fuzzy sets was applied to analyze and rank IS enablers. In this step, eight experts who had participated in IS projects were selected to ensure the reliability of the data. The experts consulted for decision-making have experience in establishing IS collaborations. Purposive sampling, a non-probability sampling technique, was employed to select industry experts with specific knowledge and experience relevant to the study's focus (Sindhvani et al., 2022). This method allowed the researchers to deliberately choose participants who could provide valuable insights and expertise in the industry under investigation. Detailed information about selected experts is provided in Table 4.

Table 4

Information About Experts

Expert	Sector	Title	Year of Experience	Explanation
Exp. 1	Bursa Eskisehir Bilecik Development Agency (BEBKA) (Bursa)	Planning Specialist	4	A researcher working on projects that aim to promote IS applications.
Exp. 2	BEBKA (Eskişehir)	Planning Specialist	10	A researcher working on projects that aim to promote IS applications.
Exp. 3	Waste Management Company	Environmental Engineer	5	An environmental engineer at a company that offers consultancy services regarding sustainability, waste management, and IS.
Exp. 4	Waste Management Company	Company Owner	11	Owner of a company that provides professional services to manufacturers in IS, waste management, disposal services, and sustainability.
Exp. 5	Waste Management Company	Environmental Engineer	5	An environmental engineer at a company that offers consultancy services regarding sustainability, waste management, and IS.
Exp. 6	United Nations Development Programme (UNDP)	Project Associate	13	An expert in conducting research to identify problems and constraints in implementing IS for regional development.
Exp. 7	Climate Change Risk Management Consulting Company	Climate Crisis and Sustainability Manager	12	An executive for coordinating operational programs and projects related to IS, cleaner production, and green efficiency.
Exp. 8	Waste Management Company	Environmental Engineer	6	An environmental engineer at a company that offers consultancy services regarding sustainability, waste management, and IS.

The experts have been asked to help assess the relative importance of enablers using linguistic variables. Thus, a questionnaire was sent to the experts to obtain input for the application of the hesitant fuzzy SWARA method. Additionally, the experts were given a thorough overview of the scoring system used in the hesitant fuzzy SWARA method. The hesitant fuzzy SWARA calculation steps were applied using the data obtained from the experts as follows:

Step 1: *Ranking the IS enablers based on their level of importance.* Each expert ranked the main enablers and their sub-enablers based on their level of importance. For example, the most important main enablers are ranked first, and the least important enablers are ranked last. Then, a final ranking was

created by averaging the experts' rankings. Table 5 presents the rankings of the main enablers provided by each expert, along with the average ranking.

Table 5

Ranking of Main Category Enablers

Main Enabler	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 6	Exp.7	Exp. 8	Avg.	Rank
Economic	1	1	4	1	3	1	1	1	1.625	1
Organizational	3	3	5	2	2	2	2	2	2.625	2
Geographical	2	2	3	4	5	4	3	3	3.25	3
Social	5	5	1	3	4	3	5	5	3.875	5
Political & Legal	4	4	2	5	1	5	4	4	3.625	4

Step 2: *Determining the relative importance of each enabler.* Experts compare the enabling factor of j to the previous enabler $j - 1$ using the triangular hesitant fuzzy scale provided in Table 2. After evaluating all the enabling factors, the main enablers, derived from the collective opinions of experts' linguistic evaluations, are presented in Table 6. The detailed sub-enablers can be found in Appendix B, Table B1. Then, linguistic evaluations were transformed into Hesitant Fuzzy Linguistic Terms Set (HFLTTS). Finally, the average comparative importance $\tilde{s}_j$ values of the enablers were calculated using Eq. 18.

Table 6

Linguistic Expressions of Comparative Importance Degree of Main Enablers

Main Enabler	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 6	Exp.7	Exp. 8	Agg.
Economic									
Organizational	EI	VLI	MI	VLI	EI	EI	VLI	EI	VLI, MI, EI
Geographical	EI	MI	between VLI-MI	MI	LI	greater than LI	VLI	LI	VLI, LI, MI, EI
Political & Legal	MI	LI	VLI	VLI	MLI	between LI-EI	LI	MLI	MLI, VLI, LI, MI, EI
Social	MI	VLI	VLI	greater than LI	MI	MI	VLI	MLI	MLI, VLI, MI, EI

Step 3: *Computing the coefficient for each IS enabler.* The coefficient $\tilde{k}_j$ values for each main and sub-enabler were calculated using Eq. 19.

