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From theory to practice: a methodological roadmap for mapping, assessing, and implementing industrial symbiosis

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A R T I C L E I N F O

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A B S T R A C T

Industrial symbiosis (IS) is a collaborative approach where industries share and reallocate resources, such as materials, energy, water, and by-products, create mutual benefits and contribute to a circular economy. This concept is limited due to the complexity of implementation and challenges with understanding the roadmap for their establishment. This study aims to bridge the gap between theory and practice by developing a comprehensive, methodologically grounded roadmap for implementing industrial symbiosis. The research combines a review of existing literature with the analysis of real-world case studies to identify and systematize the essential phases, tools, and success factors involved in the industrial symbiosis implementation process.

A detailed roadmap comprised key phases: mapping the current situation, identifying potential synergies, assessing feasibility, selecting the most appropriate opportunities, and implementing initiatives. The paper analyzes the relevant methods, tools and criteria for each phase. Particular attention is paid to key success factors, including resource and technology compatibility, geographical aspects, environmental impact, economic viability, and regulatory compliance. The importance of collaboration between different stakeholders and the role of intermediaries in the industrial symbiosis implementation process are highlighted. Based on the realized industrial symbiosis case studies, a few recommendations are given to support adopting industrial symbiosis strategies. The proposed roadmap emphasizes the importance of detailed resource flow mapping, multi-criteria assessment, and stakeholder collaboration with key success factors laying in evaluating technical, economic, environmental, and regulatory dimensions using appropriate tools.

Based on the research findings, the proposed roadmap consolidates fragmented approaches, supports strategic planning and provides practical guidance for companies and practitioners looking to integrate industrial

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symbiosis into their business. It contributes to a better understanding of the complexity of industrial symbiosis implementation and provides a framework for the wider adoption of these practices in the industry. This research contributes to the operationalization of industrial symbiosis by offering a replicable and adaptable roadmap. Further research should explore digital tools for synergy identification and assess policy mechanisms that can incentivize industrial symbiosis implementation at regional and national levels.

List of abbreviations

AB	Agent-based
CE	Circular Economy
CHP	Combined heat and power
DEA	Data envelopment analysis
DES	Discrete Event Simulation
ECER	Energy conservation and emission reduction
EEI	Eco-efficiency improvement
EIO	Enterprise input-output
EIP	Eco-Industrial Park
ENA	Ecological network analysis
EoL	End of life
EWC	European Waste Catalogue
FAI	Flows adaptability Index
GHG	Green House Gas
IE	Industrial Ecology
IEI	Industrial eco-efficiency index
IO	Input-output
IOA	Input-output analysis
IOM	Input-output model
IS	Industrial symbiosis
ISI	Industrial sustainability index
ISN	Industrial symbiosis Network
LCA	Life Cycle Assessment
LCC	Life cycle cost
LoW	List of Wastes
MFA	Material Flow Analysis
MILP	Mixed integer linear programming
N/A	Not available
NCI	Network connectivity Index
PCA	Principal component analysis
QCA	Qualitative content analysis
R&D	Research and development
SD	System Dynamics
SDI	Sustainability disparity Index
SIC	Standard Industrial Classification
SME	Small and medium-sized enterprises
SRL	Symbiosis Readiness Level
SSC	Symbiotic supply chain
SVN	Stakeholder Value Network
SWM	Solid waste management
TEA	Techno-economic assessment
TRL	Technology Readiness Level
TSPI	Total Site Process Integration

1. Introduction

Building on the principles of Industrial Ecology (IE), the Circular Economy (CE) concept has emerged as a transformative approach and alternative to traditional linear economy to promote long-term sustainability and economic resilience. CE aims to create closed-loop systems where products, materials, and resources are reused, repaired, refurbished, and recycled, thereby reducing waste and conserving natural resources. Within IE and CE, industrial symbiosis (IS) stands out as a practical and targeted strategy (Domenech et al., 2019).

IS is a collaborative process involving the sharing, repurposing, and joint utilization of underutilized resources, including wastes, by-products, residues, materials, energy, water, logistics, capacity, expertise and equipment, between industries to create mutual benefits (Chertow, 2007; CENELEC, 2018).

While both CE and IS concepts aim for sustainability, CE emphasizes materials and products of all kinds, whereas IS specifically focuses on industrial waste and by-products. IS is a more targeted action and a tool to implement CE concept in industries, aiming at downstream actions for better use of resources. Still, it does not necessarily have to be completely circular. This is because actions focused on waste minimization and resource efficiency increase, e.g., by extending a lifetime of a resource, does not necessarily imply circularity. CE has a broader scope than IS, and it is a more complex approach that includes upstream actions and prevention, closing the loops, and acting as a philosophy we want to follow as a sustainable society. IS, built on sustainability principles, has emerged as a promising strategy for enhancing resource efficiency, reducing waste, and contributing to the transition toward a CE (Albino et al., 2016).

The goal is to minimize resource consumption, improve sustainability, and lower environmental impact while maximizing economic and environmental benefits, creating a CE (Fallahi et al., 2024). Similar to natural ecosystems, where organisms share and recycle resources, IS works on the principle of shared value and collaboration among various industries. This maximizes the utility of available resources across different sectors by rethinking how materials, energy, water, waste, and/or expertise can be reused or shared (Lawal et al., 2021; Uusikartano et al., 2022). This collaboration benefits the environment and the economy, helping industries lower costs, reduce environmental impact, and create a more sustainable future (Chen et al., 2022b; Wadström et al., 2021). Nevertheless, the benefits of IS extend beyond the involved companies (Neves et al., 2019a; Lombardi and Laybourn, 2012). It promotes overall environmental sustainability within the industrial sector and local communities (Taddeo et al., 2017; Fraccascia et al., 2016). By enabling the reuse of resources such as materials and energy, IS plays a key role in driving more sustainable industrial practices (Costa and Ferrão, 2010; de Abreu and Ceglia, 2018; De Gobbi, 2022; Fan et al., 2021).

With the concept of IS, it is possible to divert waste from landfills and reduce the negative impact on the environment. From an environmental point of view, the benefits of IS are the reduction of consumption of natural resources and waste disposal, as well as the reduction of emissions to air, water and soil resulting from the production of saved raw materials (Chertow, 2007). As such, it offers a significant opportunity to lower the environmental footprint. From a business perspective, IS can reduce the need for raw materials and waste disposal costs (Chen et al., 2022a).

However, despite its benefits and growing recognition, the worldwide spread of IS adoption remains restricted (Neves et al., 2020). Although the amount of waste produced is large, circular material usage is still low. In 2022, the EU's circular material use rate was 11.5% (Eurostat, 2023a). Moreover, around 40% of waste in the EU still ends up in landfills (Fig. 1). Within the circularity ladder and waste hierarchy, and after waste prevention and reuse, recycling is the most desirable strategy, as it conserves resource value and enables repeated use. Backfilling and energy recovery provide lower levels of circularity, since they replace other resources or recovery energy but usually at a reduced value. Landfilling is the least favorable option, as it recovers no resource and entails environmental burdens.

Implementing IS requires intricate systems, various industries, and multiple stakeholders, making it challenging to scale up its adoption. Although examples of successful IS initiatives exist (Valentine, 2016; Oughton et al., 2021), their implementation often remains fragmented, with very limited guidance on best practices for overcoming the inherent challenges (Lybæk et al., 2021).

Several reviews and studies have examined IS, particularly its benefits, challenges, and case studies (Golev et al., 2014; Henriques et al., 2021a; Fraccascia et al., 2021; Erceg et al., 2024). These reviews consistently highlight IS's positive impact on resource efficiency, cost reduction, and environmental sustainability, while also identifying key barriers, such as limited institutional support, economic disincentives, and technological constraints (Fraccascia et al., 2021; Neves et al., 2019b). Nonetheless, most studies stop short of providing actionable steps or clear guidance for organizations that wish to integrate IS into their operations (Kosmol and Otto, 2020; Rahman et al., 2016; Krzeminski et al., 2025). Although several recent studies have advanced understanding through strategic frameworks and conceptual models (Azevedo et al., 2021a; Dias et al., 2020; Iver et al., 2024) these frameworks exhibit persistent limitations and unresolved issues. They often lack clear operational pathways, making it difficult for practitioners to translate conceptual models into practice; they provide insufficient consideration of contextual variability across industries and organizational scales; and they rarely incorporate integration of IS with existing management or digital transformation processes. Consequently, current IS frameworks remain difficult to scale and adapt across diverse industrial and policy settings. Despite multiple conceptual syntheses, no study yet consolidates a unified implementation logic that links decision points, stakeholder roles, and evaluation criteria throughout the IS project lifecycle (Azevedo et al., 2021b; Henriques et al., 2021b; Afshari et al., 2020). Addressing these deficiencies requires a structured, evidence-based roadmap that connects theory to practice and supports decision-making under real-world constraints.

Therefore, a well-defined roadmap is needed to provide clear, actionable strategies for implementing IS. As such, the roadmap can be pivotal in implementing IS and thus accelerating the transition to more sustainable, resource-efficient industrial ecosystems.

The novelty of this article lies in translating existing conceptual frameworks into a structured, operational roadmap that delineates key decision stages, stakeholder responsibilities, and assessment criteria for implementation. The scope of this roadmap is directed at industrial sectors characterized by resource-intensive operations—particularly manufacturing and process industries in the European context—while acknowledging that its methodological logic can be adapted to other geographies and scales. The roadmap is developed under the assumption of multi-stakeholder engagement and data accessibility as preconditions for IS planning and evaluation.

This article aims to develop a comprehensive roadmap for implementing IS practices, supporting industries in realizing the environmental and economic benefits of this type of relationship. It addresses the need for a structured framework to guide stakeholders — from companies and industry leaders, transition mediators to policymakers and government — in the effective implementation of IS practices. The article's objective is to contribute to the body of knowledge by bridging the gap between theory and practice. To this end, the roadmap is derived through conceptual synthesis of prior frameworks, systematic review of IS literature, and comparative analysis of real-world case studies that inform the evaluation logic adopted in later sections. This bridge between conceptual and empirical evidence ensures methodological transparency and cohesion leading into the Methods section.

The article is organized into three main parts. Section 2 describes the methodology adopted. Sections 3 to 7 presents the roadmap for the effective implementation of IS, structured around five key stages of the roadmap (Fig. 2). The key stages include mapping the current state to identify opportunities for symbiotic transactions (section 3), establishing IS synergies and associated methodologies (section 4), evaluating potential/feasibility and outlines the evaluation criteria as well as selection process of the most promising IS opportunities (section 5), realizing IS initiatives and presenting case studies of successful IS initiatives worldwide (section 6). Sections 7 and 8 concludes the paper with overall reflections, research findings, provides recommendations, and proposes directions for further studies.

2. Methodology

In order to develop a comprehensive roadmap for the implementation and evolution of IS practices, an extensive and in-depth literature review was conducted. The objective of this review was to create an overview of the different phases of industrial symbiosis implementation,

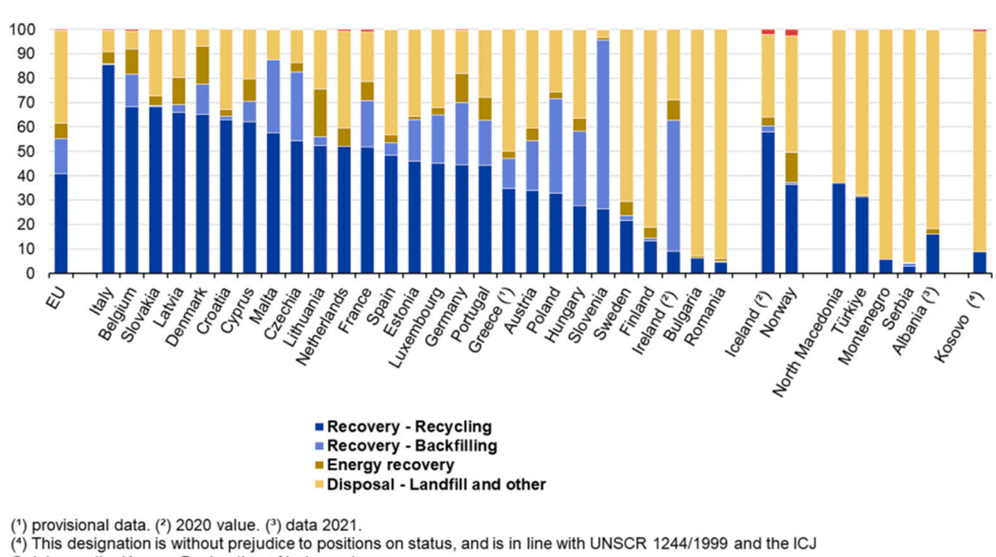

Fig. 1. Waste treatment by type of recovery and disposal in Europe. Source: Eurostat (2023b).

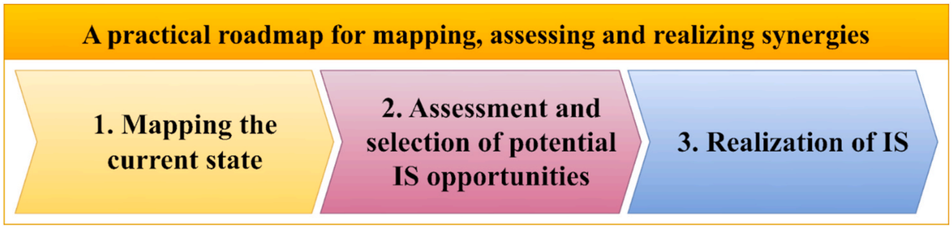

Fig. 2. A practical roadmap for exploring and implementing industrial symbiosis (IS).

from mapping to realization, in order to support companies, industrial leaders, and even policy makers and government in its strategic implementation.

The review of the literature was conducted in three main stages: in-depth collection of literature, screening of relevant articles, and content analysis of selected publications. The literature was collected using the two scientific databases Scopus and Web of Science. Scientific articles, conference papers, and book chapters were included, with no time restrictions to maximize completeness of the literature search.

During a more detailed analysis of the selected publications, and through interpretation, it was possible to identify five key steps for the effective implementation of IS: Mapping the current state; Methods for establishing IS synergies; Assessment and selection of potential IS opportunities; Realization of IS; and Recommendations. These constitute the phases of the roadmap, which are detailed in the following sections.

To make the proposed roadmap as comprehensive and feasible as possible, all this information resulting from the literature review was supplemented with real case studies in different industrial and geographical contexts. These case studies were identified through a literature review and by surveying members of the LIAISE COST Action network. Cases covering the implementation phases of IS, and most frequently mentioned, were selected for detailed analysis. The selected case studies provided qualitative evidence illustrating different ways of identifying, evaluating, and selecting potential synergies, thereby supporting and validating the proposed roadmap. They also serve as examples of good practice and facilitate implementing and disseminating IS. The aim was to create a better understanding of the implementation and realization phase of IS by providing a model that is as general as possible.

3. Mapping the current state

The mapping of current situations is a first step when exploring IS opportunities. It sets the basis by identifying relevant stakeholders and providing information about available resources and the type of synergies possible. Through data collection, it allows for the identification and quantification of resource flows (Fig. 3).

3.1. Identification of symbiosis/resources available

For any IS to be realized, opportunities for symbiosis need to be identified. This process starts with understanding available resources and the types of synergies possible.

The resources that could be involved in IS can be grouped into various categories (Table 1). The core group consists of material resources, energy resources, water resources, waste and by-products (Chertow, 2000), knowledge and expertise (Fraccascia and Yazan, 2018; Katana et al., 2024), infrastructure (Molinier & da Costa, 2019), economics and financial resources (Neves et al., 2020; Wadström et al., 2021), social and organizational resources (Doménech and Davies, 2009), and environmental and regulatory resources (Paquin et al., 2015).

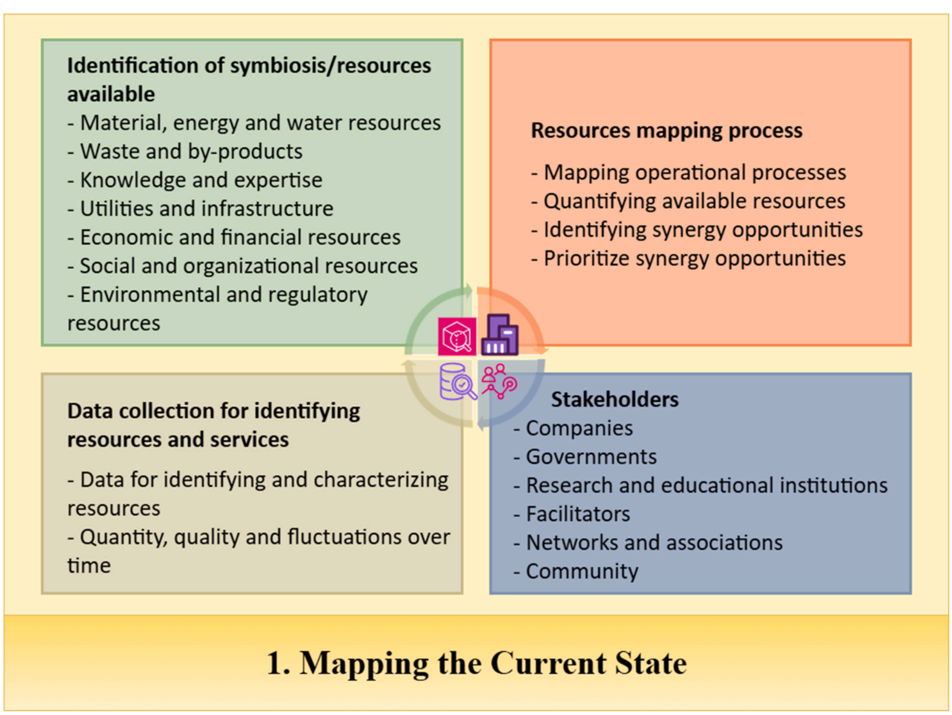

Fig. 3. Approach for the mapping of current situations as the first step of guiding potential IS.

Table 1
Different resource types in Industrial Symbiosis. Adopted from Chertow (2000); Fraccascia and Yazan (2018); Katana et al. (2024); Molinier & da Costa (2019); Neves et al. (2020); Wadström et al. (2021); Doménech and Davies, 2009; Paquin et al. (2015).

