LIAISE | Cooperation, development and cross-border transfer of industrial symbiosis

D1.4 Identification of technical and non-technical barriers related to the implementation of Industrial Symbiosis

Author: LIAISE WG1 & WG2
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Editors
Pawel Krzeminski, Ph.D., Norwegian Institute for Water Research (NIVA), Oslo, Norway
Aleksandar Erceg, Ph.D., Josip Juraj Strossmayer University of Osijek, Faculty of Economics and Business in Osijek, Croatia
Aleksandar Anastasovski, Ph.D., International Balkan University, Skopje, North Macedonia
Hasan Volkan Oral, Ph.D., Istanbul Aydin University, Istanbul, Türkiye
Istemi Berk, Ph.D., Dokuz Eylul University, Izmir, Türkiye
Azemina Mašović, Ph.D., American University of Europe-FON, Skopje, North Macedonia

Contributors
Chapter 1 - Karol Izdinsky, Pawel Krzeminski, Aleksandar Erceg, Biljana Činčurak Erceg
Chapter 2 - Pawel Krzeminski, Aleksandar Erceg, Aleksandar Anastasovski, Hasan Volkan Oral, Istemi Berk, Azemina Mašović
Chapter 3 - Azemina Mašović, Istemi Berk, Hasan Volkan Oral
Chapter 4 - Pawel Krzeminski, Aleksandar Erceg, Aleksandar Anastasovski, BIljana Činčurak Erceg, Jovanka Damoska Sekuloska, Carlos Dosoretz, Tine Lehmann, Estelle Giacomi, Paul Refalo, Massimo Borg, Branko Dunjić, Vladan Pavlović, Angela Neves, Hugo Ferreira, Radu Godina, Vicky Skoulou, Aida Szilagyi
Chapter 5 - Hasan Volkan Oral, Istemi Berk, Azemina Mašović, Biljana Činčurak Erceg, Merim Kasumović, Lára Jóhannsdóttir, Mine Güngörmüşler, Brynhildur Davíðsdóttir, Gulesin Sena Das, Emel Yontar, Ayham Jaaron, Olivija Filipovska, Ebru Kasnak, Katarina Vitálišová, Angela Neves, Hugo Ferreira, Radu Godina
Chapter 6 - Aleksandar Erceg, Pawel Krzeminski, Aleksandar Anastasovski, Istemi Berk
Chapter 7 - Apostolos Michopoulos, Andreas Kyriakidis
Chapter 8 - Aleksandar Erceg, Pawel Krzeminski, Aleksandar Anastasovski, Istemi Berk
Chapter 9 - Aleksandar Erceg, Pawel Krzeminski, Aleksandar Anastasovski, Aida Szilagyi,
Chapter 10 - Aleksandar Erceg, Pawel Krzeminski, Aleksandar Anastasovski, Istemi Berk

This report is part of LIAISE COST Action. Concretely, it is D1.4. Identification of technical and non-technical barriers related to the implementation of Industrial Symbiosis. LIAISE COST Action (CA22110) is a project funded by the COST Action Programme in 2023, whose objective is to ensure an inclusive and holistic Industrial Symbiosis approach by generating relevant synergies among different actors from the q-helix stakeholder model and by setting the groundwork for increased and robust development of knowledge, apart from promoting future results-oriented R&D.

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Table of abbreviations

BSR	Baltic Sea Region
CE	Circular Economy
CEN	European Committee for standarsation
DG	Directorates- General
HEN	Heat Exchanger Network
HSE	Health, safety and environmental
IE	Industrial Ecology
IS	Industrial Symbiosis
MRF	Material recovery facilities
ORC	Organic Rankine Cycle
SRL	Symbiosis Readiness Level
TSHI	Total Site Heat Integration
WGs	Working Groups
WWTP	Wastewater treatment plan

Project Action Context

In the context of addressing climate change, industrial sectors play a significant role as major contributors to carbon dioxide emissions, energy consumption, and waste generation. To combat these challenges, adopting a Circular Economy strategy is imperative. The Circular Economy model diverges from the traditional linear approach by promoting sustainable production and consumption practices while considering societal, environmental, and economic factors in a balanced manner.

Industrial Symbiosis (IS) emerges as a practical solution within this framework. In IS, waste or by-products generated by one industry are repurposed as resources for another, presenting opportunities for environmental sustainability and economic efficiency. Despite its potential, many companies and industrial actors lack awareness of IS, and its development is hindered by various barriers, including environmental, economic, technical, regulatory, organizational, social, and cultural challenges.