Step 4: *Computing the hesitant fuzzy weights $\tilde{q}_j$ for each IS enabler.* Hesitant fuzzy weights of enablers were calculated using Eq. 20.

Step 5: *Calculating weights $\tilde{w}_j$ for each IS enabler.* The relative hesitant fuzzy weights of each main enabler and sub-enabler were determined using Eq. 21. Appendix B (Table B2 and B3) display the $\tilde{s}_j$ values of the main enablers and their sub-enablers calculated in step 2, the $\tilde{k}_j$ values determined in step 3, the $\tilde{q}_j$ values computed in step 4, and finally the $\tilde{w}_j$ values calculated in step 5.

Step 6: *Conducting the defuzzification procedure.* After calculating the enablers' relative hesitant fuzzy weight values, the crisp weights were obtained through Eq. 22.

Finally, the global weights for each sub-enabler were determined by multiplying the main barrier weight by the related sub-enabler local weight. The crisp weights, as well as the ranking of all enablers, are illustrated in Table 7.

Table 7*Weight Values for IS Enablers*

Main enablers	Main enablers weight	Main enablers rank	Code	Sub-enablers local weight	Local rank	Sub-enablers global weight	Global rank
Economic	0.4633	1	ECO1	0.2519	2	0.1153	3
			ECO2	0.4622	1	0.2106	1
			ECO3	0.0774	4	0.0357	10
			ECO4	0.0483	5	0.0224	15
			ECO5	0.1266	3	0.0582	6
			ECO6	0.0276	6	0.0128	19
			ECO7	0.0170	7	0.0079	22
Organizational	0.2526	2	ORG1	0.4788	1	0.1230	2
			ORG2	0.1484	3	0.0387	9
			ORG3	0.2393	2	0.0620	5
			ORG4	0.0874	4	0.0229	14
			ORG5	0.0545	5	0.0144	18
Geographical	0.1476	3	GEO1	0.5387	1	0.0812	4
			GEO2	0.1718	3	0.0265	13
			GEO3	0.2930	2	0.0447	8
Social	0.0571	5	SOC1	0.0938	4	0.0056	23
			SOC2	0.1663	3	0.0098	20
			SOC3	0.4728	1	0.0272	11
			SOC4	0.2693	2	0.0156	17
Political & Legal	0.0928	4	POL1	0.2778	2	0.0265	12
			POL2	0.1629	3	0.0158	16
			POL3	0.4756	1	0.0448	7
			POL4	0.0894	4	0.0088	21

5. Results and Discussion

The current study applied a fuzzy sets-based MCDM approach to rank enablers encouraging companies in Türkiye to adopt IS. Table 7 illustrates the ranking of all enablers based on their weight values. The hesitant fuzzy SWARA method was used to compare the five main enablers and 23 sub-enablers, providing prioritization and sequencing to help experts select and categorize the most critical enablers based on their critical level. The findings of this research have significant implications for policymakers, industry stakeholders, and researchers.

According to the analysis results, the economic dimension ranks first with the highest weight among the main enablers in the establishment of IS collaborations. The primary expectation of companies is that the projects they invest in will yield economic returns. Therefore, the financial benefits it can provide are the most significant factor that will drive the implementation of IS. This finding aligns with recent research by Yazıcı and colleagues (2024), which highlights the critical role of economic factors in facilitating IS. Their study specifically emphasizes the importance of economic considerations in identifying suitable partners for utilizing waste generated in the foundry industry in Türkiye. Additionally, numerous studies have extensively examined the environmental and economic benefits that can be obtained through IS (Yeşilkaya et al., 2020). The sub-criteria of reduction raw material costs (ECO2), located under the heading of economic main criteria, was determined as the most important enabling factor. Moreover, the sub-criterion of reducing raw material costs ranks first among 23 criteria