Type of resource	What is exchanged	Examples
Material resources	Raw materials, by-products	Another industry may use fly ash, sludge, and scrap metals as raw materials or inputs.
Energy resources	Thermal, electrical, or mechanical energy	Waste heat from a power plant or manufacturing process can be harnessed to generate steam or heat for nearby industries through district heating.
Water resources	Water in industrial processes	Process and/or wastewater from one facility may be used by another industry for purposes such as cooling, cleaning, or irrigation after appropriate treatment.
Waste and by-products	Inputs from other industries help reduce waste production and optimize resource utilization.	CO_2 emissions or organic waste can serve as feedstock for bioenergy production or chemical manufacturing
Knowledge and expertise, skills	Intellectual capital, technologies, and know-how	Shared research and development efforts can explore CE practices, waste-to-resource technologies, or eco-friendly designs.
Utilities and infrastructure	Physical and organizational structures	Shared warehouses, transportation networks, and distribution systems;
Economic and financial resource	Investments, financial incentives, and economic mechanisms	cost-sharing or revenue generation from resource sharing. Investment in green technologies or resource-sharing systems
Social and organizational resources	Relationships, networks, and organizational structures	industry clusters or networks, such as eco-industrial parks, collaboration agreements, shared governance structures
Environmental and regulatory resource	Environmental regulations, policies, and guidelines	sustainability incentives, enforce pollution penalties and promote recycling, waste reduction, and sustainable resource usage

By categorizing resources into the above-stated categories, companies can identify areas where they can collaborate to improve their environmental and economic outcomes (Neves et al., 2019b; Azevedo et al., 2021a) and move to the resource mapping stage.

3.2. Resources mapping process

A crucial step in identifying opportunities for resource exchange/sharing and understanding processes and local conditions is mapping resource flows at a site (Fig. 4). This involves spotting surplus resources, such as materials or energy, within one company that another can repurpose, creating a mutually beneficial relationship (Azevedo et al., 2021a). Resource mapping involves documenting how resources are used, where waste is generated, and where surplus materials can be reused (Anastasovski, 2020). This step is vital for uncovering opportunities for collaboration between companies and optimizing available resources.

The resource mapping, being an integral part of the mapping of current situations process, typically involves four key steps (Erceg et al., 2024):

Mapping Operational Processes: This step entails breaking down each company's operations to understand what resources are consumed, what waste is generated, and where inefficiencies exist (Domenech et al., 2019). It helps identify areas where resources (e.g., material or energy) flow and can be optimized and reused (Branca et al., 2022).

Quantifying Available Resources: After identifying resource flows, it is essential to quantify the amount of each resource (e.g., energy, materials, and water) consumed or wasted (Benedict et al., 2018; Fraccascia, 2019). This step helps to understand the scale of the available resources for potential exchanges.

Identifying Synergy Opportunities: The next step is to explore how another company can use one company's surplus resources (Yu et al., 2023). Synergy opportunities are identified by analyzing proximity, material compatibility, and resource requirements (Fig. 5).

Prioritize Synergy Opportunities: The process of prioritizing identified synergies based on selected criteria and selecting the synergies for realization (Walls and Paquin, 2015; Lybæk et al., 2021).

3.3. Data collection for identifying available resources and services

A crucial step in implementing IS is identifying the resources, such as those defined in Table 1, that can be exchanged between companies. To facilitate these synergies efficiently, a robust data collection system is essential, one that ensures secure and reliable information (i.e., for identifying and matching potential synergistic opportunities) sharing among companies, stakeholders, and all parties involved in IS realization processes (Akrivou et al., 2021; Zhang et al., 2023). This system should help identify potential synergies by analyzing available resources' quantitative and qualitative aspects.

At a more advanced stage of IS implementation, additional data is needed to characterize resources in greater detail, including their quantity, quality, and fluctuations over time (Yeo et al., 2019). This enables companies to identify synergies that are viable, technically feasible, and economically beneficial. Companies can employ a range of methods for data collection. They may utilize publicly available environmental data sources, conduct on-site visits to companies and key stakeholders for direct data gathering, and encourage voluntary submissions of resource information to central platforms or databases (Akrivou et al., 2021). Moreover, some IS initiatives may incorporate workshops, interviews, and collaborative efforts to uncover resource exchange opportunities that automated systems might overlook. Additionally, digital platforms that facilitate data entry, modeling, and the identification of synergies can be leveraged (Iyer and Sangwan, 2023; Krom et al., 2022).

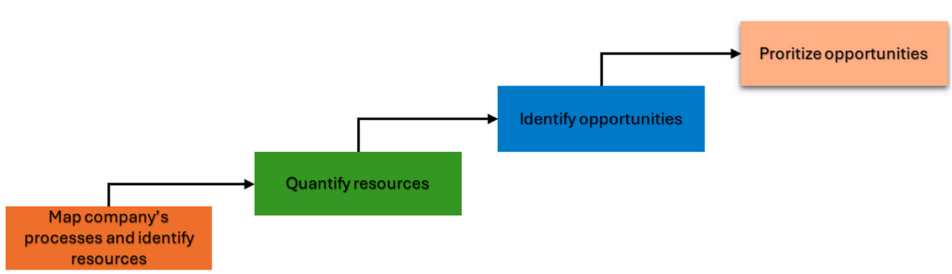

Fig. 4. Steps of the resource mapping process for IS.

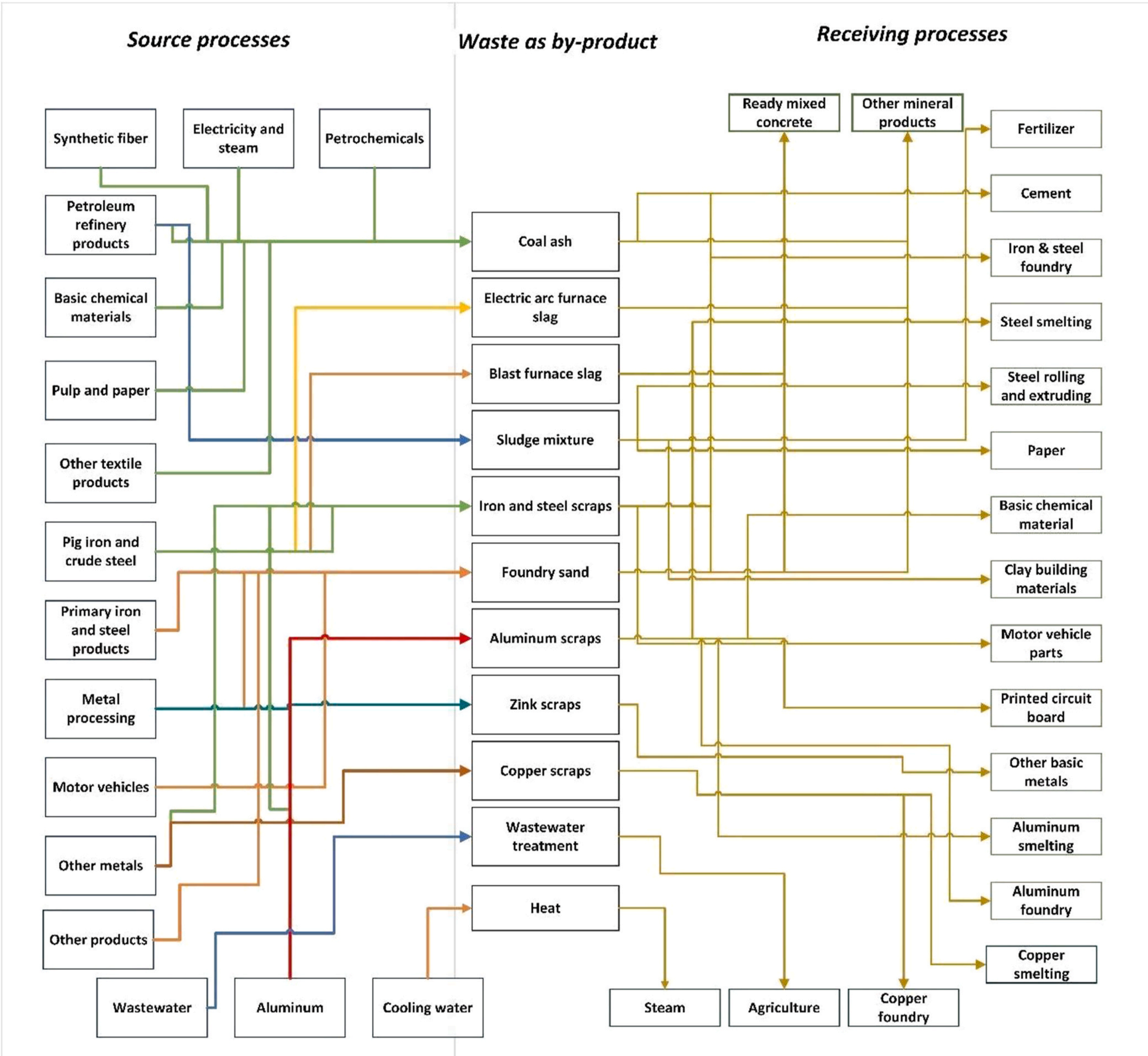

Fig. 5. Examples of IS are where wastes are used as raw materials in production processes. Source: adapted from Pi-Cheng and Hwong-Wen (2015).

Integrating technological platforms that leverage data digitization, security measures, and modeling tools (including artificial intelligence) can significantly enhance the identification and analysis of potential resource exchanges (Lawal et al., 2021). These systems can assist companies in discovering symbiotic opportunities by analyzing resource flows and identifying areas where another can reuse waste or surplus materials from one company (Benedict et al., 2018). However, developing such platforms requires substantial effort and input from multiple stakeholders to ensure data security, reliability, and scalability (Eurostat, 2023a). Therefore, these are typically paid platforms like SYNERGie®, Syner or Excess Materials Exchange. Several platforms have been developed for Research and Development (R&D) projects, but most are not functional shortly after the project is completed.

Data-sharing constraints, such as confidentiality agreements and intellectual property concerns, pose significant challenges to the availability of information. Companies are often reluctant to share proprietary data, limiting the identification of new symbiotic opportunities (Krom et al., 2022; Tseng et al., 2018). Therefore, IS tools must be designed to respect intellectual property rights, enabling companies to share only the information they feel comfortable disclosing. The overall effectiveness of these platforms relies on a critical mass of registered users and a comprehensive resource database (Fraccascia and Yazan, 2018; Halstenberg et al., 2017). In the early stages, the focus should be collecting easily available data, as little data is better than no data, and attempting to identify opportunities. At the later stage of IS realization, more detailed and/or restricted data can be sought to be included.

Despite these challenges, the lack of comprehensive and reliable data across many industrial sectors highlights the need for improved data collection methods (Song et al., 2017). Open access to datasets, such as those compiled by Eurostat, UNIDO, and other research organizations, can be a foundation for effective IS platforms (Lawal et al., 2021). These datasets can also provide valuable case studies for IE and sustainability research.

Patricio et al. (2022) propose a methodology for mapping industrial material flows using a standardized system to classify industries, materials, and waste streams. This classification framework is based on nomenclatures such as NACE (Statistical Classification of Economic Activities in the European Community), Standard Industrial Classification (SIC), and the European List of Wastes (LoW) or European Waste Catalogue (EWC), which should ease the matching process. By applying this methodology, potential matches between waste generators and material receivers are identified, enabling companies to recognize opportunities for material reuse and energy recovery. For example, their approach identified over 96,000 potential matches between waste producers and material receivers across various European industries. Standardized classification systems like SIC and LoW/EWC are often used in paid platforms.

3.4. Roles of different stakeholders in IS implementation

The successful implementation of IS requires the involvement of several stakeholders with varying roles during the identification, evaluation, selection, and realization stages of symbiosis opportunities. Research conducted in the field of IS emphasizes the importance of having a favorable context, i.e., social, economic, technical, political, and geographical conditions, that allows collaborations to emerge and develop (Costa and Ferrão, 2010; Fraccascia, 2018; Van Berkel et al., 2009). However, the role of other stakeholders should not be ignored. Stakeholders are any group or individual who can affect or is affected by creating, maintaining, or extending a symbiosis (Hein et al., 2017).

Harfeldt-Berg et al. (2022) identified relevant stakeholders as public authorities, state-owned enterprises, private companies, and various associations, with IS networks often comprising a mix of these entities. They describe symbiosis collaborations as involving multiple independent and potentially diverse stakeholders working together to utilize underused or leftover resources. Costa and Ferrão (2010) suggest that a conducive environment for fostering IS can be created through an interactive process in which the government, industries, and other institutions work together to align their strategies to support collaborative business approaches in resource management. Their study analyses key stakeholders such as the government, public institutions, private associations, universities, and businesses. Fraccascia (2018) refers to "multiple stakeholders" such as citizenships, companies producing and using waste, governments, and waste collection firms. Drawing from existing literature, Hein et al. (2017) highlight stakeholders like industry associations, regional and local governments, and national symbiosis programs as stakeholders who facilitate the development of IS. Similarly, Dai et al. (2022) identify government authorities, research organizations (including universities, technology consulting firms, or in-house research departments), boundary spanners (agents like IS champions, central management organizations, or third-party coordination agencies), companies, and communities as key stakeholders in eco-industrial parks.

Therefore, stakeholders are important to the mapping process and exploring IS opportunities, as well as later IS phases, including governments, businesses (companies), research institutions, and specialized facilitators or transition brokers (Henriques et al., 2021a). Each actor brings specific expertise and capabilities to the table, helping to create a conducive environment for resource transaction. The different groups of stakeholders have different, sometimes overlapping, roles in the IS implementation.

Governments play a central role in supporting IS by creating policies, incentives, and regulations that encourage adopting resource-efficient practices. For example, providing tax breaks, subsidies, or other financial incentives (Costa and Ferrão, 2010) for companies adopting IS strategies can help lower the initial implementation costs. Additionally, governments can establish regulations that mandate waste reduction and promote resource sharing among companies. Usually, it is stressed that the government is essential in overseeing and supporting IS while promoting collaboration among businesses. Its involvement strengthens the network's sustainability and resilience (Escandon-Barbosa et al., 2024). Regulatory bodies should create a legislative framework that enables or encourages IS, such as legislation that facilitates using waste as raw material.

As part of a government group, local authorities play a key role in creating the appropriate spatial plans, infrastructure, and framework to encourage business collaboration and developing local policies that encourage sustainable industrial practices (Södergren and Palm, 2021). However, they also benefit from IS, as it reduces pollution, improves quality of life and creates new jobs in sustainable production and waste management sectors (Neves et al., 2019b). Local governments also act as "information brokers" intermediaries who gather, process and share critical information between key stakeholders. They facilitate communication, collaboration, and decision-making by connecting different parties, such as businesses, government agencies, and other organizations (Costa and Ferrão, 2010). Doing so ensures that relevant information is exchanged and everyone involved has access to the data and insights needed to move the project forward effectively. Local and regional governments have a significant role, also given their overview and knowledge about the characteristics of local industry, as they can promote, support and drive programs and initiatives aimed at connecting various industries and businesses in their regions (Velenturf, 2016; Södergren and Palm, 2021). In short, local governments, in this case, help bridge gaps between stakeholders, ensuring the smooth flow of information and helping in the overall success of transformation projects (Dai et al., 2022).

Companies are the main actors in IS, as they are responsible for identifying and implementing symbiosis opportunities. Through innovative approaches, industries can maximize the use of raw materials and reduce the negative impact on the environment (Velenturf, 2016). They play a key role in exchanging materials, energy, water or by-products with each other (Rentería Núñez and Perez-Castillo, 2023). They must actively participate in resource mapping, data sharing, and collaboration with other industrial parks or cluster businesses. Companies can create dedicated departments to oversee the adoption of IS practices, manage resource inventories, and track performance over time. Unfortunately, companies are often unaware of opportunities provided by introducing the IS concepts into their business (Fraccascia et al., 2021). Lybæk et al. (2021) emphasize the need for stronger cooperation between companies. In this sense, they propose accessibility to platforms that allow them to meet and collaborate. Such platforms would encourage more self-organizing initiatives between companies, drive further progress (Lybæk et al., 2021), and support companies to visualize waste-to-resource conversion pathways and promote synergies (Abreu and Ceglia, 2018). Municipalities or other local stakeholders should be involved in these platforms to help maintain and develop them.

Research and educational institutions provide support by offering expertise on resource efficiency, designing IS models and conducting feasibility studies to evaluate the viability of potential synergies. Research and educational institutions are vital to initiate IS in participatory and collaborative processes. They act as transition brokers or coordinators by providing reliable information (Mortensen and Kørnøv, 2019). Additionally, these institutions help identify the best practices and technologies for waste management, energy recovery, and water reuse, enabling businesses to make informed decisions and implement effective IS strategies. They also organize educational programs and workshops for businesses, local authorities, and other stakeholders to enhance awareness and understanding of IS and sustainable practices. Furthermore, their experience and knowledge of IS and technology can help formulate government policies and goals, create interest among firms, disseminate knowledge of IS, and lead experimental projects (Dai et al., 2022).

Facilitators or transition brokers — governmental, non-governmental, or business entities — play an essential role in identifying IS opportunities, mapping resources, and building partnerships between companies. "Facilitation refers to helping a group of actors to achieve a common goal and assisting them in obtaining desired results and outcomes through mediating frameworks and dialogue" (Schlüter et al., 2022). Therefore, their role is crucial in the emergence process by supporting knowledge sharing and information dissemination among IS network actors through structured activities and interactions (Katana et al., 2024). They act as intermediaries, bridging gaps between industries, municipalities, and research institutions to create business opportunities and ensure the smooth implementation of IS. A detailed characterization of the IS facilitators/transition brokers role identifies different actions performed by facilitators of the IS study (Schlüter et al., 2022). The actions can be categorized into five key tasks: building connections, coordination, managing knowledge and capacity, assessing and distributing value, and fostering favorable conditions for scaling up. In addition, the research highlights five essential skills relevant to the role of a leader: social skills, approach to work, motivation and interest, ethics and responsibility, and knowledge. These findings suggest that the role of the IS transition brokers is intensive and context-dependent, requiring an implicit and adaptive skill set.

Networks and Associations act as intermediaries between different groups, departments, organizations or sectors, facilitating the sharing of information, knowledge and resources (Williams, 2002). Regarding IS, networks and associations play a significant role in connecting companies that may use waste resources from other companies and increasing sustainability and CE (Velter et al., 2020).

Community and citizens' roles are often forgotten in traditional IS models that focus mainly on collaboration between companies (Chertow, 2007). However, community and citizens have a significant role in allowing and sustaining IS (Uusikartano et al., 2022). Their involvement can significantly improve IS sustainability and success through education, behavior changes, supporting sustainable policies, boycotting dangerous policies, activities or products, and local economic development (Svendsen et al., 2019).

All these stakeholders' roles are becoming extremely significant within the framework of European environmental policy. A diagram of actions between key stakeholders in transformation projects is shown in Fig. 6. IS gained significant attention after the European Commission established sustainable development as a priority for the European Union. IS is widely viewed as a central strategy for advancing the CE and achieving sustainable development goals (Borbon-Galvez et al., 2021; Doménech and Davies, 2011). Although it has excellent potential, IS is not sufficiently represented in practice as a model for achieving greater circularity. However, there is a lack of an appropriate legal framework for IS. Namely, the IS legal regulation is not separated into special regulations and is rarely mentioned directly. IS systems are shaped by policies in complex ways, often influenced by frameworks created for other purposes (Lybæk et al., 2021). In this regard, developing appropriate legislation for IS is necessary, so the role of government, regulators, and other stakeholders is crucial.