in terms of global weight value. These findings underscore the priority companies place on minimizing raw material expenses in the context of IS networks. Similarly, Neves and colleagues (2019) highlighted that IS networks can significantly benefit participants not only by reducing waste processing and landfill costs but also through savings in raw material procurement. Supporting this, numerous studies (Domenech et al., 2019; Mirata, 2004; Chertow, 2007) have identified raw material cost reduction as a pivotal factor in fostering and sustaining IS networks, illustrating its central role in driving such collaborations. The sub-enabler of reducing waste disposal costs (ECO1) ranks second within the main economic enabler and third in terms of global weight value. In the context of IS applications, utilizing waste products from one facility as raw materials for another not only reduces disposal efforts but also generates significant cost savings (Neves et al., 2020). Similarly, in the report on the current status of IS in Türkiye prepared by Alkaya (2021), it is emphasized that one of the benefits of IS is the reduction of waste disposal costs. In line with this, Khan and colleagues (2023) noted that most waste generated in production facilities is typically disposed of, leading to substantial costs, and emphasized that these costs can be mitigated by redirecting waste products to serve as raw materials for other facilities. The economic advantages of IS (ECO5) are ranked third under the economic main dimension. These benefits include cost savings through reduced raw material purchasing, increased efficiency in waste management, and the creation of new revenue streams for participating organizations (Neves et al., 2020). Such benefits not only enhance the profitability of individual enterprises but also contribute to the overall competitiveness of industries adopting IS practices (Corder et al., 2014; Taqi et al., 2022). The other economic sub-criteria include the reduction of logistics costs (ECO3), the offering new business opportunities (ECO4), and providing a competitive advantage in the market (ECO6), which are ranked fourth, fifth, and sixth in importance, respectively, under the economic dimension.

Organizational factors are the second most important criterion among the main enablers. Taqi and colleagues (2022) stated that organizational factors play the most important role in companies creating IS relationships. In this study, the organizational dimension is ranked second in terms of importance in the context of Türkiye. The culture of an organization significantly influences the implementation of IS practices (Yang et al., 2022). In this respect, organizations need to be capable of implementing organizational changes to embrace new business models. By fostering a culture that values sustainability, collaboration, innovation, and continuous improvement, organizations can effectively leverage IS to obtain environmental and economic benefits. In order of importance, interest and support from senior management (ORG1), being open to new business ideas (ORG3), establishing a culture of collaboration (ORG2), university-industry collaboration (ORG4), and digitalization of sectors (ORG5) are the sub-facilitators at the organizational level, which are crucial for building robust IS relationships. Interest and support from senior management (ORG1) has a considerable influence as the second-ranked factor among all the sub-enablers. Senior management has the authority to allocate resources, including financial investments, human resources, and technological assets necessary for developing and implementing IS initiatives (Ji et al., 2020). Therefore, the interest and support of senior management are crucial for the successful creation and maintenance of IS networks (Sellitto et al., 2021). Likewise, Alakaş and colleagues (2020) emphasized that the management criterion is the most crucial aspect in the application of sustainable IS. Furthermore, various studies highlighted that a lack of attention or awareness among enterprise managers or stakeholders is a critical barrier to IS (Ji et al., 2020). The commitment of senior management and the integration of sustainable practices into corporate culture is crucial for fostering IS applications. Leadership is pivotal in prioritizing resource efficiency, which is essential for symbiotic relationships (Chrysikopoulos et al., 2024). The sub-enabler of being open to new business ideas (ORG3), ranked second under the organizational dimension and fifth according to global weight values. Henriques and colleagues (2021) have indicated that companies can generate new revenues by adopting a business approach that creates both economic and environmental benefits through collaborations in IS. The sub-enabler of establishing a culture of

collaboration (ORG2) ranked third under the organizational dimension. According to Mortensen and Kørnøv (2019), fostering a collaborative culture is essential in the early phases of IS, as it enables the formation of trust and mutual understanding among participants. Moreover, a collaborative culture facilitates not only the establishment of initial ties but also the ongoing management of dynamic interactions, which are crucial for the sustainability of IS practices (Boons et al., 2017). Research also indicates that collaboration is not limited to direct exchanges but includes co-creation processes involving various stakeholders, such as businesses, policymakers, and research institutions (Mortensen & Kørnøv, 2019).

Geographical factors were ranked as the third most important enabler among the main enablers. On the other hand, geographical proximity (GEO1) was identified as the fourth most important enabling factor among all sub-enablers. According to Henriques and colleagues (2021) geographical factors play a significant role in promoting IS collaborations. Ji and colleagues (2020) also pointed out that in IS, the proper location of firms in the network can help firms reduce material transportation costs and facilitate communication between firms. For many industries, proximity to specific geographic locations is a crucial factor due to the high volumes of goods being transported (Henriques et al., 2021). Geographical proximity is an important factor to consider when implementing IS, as frequently emphasized in the literature (Neves et al., 2020; Chertow, 2000; Ji et al., 2020; Jensen et al., 2011). However, Neves et al. (2020) emphasized that the geographical location of companies should not be seen as a limiting factor for symbiotic collaborations. For instance, waste materials common to many industries and available in most countries can be utilized to expand the range of applications for IS. The sub-enabler of strategic location (GEO3), ranked second under the geographic dimension and eighth globally, highlights the importance of being situated in regions with a diverse industrial base for effective IS. The presence of sectoral diversity within a region significantly enhances the potential for IS by increasing the variety of waste and resource streams available for exchange (Jensen, 2016). In Türkiye, the widespread establishment of organized industrial zones (OIZs) strongly supports this criterion (International Synergies, 2019). OIZs bring together companies from various sectors within close proximity, creating opportunities for waste and resource exchanges that are fundamental to IS.

The political and legal factors were ranked fourth among the five main enablers. A comprehensive literature review by Harfeldt-Berg and colleagues (2022) highlights these factors considerably influence collaborations within IS. Further, Agudo and colleagues (2022) assert that robust political backing is essential for the large-scale implementation of IS. In line with this, Tao and colleagues (2019) advocates for governmental action to foster, incentivize, or mandate corporate engagement in IS practices. In this study, the sub-enablers under the political and legal dimension were ranked as follows: facilitating legal processes (POL3) emerged as the most important sub-enabler, followed by government support for environmentally friendly practices (POL1), introduction of environmental tax policies (POL2), and support from the administrations of Organized Industrial Zones (OIZ) (POL4). The prominence of POL3 highlights the critical need for streamlining legal frameworks to eliminate bureaucratic barriers and ensure clarity in regulatory procedures. Inadequate or overly complex legal processes can act as significant barriers, delaying or even halting IS initiatives (Chrysikopoulos et al., 2024). The second-ranked POL1 reflects the importance of active governmental support in promoting eco-friendly practices, such as through grants, subsidies, or strategic policy frameworks that encourage symbiotic collaborations. POL2, concerning environmental tax policies, showcases the dual potential of such measures: while they can incentivize industries to adopt sustainable practices, poorly designed or punitive tax structures might inadvertently discourage participation. Lastly, POL4 underscores the unique role of OIZ administrations in facilitating IS by providing localized support, infrastructure, and guidance in Türkiye. As Gibbs (2003) notes, the interplay between government policies, regulations, and institutional systems critically shapes IS outcomes. Türkiye's regulatory environment, in particular, can act as both a catalyst and a constraint. Supportive measures such as financial incentives, transparent

and harmonized regulations (Harfeldt-Berg et al., 2022; Yang et al., 2022), and the active involvement of OIZ administrations (Dolgen & Alpaslan, 2020) can significantly advance IS practices.

Social factors play a critical role in the practical implementation of IS, as demonstrated by Taqi and colleagues (2022). In this study, however, these factors were ranked fifth in terms of overall importance. Despite this, among the sub-social enablers, community awareness (SOC3) emerged as a leading factor. Raising awareness helps create a supportive atmosphere for sustainable practices, encouraging local businesses and residents to actively engage in sharing resources (Lasthein et al., 2021). The sub-enabler of ensuring an environment of trust (SOC4) ranks second under the social dimension. Trust among stakeholders is pivotal for resource sharing, as it mitigates concerns about potential risks and ensures transparent, cooperative interactions. Without mutual trust, efforts to establish or sustain IS partnerships can falter, as industries may be reluctant to collaborate (Agudo et al., 2022). The third sub-enabler is providing new job opportunities (SOC2), reflecting IS's socioeconomic benefits. IS initiatives can gain broader community support by fostering green jobs and creating employment opportunities linked to recycling, waste management, and resource optimization (Khan et al., 2023). Finally, while ranked fourth, a positive image of environmentally friendly practices (SOC1) plays a crucial role in shaping public and stakeholder attitudes. As communities become better informed about the benefits of IS for both the environment and the economy, they are more inclined to support and take part in such initiatives, establishing a strong cooperative network across various sectors (Harfeldt-Berg et al., 2022). Moreover, increased awareness among the community can catch the attention of regulators, potentially leading to the creation of policies that favor symbiotic partnerships.

6. Conclusion

IS is a process that involves the collaboration of industries to create a closed-loop system where waste from one industry becomes a resource for another. The success of this process is dependent on various factors, and according to the existing literature, the presence of key enablers is critical (Henriques et al., 2021). This research aims to develop an approach to identify and prioritize the various enablers that facilitate IS collaborations in Türkiye. First, a comprehensive literature review was conducted to identify the enablers. Subsequently, the main enablers and sub-enablers were finalized through expert interviews. Finally, the importance levels of these enablers were determined using the hesitant fuzzy SWARA method.