Five groups of key stakeholders - governments, companies, research and education institutions, communities, networks and associations have different roles and activities in implementing transformation projects (Dai et al., 2022). Their collaboration is needed for the successful implementation of IS.

4. Methods for establishing IS synergies

Mapping, as analysis, matching, planning, design and realization of IS, can be done using different tools and methods. Many use technical parameters in systems, but some are linked to the environment, supply chain, geographic distances and cost analysis. The methods related to establishing IS found in the literature include:

1. **Material Flow Analysis (MFA)** analyses and quantifies the flow of materials within a defined system over a specified period (Bringezu and Moriguchi, 2018; Graedel, 2019). MFA is an invaluable tool for designing and optimizing resource efficiency among different industrial processes (Demartini et al., 2021). This involves systematically mapping material inputs, outputs, and internal flows to pinpoint inefficiencies, uncover opportunities for waste reduction, and identify potential areas for recycling or reuse (Sendra et al., 2007). Primarily, it assesses macro entities at national and regional levels. However, it lacks a life cycle perspective and fails to reflect impacts on the ecosystem adequately.

   The data collected from MFA can be shown visually to understand the points of sources and sinks better. That kind of visual tool is the Sankey diagram (Fig. 7). It visualizes resource flows (streams) (Lupton and Allwood, 2017). These diagrams help trace materials, energy, and waste flows and identify inefficiencies and opportunities for resource optimization (Valero et al., 2021). Sankey diagrams can also visualize the potential for reducing waste and emissions and progress toward sustainability goals.

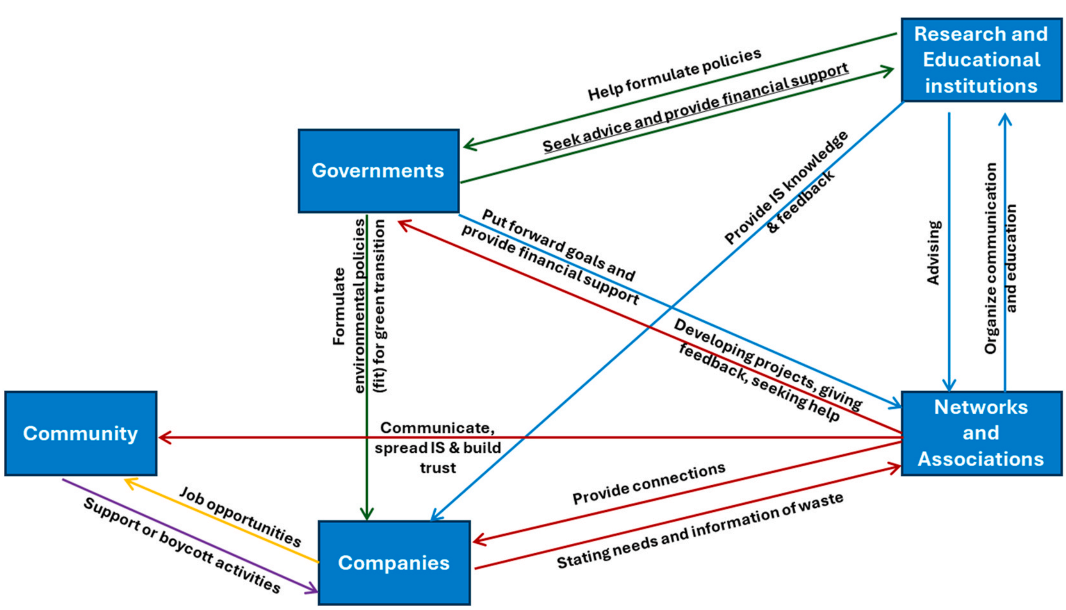

Fig. 6. Actions between key stakeholders. Source: adapted from Dai et al. (2022).

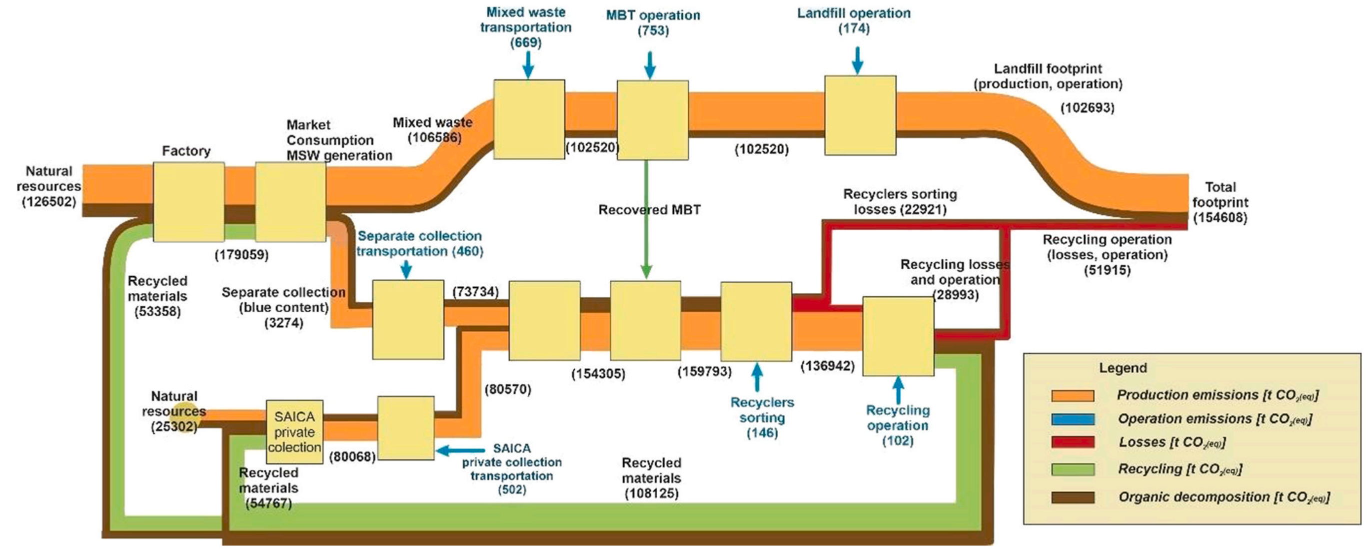

Fig. 7. Example of Sankey diagram used for tracing carbon footprint in the industrial ecosystem for paper and cardboard in Zaragoza, Spain. (values are expressed in equivalent tons of CO_2 emission) Source: adapted from Valero et al. (2021).

2. **Life Cycle Assessment (LCA) -** LCA assesses the environmental impacts of products, processes, or systems throughout their life cycle (Mattila et al., 2010). LCA can be used for IS to evaluate the potential for waste reduction and resource optimization, thereby assisting businesses in identifying areas for improved resource efficiency (Niederl-Schmidinger and Narodoslawsky, 2008; Daddi et al., 2017; Su et al., 2017). Uncertainty and risks are associated with data unavailability, attributable to the extensive and heterogeneous nature of the required data. Moreover, a novel approach named M3-IS-LCA was created to design the Industrial Symbiosis Network (ISN) (Kerdlap et al., 2020a,b).
3. **Input-output analysis (IOA) or input-output model (IOM)** examines the interdependencies between economic sectors and quantified goods and services flows between industries (Mattila et al., 2010). IOA in IS is employed to quantify and map the resources of various entities, enabling the identification of potential symbiotic relationships and optimization of resource flows (Chen et al., 2022b; Demartini et al., 2021). Fraccascia et al. (2016) used an IO approach at the enterprise level to model symbiotic flows within ISNs and develop a measure of technical exchange efficiency. This approach aids in driving the development of existing ISNs and designing new industrial systems that exploit the IS approach (Fraccascia et al., 2016).
4. **Process Integration (PI)** - PI and Pinch technology, as its integral part, are powerful tools for designing ISNs that offer systematic approaches to optimize resource utilization and enhance sustainability in industrial settings (Tan et al., 2016). Pinch Analysis has been extended to Total Site Process Integration (TSPI) and Total EcoSite Integration for urban and IS (Fan and Fang, 2020). This approach showed promising results for increasing energy and mass recovery (Branca et al., 2021a). Heat pinch analysis has also been developed to account for piping distances, fluctuations, and limited availability of energy flows in ISNs (Yong et al., 2021). Pinch technology utilizes material and energy flows in the system to match the potential exchange of materials, heat, and supply chain items and optimize the footprint. Various solutions can be found for continuous and batch processes, especially for repeatable and non-repeatable batch processes (Anastasovski, 2014, 2020).
5. **Mixed integer linear programming (MILP)** – This approach employs a multi-objective methodology, providing an exact resolution to study various resource flows simultaneously (Kantor et al., 2020). However, it does not investigate the nature of the relationships between nodes, nor does it capture dynamic behaviors and heterogeneity among companies. MILP models for IS design typically aim to optimize multiple objectives simultaneously, encompassing environmental, economic, and social aspects (Yu et al., 2023).
6. **DEMATEL** - The DEMATEL model can be exceptionally valuable in examining intricate problems involving multiple interconnected criteria (Bacudio et al., 2016). Simplifying and visualizing relationships among various factors enhances the decision-maker's ability to prioritize actions and formulate effective strategies (Hsu, 2012; Manoharan et al., 2021). In the context of IS, DEMATEL can determine crucial obstacles, such as inadequate communication, confidentiality concerns, and insufficient support services, potentially obstructing sustainable ISNs (Bacudio et al., 2016; Che et al., 2022; Hsu, 2012).
7. **Social Network Analysis (SNA)** - Social network analysis has been predominantly employed to quantify the structural characteristics of ISNs. In this context, organizations within the network are represented as nodes, and a link between two nodes signifies a waste flow between the respective entities (Vahidzadeh et al., 2021). SNA is employed as a primary methodology to evaluate the positioning of organizations in ISNs and their interconnections. It facilitates network connections visualisations (Zhang et al., 2022) and understanding of collaboration aspects (Herczeg et al., 2018), quantifies patterns in various relationships among firms and managers (Ashton, 2009) and identifies anchor firms with diminished influence on IS (Song et al., 2018)
8. **The Stakeholder Value Network (SVN)** approach models the value flows among companies within ISNs (Hein et al., 2017). A value flow represents a transfer of utility between two entities. Based on the utility flows, the relative power can be calculated for each company, and the most significant wastes for the ISN can be identified (Yazıcı et al., 2023). It facilitates implementation of symbiotic exchanges (Teng et al., 2017) and continuously assess the power dynamics and resource dependencies within the network (Song et al., 2018)
9. **Ecological network analysis (ENA)** is focused on the integrated evaluation of possible benefits from waste exchange among companies within ISN (Dong et al., 2022). This analysis reveals the ecological connections between ISN members, such as

exploitation, control, competition, and mutualism. It facilitates evaluation of potential environmental enhancements (Genc et al., 2019) and conducts a more comprehensive IS internal attribute analysis (Zhang et al., 2015). However, it does not explore the nature of connections between nodes or account for the dynamic behaviors and diversity among companies.

10. **Agent-based model (AB)** - The primary function of agent-based models is to generate macroscopic patterns from the bottom-up, incorporating assumptions at the microscopic level regarding agent attributes and behavior with minimal top-down macroscopic constraints (Raimbault et al., 2020). Throughout the simulation, every company selects partners to establish symbiotic connections. This modeling can investigate transportation cost's influence, optimize total cost and waste, or examine the impact of spatial correlations (Fraccascia, 2020; Yazan and Fraccascia, 2020).
11. **System Dynamics (SD)** - It is an approach that integrates quantitative and qualitative analysis, drawing from feedback control theory and computer simulation. This method has applications across various domains (Rodrigues and Bowers, 1996; Sterman, 2001). Recognized as an effective tool for addressing non-linear and dynamic complexity issues (Geng et al., 2017; Morales and Diemer, 2019; Saysel et al., 2002), SD aims to comprehend the mechanisms behind dynamic changes and identify policies to enhance system performance (Vlachos et al., 2007). The study about Hai Hua IS employed SD to construct a model of IS evolution. The SD model enables the quantification of IS evolutionary pathways and characteristics. This modeling can be applied to create models of IS evolution (Cui et al., 2018). It effectively and intuitively reveals trends and system-level behavior (Cao et al., 2020a; Huang et al., 2020), but it lacks flexibility.
12. **AB - SD hybrid method** - Several scholars propose that integrating AB modeling with SD offers a convenient approach for designing and analyzing IS. This combined methodology can effectively capture the intricate interactions among stakeholders and the evolving nature of IS networks, yielding a more thorough understanding of the system (Demartini et al., 2021).
13. **Discrete Event Simulation (DES) -SD hybrid method** – This combined approach utilizes SD to offer a feedback-oriented perspective, enabling the observation of how DES components influence the overall system. It captures the connections and temporal delays between DES elements by employing feedback loops. Furthermore, it identifies cause-and-effect relationships among components by examining the system's dynamic and evolving behaviors. This method represents a top-down strategy (Demartini et al., 2021).
14. **AB – DES hybrid method** – AB modeling exhibits high flexibility and autonomy encapsulation. It possesses the capability to model and capture autonomous behaviors of DES entities. Furthermore, events modeled with DES enable AB to provide a high level of flexibility in modeling various agent behaviors, cognition, and decisions (Demartini et al., 2021).
15. **AB - DES – SD hybrid method** – AB utilizes self-organizing characteristics to comprehend complex adaptive systems, enabling it to simulate emergent and learning behaviors. In contrast, DES represents the actions of specific agents through a chronological series of events, considering resources, capacities, and interaction protocols. Meanwhile, SD investigates the patterns of behavior and interactions within the network, employing aggregate variables in its analysis (Demartini et al., 2021).

These methodologies enable companies to determine and prioritize prospective synergies involving exchanging materials, energy, water or other goods. The expected contributions and deliverables of these methods to different phases of establishing IS synergies are detailed in Table 2.

Depending on the needs of the company establishing and/realizing IS synergies different methods may be used. Considering that several of the methods can be used for the same goal, Table 3 presents an overview of company goals in establishing and/or realizing IS synergies, along with the methods that can be utilized to address them.

5. Assessment and selection of potential IS opportunities

Assessment and selection of potential IS opportunities represent the second phase of IS implementation. The assessment and subsequent selection process uses key assessment considerations and criteria to decide if the IS has potential, with all potential stakeholders in mind. Companies and other stakeholders can also use one or more available methods, frameworks or tools (Section 4) to assess IS opportunities (Fig. 8).

5.1. *Key assessment criteria*

A robust and resilient implementation of IS requires considering key factors as criteria. Regarding the need for best practices, a three-stage assessment involving 12 key criteria is proposed as the best practice for determining the potential of future IS projects. As shown in Fig. 2, the 1st stage is to understand the current situation in the industrial area of interest by mapping the current economic activity(ies), corresponding material and energy flows, supply chain components, relevant stakeholders, limitations set by the current legislation and potential synergies with defining potential IS projects. The 2nd stage proposes a further assessment of the potential IS projects based on the mapping study conducted in the first stage. This assessment involves three aspects: economic, technological and environmental. The social aspect is referred to as the last dimension in a robust IS implementation in the 3rd step. Potential IS projects regarding stakeholder engagement in the proposed actions, company-level capacity assessment, and regional development opportunities are analyzed.

Even though the ideal implementation requires all three steps in Fig. 2, real scenarios require an optimal solution to start with the IS implementation. Thus, a subset of key factors is considered to propose optimal guidance. These factors are 1) resource and technological compatibility, 2) geographical considerations, 3) environmental impacts, 4) economic viability, and 5) regulatory compliance.

Resource and technological compatibility is a key consideration when establishing industrial symbiosis collaborations. Companies must assess whether their resources and technologies are compatible to ensure efficient material and energy exchanges with minimal modifications, often making this the first factor evaluated before collaboration. (Yeo et al., 2019). A significant challenge however, is the reluctance of companies to share information (Chen et al., 2022b). Tools have been developed to address this, including database-based tools to predict material flow and waste and multi-criteria tools that automate partnership selection based on user-defined criteria (Yeo et al., 2019).

Technological advancements further drive companies to innovate and improve material processing, fostering new partnerships. Larger enterprises with greater resources often lead these efforts (Atanasovska et al., 2022; Patricio et al., 2018; Ramin et al., 2024). For example, construction waste such as limestone, furnace slag, and fly ash is now reused to create alkali-activated cement (Xie et al., 2023). Similarly,

Table 2
Possible methods and their expected suitability for establishing and/or realization of IS. Legend: green – high suitability; yellow – moderate suitability; gray – low suitability of a tool.

Method	Mapping	Assessment	Realization	Highlights / Usage Tips
MFA	green	green	green	Best for quantifying flows and scenario comparison.
LCA	green	green	yellow	Excellent for environmental impact; watch for burden shifting.
IOA / IOM	green	yellow	green	Sectoral analysis and performance monitoring.
Process Integration	green	green	green	Good for heat/mass integration; technical implementation support.
MILP	yellow	green	green	Powerful for optimization, planning, and operations.
DEMATEL	yellow	green	gray	Identify and prioritize barriers; good for policy/action planning.
SNA	green	yellow	green	Reveals relationships and influence in IS networks.
SVN	green	yellow	green	Maps stakeholders and resources; supports governance & value exchange.
ENA	green	green	green	Strong for ecosystem-like analysis of IS performance.
Agent-Based (AB)	green	green	green	Simulates actor behavior and IS evolution over time.
System Dynamics (SD)	yellow	green	green	Good for testing IS scenarios and optimizing long-term outcomes.
AB–SD Hybrid	green	green	green	Combines individual behavior and system-wide feedback for realism.
DES–SD Hybrid	yellow	green	green	Adds time-based operations (DES) to system-level insights.
AB–DES Hybrid	green	green	green	Combines agent interaction and discrete processes.
AB–DES–SD Hybrid	green	green	green	Most comprehensive; use for large, dynamic IS ecosystems.

Table 3
Overview of methods for establishing Industrial Symbiosis synergies aligned with company goals.

Company Goal	Suggested Methods
Identify resource flows and opportunities	MFA, LCA, IOA, SNA
Assess environmental/economic impacts	LCA, MFA, MILP, SD
Implement IS exchanges or optimize networks	Process Integration, MILP, AB, ENA, Hybrid Models
Understand stakeholders and barriers	DEMATEL, SVN, SNA
Simulate dynamic IS behavior over time	AB, SD, AB–SD, AB–DES–SD

combining organic waste with chlorine-depleted pyrolyzate in energy production enhances combustibility, mainly benefiting developing countries where organic matter constitutes 60% of waste (Kyriakopoulos et al., 2019). These innovations show that compatibility challenges should not hinder IS adoption, as alternative solutions can unlock its significant benefits.