The findings highlight the significance of economic, organizational, geographical, political, legal, and social factors in promoting IS. Among these factors, economic drivers were found to be the most influential. Specifically, the reduction in raw material and waste disposal costs was identified as crucial, underscoring the financial feasibility of IS as a strong incentive for companies. The results emphasize the importance of organizational support, especially from senior management, in implementing sustainable practices. It stresses the necessity of dedicated leadership that prioritizes resource efficiency and sustainability. Additionally, it suggests that geographical proximity is not as limiting as traditionally believed, indicating that innovative technological solutions and logistic strategies can help overcome distance-related challenges.

The political and legal frameworks in Türkiye have a significant impact on the development and implementation of IS projects. This study points out the need for increased government support and clearer regulations to better facilitate IS initiatives. While social factors were ranked as less important overall, the influence of community awareness on the success of these initiatives should not be underestimated, as public support is crucial for the long-term sustainability of symbiosis networks.

This study presents a comprehensive framework designed for practitioners and policymakers to systematically evaluate the critical enabling factors (enablers) that play a crucial role in successfully implementing IS initiatives in the context of Türkiye, an emerging economy. This study addresses the

complexities of decision-making under uncertainty by employing the hesitant fuzzy SWARA method. It provides a practical tool for experts and decision-makers to prioritize enablers effectively based on their significance, enabling them to focus on the most critical factors. By identifying and prioritizing these enablers, the framework aims to facilitate a deeper understanding of the conditions necessary to promote IS collaboration among industries, thereby promoting resource efficiency, waste reduction, and sustainable development in various sectors in Türkiye.

This study has some limitations. Firstly, it did not explore the relationships between the enablers of IS, which may limit the depth of insights into the interconnected dynamics of these factors. For instance, understanding the causal relationships could refine the prioritization of enablers and provide more targeted strategies for effective IS implementation. Future studies could address this limitation by employing methods such as DEMATEL and ISM, integrated with fuzzy sets, to uncover the underlying cause-and-effect relationships among enablers. Such an approach could enhance the robustness and applicability of findings, offering strategic insights into the complex interactions within IS systems. Additionally, while this study offers a general framework, future research could delve into barriers or hindering factors that may impede IS collaborations. Such analyses could provide a more comprehensive understanding of the challenges in implementing IS, particularly in key sectors such as food, textiles, and agriculture, where unique obstacles and opportunities exist.

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Appendix A

Table A1

Industrial Symbiosis Projects in Türkiye

Project Title and Years	Supporting Institution	Implementing Organization	Focus Region	Main Objectives	Key Outputs/Expected Outcomes
Industrial Symbiosis Project in Iskenderun Bay: Feasibility Phase (2008-2009)	BTC Crude Oil Pipeline Company	United Nations Development Program (UNDP), Adana Chamber of Industry	Adana, Mersin, Osmaniye, Iskenderun	- Raising awareness about the concept of IS in the Iskenderun Bay Region	- Identifying sectors with high IS potential - Creating a platform for idea exchange among industrialists
Industrial Symbiosis in Iskenderun Bay: Implementation Phase (2011-2014)	Technology Development Foundation of Türkiye (TTGV), BTC Crude Oil Pipeline Company	TTGV, International Synergies	Adana, Mersin, Osmaniye, Iskenderun	- Reuse of industrial waste - Energy efficiency - Conservation of natural resources	- Recovery of 330,000 tons of waste/year - Energy savings of 34 million kWh/year - Reduction of 37,000 tons of CO ₂ /year
Bursa-Eskişehir-Bilecik Industrial Symbiosis Program (2014-2016)	Bursa Eskişehir Bilecik Development Agency (BEBKA)	BEBKA, TTGV	Bursa, Eskişehir, Bilecik	- Raising awareness of the IS approach in the region - Identifying the existing potential and strategy	- Creation of a regional waste exchange network - Increased industrial cooperation
Investigation of Industrial Symbiosis Potential for Trakya Region (2014-2016)	Trakya Development Agency	TTGV	Thrace Region	- Implementing IS as effective regional development and planning tools to reduce environmental impacts and enhance competitiveness	- Conducting sectoral and environmental analyses for identifying IS potential and strategies - Strengthening inter-industry collaboration
Identification of Industrial Symbiosis Opportunities in Ankara OSTIM (2014-2015)	The Small and Medium Enterprises Development Organization of Türkiye (KOSGEB)	Ankara OSTIM Organized Industrial Zone (OIZ)	Ankara	- Identifying IS opportunities in the OSTIM OIZ - Conducting preliminary feasibility analyses	- Identification of 252 potential IS opportunities, - Savings in raw materials and energy, - Enhancements in waste management - Decrease in carbon footprint
Gaziantep Industrial Symbiosis Project (2015-2016)	Silkroad Development Agency	Gaziantep Chamber of Industry	Gaziantep	- Valorization of industrial waste - Increasing employment and competitiveness - Promoting efficient use of resources	- Identifying IS opportunities in five selected companies from various sectors in the Gaziantep OIZ

Table A1 (Continued)

Industrial Symbiosis and Eco-efficiency Project in Antalya OIZ (2015–2017)	KOSGEB	TTGV, Directorate of Antalya OIZ	Antalya	-Developing a culture of resource-sharing among businesses operating in the Antalya OIZ -Raising awareness of IS	-Establishing a current and potential IS network within the Antalya OSB. -Recovery of 85,050 tons of waste savings of 75,000 m ³ of water -Substitution of 91,600 tons of raw materials
Investigation of Industrial Symbiosis Opportunities in Aksaray OIZ (2018)	Ahiler Development Agency	GTE consultancy firm	Aksaray	- Identification of symbiosis opportunities - Resource optimization	-Preparation of a feasibility report on potential opportunities for IS
Investigation of Industrial Symbiosis Opportunities in Eskisehir (2019)	BEBKA	GTE consultancy firm	Eskişehir OIZ	- Exploring IS collaboration opportunities - Achieving environmental and economic benefits through the IS approach in the region.	-Feasibility studies conducted for 5 symbiosis opportunities, leading to estimated gains including: 10–38% raw material savings and waste reduction 3–30% energy savings 13–38% reduction in CO ₂ emissions
Petroleum Waste Utilization Industrial Symbiosis Opportunities Project (2017)	Dicle Development Agency, Batman Chamber of Commerce and Industry	Ekodenge consultancy firm	Mardin, Siirt, Şırnak, Batman, Diyarbakır, Gaziantep	-Assessing the current state of petroleum waste management - Identifying sectors that can use petroleum-derived waste as a resource or raw material	-Identification of sectors and companies capable of utilizing petroleum-derived waste.
Investigation of Industrial Symbiosis Opportunities in Kayseri OIZ (2017)	Central Anatolia Development Agency	Kayseri OIZ, Ekosmart consultancy firm	Kayseri OIZ	-Identifying the waste and surplus products of businesses in Kayseri OIZ	-On-site analysis conducted through visits to 207 businesses within Kayseri OIZ - Comprehensive assessment of the current state and potential IS opportunities
FISSAC Project (2015–2020)	European Union (EU) Horizon 2020	Acciona company, Turkish Cement Manufacturers' Association (TürkÇimento), AKG Gazbeton Enterprises, Ekodenge consultancy firm	TürkÇimento, AKG Gazbeton Enterprises	-Developing an innovative IS model focused on the zero-waste approach - Developing an innovative IS model focused on the zero-waste approach	-Utilization of glass waste, ceramic waste, aluminum slag, and ladle furnace slag for the production of CSA cement -20% increase in energy efficiency -12% improvement in waste treatment efficiency

Table A1 (Continued)

Industrial Symbiosis in İzmir Region Project (2021-ongoing)	UNDP Türkiye, İzmir Development Agency	İzmir Development Agency	İzmir	-Establish a digital-based governance platform to facilitate IS among businesses in İzmir -Develop a model application for a nationwide IS program	-Execution of pilot studies in İzmir to serve as models for potential nationwide implementation. -Development of a digital platform to connect businesses for resource sharing, including waste, by-products, and technology.
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Sources: (Alkaya, 2021; Çevre Şehircilik ve İklim Değişikliği Bakanlığı, 2023; Dolgen & Alpaslan, 2020)