Geographical considerations are also crucial for companies to consider during IS collaboration and should be analyzed early in the process (Yeo et al., 2019). Proximity is significant, as companies operating nearby can transport materials more easily, reducing both logistical costs and transportation emissions. This is even more pronounced regarding the excess energy use, particularly thermal energy. Industrial parks are often concentrated in single areas (Faria et al., 2022), such as the Kalundborg eco-industrial park in Denmark, which hosts 13 public and private companies within a 4 km radius, enabling efficient material, water and energy exchange (Kalundborg Symbiosis, 2024). However, while proximity is important it is not a determining factor; often, the individual resource value under local conditions determines the feasibility of establishing IS synergies. For instance, synergies based on sharing high-value, low-volume resources such as aluminum can economically justify transportation over longer distances, whereas low-value, high-volume resources like water typically require short transport distances to remain viable.

Other regional factors also play a role, such as waste disposal and processing methods, which vary widely. In less developed regions, limited information on material flow can hinder IS adoption (Zhang et al., 2021, 2023). Conversely, in China, industrialization has driven significant technological and financial incentives, making resource sharing easier. A comprehensive review by Neves et al. (2020) found that 34% of IS case studies originated from China, highlighting its advancements in this area. For perspective, studies covering Europe accounted for 39% of the total. These examples underscore the importance of tailoring IS approaches to regional characteristics and leveraging local advantages to facilitate IS collaboration.

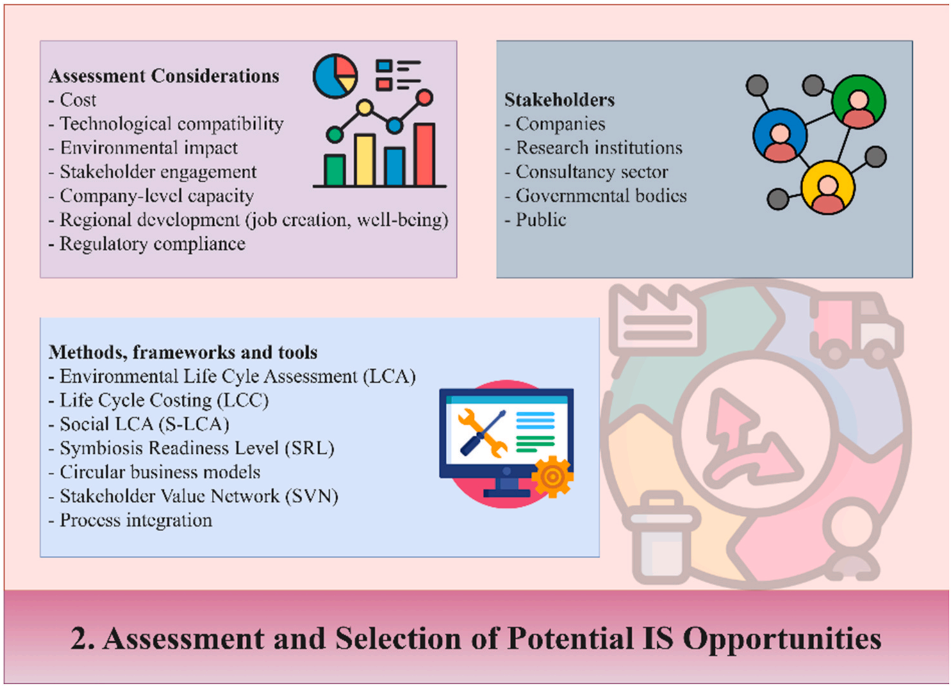

Fig. 8. The second step activities - assessment and selection of potential IS opportunities.

Mitigating **environmental impacts** is one of the primary objectives driving the development of the IS concept. IS seeks to reduce negative environmental effects, such as global warming, by minimising waste generation, improving resource efficiency, and reducing emissions to align with broader sustainability goals (Nyakudya et al., 2022). This has proved successful, especially in China, with one example being the Suzhou Industrial Park. In fact, through various material loops, savings of 2.1% in energy consumption per unit GDP and a 91% industrial water-reuse rate were claimed in 2017 (Zhao and Kai, 2021). Indeed, by realizing that China's industrial sector contributed to copious amounts of greenhouse emissions, with 2019 figures showing that China contributed to 43% of the global emissions from this sector, resource sharing was heavily promoted (Sandalow et al., 2022). In fact, through energy-based IS synergies, including the reuse of excess heat, the energy consumption from the iron and steel sector is on track to reduce by 6% from 2017 levels, which directly results in emission reductions (Fraccascia et al., 2021).

Despite this, multiple studies claim that the main objective for companies to consider IS relates to financial reasons, including government incentives and less money spent on resources, with environmental savings being considered as a by-product (Barona et al., 2023; Walls and Paquin, 2015; Yang et al., 2022). This highlights that further work is required to shift company culture towards prioritizing environmental sustainability.

Economic viability is the primary motivation for companies to adopt resource-sharing practices, transitioning from costly manufacturing to income-generating production (Ramin et al., 2024). Benefits include reduced material and energy costs, while by-products, often seen as disposal burdens, can serve as valuable inputs for other companies, creating new revenue streams (Kyriakopoulos et al., 2019). For instance, material exchange in Singapore's construction sector, using recycled materials, increased productivity by 50% through faster sourcing (Kerdlap et al., 2019). Environmental awareness drives consumer demand for eco-friendly products, enabling companies to incorporate resource sharing into green marketing strategies and boost sales (Patricio et al., 2018).

However, implementing IS practices faces challenges, particularly technological barriers. Governments have introduced incentives like tax breaks and grants to promote adoption (Xie et al., 2023; Yang et al., 2022). China excels in IS adoption due to such incentives, which are critical for small and medium enterprises with limited resources (Neves et al., 2020; Patricio et al., 2018). Despite these incentives, improvements are still required. Barona et al. (2023) noted issues like double taxation on upcycled products discouraging circular models. Additional tax incentives to lower labor costs are also essential, as virgin materials remain cheaper. Limited incentives and inadequate information hinder IS adoption in developing countries (Zhang et al., 2021). Addressing these gaps is crucial to expand resource-sharing practices.

Finally, **regulatory compliance** also plays a crucial role in facilitating the implementation of IS, as several challenges persist, including organisational and cultural barriers such as risk-averse company cultures, and a lack of systems thinking, which continue to hinder its practical adoption (Kristensen and Mosgaard, 2020). In this regard, policies such as the European Green Deal, targeting net-zero emissions in Europe by 2050, aim to address these issues (European Commission, 2020). Over the past decade, global efforts to accelerate IS adoption have increased, with Walls and Paquin (2015) emphasizing the critical role of directives in resource-sharing practices and noting limited policy literature before 2015. However, challenges remain, such as the lack of standardized processes for recycled materials (Kyriakopoulos et al., 2019). In the Netherlands, insurance companies hesitate to cover structures using recycled construction materials due to quality concerns (Chen et al., 2022b). The petroleum industry also lacks resource exchange regulations (Fraccascia et al., 2021), and inadequate disassembly standards hinder IS implementation (Cappelletti et al., 2022).

Consumer social responsibility further drives IS adoption, supported by policies like the EU Energy Labelling regulation, which guides consumers toward energy-efficient products (European Commission, 2024). A similar approach could promote IS in developing countries where information is scarce (Ghisellini et al., 2016; Merli et al., 2018). Tailored regulations are crucial, as a one-size-fits-all approach is ineffective (Xavier et al., 2023; Zhang et al., 2023). For example, the UK's low-carbon plan balances emission reductions with regional economic needs, easing regulations in steel-dependent areas like Redcar (Xie et al., 2023).

In summary, the five evaluation criteria should be thoroughly assessed to develop a well-executed IS, ensuring seamless integration, strategic placement, minimal ecological impact, financial sustainability, and legal adherence for long-term success.

5.2. Evaluation of techno-feasibility and viability of IS

A practical concern for evaluating IS outcomes is the hierarchy of scales involved in the synergistic activities, ranging from single unit-processes to multi-unit-process plants, through to the interconnected network of plants and utilities systems and sub-systems, creating a high degree of complexity. The most successful and prominent cases of IS comprise energy-intensive industries within eco-industrial parks or clusters. These industries produce the largest amount of waste. However, they also have the highest capacity to absorb available waste and by-products, sharing infrastructure and utilities and have the highest potential for introducing measures to reduce energy consumption as well as perform efficient solid waste and wastewater treatment (Fraccascia and Giannoccaro, 2020; Neves et al., 2020; Noori, 2022). A summary of the different scenarios for techno-feasibility assessment of IS is presented in Fig. 9.

Simplified models combining heuristic methods, thermodynamic principles, and mass and energy balances at the plant level and the entire complex may facilitate the IO metrics. Numerous methods, analyses and indicators are used to evaluate the IS concerning sustainability, development, performance, relations between companies and suitability for stakeholders, followed by economic impact and investment profitability, and environmental and social outcomes, among others. Although several have a comprehensive application, others have been explicitly created for IS (Krom et al., 2022; Shi, 2019). Quantitative tools, methodologies, platforms, frameworks, databases, repositories, and information and communication tools reported in many reviews and case studies publications are summarized in Table 4 for detailed information.

Several numeric indexes that help evaluate the techno-economical, environmental and social impact of IS and industrial sustainability have been formulated (see Table 4). Some examples are detailed below. An *industrial sustainability index (ISI)* and four sub-indices (inputs, firm activities, outputs and resource efficiency outcomes) have been developed to evaluate industrial performance and its outcomes with respect to IS, sustainability and CE (Arbolino et al., 2022). An *industrial eco-efficiency index* was defined for urban-IS correlating industrial waste consumption and energy with gross industrial production output as a function of time, emphasizing the trade-offs between environmental and economic aspects (Shah et al., 2020). A simplified version of ISI relates in a simple arithmetic equation on an annual basis the resource value addition (economic value of materials and energy: outputs-inputs) with the total number of employees and the total CO_2 emitted during production (Briassoulis et al., 2023; Latif et al., 2017; Pandey and Prakash, 2019).

Environmental savings, part of the intrinsic sustainability of IS, is an important family of assessment-metrics often assessed by classical energy and solid waste flow analysis during manufacturing processes and diversion from landfills or incineration. Due to the importance of climate change and stringent regulations, Green House Gas (GHG) emissions using metrics such as carbon dioxide equivalent has become a gold standard, especially in the long run (Di Pasquale et al., 2024; Gast et al., 2022; Mendez-Alva et al., 2021). The quantitative impact of IS on efficient energy utilization and GHG reduction has been widely documented over the years, especially in the case of industries characterized by high energy consumption, such as chemical, plastic, cement, metal and paper, which have the highest potential for introducing measures to reduce raw fuel consumption (Ohnishi et al., 2017; Zhang et al., 2017). Small manufacturing businesses and the agro-industrial sector are more critical and less quantified fields, which are generally associated with IS at a regional scale. Co-integration of urban and industrial clusters is envisioned to reduce carbon fingerprint and GHG emissions and improve energy recovery from solid waste management in both sites (Fan et al., 2021; Zhang et al., 2022). A more theoretical understanding of environmental savings based on fundamental thermodynamics can be achieved through energy-related metrics such as Pinch and emergy/exergy analyses (Cao et al., 2020b; Fan et al., 2021; Geng et al., 2014; Shi, 2019) (see Table 4 for details). While the feasibility criteria and viability examples seem clear regarding the exchange of materials, resources and by-products, they are less straightforward regarding energy generation and transformation (with exception of waste-to-energy conversion or share of common energy generation plants). EU regulations and policies are focused on reducing emissions, improving energy efficiency and encouraging renewable energy to improve sustainability and economic competitiveness (Branca et al., 2021b; Fraccascia et al., 2021). Private companies prioritize value-added processes over energy-related projects, especially those requiring specific expertise, which is often unavailable individually. Cooperation within the framework of industrial parks is a suitable model for promoting the integration of renewable energies and low-carbon technologies, reducing maintenance and management costs, and investing in infrastructure (Butturi et al., 2019). Cooperation within different industrial sectors can overcome the lack of technical knowledge on low carbon and renewable technologies, reduce

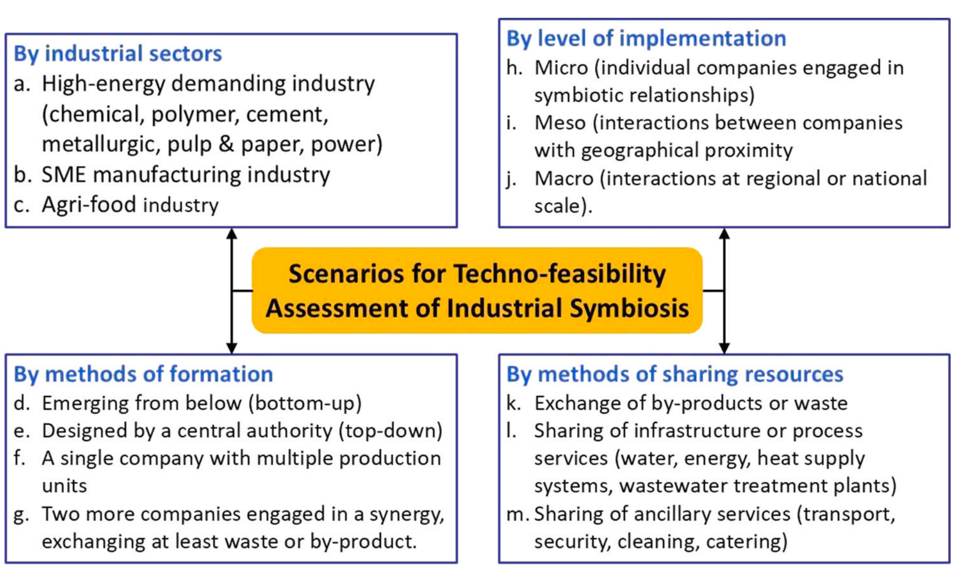

Fig. 9. Different scenarios for techno-feasibility assessment of IS.

Table 4
Summary of tools, platforms and models for quantitative and qualitative evaluation of techno-feasibility of IS.

Tool/Platform/ Framework	Case Study	Methodology	Source
Industrial Sustainability Index	Various, OECD	Principal component analysis, Sustainability disparity i ndex	Arbolino et al. (2022)
Skills Alliance for IS: A Cross-Sectoral Blueprint for a Sustainable Process Industry (SPIRE-SAIS	European energy-intensive sectors	Data analysis/ CO_2 emission, Skills demand, energy efficiency	Branca et al., 2021a; Branca et al., 2021b; Branca et al., 2022
Lifecycle sustainability (LCS)	Biopolymers industry	s-LCA, TEA, Life cycle cost (LCC), End of life	Briassoulis et al. (2023)
Energy conservation and emission reduction framework	Iron and steel industry, cement and thermal power industries and social sector (Nationwide China)	Bottom-up modeling, material metabolism LCA, simulation & validation	Cao et al., 2020b
Technical Viability Analysis of Industrial Synergies (TVAIS)	Large-scale European industries/ SCALER project	Data analysis/ Synergy	Azevedo et al., 2019; Dias et al., 2020; Ogé et al., 2019
Total EcoSite Integration for Urban and IS	Generic	SWM-Pinch Analysis, mathematical programming, TSPI	Fan et al., 2021; Liew et al., 2017
Thermo-economic assessment & optimization	Kawerau Industrial Cluster, New Zealand	Monte-Carlo analysis, utility demand model, TEA	Fahmy et al. (2021)
Techno-economic disruptions	Generic IS within eco-industrial parks/industrial clusters	Enterprise input-output numerical model	Fraccascia (2019)
Symbiotic supply chain (SSC) model	Generic IS/ resilience of SSCs to disruptions	DES, Bullwhip Effect	Fussone et al. (2024)
Emergy-based Indicators of IS	Shenyang Economic & Technological Development Zone (China)	IO data analysis, emergy analysis, performance indicators formulation	Geng et al. (2014)
Integrated LCA	Generic waste-to-resource	Multi-level data IO analysis, LCA/ LCC	Kerdlap et al., 2020a
Sustainability index (SI)	Generic manufacturing industry	IO data analysis, Pairwise comparison, Numerical modeling	Latif et al., 2017
ISI	Synergy between pulp & paper (CHP) and soda ash (chemicals) industries	Material and energy IO data analysis, numerical modeling	Pandey and Prakash (2019)
Eco-efficiency improvement approach	Industrial and agricultural complexes, Ulsan (Korea)	Eco-efficiency approach, decomposition analysis, Data envelopment analysis	Shah et al. (2020)
Resilience indicator (RI)	Kalundborg (Denmark); Ulsan (South Korea)	Mathematical Programming Computation/ Optimization, Nnetwork connectivity Index, Flows adaptability Index	Valenzuela-Venegas et al. (2018)
IS outcomes framework	Generic IS	Bibliometric analysis, computational Qualitative content analysis/ Inductive-deductive coding	Wadström et al. (2021)

emissions, and increase cost savings. Technological development, closely linked to process optimization and improved energy efficiency of the symbiotic network, is expected to affect all areas of industrial production further, but especially energy-intensive industries, while increasing productivity and reducing emissions (Branca et al., 2021b; Dias et al., 2020; Zhang et al., 2024).

Though economic benefits, both in the form of reduced raw material costs and waste disposal and potential revenues, are amenable to effective quantification and environmental benefits and encouraged by local and national incentives and policies, the social dimension is the most difficult to quantify and the least analyzed. The associated benefits are expected from stimulating new jobs, creating new companies, and developing new relationships between firms. IS, either at confined geographical interaction or regional activities, tends to encourage employment and has a positive effect on job development and job retention (Branca et al., 2022; De Gobbi, 2022; Di Pasquale et al., 2024; Pandey and Prakash, 2019). The success or failure of a synergistic relationship depends on multiple factors and a combination of variables that generate a positive or negative influence on part or all the symbiotic interaction. Good training and efficient networking among participants can be critical to the long-term success of IS. Assessing the synergies and dynamics of networked industrial cooperation to achieve business advantages must be understood beyond possible valorization pathways, paying more attention to the role of trust and leadership (Kusch-Brandt, 2020).

A critical issue in IS assessment is the network's vulnerability to disruptive events that reduce the willingness of companies to cooperate on IS synergies. Most, if not all, tools for predicting IS feasibility/ viability have disregarded IS vulnerability. In contrast, vulnerability is mainly discussed concerning ongoing IS synergies. Disruptions affecting a given IS relationship may be responsible for creating a technical and economic impact on the overall supply chain performance, incorporating waste or by-products through remanufacturing IS (Di Pasquale et al., 2024; Fussone et al., 2024). IS between companies creates specific supply chains triggered by resource use (Fraccascia, 2019). A resilience indicator of material flow that can be adapted or extended for heat and energy transfer within the network has been developed and verified based on the data of two well-established eco-parks, Kalundborg in Denmark and Ulsan in South Korea (Valenzuela-Venegas et al., 2018). Models predicting disruption of the supply chain and disturbance of IS on either material or energy flow could facilitate the design of appropriate countermeasures of partners and policymaker's policy actions and help towards the development of IS relationships resilient to perturbations (Fraccascia et al., 2021).

A challenging sector for implementing industrial networking is the agroindustry system - both plant crops and animal breeding - in general and agri-food. IS is being applied in aquaculture and animal husbandry despite its complexity. Water reclamation for irrigation in agriculture, which is by far the most significant water volume reused worldwide, is a kind of symbiotic activity indirectly connected to the agri-food industry and food security and directly linked to climate change/water scarcity/water saving (Dosoretz, 2019; Ramin et al., 2024). However, unlike high throughput industries, in which IS is of a local nature, i.e., industrial parks, the agricultural sector, both plant crops and animal breeding, has the potential for symbiotic interaction at the regional and transregional level. Therefore, IS in the agricultural sector is often harmed by the cost of transporting materials. The distance between the waste producer and the potential consumer is, in fact, one of the most important economic factors that must be considered when evaluating the viability of symbiosis.

Nevertheless, the greater the variety of industries in a given region or adjacent regions, the greater the potential for creating synergies (Hamam et al., 2023). Research and innovative initiatives on this constriction may advance IS in the agro-industrial sector. The proximity of eco-parks to agri-food clusters may help push forward CE and sustainability, so rethinking and redesigning this aspect is also required.

While these IS parks often feature large corporations focused on sharing physical resources and utilities, clusters can also comprise small and medium-sized enterprises (SMEs). These SME clusters evolve through knowledge exchange and innovation (Daddi et al., 2017). Their smaller size makes them more agile and adaptable than larger companies, allowing ideas to spread rapidly throughout the network. However, including recycling companies in business networks is crucial, particularly since more than half of SMEs dispose of their waste in landfills rather than recycling it (King et al., 2020). These characteristics are particularly valuable when planning for alternative future scenarios, especially when those futures envision significant changes to the industrial landscape (Giurco et al., 2011). When companies work together in a cluster, their managers can create a shared strategy to enhance their market position by developing more environmentally friendly products, using LCA data to support their claims (Daddi et al., 2017). For SMEs within the IS parks, managers can leverage IS opportunities to gain a competitive edge by reducing their environmental impact and seizing the opportunities of the IS to stimulate their product design and R&D.

Currently, existing tools are insufficient to identify an IS implementation's initial requirements and synergies. Therefore, it is necessary to establish a methodology that helps companies assess their maturity level, i.e., symbiotic readiness, and identify priority areas for carrying out actions to promote circular production. This level of maturity (symbiotic readiness) implies that the company is willing and able to implement IS.

The European Commission proposed using the Symbiosis Readiness Level (SRL) to identify and define the level of maturity of symbiotic interactions and to measure the progress of implementing IS (Sommer, 2020). Inspired by the Technology Readiness Level, which alone is not sufficient to assess the implementation of IS as it is necessary to consider readiness across technology, business, ecology, and management dimensions. The nine-level framework of SRL is proposed as a practical tool to guide and aims at fostering gradual progress from conceptualization to full implementation (Skjodt, 2021). The nine levels of SRL can be grouped into emergent, revelation, and embedding phases. These levels evolve from a good idea to more advanced stages of development to the final phase of full implementation, resulting in a permanent partnership.

However, SRLs are still in the early stages of development and require significant development to reach the desired maturity, so a consensus can be reached on moving from a specific SRL to the next level. Although SRLs simplify the process of IS with a step-by-step approach, no generic model works for all companies and symbiosis relationships exist. However, these practices serve as a guide and facilitate the implementation of IS.

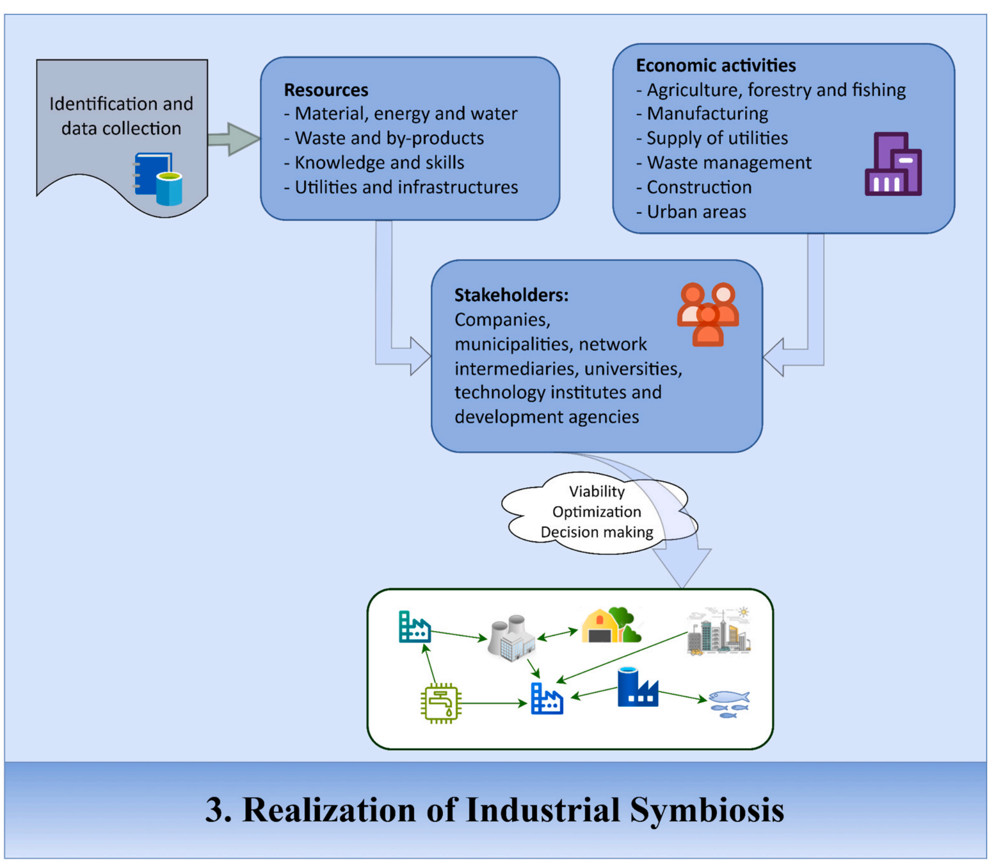

Fig. 10. The third step activities for realization of IS.

Table 5
Overview of the selected case studies, structured according to the roadmap phases applied.

Roadmap phases implemented	Tools/Methods used	Region (Country)	No. involved companies	Economic Activities	Driving force	Existing or new IS	Ref.
1. Mapping	- Collection of information on the activity and location of companies through industrial guides, statistical and commercial databases, and geographical visualizers - Gathering information on companies' environmental data through information provided by the Environment Department of the Government of Cantabria - Questionnaires to collect information on companies - Programmed visits to companies to inform them about the project and to collect information	Besaya (Spain)	80	Manufacture of food products, beverages and tobacco products; manufacture of wood and products of wood and cork; manufacture of paper and paper products; printing and reproduction of recorded media; manufacture of chemicals and chemical products; manufacture of rubber and plastic products; manufacture of other non-metallic mineral products; manufacture of essential metals and fabricated metal products; manufacture of machinery and equipment; manufacture of transport equipment; other manufacture activities; construction; commerce, repair of motor vehicles and motorcycles; and transportation and storage	Torrelavega Local Administration, through its Local Development Agency	Several companies already have IS relationships, but there is no concrete information on the companies and the synergies.	Ruiz Puente et al. (2015)
1. Mapping 2. Assessment (economic and environmental dimensions)	- Collection of data on the annual fuels and electricity consumption of energy-consuming companies in Ulsan - Interview with the manager of each company and the results of the questionnaire survey carried out by Korea Energy Management Corporation Busan/Ulsan branch office - Consultation of the district office record book for each building, documentation for the integrated energy proposal, the KyungDong City Gas report, and 2006 IPCC guidelines - Application of the 'heat load analysis procedure' - Determining the reduction in fuel costs and CO_2 emissions - Pinch analysis and energy balance	Ulsan (South Korea)	N/A	Industrial areas (companies, factories, and industries) and/or urban areas (residential and non-residential buildings such as office buildings, department stores, hypermarkets, and hospitals)	N/A	Existing IS relationships, extension to industrial and urban symbiosis	Kim et al. (2018)
1. Mapping 2. Assessment (economic, environmental and technical dimensions)	- Workshop followed the "Quick Wins Workshops" - Focus group session - Affinity diagrams - Hierarchical cluster analysis - k-means cluster analysis	Valencia, Sagunto, and Gandía (Spain)	18	Waste Management; Multipurpose Port Terminal, Container Terminal; Oil Terminal; RoPax Terminal; RoRo Terminal; Vessels Stowage & Warehousing; Temperature-controlled Warehouse and Logistic; LNG Management & Distribution; Towage; Yacht Club; Port Authority; Port Research Centre; and Environmental Knowledge and Innovation Community	Does staff form a team from the Port Authority of Valencia and experts from the Universitat Politècnica de València and the Instituto de Tecnología Cerámica	IS already exists, but in very small numbers. Aim to extend to the Valenciaport industrial cluster.	Artacho-Ramírez et al. (2020)
1. Mapping 2. Assessment (economic dimension)	- Twenty years of hourly climate data and data on import quantities of greenhouse crops - Greenhouse visits - Proposed optimization model	N/A (Switzerland)	N/A	Agricultural greenhouses, municipal solid waste incinerators, cement production plants, biogas plants, and biomethane production plants	N/A	There is no reference to the existence of IS	Rezaei et al. (2024)

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Table 5 (*continued*)

Roadmap phases implemented	Tools/Methods used	Region (Country)	No. involved companies	Economic Activities	Driving force	Existing or new IS	Ref.
	(minimization of the total cost, considering the operating cost, the investment cost, and the potential return on the realization of IS)						
1. Mapping 2. Assessment (economic and technical dimensions)	- AB model - Python - Libraries: Pulp and CoolProp - Objective function of the optimization problem: maximization of the economic benefit of symbiosis under environmental, economic, and physical constraints	Tehran (Iran)	5	Cow farm, chicken farm, edible oil plant, dairy, and CHP plant	Network intermediary	There is no reference to the existence of IS	Saghafi and Roshandel (2024)
1. Mapping 2. Assessment (economic dimension)	-LCC: economic, environmental and societal LCC - Net present value	Sodankylä (Finland)	6	Power plant, biogas reactor, CHP plant, fish farm, greenhouse farm, and insect farm	Municipality of Sodankylä	There is no reference to the existence of IS	Haq et al. (2020)
1. Mapping 2. Assessment (economic, environmental, and social dimensions)	- Data obtained through telephone interviews, field research and regional averages - Multi-objectiveMILP model developed to optimize total operating costs, environmental impacts, and job creation - Augmented ε-constraint method - General algebraic modeling system - Lexicographic optimization method	Alxa Left Banner, Inner Mongolia Autonomous Region (China)	19	Cow breeding sector, grape growing and wine processing chain, concentrated feed processing sector, organic fertilizer processing sector, roughage processing sector, and herbal medicine planting and processing industry	N/A	There is no reference to the existence of IS	Yu et al. (2023)
1. Mapping 2. Assessment (social and technical dimensions)	- Data collection: GRASS GIS, SLU forest map, national databases provided by the Swedish Board of Agriculture, and National Bureau of Statistics - Workshops and informant interviews - Software Mural - Pick chart method - Material flow inventory	Härnösand (Sweden)	7	Aquaponic production of vegetables and fish; craft gin producer; electricity grids, district heating, water supply, waste recycling municipality-owned company; microalgae company; digital resource matchmaking and optimization of logistics company; timber, pulp and paper manufacturer; and insect-based products company	N/A	There is no reference to the existence of IS	Haller et al. (2022)
1. Mapping 2. Assessment (technical dimension)	- Data obtained from the databases provided by the National Statistics Institute and the ISPRA Technical Report on Special Waste and per waste category - Methodology to support the design of regional IS relationships	Apulia region (Italy)	39 (Bari); 25 (Foggia); 11 (Barletta-Andria-Trani); 7 (Brindisi); 23 (Taranto); 25 (Lecce)	Agricultural cultivation and production of animal products, hunting and related services; aquaculture in seawater, brackish or lagoon and related services; dairy industry, sanitation, milk storage; production of olive oil; distillation, rectification and mixing of alcohol; beer production; manufacture of paper and cardboard; manufacturing fertilizers and nitrogen compounds; manufacture of plastic materials; manufacture of soaps and detergents, cleaning and polishing products; manufacture of other chemical products; manufacture of glass and glass products; manufacture of medicines and	N/A	Few IS relationships in the region.	Giannoccaro et al. (2023)

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Table 5 (*continued*)

Roadmap phases implemented	Tools/Methods used	Region (Country)	No. involved companies	Economic Activities	Driving force	Existing or new IS	Ref.
				pharmaceutical preparations; manufacture of ceramic tiles for floors and walls; manufacture of plaster products for construction; lime production; concrete production; manufacturing of concrete products for construction; brickmaking, tiles and other terracotta building products; casting of light metals; manufacture of bitumen, tar and road emulsions; manufacture of insulators and ceramic insulation pieces; cutting, shaping and finishing of stones; sawing and processing of stones and marble; manufacture of iron, steel and ferro-alloys; textile finishing; electricity production; collection and purification of wastewater; treatment and disposal of other non-dangerous waste; recovery and preparation for the recycling of metal waste and scrap, and of plastic slathering; and recovery and preparation for recycling of municipal, industrial and biomass solid waste			

6. Realization of IS: examples and case studies

The realization of IS involves several steps described in the previous sections and corresponds to a continuous effort and commitment from the various stakeholders involved. Fig. 10 illustrates the most important aspects involved in realizing IS.

The robustness of the proposed roadmap is validated through the analysis of the presented case studies (Table 5), which exemplify its practical applicability in real-world IS contexts. By showcasing diverse methods of identifying, assessing, and selecting potential synergies, these cases demonstrate the roadmap's relevance, methodical soundness, and adaptability. Furthermore, they serve as examples of good practice that can facilitate the implementation and wider dissemination of IS initiatives.

Table 5 illustrates some examples in the literature grouped according to the roadmap phases. The main aim was not to show all the case studies found exhaustively or to choose only those that applied all the phases but rather to illustrate the viability of the proposed roadmap and the diversity of tools and methods that can be used to implement IS relationships efficiently.

From a comprehensive analysis of the presented case studies, an apparent geographical diversity emerges, with implementations spanning across Europe (Spain, Finland, Sweden, Switzerland), Asia (South Korea, Iran, China), and multiple distinct regions within these countries. By observing Tables 5 and it can be seen that the case studies vary in scale and scope – from concentrated urban-industrial zones like Valencia's port area (Artacho-Ramírez et al., 2020) to rural agricultural regions like Härnösand in Sweden (Haller et al., 2022). This geographical spread demonstrates the adaptability of IS methodologies across different socio-economic, governmental structures and industrial contexts.

The maturity level of IS initiatives shows a distinct pattern. Well-established initiatives are primarily found in regions like Ulsan, South Korea (Kim et al., 2018) and Besaya, Spain (Ruiz Puente et al., 2015), where existing IS relationships are documented and formal driving forces (such as local administrations or development agencies) are present. In contrast, newer initiatives are emerging in areas like Tehran, Iran (Saghafi and Roshandel, 2024) and the Alxa Left Banner, Inner Mongolia, China (Yu et al., 2023), where the focus is primarily on potential IS project identification and optimization modeling. This contrast between established and emerging initiatives is reflected in the methodological approaches – mature regions tend to employ more sophisticated analytical tools and have more comprehensive data collection processes. In contrast, newer initiatives rely on preliminary assessment tools and theoretical optimization models.

The evolution from simple data collection and mapping exercises to complex multi-objective optimization approaches stands out from a methodological perspective. The tools range from basic questionnaires and workshops (seen in the Besaya case) to sophisticated AB models and LCAs (as demonstrated in the Tehran and Sodankylä cases). This progression suggests that the implementation of IS follows a maturity curve, where regions start with fundamental assessment tools and gradually adopt more complex methodologies as their IS networks develop. Notably, the number of participating entities (NCI) varies significantly across cases, from 5 to 7 participants in newer initiatives to 80+ in more established ones. This indicates that successful IS networks grow through demonstrated success and participant trust-building.

As mentioned above, several case studies in scientific literature illustrate the proposed roadmap's applicability. Although Table 5 contains only a few examples, the variety of locations, tools and network sizes is apparent. Fig. 11 illustrates the cases covered from the perspective of the proposed roadmap.

7. Recommendations

For a robust and resilient implementation of IS, thorough and

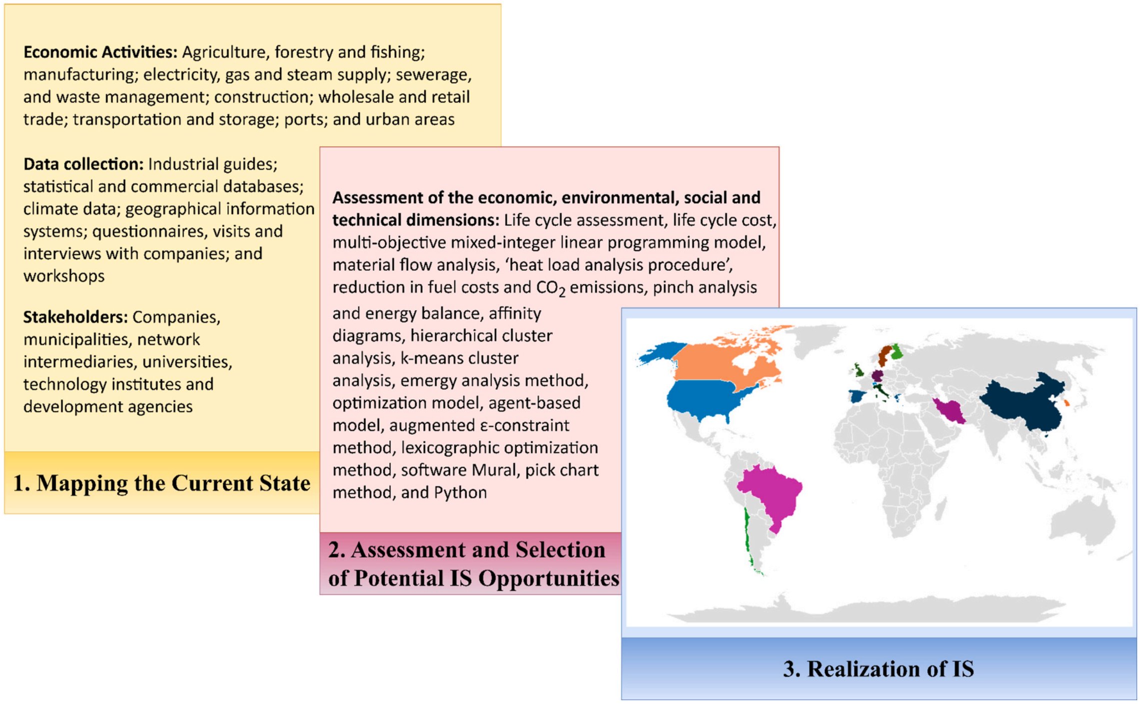

Fig. 11. Examples of implemented IS - a roadmap approach.

systematic guidance is needed. Several authors defined the evolution of IS through already realized systems and theoretical approaches. Jelinski et al. (1992) determined that the evolution process of industrial ecosystems can be divided into three stages: type I (pre-network development), type II (earlier network development) and type III (later network development). This process was tested by Korhonen and Snäkin (2005; 2003), who approved these evolutionary stages. Moreover, the three evolutionary steps are sprouting, uncovering, embeddedness, and institutionalization (Chertow and Ehrenfeld, 2012). Another classification gives the following steps: linear material and energy flows, expansion of the system with increased diversity of actors who form few connections and increasing the complexity of the created system. According to Doménech and Davies (2011), IS can be designed to include emergence, probation, development and expansion. As evolution steps, Paquin and Howard-Grenville (2012) identified the potential and pre-existing companies, deepening the cooperation among companies, expanding symbiotic exchanges and goal-directed progress (Cui et al., 2018b). Besides, Azevedo et al. (2021a) proposed a step-by-step guideline as a systematic approach to promote IS applications.