Appendix B

Table B1

Linguistic Expressions of Comparative Importance Degree of Sub-Enablers

Sub-enablers	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 6	Exp.7	Exp. 8	Agg.
ECO2									
ECO1	greater than LI	MI	EI	LI	EI	greater than MI between MI-EI	MI	EI	LI, MI, EI
ECO4	EI	EI	EI	MI	MI		EI	MI	MI, EI
ECO5	EI	EI	EI	VLI	MI	MI	EI	lower than VLI	MLI, VLI, MI, EI
ECO3	LI	MLI	EI	at most MI	VLI	MI	MLI	MI	MLI, VLI, LI, MI, EI
ECO6	MI	EI	VLI	VLI	EI	MI	MI	MI	VLI, MI, EI
ECO7	EI	EI	MLI	VLI	MLI	MI	EI	MI	MLI, VLI, MI, EI
ORG1									
ORG3	MI	EI	EI	EI	at least MI	between MI-EI	MI	EI	MI, EI
ORG2	between MI-EI	LI	EI	VLI	lower than LI	between MI-EI	EI	EI	MLI, VLI, LI, MI, EI
ORG4	MI	VLI	EI	greater than VLI	EI	MI	VLI	MI	VLI, LI, MI, EI
ORG5	between MI-EI	MI	EI	VLI	LI	LI	MLI	MLI	MLI, VLI, LI, MI, EI
GEO1									
GEO3	MI	EI	EI	EI	at least MI	MI	LI	LI	LI, MI, EI
GEO2	EI	MI	EI	LI	VLI	between MI-EI	VLI	EI	VLI, LI, MI, EI
SOC4									
SOC3	EI	LI	EI	EI	LI	EI	LI	LI	LI, EI
SOC1	EI	LI	VLI	MI	EI	between MI-EI	EI	lower than VLI	MLI, VLI, LI, MI, EI
SOC2	between MI-EI	MI	VLI	EI	EI	MI	EI	EI	VLI, MI, EI

Table B1 (Continued)

POL2									
POL3	EI	VLI	at least EI	MI	LI	between MI-EI	EI	MI	VLI, LI, MI, EI
POL1	EI	VLI	LI	MI	EI	between MI-EI	EI	MI	VLI, LI, MI, EI
POL4	between MI-EI	EI	MI	LI	EI	MI	LI	MI	LI, MI, EI

Table B2*Outcomes of Main Enablers Calculated Using Hesitant Fuzzy SWARA Method*

Main Enabler	$\tilde{s}_j$	$\tilde{k}_j = \tilde{s}_j + 1$	$\tilde{q}_j = \frac{\tilde{q}_{j-1}}{\tilde{k}_j}$	$\tilde{w}_j = \left(\frac{\tilde{q}_j}{\sum \tilde{q}_j} \right)$
Economic		(1; 1; 1)	(1; 1; 1)	(0.4163; 0.4506; 0.4966)
Organizational	(0.651; 0.7777; 0.9667)	(1.651; 1.7777; 1.9667)	(0.5085; 0.5625; 0.6057)	(0.2117; 0.2535; 0.3008)
Geographical	(0.5883; 0.7083; 0.8918)	(1.5883; 1.7083; 1.8918)	(0.2688; 0.3293; 0.3814)	(0.1119; 0.1484; 0.1894)
Political&Legal	(0.515; 0.6166; 0.7706)	(1.515; 1.6166; 1.7706)	(0.1518; 0.2037; 0.2517)	(0.0632; 0.0918; 0.125)
Social	(0.5438; 0.6458; 0.7965)	(1.5438; 1.6458; 1.7965)	(0.0845; 0.1238; 0.1631)	(0.0352; 0.0558; 0.081)

Table B3*Outcomes of Sub-Enablers Are Determined Using the Hesitant Fuzzy SWARA Method*