This work proposes practical, actionable steps to effectively

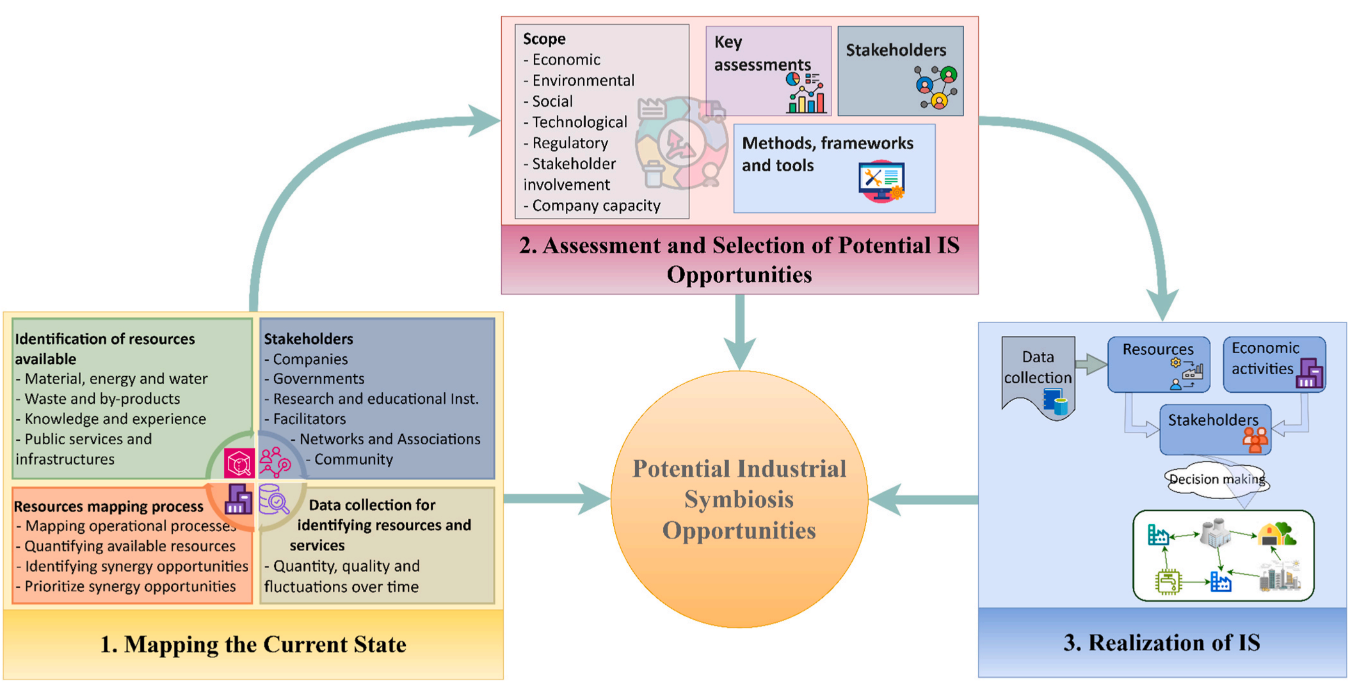

Fig. 12. The three-step approach proposed by the study in guiding the implementation of potential IS initiatives.

implement and realize IS initiatives (Fig. 12). For the successful implementation of IS, it is necessary to conduct a detailed mapping of the resource flows in companies and relevant stakeholders and, on this basis, to identify potential underutilized streams that could represent valuable resources for other companies. However, before companies start implementing an IS initiative, they need to assess, among other criteria, the technical feasibility and economic viability. All factors must be considered, from transportation costs and processing to regulatory requirements and potential benefits for all stakeholders. Tools such as LCA, TEA and SRL are used for this purpose. The main areas needing improvement are identified using these tools, and efforts are focused on building the capacity required to implement IS successfully. In the realization stage, after identifying synergies within individual companies, the scope of IS is often extended to include other businesses located nearby within the industrial park or region. This expansion of synergies to multiple companies helps create more extensive, more efficient ISNs.

The main limitation of this work lies in the fact that most companies' primary motivation for implementing IS is economic. At the same time, ecological reasons are only a by-product. Therefore, the overall mapping and assessment of the potential of IS adoption is influenced by economic benefits and may significantly affect the results. In addition, the lack of standardized processes for recycled materials also affects the proposed roadmap for IS. Most of the proposed tools for predicting the application of IS ignore the vulnerability of supply chains to disruptive events, which can also act as a limiting factor. IS is not presented as a model for achieving a more excellent CE in practice, which only points to the need for an appropriate legal framework and support from governments and regulators. A final limitation of the work is the social dimension of IS, as it is the least measured and analyzed. However, it involves incentives such as new jobs and the development of relationships between companies. These limitations highlight the need to continue researching IS to develop strategies to overcome barriers and maximize its potential.

8. Conclusions

This paper provides a comprehensive overview and analysis of the key steps for the effective implementation of IS. It contributes to a better understanding of the complexity of implementing IS and provides a practical framework for companies and practitioners wishing to use this approach.

Through a synthesis of existing literature and case studies, a detailed roadmap has been developed to provide practical guidance to organizations looking to integrate IS into their operations. The research has shown that an inventory of the current situation is essential to identify the potential of IS. This includes a detailed mapping of resources, material and energy flows and identifying relevant stakeholders. The assessment of potential IS projects should be based on five key criteria: resource and technology compatibility, geography, environmental impact, economic viability and regulatory compliance. Selecting the most suitable IS opportunities requires a multi-dimensional approach considering technical, economic, environmental, and social factors. The successful implementation of IS projects depends on stakeholders' active involvement and cooperation, including businesses, public authorities, research institutions and intermediaries. While the proposed roadmap offers a practical guide based on literature and real-world experiences, certain limitations should be acknowledged. The study relies primarily on qualitative analysis and the generalizability of the roadmap may vary depending on regional, sectoral, and organizational contexts. Furthermore, the availability of detailed data from case studies posed some constraints on cross-case comparison.

The research contributes to knowledge by offering a structured methodological framework that consolidates fragmented approaches to IS implementation. It advances the understanding of how specific factors—such as technological compatibility, regulatory context and economic evaluation—interact in practice to shape IS outcomes.

From a practical perspective, the roadmap serves as a hands-on guide for companies, facilitators/transition brokers and policymakers aiming to integrate IS into industrial operations. It provides a basis for strategic planning, stakeholder engagement and policy alignment, supporting the transition toward a more circular and resource-efficient economy.

Future research should focus on continuous improvements and developments in area of IS, in particular the following: (i) developing standardized methodologies to quantify and value the intangible benefits of IS; (ii) developing strategies for overcoming technical and non-technical barriers for implementation of IS; (iii) exploring the role of digital technologies and platforms in facilitating the identification and implementation of IS opportunities; (iv) analyzing the long-term sustainability of IS networks and the factors that influence their resilience; (v) exploring the potential for scaling up IS approaches beyond traditional industrial sectors; and (vi) exploring effective policies and incentives to encourage wider adoption of IS practices.

CRediT authorship contribution statement

Pawel Krzeminski: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Aleksandar Anastasovski:** Writing – review & editing, Visualization, Methodology, Conceptualization. **Aleksandar Erceg:** Writing – review & editing, Visualization, Conceptualization. **Biljana Činčurak Erceg:** Writing – review & editing. **Carlos G. Dosoretz:** Writing – review & editing. **Massimo Borg:** Writing – review & editing. **Paul Refalo:** Writing – review & editing. **Radu Godina:** Writing – review & editing. **Angela Neves:** Writing – review & editing, Visualization. **Vaida Jonaitienė:** Writing – review & editing. **Cansu Özcan Kılcan:** Writing – review & editing, Visualization. **Alan H. Tkaczyk:** Writing – review & editing. **Aida Szilagyi:** Writing – review & editing. **Vasiliki Skoulou:** Writing – review & editing. **Yvonne Ryan:** Writing – review & editing. **Almudena Muñoz Puche:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

Afshari, H., Tosarkani, B.M., Jaber, M.Y., Searcy, C., 2020. The effect of environmental and social value objectives on optimal design in industrial energy symbiosis: a multi-objective approach. Resour. Conserv. Recycl. 158, 104825. https://doi.org/10.1016/J.RESCONREC.2020.104825.

Akrivou, C., Łękawska-Andrinopoulou, L., Tsimiklis, G., Amditis, A., 2021. Industrial symbiosis platforms for synergy identification and their most important data points: a systematic review. Open Research Europe 1, 101. https://doi.org/10.12688/openreseurope.13893.2.

Albino, V., Fraccascia, L., Giannoccaro, I., 2016. Exploring the role of contracts to support the emergence of self-organized industrial symbiosis networks: an agent-based simulation study. J. Clean. Prod. 112, 4353–4366. https://doi.org/10.1016/j.jclepro.2015.06.070.

Anastasovski, A., 2014. Design of common heat exchanger network for batch processes. Appl. Therm. Eng. 65. https://doi.org/10.1016/j.applthermaleng.2014.01.045.

Anastasovski, A., 2020. Design of heat storage networks for repeatable batch processes. Energy Storage 3. https://doi.org/10.1002/est2.220.

Arbolino, R., Boffardi, R., Ioppolo, G., Lantz, T.L., Rosa, P., 2022. Evaluating industrial sustainability in OECD countries: a cross-country comparison. J. Clean. Prod. 331, 129773. https://doi.org/10.1016/j.jclepro.2021.129773.

Artacho-Ramírez, M.A., Pacheco-Blanco, B., Cloquell-Ballester, V.A., Vicent, M., Celades, I., 2020. Quick wins workshop and companies profiling to analyze industrial symbiosis potential. Valenciaport's cluster as case study. Sustainability 12, 7495. https://doi.org/10.3390/su12187495.

Ashton, W.S., 2009. The structure, function, and evolution of a regional industrial ecosystem. J. Ind. Ecol. 13 (2), 228–246. https://doi.org/10.1111/j.1530-9290.2009.00111.x.

Atanasovska, I., Choudhary, S., Koh, L., Ketikidis, P.H., Solomon, A., 2022. Research gaps and future directions on social value stemming from circular economy practices in agri-food industrial parks: insights from a systematic literature review. J. Clean. Prod. 354, 131753. https://doi.org/10.1016/j.jclepro.2022.131753.

Azevedo, J.; Dias, R.; Ferreira, I.; Henriques, J.; Estrela, M.; Ascenço, C. (2019) SCALER Deliverable 3.2—Technology Database Template and Guide for Upgrading. Available online: https://www.scalerproject.eu/wp-content/uploads/2019/10/Technology-database-for-synergies-setup-SCALER-D3.2.pdf (accessed on 11 July 2025).

Azevedo, J., Henriques, J., Estrela, M., Dias, R., Vladimirova, D., Miller, K., Iten, M., 2021a. Guidelines for industrial Symbiosis—A systematic approach for content definition and practical recommendations for implementation. Circ. Econ. Sustain. 1, 507–523. https://doi.org/10.1007/s43615-021-00006-3.

Azevedo, J., Ferreira, I., Dias, R., Ascenço, C., Magalhães, B., Henriques, J., Iten, M., Cunha, F., 2021b. Industrial symbiosis implementation potential—an applied assessment tool for companies. Sustainability 13 (3), 1420.

Bacudio, L.R., Benjamin, M.F.D., Eusebio, R.C.P., Holaysan, S.A.K., Promentilla, M.A.B., Yu, K.D.S., Aviso, K.B., 2016. Analyzing barriers to implementing industrial symbiosis networks using DEMATEL. Sustain. Prod. Consum. 7, 57–65. https://doi.org/10.1016/j.spc.2016.03.001.

Barona, J., Ballini, F., Canepa, M., 2023. Circular developments of maritime industrial ports in Europe: a semi-systematic review of the current situation. J. Shipp. Trade 8 (1), 1–35. https://doi.org/10.1186/s41072-023-00153-w.

Benedict, M., Kosmol, L., Esswein, C., 2018. Designing industrial symbiosis platforms: from platform ecosystems to industrial ecosystems. In: The 22nd Pacific Asia Conference on Information Systems. June 28-29, Yokohama, Japan.

Branca, T.A., Colla, V., Fornai, B., Petrucciani, A., Pistelli, M.I., Faraci, E.L., Cirilli, F., Schröder, A.J., 2021a. Current state of industrial symbiosis and energy efficiency in the European energy intensive sectors. Matériaux Tech. 109, 504. https://doi.org/10.1051/mattech/2022014.

Branca, T.A., Fornai, B., Colla, V., Pistelli, M.I., Faraci, E.L., Cirilli, F., Schröder, A.J., 2021b. Industrial symbiosis and energy efficiency in European process industries: a review. Sustainability 13, 9159. https://doi.org/10.3390/su13169159.

Branca, T.A., Fornai, B., Colla, V., Pistelli, M.I., Faraci, E.L., Cirilli, F., Schröder, A.J., 2022. Skills demand in energy intensive industries targeting industrial symbiosis and energy efficiency. Sustainability 14, 15615. https://doi.org/10.3390/su142315615.

Briassoulis, D., Pikasi, A., Hiskakis, M., Arias, A., Moreira, M.T., Ioannidou, S.M., Ladakis, D., Koutinas, A., 2023. Life-cycle sustainability assessment for the production of bio-based polymers and their post-consumer materials recirculation through industrial symbiosis. Curr. Opin. Green Sustainable Chem. 41, 100818. https://doi.org/10.1016/j.cogsc.2023.100818.

Bringezu, S., Moriguchi, Y., 2018. Material flow analysis. In: Bartelmus, P., Seifert, E.K. (Eds.), Green Accounting. Routledge, pp. 149–166. https://doi.org/10.4324/9781315197715-6.

Butturi, M.A., Lolli, F., Sellitto, M.A., Balugani, E., Gamberini, R., Rimini, B., 2019. Renewable energy in eco-industrial parks and urban-industrial symbiosis: a literature review and a conceptual synthesis. Appl. Energy 255, 113825. https://doi.org/10.1016/j.apenergy.2019.113825.

Cao, X., Wen, Z., Xu, J., Clercq, D. de, Wang, Y., Tao, Y., 2020a. Many-objective optimization of technology implementation in the industrial symbiosis system based on a modified NSGA-III. J. Clean. Prod. 245, 118810.

Cao, X., Wen, Z., Zhao, X., Wang, Y., Zhang, H., 2020b. Quantitative assessment of energy conservation and emission reduction effects of nationwide industrial symbiosis in China. Sci. Total Environ. 717, 137114. https://doi.org/10.1016/j.scitotenv.2020.137114.

Cappelletti, F., Rossi, M., Germani, M., 2022. How de-manufacturing supports circular economy linking design and EoL - a literature review. J. Manuf. Syst. 63, 118–133. https://doi.org/10.1016/j.jmsy.2022.03.007.

CENELEC, 2018. Industrial symbiosis: core elements and implementation approaches. Cen Workshop Agreement. CWA, 17354. Available at: https://www.cencenelec.eu/media/CEN-CENELEC/CWAs/RI/cwa17354_2018.pdf#:~:text=URL%3A%20https%3A%2F%2Fwww.cencenelec.eu%2Fmedia%2FCEN. (Accessed 20 December 2024).

Che, Y., Deng, Y., Yuan, Y.-H., 2022. Maximum-entropy-based decision-making trial and evaluation laboratory and its application in emergency management. J. Organ. End User Comput. 34, 1–16.

Chen, X., Dong, M., Zhang, L., Luan, X., Cui, X., Cui, Z., 2022a. Comprehensive evaluation of environmental and economic benefits of industrial symbiosis in industrial parks. J. Clean. Prod. 354, 131635. https://doi.org/10.1016/j.jclepro.2022.131635.

Chen, Q., Feng, H., Garcia de Soto, B., 2022b. Revamping construction supply chain processes with circular economy strategies: a systematic literature review. J. Clean. Prod. 335, 130240. https://doi.org/10.1016/j.jclepro.2021.130240.

Chertow, M.R., 2000. Industrial symbiosis: literature and taxonomy. Annu. Rev. Energy 25, 313–337. https://doi.org/10.1146/annurev.energy.25.1.313.

Chertow, M.R., 2007. Uncovering industrial symbiosis. J. Ind. Ecol. 11 (1), 11–30. https://doi.org/10.1162/jiec.2007.1110.

Chertow, M., Ehrenfeld, J., 2012. Organizing self-organizing systems. J. Ind. Ecol. 16, 13–27. https://doi.org/10.1111/J.1530-9290.2011.00450.X.

Costa, I., Ferrão, P., 2010. A case study of industrial symbiosis development using a middle-out approach. J. Clean. Prod. 18 (10–11), 984–992. https://doi.org/10.1016/j.jclepro.2010.03.007.

Cui, H., Liu, C., Côté, R., Liu, W., 2018. Understanding the evolution of industrial symbiosis with a system dynamics model: a case study of Hai Hua industrial symbiosis, China. Sustainability 10, 3873. https://doi.org/10.3390/SU10113873.

Daddi, T., Nucci, B., Iraldo, F., 2017. Using Life Cycle Assessment (LCA) to measure the environmental benefits of industrial symbiosis in an industrial cluster of SMEs. J. Clean. Prod. 147, 157–164. https://doi.org/10.1016/j.jclepro.2017.01.090.

Dai, Y., Day, S., Masi, D., Gölgeci, I., 2022. A synthesised framework of eco-industrial park transformation and stakeholder interaction. Bus. Strat. Environ. 31 (7), 3122–3151. https://doi.org/10.1002/bse.3067.

de Abreu, M.C.S., Ceglia, D., 2018. On the implementation of a circular economy: the role of institutional capacity-building through industrial symbiosis. Resour. Conserv. Recycl. 138, 99–109. https://doi.org/10.1016/j.resconrec.2018.07.001.

De Gobbi, S., 2022. Industrial symbiosis networks as part of a circular economy: employment effects in some industrializing countries. Int. Labor Organ. Available at: 25.

Demartini, M., Tonelli, F., Govindan, K., 2021. An investigation into modelling approaches for industrial symbiosis: a literature review and research agenda. Cleaner Logistics and Supply Chain 3, 100020. https://doi.org/10.1016/J.CLSCN.2021.100020.

Di Pasquale, V., Caterino, M., Riemma, S., Rinaldi, M., Fruggiero, F., Iannone, R., 2024. Analysis of strategies and models for industrial symbiosis in manufacturing ecosystems. In: Fera, M., Caterino, M., Macchiaroli, R., Pham, D.T. (Eds.), Advances in Remanufacturing. Springer, Nature Switzerland, Cham, pp. 317–328. https://doi.org/10.1007/978-3-031-52649-7_25.

Dias, R., Azevedo, J., Ferreira, I., Estrela, M., Henriques, J., Ascenço, C., Iten, M., 2020. Technical viability analysis of industrial synergies - an applied framework perspective. Sustainability 12, 7720. https://doi.org/10.3390/su12187720.

Doménech, T., Davies, M., 2009. The social aspects of industrial symbiosis: the application of social network analysis to industrial symbiosis networks. Prog. Ind. Ecol. Int.J. 6 (1), 68–99. https://doi.org/10.1504/PIE.2009.026583.

Doménech, T., Davies, M., 2011. The role of embeddedness in industrial symbiosis networks: phases in the evolution of industrial symbiosis networks. Bus. Strat. Environ. 20, 281–296. https://doi.org/10.1002/BSE.695.

Domenech, T., Bleischwitz, R., Doranova, A., Panayotopoulos, D., Roman, L., 2019. Mapping industrial symbiosis development in Europe_ typologies of networks, characteristics, performance and contribution to the circular economy. Resour. Conserv. Recycl. 141, 76–98. https://doi.org/10.1016/j.resconrec.2018.09.016.

Dong, L., Taka, G.N., Lee, D., Park, Y., Park, H.S., 2022. Tracking industrial symbiosis performance with ecological network approach integrating economic and environmental benefits analysis. Resour. Conserv. Recycl. 185, 106454. https://doi.org/10.1016/j.resconrec.2022.106454.

Dosoretz, C.G., 2019. Removal of contaminants of emerging concern from wastewater. In: Maurice, P. (Ed.), Encyclopedia of Water. Wiley, pp. 1–13. https://doi.org/10.1002/9781119300762.wsts0044.

Erceg, A., Krzeminski, P., Jonaitiene, V., Munoz Marti, M., Dunjić, B., Szilagyi, A., Burmaoglu, S., Činčurak Erceg, B., Giacomi, E., Anastasovski, A., Ryan, Y., Skolou, V., Chrabak, P., Refalo, P., Borg, M., Dosoretz, C., Plaza, J.P., Hurtado Ruiz, A.M., Özcan Kilcan, C., Tkaczyk, A.H., Godina, R., Neves, A., 2024. State-of-the-art report on industrial symbiosis topic and its different sub-areas (settling the basis for further improvements and their introduction in the industry). Available at: https://www.liaise-action.eu/publication/d1-1-state-of-the-art-report-on-industrial-symbiosis-topic-and-its-different-subareas/accessDecember8.

Escandon-Barbosa, D., Salas-Paramo, J., Paque, V.C., 2024. The role of trophic, mutualistic, and competitive interactions in an industrial symbiosis process implementation: an ecological network perspective. Environ. Sci. Pollut. Control Ser. 31, 41905–41913. https://doi.org/10.1007/s11356-024-33454-z.

European Commission, 2020. The European green deal. Available at: https://ec.europa.eu/stories/european-green-deal/access. (Accessed 17 December 2024).

European Commission, 2024. Understanding the energy label. Available at: https://energy-efficient-products.ec.europa.eu/ecodesign-and-energy-label/understanding-energy-label_en. (Accessed 17 December 2024).

Eurostat, 2023a. EU's circular material use rate slightly up in 2022. Available at: https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20231114-2. (Accessed 5 January 2025).

Eurostat, 2023b. Waste statistics. Available at: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics. (Accessed 5 January 2025).

Fahmy, M., Hall, P.W., Suckling, I.D., Bennett, P., Wijeyekoon, S., 2021. Identifying and evaluating symbiotic opportunities for wood processing through techno-economic superstructure optimisation – a methodology and case study for the Kawerau industrial cluster in New Zealand. J. Clean. Prod. 328, 129494. https://doi.org/10.1016/j.jclepro.2021.129494.

Fallahi, A., Taheriyoun, M., Asghari, K., 2024. Water footprint assessment in an industrial symbiosis system based on environmental, economic, and social sustainability indices. J. Clean. Prod. 454, 142227. https://doi.org/10.1016/j.jclepro.2024.142227.

Fan, Y., Fang, C., 2020. Assessing environmental performance of eco-industrial development in industrial parks. Waste Manag. 107, 219–226. https://doi.org/10.1016/j.wasman.2020.04.008.

Fan, Y.V., Varbanov, P.S., Klemeš, J.J., Romanenko, S.V., 2021. Urban and industrial symbiosis for circular economy: total ecosite integration. J. Environ. Manag. 279, 111829. https://doi.org/10.1016/j.jenvman.2020.111829.

Faria, E., Barreto, C., Caldeira-Pires, A., Lima-Silva, A., 2022. Evolution of industrial symbiosis scientific field in Brazil: insights from a systematic literature review and a bibliometric analysis. In: Joint Conference – Proceedings 2022 IEEE 28th International Conference on Engineering, Technology and Innovation, ICE/ITMC 2022 and 31st International Association for Management of Technology, IAMOT 2022 Joint Conference – Proceedings, pp. 1–7. https://doi.org/10.1109/ICE/ITMC-IAMOT55089.2022.10033312.

Fraccascia, L., 2018. Industrial symbiosis and urban areas: a systematic literature review and future research directions. Procedia Environ. Sci. Eng. Manag. 5 (2), 73–83.

Fraccascia, L., 2019. The impact of technical and economic disruptions in industrial symbiosis relationships: an enterprise input-output approach. Int. J. Prod. Econ. 213, 161–174. https://doi.org/10.1016/j.ijpe.2019.03.020.

Fraccascia, L., Giannoccaro, I., 2020. What, where, and how measuring industrial symbiosis: a reasoned taxonomy of relevant indicators. Resour. Conserv. Recycl. 157, 104799. https://doi.org/10.1016/j.resconrec.2020.104799.

Fraccascia, L., Yazan, D.M., 2018. The supply chain implications of industrial symbiosis. Procedia Environ. Sci. Eng. Manag. 5 (2), 104974. https://doi.org/10.1016/j.resconrec.2020.1049.

Fraccascia, L., 2020. Quantifying the direct network effect for online platforms supporting industrial symbiosis: an agent-based simulation study. Ecol. Econ. 170, 106587.

Fraccascia, L., Magno, M., Albino, V., 2016. Business models for industrial symbiosis: a guide for firms. Procedia Environ. Sci. Eng. Manag. 3, 83–93.

Fraccascia, L., Yazdanpanah, V., van Capelleveen, G., Yazan, D.M., 2021. Energy-based industrial symbiosis: a literature review for circular energy transition. Environ. Dev. Sustain. 23 (4), 4791–4825. https://doi.org/10.1007/s10668-020-00840-9.

Fussone, R., Cannella, S., Corsini, R., Framiñan, J.M., 2024. Assessing the impact of remanufacturing through industrial symbiosis on supply chain performance. In: Fera, M., Caterino, M., Macchiaroli, R., Pham, D.T. (Eds.), Advances in Remanufacturing. Springer, Nature Switzerland, Cham, pp. 329–339. https://doi.org/10.1007/978-3-031-52649-7_26.

Gast, L., Cabrera Serrenho, A., Allwood, J.M., 2022. What contribution could industrial symbiosis make to mitigating industrial greenhouse gas (GHG) emissions in bulk material production? Environ. Sci. Technol. 56, 10269–10278. https://doi.org/10.1021/acs.est.2c01753.

Genc, O., van Capelleveen, G., Erdis, E., Yildiz, O., Yazan, D.M., 2019. A socio-ecological approach to improve industrial zones towards eco-industrial parks. J. Environ. Manag. 250, 109507.

Geng, X., Wen, Y., Zhou, C., Xiao, C., 2017. Establishment of the sustainable ecosystem for the regional shipping industry based on system dynamics. Sustainability 9, 742. https://doi.org/10.3390/SU9050742.

Geng, Y., Liu, Z., Xue, B., Dong, H., Fujita, T., Chiu, A., 2014. Emergy-based assessment on industrial symbiosis: a case of Shenyang economic and technological development zone. Environ. Sci. Pollut. Control Ser. 21, 13572–13587. https://doi.org/10.1007/s11356-014-3287-8.

Ghisellini, P., Cialani, C., Ulgiati, S., 2016. A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. J. Clean. Prod. 114, 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007.

Giannoccaro, I., Zaza, V., Fraccascia, L., 2023. Designing regional industrial symbiosis networks: the case of Apulia region. Sustain. Dev. 31, 1475–1514. https://doi.org/10.1002/sd.2462.

Giurco, D., Cohen, B., Langham, E., Warnken, M., 2011. Backcasting energy futures using industrial ecology. Technol. Forecast. Soc. Change 78 (5), 797–818. https://doi.org/10.1016/j.techfore.2010.09.004.

Golev, A., Corder, G.D., Giurco, D.P., 2014. Barriers to industrial symbiosis: insights from the use of a maturity grid. J. Ind. Ecol. 19 (1), 141–153. https://doi.org/10.1111/jiec.12159.

Graedel, T.E., 2019. Material flow analysis from origin to evolution. Environ. Sci. Technol. 53, 12188–12196. https://doi.org/10.1021/acs.est.9b03413.

Haller, H., Fagerholm, A.-S., Carlsson, P., Skoglund, W., Van Den Brink, P., Danielski, I., Brink, K., Mirata, M., Englund, O., 2022. Towards a resilient and resource-efficient local food system based on industrial symbiosis in härnösand: a Swedish case study. Sustainability 14, 2197. https://doi.org/10.3390/su14042197.

Halstenberg, F.A., Lindow, K., Stark, R., 2017. Utilization of product lifecycle data from PLM systems in platforms for industrial symbiosis. Procedia Manuf. 8, 369–376. https://doi.org/10.1016/j.promfg.2017.02.047.

Hamam, M., Spina, D., Raimondo, M., Di Vita, G., Zanchini, R., Chinnici, G., Tóth, J., D'Amico, M., 2023. Industrial symbiosis and agri-food system: themes, links, and relationships. Front. Sustain. Food Syst. 6, 1012436. https://doi.org/10.3389/fsufs.2022.1012436.

Haq, H., Välisuo, P., Kumpulainen, L., Tuomi, V., Niemi, S., 2020. A preliminary assessment of industrial symbiosis in Sodankylä. Curr. Res. Environ. Sustain. 2, 100018. https://doi.org/10.1016/j.crsust.2020.100018.

Harfeldt-Berg, L., Broberg, S., Ericsson, K., 2022. The importance of individual actor characteristics and contextual aspects for promoting industrial symbiosis networks. Sustainability 14, 4927. https://doi.org/10.3390/su14094927.

Hein, A.M., Jankovic, M., Feng, W., Farel, R., Yune, J.H., Yannou, B., 2017. Stakeholder power in industrial symbioses: a stakeholder value network approach. J. Clean. Prod. 148, 923–933. https://doi.org/10.1016/j.jclepro.2017.01.

Henriques, J.D., Azevedo, J., Dias, R., Estrela, M., Ascenco, C., Vladimirova, D., Miller, K., 2021b. Implementing industrial symbiosis incentives: an applied assessment framework for risk mitigation. Circ. Econ. Sustain. 2, 669–692. https://doi.org/10.1007/s43615-021-00069-2.

Henriques, J., Ferrão, P., Castro, R., Azevedo, J., 2021a. Industrial symbiosis: a sectoral analysis on enablers and barriers. Sustainability 13, 1723. https://doi.org/10.3390/su13041723.

Herczeg, G., Akkerman, R., Hauschild, M.Z., 2018. Supply chain collaboration in industrial symbiosis networks. J. Clean. Prod. 171, 1058–1067.

Hsu, C.-C., 2012. Evaluation criteria for blog design and analysis of causal relationships using factor analysis and DEMATEL. Expert Syst. Appl. 39, 187–193. https://doi.org/10.1016/j.eswa.2011.07.006.

Huang, Q., Song, W., Song, C., 2020. Consolidating the layout of rural settlements using system dynamics and the multi-agent system. J. Clean. Prod. 274, 123150. https://doi.org/10.1016/j.jclepro.2020.123150.

Iyer, S.V., Sangwan, K.S., 2023. Development of an industrial symbiosis framework through digitalization in the context of industry 4.0. Proced. CIRP 122, 515–520. https://doi.org/10.1016/j.procir.2024.01.075.

Jelinski, L.W., Graedel, T.E., Laudise, R.A., Mccall, D.W., Patel, C.K.N., 1992. Industrial ecology: concepts and approaches. Proc. Natl. Acad. Sci. 89, 793–797. https://doi.org/10.1073/PNAS.89.3.793.

Kalundborg Symbiosis, 2024. Kalundborg symbiosis. Available at: https://www.symbiosis.dk/en/access. (Accessed 22 January 2025).

Kantor, I., Robineau, J., Bütün, H., Maréchal, F., 2020. A mixed-integer linear programming formulation for optimizing multi-scale material and energy integration. Front. Energy Res. 8, 507123. https://doi.org/10.3389/fenrg.2020.00049.

Katana, K., Glaa, B., Mirata, M., 2024. Facilitator roles for knowledge sharing in industrial symbiosis networks during emergence. Bus. Strat. Environ. 33 (8), 8540–8558. Wiley Blackwell.

Kerdlap, P., Low, J.S.C., Ramakrishna, S., 2019. Zero waste manufacturing: a framework and review of technology, research, and implementation barriers for enabling a circular economy transition in Singapore. Resour. Conserv. Recycl. 151. https://doi.org/10.1016/j.resconrec.2019.104438.

Kerdlap, P., Low, J.S.C., Ramakrishna, S., 2020a. Life cycle environmental and economic assessment of industrial symbiosis networks: a review of the past decade of models and computational methods through a multi-level analysis lens. Int. J. Life Cycle Assess. 25, 1660–1679. https://doi.org/10.1007/s11367-020-01792-y.

Kerdlap, P., Low, J.S.C., Tan, D.Z.L., Yeo, Z., Ramakrishna, S., 2020b. M3-IS-LCA: a methodology for multi-level life cycle environmental performance evaluation of industrial symbiosis networks. Resour. Conserv. Recycl. 161, 104963.

Kim, H.-W., Dong, L., Choi, A.E.S., Fujii, M., Fujita, T., Park, H.-S., 2018. Co-benefit potential of industrial and urban symbiosis using waste heat from industrial park in Ulsan, Korea. Resour. Conserv. Recycl. 135, 225–234. https://doi.org/10.1016/j.resconrec.2017.09.027.

King, S., Lusher, D., Hopkins, J., Simpson, G.W., 2020. Industrial symbiosis in Australia: the social relations of making contact in a matchmaking marketplace for SMEs. J. Clean. Prod. 270, 122146. https://doi.org/10.1016/j.jclepro.2020.122146.

Korhonen, J., Snäkin, J.-P., 2003. Industrial ecosystem evolution of North Karelia heating energy system. Reg. Environ. Change 3, 128–139. https://doi.org/10.1007/S10113-003-0056-5/METRICS.

Korhonen, J., Snäkin, J.-P., 2005. Analysing the evolution of industrial ecosystems: concepts and application. Ecol. Econ. 52, 169–186. https://doi.org/10.1016/J.ECOLECON.2004.07.016.

Kosmol, L., Otto, L., 2020. Implementation barriers of industrial symbiosis: a systematic review. Proceedings of the 53rd Hawaii International Conference on System Sciences. https://doi.org/10.24251/HICSS.2020.741.

Kristensen, H.S., Mosgaard, M.A., 2020. A review of micro level indicators for a circular economy – moving away from the three dimensions of sustainability? J. Clean. Prod. 243, 118531. https://doi.org/10.1016/j.jclepro.2019.118531.

Krom, P., Piscicelli, L., Frenken, K., 2022. Digital platforms for industrial symbiosis. J. Innov. Econ. Manag. 39, 215–240. https://doi.org/10.3917/jie.039.0215.

Krzeminski, P., Erceg, A., Anastasovski, A., Oral, H.V., Berk, I., Mašović, A., et al., 2025. Identification of Technical and Non-technical Barriers Related to the Implementation of Industrial Symbiosis. LIAISE COST Action & CETEM. https://www.liaise-action.eu/wp-content/uploads/2025/04/D1.4-Identification-of-technical-and-non-technical-barriers-related-to-the-implementation-of-IS.pdf.

Kusch-Brandt, S., 2020. Industrial symbiosis: unlocking synergies to achieve business advantages and resource efficiency. In: Leal Filho, W., Azul, A.M., Brandli, L., Lange Salvia, A., Wall, T. (Eds.), Industry, Innovation and Infrastructure. Springer International Publishing, Cham, pp. 1–12. https://doi.org/10.1007/978-3-319-71059-4_110-1.

Kyriakopoulos, G.L., Kapsalis, V.C., Aravossis, K.G., Zamparas, M., Mitsikas, A., 2019. Evaluating circular economy under a multi-parametric approach: a technological review. Sustainability 11 (21), 6139. https://doi.org/10.3390/su11216139.

Latif, H.H., Gopalakrishnan, B., Nimbarte, A., Currie, K., 2017. Sustainability index development for manufacturing industry. Sustain. Energy Technol. Assessments 24, 82–95. https://doi.org/10.1016/j.seta.2017.01.010.

Lawal, M., Wan Alwi, S.R., Manan, Z.A., Ho, W.S., 2021. Industrial symbiosis tools—A review. J. Clean. Prod. 280, 124327. https://doi.org/10.1016/j.jclepro.2020.124327.

Liew, P.Y., Theo, W.L., Wan Alwi, S.R., Lim, J.S., Abdul Manan, Z., Klemeš, J.J., Varbanov, P.S., 2017. Total site heat integration planning and design for industrial, urban and renewable systems. Renew. Sustain. Energy Rev. 68, 964–985. https://doi.org/10.1016/j.rser.2016.05.086.

Lombardi, R.D., Laybourn, P., 2012. Redefining industrial symbiosis. J. Ind. Ecol. 16 (1), 28–37. https://doi.org/10.1111/j.1530-9290.2011.00444.x.

Lupton, R., Allwood, J., 2017. Hybrid Sankey diagrams: visual analysis of multidimensional data for understanding resource use. Resour. Conserv. Recycl. 124, 141–151. https://doi.org/10.1016/j.resconrec.2017.05.002.