Sub-enablers	$\tilde{s}_j$	$\tilde{k}_j = \tilde{s}_j + 1$	$\tilde{q}_j = \frac{\tilde{q}_{j-1}}{\tilde{k}_j}$	$\tilde{w}_j = \left(\frac{\tilde{q}_j}{\sum \tilde{q}_j} \right)$	weighted $\tilde{w}_j$
ECO2		(1; 1; 1)	(1; 1; 1)	(0.4167; 0.4589; 0.5142)	(0.1735; 0.2068; 0.2554)
ECO1	(0.689; 0.8333; 1.0557)	(1.689; 1.8333; 2.0557)	(0.4865; 0.5455; 0.5921)	(0.2027; 0.2503; 0.3044)	(0.0844; 0.1128; 0.1512)
ECO4	(0.8335; 1; 1.25)	(1.8335; 2; 2.25)	(0.2162; 0.2727; 0.3229)	(0.0901; 0.1252; 0.166)	(0.0375; 0.0564; 0.0825)
ECO5	(0.5438; 0.6458; 0.7965)	(1.5438; 1.6458; 1.7965)	(0.1203; 0.1657; 0.2092)	(0.0501; 0.076; 0.1076)	(0.0209; 0.0343; 0.0534)
ECO3	(0.515; 0.6166; 0.7706)	(1.515; 1.6166; 1.7706)	(0.068; 0.1025; 0.1381)	(0.0283; 0.047; 0.071)	(0.0118; 0.0212; 0.0353)
ECO6	(0.651; 0.7777; 0.9667)	(1.651; 1.7777; 1.9667)	(0.0346; 0.0577; 0.0836)	(0.0144; 0.0265; 0.043)	(0.006; 0.0119; 0.0214)
ECO7	(0.5438; 0.6458; 0.7965)	(1.5438; 1.6458; 1.7965)	(0.0192; 0.035; 0.0542)	(0.008; 0.0161; 0.0279)	(0.0033; 0.0072; 0.0138)
ORG1		(1; 1; 1)	(1; 1; 1)	(0.4383; 0.4757; 0.5255)	(0.0928; 0.1206; 0.1581)
ORG3	(0.8335; 1; 1.25)	(1.8335; 2; 2.25)	(0.4444; 0.5; 0.5454)	(0.1948; 0.2378; 0.2866)	(0.0412; 0.0603; 0.0862)
ORG2	(0.515; 0.6166; 0.7706)	(1.515; 1.6166; 1.7706)	(0.251; 0.3093; 0.36)	(0.11; 0.1471; 0.1892)	(0.0233; 0.0373; 0.0569)
ORG4	(0.5883; 0.7083; 0.8918)	(1.5883; 1.7083; 1.8918)	(0.1327; 0.1811; 0.2267)	(0.0582; 0.0861; 0.1191)	(0.0123; 0.0218; 0.0358)
ORG5	(0.515; 0.6166; 0.7706)	(1.515; 1.6166; 1.7706)	(0.0749; 0.112; 0.1496)	(0.0328; 0.0533; 0.0786)	(0.007; 0.0135; 0.0236)
GEO1		(1; 1; 1)	(1; 1; 1)	(0.5089; 0.5363; 0.5735)	(0.057; 0.0796; 0.1086)
GEO3	(0.689; 0.8333; 1.0557)	(1.689; 1.8333; 2.0557)	(0.4865; 0.5455; 0.5921)	(0.2476; 0.2925; 0.3396)	(0.0277; 0.0434; 0.0643)
GEO2	(0.5883; 0.7083; 0.8918)	(1.5883; 1.7083; 1.8918)	(0.2571; 0.3193; 0.3728)	(0.1309; 0.1712; 0.2138)	(0.0146; 0.0254; 0.0405)
SOC4		(1; 1; 1)	(1; 1; 1)	(0.4521; 0.4709; 0.4975)	(0.0159; 0.0263; 0.0403)
SOC3	(0.7; 0.75; 0.8335)	(1.7; 1.75; 1.8335)	(0.5454; 0.5714; 0.5882)	(0.2466; 0.2691; 0.2926)	(0.0087; 0.015; 0.0237)
SOC1	(0.515; 0.6166; 0.7706)	(1.515; 1.6166; 1.7706)	(0.308; 0.3535; 0.3883)	(0.1393; 0.1664; 0.1932)	(0.0049; 0.0093; 0.0156)
SOC2	(0.651; 0.7777; 0.9667)	(1.651; 1.7777; 1.9667)	(0.1566; 0.1988; 0.2352)	(0.0708; 0.0936; 0.117)	(0.0025; 0.0052; 0.0095)

Table B3 (Continued)

POL2		(1; 1; 1)	(1; 1; 1)	(0.4423; 0.4728; 0.5144)	(0.028; 0.0434; 0.0643)
POL3	(0.5883; 0.7083; 0.8918)	(1.5883; 1.7083; 1.8918)	(0.5286; 0.5854; 0.6296)	(0.2338; 0.2768; 0.3239)	(0.0148; 0.0254; 0.0405)
POL1	(0.5883; 0.7083; 0.8918)	(1.5883; 1.7083; 1.8918)	(0.2794; 0.3427; 0.3964)	(0.1236; 0.162; 0.2039)	(0.0078; 0.0149; 0.0255)
POL4	(0.689; 0.8333; 1.0557)	(1.689; 1.8333; 2.0557)	(0.1359; 0.1869; 0.2347)	(0.0601; 0.0884; 0.1207)	(0.0038; 0.0081; 0.0151)