Lybæk, R., Christensen, T.B., Thomsen, T.P., 2021. Enhancing policies for deployment of industrial symbiosis – what are the obstacles, drivers and future way forward? J. Clean. Prod. 280, 124351. https://doi.org/10.1016/j.jclepro.2020.124351.
Manoharan, S., Kumar Pulimi, V.S., Kabir, G., Ali, S.M., 2021. Contextual relationships among drivers and barriers to circular economy: an integrated ISM and DEMATEL approach. Sustain. Oper. Comput. 3, 43–53. https://doi.org/10.1016/j.susoc.2021.09.003.
Mattila, T.J., Pakarinen, S., Sokka, L., 2010. Quantifying the total environmental impacts of an industrial symbiosis-a comparison of process-, hybrid and input− output life cycle assessment. Environ. Sci. Technol. 44 (11), 4309–4314. https://doi.org/10.1021/es902673m.
Mendez-Alva, F., Cervo, H., Krese, G., Van Eetvelde, G., 2021. Industrial symbiosis profiles in energy-intensive industries: sectoral insights from open databases. J. Clean. Prod. 314, 128031. https://doi.org/10.1016/j.jclepro.2021.128031.
Merli, R., Preziosi, M., Acampora, A., 2018. How do scholars approach the circular economy? A systematic literature review. J. Clean. Prod. 178, 703–722. https://doi.org/10.1016/j.jclepro.2017.12.112.
Molinier, R., da Costa, P., 2019. Infrastructure sharing synergies and industrial symbiosis: optimal capacity oversizing and pricing. J. Ind. Intell. Inform. 7 (1), 24–32. https://doi.org/10.18178/jiii.7.1.24-32.
Morales, M.E., Diemer, A., 2019. Industrial symbiosis dynamics, a strategy to accomplish complex analysis: the dunkirk case study. Sustainability 11, 1971.
Mortensen, L., Kørnøv, L., 2019. Critical factors for industrial symbiosis emergence process. J. Clean. Prod. 212, 56–69. https://doi.org/10.1016/j.jclepro.2018.11.222.
Neves, A., Godina, R., Azevedo, S.G., Matias, J.C.O., 2019a. Environmental, economic, and social impact of industrial symbiosis: methods and indicators review. In: Reis, J., Pinelas, S., Melão, N. (Eds.), Industrial Engineering and Operations Management II. Springer International Publishing, Cham, pp. 157–165. https://doi.org/10.1007/978-3-030-14973-4_15.
Neves, A., Godina, R., Azevedo, S.G., Matias, J.C.O., 2020. A comprehensive review of industrial symbiosis. J. Clean. Prod. 247, 119113. https://doi.org/10.1016/j.jclepro.2019.119113.
Neves, A., Godina, R., Azevedo, S.G., Pimentel, C., Matias, J.C.O., 2019b. The potential of industrial symbiosis: case analysis and main drivers and barriers to its implementation. Sustainability 11 (24), 7095. https://doi.org/10.3390/su11247095.
Niederl-Schmidinger, A., Narodoslawsky, M., 2008. Life cycle assessment as an engineer's tool? J. Clean. Prod. 16 (2), 245–252. https://doi.org/10.1016/j.jclepro.2006.08.024.
Noori, S., 2022. Industrial Symbiosis in Emerging Economies: a System Approach to Study Industrial Symbiosis in Industrial Clusters. Delft University of Technology. https://doi.org/10.4233/uuid:d33a5a8a-8423-4854-833c-403f8ed214e2.
Nyakudya, P., Madushele, N., Madyira, D.M., 2022. A review of industrial symbiosis in influencing green manufacturing. In: Proceedings 2022 IEEE 13th International Conference on Mechanical and Intelligent Manufacturing Technologies, ICMIMT, pp. 80–84. https://doi.org/10.1109/ICMIMT55556.2022.9845273.
Ohnishi, S., Dong, H., Geng, Y., Fujii, M., Fujita, T., 2017. A comprehensive evaluation on industrial & urban symbiosis by combining MFA, carbon footprint and emergy methods—Case of Kawasaki, Japan. Ecol. Indic. 73, 513–524. https://doi.org/10.1016/j.ecolind.2016.10.016.
Oughton, C., Anda, M., Kurup, B., Ho, G., 2021. Water circular economy at the Kwinana industrial area, Western Australia—The dimensions and value of industrial symbiosis. Circ.Econ. Sust. 1, 995–1018. https://doi.org/10.1007/s43615-021-00076-3.
Pandey, A.K., Prakash, R., 2019. Impact of industrial symbiosis on sustainability. Open J. Energy Effic. 8, 81–93. https://doi.org/10.4236/ojee.2019.82006.
Paquin, R.L., Howard-Grenville, J., 2012. The evolution of facilitated industrial symbiosis. J. Ind. Ecol. 16 (1), 83–93. https://doi.org/10.1111/j.1530-9290.2011.00437.x.
Paquin, R.L., Busch, T., Tilleman, S.G., 2015. Creating economic and environmental value through industrial symbiosis. Long. Range Plan. 48 (2), 95–107. https://doi.org/10.1016/j.lrp.2013.11.002.
Patricio, J., Axelsson, L., Blomé, S., Rosado, L., 2018. Enabling industrial symbiosis collaborations between SMEs from a regional perspective. J. Clean. Prod. 202, 1120–1130. https://doi.org/10.1016/j.jclepro.2018.07.230.
Patricio, J., Kalmykova, Y., Rosado, L., Cohen, J., Westin, A., Gil, J., 2022. Method for identifying industrial symbiosis opportunities. Resour. Conserv. Recycl. 185, 106437. https://doi.org/10.1016/j.resconrec.2022.106437.
Rahman, M.F., Islam, K., Islam, K.N., 2016. Industrial symbiosis: a review on uncovering approaches, opportunities, barriers and policies. J. Civil Eng. Environ. Sci. 2 (1), 11–19. https://doi.org/10.17352/2455-2976.000009.
Raimbault, J., Broere, J., Somveille, M., Serna, J.M., Strombom, E., Moore, C., Zhu, B., Sugar, L., 2020. A spatial agent based model for simulating and optimizing networked eco-industrial systems. Resour. Conserv. Recycl. 155, 104538. https://doi.org/10.1016/j.resconrec.2019.104538.
Ramin, E., Faria, L., Gargalo, C.L., Ramin, P., Flores-Alsina, X., Andersen, M.M., Gernaey, K.V., 2024. Water innovation in industrial symbiosis - a global review. J. Environ. Manag. 349, 119578. https://doi.org/10.1016/j.jenvman.2023.119578.
Rentería Núñez, G., Perez-Castillo, D., 2023. Business models for industrial symbiosis: a literature review. Sustainability 15 (12), 9142. https://doi.org/10.3390/su15129142.
Rezaei, F., Burg, V., Pfister, S., Hellweg, S., Roshandel, R., 2024. Optimization framework of clean heat and CO2 supply for agricultural greenhouses exploiting industrial symbiosis. Energy Strategy Rev. 55, 101509. https://doi.org/10.1016/j.esr.2024.101509.
Rodrigues, A., Bowers, J., 1996. The role of system dynamics in project management. Int. J. Proj. Manag. 14, 213–220. https://doi.org/10.1016/0263-7863(95)00075-5.
Ruiz Puente, M.C., Arozamena, E.R., Evans, S., 2015. Industrial symbiosis opportunities for small and medium sized enterprises: preliminary study in the Besaya region (Cantabria, Northern Spain). J. Clean. Prod. 87, 357–374. https://doi.org/10.1016/j.jclepro.2014.10.046.
Saghafi, Z., Roshandel, R., 2024. Agent-based simulation for technology implementation in an energy-based industrial symbiosis network. Res. Conserv. Recycl. Adv. 21, 200201. https://doi.org/10.1016/j.rcradv.2023.200201.
Sandalow, D., Meidan, M., Andrews-Speed, P., Hove, A., Qiu, S., Downie, E., 2022. Guide to Chinese climate change policy 2022. Available at: https://chineseclimatepolicy.oxfordenergy.org/access. (Accessed 31 January 2025).
Saysel, A.K., Barlas, Y., Yenigün, O., 2002. Environmental sustainability in an agricultural development project: a system dynamics approach. J. Environ. Manag. 64, 247–260. https://doi.org/10.1006/JEMA.2001.0488.
Schlüter, L., Mortensen, L., Drustrup, R., Gjerding, A.N., Kørnøv, L., Lyhne, I., 2022. Uncovering the role of the industrial symbiosis facilitator in literature and practice in Nordic countries: an action-skill framework. J. Clean. Prod. 379, 134652. https://doi.org/10.1016/j.jclepro.2022.134652.
Sendra, C., Gabarrell, X., Vicent, T., 2007. Material flow analysis adapted to an industrial area. J. Clean. Prod. 15, 1706–1715.
Shah, I.H., Dong, L., Park, H.-S., 2020. Tracking urban sustainability transition: an eco-efficiency analysis on eco-industrial development in Ulsan, Korea. J. Clean. Prod. 262, 121286. https://doi.org/10.1016/j.jclepro.2020.121286.
Shi, L., 2019. Industrial symbiosis: context and relevance to the sustainable development goals (SDGs). In: Leal Filho, W., Azul, A.M., Brandli, L., Özuyar, P.G., Wall, T. (Eds.), Responsible Consumption and Production. Springer International Publishing, Cham, pp. 1–12. https://doi.org/10.1007/978-3-319-71062-4_19-2.
Södergren, K., Palm, J., 2021. The role of local governments in overcoming barriers to industrial symbiosis. Cleaner Environ. Sys. 2, 100014. https://doi.org/10.1016/j.cesys.2021.100014.
Sommer, K.H., 2020. Study and Portfolio Review of the Projects on Industrial Symbiosis in DG Research and Innovation: Findings and Recommendations. European Commission, Luxembourg.
Song, B., Yeo, Z., Kohls, P., Herrmann, C., 2017. Industrial symbiosis: exploring big-data approach for waste stream discovery. Proced. CIRP 61, 353–358. https://doi.org/10.1016/j.procir.2016.11.245.
Song, X., Geng, Y., Dong, H., Chen, W., 2018. Social network analysis on industrial symbiosis: a case of Gujiao eco-industrial park. J. Clean. Prod. 193, 414–423.
Sterman, J.D., 2001. System dynamics modeling: tools for learning in a complex world. Calif. Manag. Rev. 43 (4), 8–25. https://doi.org/10.2307/41166098.
Su, S., Li, X., Zhu, Y., Lin, B., 2017. Dynamic LCA framework for environmental impact assessment of buildings. Energy Build. 149, 310–320.
Svendsen, N.L., Kaarsberg, S.C., Watson, D., 2019. Policies Supporting Industrial Symbiosis in the Baltic Sea Region. Baltic Industrial Symbiosis.
Taddeo, R., Simboli, A., Morgante, A., Erkman, S., 2017. The development of industrial symbiosis in existing contexts. Experiences from three Italian clusters. Ecol. Econ. 139, 55–67. https://doi.org/10.1016/j.ecolecon.2017.04.006.
Tan, R.R., Andiappan, V., Wan, Y.K., Ng, R.T., Ng, D.K., 2016. An optimization-based cooperative game approach for systematic allocation of costs and benefits in interplant process integration. Chem. Eng. Res. Des. 106, 43–58.
Teng, Y., Mao, C., Liu, G., Wang, X., 2017. Analysis of stakeholder relationships in the industry chain of industrialized building in China. J. Clean. Prod. 152, 387–398.
Tseng, M.-L., Tan, R.R., Chiu, A.S.F., Chien, C.-F., Kuo, T.C., 2018. Circular economy meets industry 4.0: can big data drive industrial symbiosis? Resour. Conserv. Recycl. 131, 146–147. https://doi.org/10.1016/j.resconrec.2017.12.028.
Uusikartano, J., Saha, P., Aarikka-Stenroos, L., 2022. The industrial symbiosis process as an interplay of public and private agency: comparing two cases. J. Clean. Prod. 344, 130996. https://doi.org/10.1016/j.jclepro.2022.130996.
Vahidzadeh, R., Bertanza, G., Sbaffoni, S., Vaccari, M., 2021. Regional industrial symbiosis: a review based on social network analysis. J. Clean. Prod. 280, 124054. https://doi.org/10.1016/J.JCLEPRO.2020.124054.
Valentine, S.V., 2016. Kalundborg symbiosis: fostering progressive innovation in environmental networks. J. Clean. Prod. 118, 65–77. https://doi.org/10.1016/j.jclepro.2016.01.061.
Valenzuela-Venegas, G., Henríquez-Henríquez, F., Boix, M., Montastruc, L., Arenas-Araya, F., Miranda-Pérez, J., Díaz-Alvarado, F.A., 2018. A resilience indicator for Eco-industrial Parks. J. Clean. Prod. 174, 807–820. https://doi.org/10.1016/j.jclepro.2017.11.025.
Valero, A., Torrubia, J., Anía, M.Á., Torres, A., 2021. Assessing urban metabolism through MSW carbon footprint and conceptualizing municipal-industrial symbiosis—the case of Zaragoza city, Spain. Sustainability 13, 12724. https://doi.org/10.3390/su132212724.
Van Berkel, R., Fujita, T., Hashimoto, S., Fujii, M., 2009. Quantitative assessment of urban and industrial symbiosis in Kawasaki, Japan. Environ. Sci. Technol. 43, 1271–1281.
Velenturf, A.P.M., 2016. Analysing the governance system for the promotion of industrial symbiosis in the Humber region, UK. People, Place and Policy 10 (2), 146–173. https://doi.org/10.3351/ppp.0010.0002.0003.
Velter, M., Bitzer, V., Bocken, N., Kemp, R., 2020. Sustainable business model innovation: the role of boundary work for multi-stakeholder alignment. J. Clean. Prod. 247, 119497. https://doi.org/10.1016/j.jclepro.2019.119497.
Vlachos, D., Georgiadis, P., Iakovou, E., 2007. A system dynamics model for dynamic capacity planning of remanufacturing in closed-loop supply chains. Comput. Oper. Res. 34, 367–394. https://doi.org/10.1016/J.COR.2005.03.005.

Wadström, C., Johansson, M., Wallén, M., 2021. A framework for studying outcomes in industrial symbiosis. Renew. Sustain. Energy Rev. 151, 111526. https://doi.org/10.1016/j.rser.2021.111526.

Walls, J.L., Paquin, R.L., 2015. Organizational perspectives of industrial symbiosis: a review and synthesis. Organ. Environ. 28 (1), 32–53. https://doi.org/10.1177/1086026615575333.

Williams, P., 2002. The competent boundary spanner. Public Adm. 80, 103–124.

Xavier, L.H., Ottoni, M., Abreu, L.P.P., 2023. A comprehensive review of urban mining and the value recovery from e-waste materials. Resour. Conserv. Recycl. 190, 106840. https://doi.org/10.1016/j.resconrec.2022.106840.

Xie, J., Xia, Z., Tian, X., Liu, Y., 2023. Nexus and synergy between the low-carbon economy and circular economy: a systematic and critical review. Environ. Impact Assess. Rev. 100, 107077. https://doi.org/10.1016/j.eiar.2023.107077.

Yang, Y., Guan, J., Nwaogu, J.M., Chan, A.P.C., Chi, H., Luk, C.W.H., 2022. Attaining higher levels of circularity in construction: scientometric review and cross-industry exploration. J. Clean. Prod. 375, 133934. https://doi.org/10.1016/j.jclepro.2022.133934.

Yari Borbon-Galvez, Y., Curi, S., Dallari, F., Ghiringhelli, G., 2021. International industrial symbiosis: Cross-border management of aggregates and construction and demolition waste between Italy and Switzerland. Sustain. Prod. Consum. 25, 312–324. https://doi.org/10.1016/j.spc.2020.09.004.

Yazan, D.M., Fraccascia, L., 2020. Sustainable operations of industrial symbiosis: an enterprise input-output model integrated by agent-based simulation. Int. J. Prod. Res. 58, 392–414.

Yazıcı, A.F., Olcay, A.B., Arkalı Olcay, G., 2023. A framework for maintaining sustainable energy use in Bitcoin mining through switching efficient mining hardware. Technol. Forecast. Soc. Change 190, 122406. https://doi.org/10.1016/j.techfore.2023.122406.

Yeo, Z., Masi, D., Low, J.S.C., Ng, Y.T., Tan, P.S., Barnes, S., 2019. Tools for promoting industrial symbiosis: a systematic review. J. Ind. Ecol. 23 (5), 1087–1108. https://doi.org/10.1111/jiec.12846.

Yong, W.N., Liew, P.Y., Woon, K.S., Wan Alwi, S.R., Klemeš, J.J., 2021. A pinch-based multi-energy targeting framework for combined chilling heating power microgrid of urban-industrial symbiosis. Renew. Sustain. Energy Rev. 150, 111482. https://doi.org/10.1016/j.rser.2021.111482.

Yu, H., Da, L., Li, Y., Chen, Y., Geng, Q., Jia, Z., Zhang, Y., Li, J., Gao, C., 2023. Industrial symbiosis promoting material exchanges in Ulan Buh Demonstration Eco-industrial park: a multi-objective MILP model. J. Clean. Prod. 414, 137578. https://doi.org/10.1016/j.jclepro.2023.137578.

Zhang, A., Duong, L., Seuring, S., Hartley, J.L., 2023. Circular supply chain management: a bibliometric analysis-based literature review. Int. J. Logist. Manag. 34 (3), 847–872. https://doi.org/10.1108/IJLM-04-2022-0199.

Zhang, A., Wang, J.X., Farooque, M., Wang, Y., Choi, T.M., 2021. Multi-dimensional circular supply chain management: a comparative review of the state-of-the-art practices and research. Transport. Res. E Logist. Transport. Rev. 155, 102509. https://doi.org/10.1016/j.tre.2021.102509.

Zhang, Q., Xiang, T., Zhang, W., Wang, H., An, J., Li, X., Xue, B., 2022. Co-benefits analysis of industrial symbiosis in China's key industries: case of steel, cement, and power industries. J. Ind. Ecol. 26, 1714–1727. https://doi.org/10.1111/jiec.13320.

Zhang, S., Shen, Y., Zheng, C., Xu, Q., Sun, Y., Huang, M., Li, L., Yang, X., Zhou, H., Ma, H., Li, Z., Zhang, Y., Liu, W., Gao, X., 2024. Recent advances, challenges, and perspectives on carbon capture. Front. Environ. Sci. Eng. 18, 75. https://doi.org/10.1007/s11783-024-1835-0.

Zhang, Y., Duan, S., Li, J., Shao, S., Wang, W., Zhang, S., 2017. Life cycle assessment of industrial symbiosis in Songmudao chemical industrial park, Dalian, China. J. Clean. Prod. 158, 192–199. https://doi.org/10.1016/j.jclepro.2017.04.119.

Zhang, Y., Zheng, H., Chen, B., Su, M., Liu, G., 2015. A review of industrial symbiosis research: theory and methodology. Front. Earth Sci. 9, 91–104.

Zhao, K., Kai, Z., 2021. Industrial symbiosis: practices in China's industrial parks. Field Actions Sci. Rep. 23, 54–59.