To address these issues, the LIAISE COST Action seeks to foster an inclusive and holistic IS approach. By fostering synergies among stakeholders from diverse sectors and laying the groundwork for knowledge enhancement, LIAISE COST Action aims to bridge the gap between theory and practice. This initiative will involve developing a participatory approach to support cross-sector collaborations and establishing Key Performance Indicators (KPIs) for assessing the effectiveness of IS business models in industry.

The LIAISE COST Action represents a collective effort to make the Industrial Symbiosis a reality across Europe, fostering collaboration among researchers, practitioners, and policymakers. To achieve these objectives, LIAISE COST Action will leverage the expertise of four interdisciplinary Working Groups (WGs) and integrate their findings through a reference framework. This holistic approach aims to drive meaningful progress towards sustainable industrial practices and contribute to a more Circular Economy.

1. Introduction

This report focuses on Industrial Symbiosis (IS) and discusses technical and non-technical barriers to its implementation. It aims to identify and evaluate barriers and possible strategies for overcoming them.

1.1. What is Industrial Symbiosis

Industrial Ecology (IE) is commonly referred to as the study of material and energy flows through industrial systems. Some definitions also consider these flows' effects on the environment and economic, political, regulatory, and social influences on resource flow, use, and transformation. The principle of closing material loops drives industrial ecology by avoiding pollution (Fet & Deshpande, 2023). From the IE perspective, natural systems should be used as inspiration to design sustainable industrial systems. This is because industry, as a human-made ecosystem, is similar to natural ecosystems, where the waste or by-product of one process can become input into another process (Nilsson, 2016). IE is principally concerned with the flow of materials and energy through systems at different scales, from products to factories and up to national and global levels. Industrial Ecology encompasses both Circular Economy (CE) and Industrial Symbiosis (IS), which, although closely related, are not interchangeable terms.

A Circular Economy (CE) is a production and consumption system where most of the products and the resources used in production processes can be used and recycled. It minimizes waste, maximizes resource efficiency, and promotes long-lasting product design. Instead of the traditional linear model of the economy (make, use, dispose), the CE encourages continuous use, repair, and recycling of materials when the latest act is viable. The CE seeks to restore our ecosystem and reduce the consumption rate of our natural resources. CE strategies can be applied at various scales, from individual products and services to entire industries and cities. As a result, CE involves creating products and systems that minimize waste generation and their environmental impact. CE encompasses various materials and products, including consumer goods, electronics, textiles, and more (Elen MacArthur Foundation, 2019). CE encourages the continuous use, repair, and recycling of materials so that, if possible, any waste can be transformed into new feedstock. Five CE models can support the transition to a more resource-efficient society, and, as a result, the CE is 1) circular supply, 2) resource recovery, 3) product life extension, 4) sharing, and 5) product service system models.

On the other hand, Industrial Symbiosis (IS) is a subset of Industrial Ecology (IE). It involves using waste or by-products from one actor as resources for another actor, aiming to achieve environmental and economic benefits. In other words, IS is the association between industrial facilities or companies in which the waste or by-products of one become raw materials for another. IS can be described as a collaboration between several different, often geographically proximate entities, i.e., companies and factories closely co-located in clusters or industrial parks exchanging resources (e.g., materials, energy, water and by-products) that can well be used as substitutes for the much needed, and often scarce and expensive, raw materials or products, which would otherwise be imported from elsewhere or treated as waste. Therefore, Industrial Symbiosis is pivotal in terms of resource reuse and prevention of waste, driven by collaborative opportunities and synergies facilitated by geographic proximity (Chertow, 2000). IS enables the waste from one company's or secondary materials to become valuable resources for another, very often without any preparation and pretreatment, resulting in mutual financial benefits (savings) and, as a result, reduced dependence on fresh raw materials and then unpopular landfill disposal. Therefore, an Industrial Symbiosis (IS) should:

- Involve actors, entities, and organizations that consider symbiosis a business opportunity.
- Highlight the beneficial economic aspects that empowerment entails.
- It should be considered a business strategy that encourages the creation of synergies between companies.
- Frame the concept in a systemic vision of the industry to achieve a better result than that achieved by entities/organizations/activities operating individually.
- Introduce the concept of underused (residual) resources.
- Improve efficiency in the use of natural resources.
- Reduce the costs of raw materials, goods, services and waste treatment.
- Allow resources to be kept in the economic cycle for longer, reducing the exploitation of raw materials.
- Improve competitiveness.

1.2. Industrial Symbiosis definition

Traditionally, the most frequently used definition of Industrial Symbiosis (IS) is the one used by Chertow (2000): "*The part of industrial ecology known as Industrial Symbiosis engages traditionally separate entities in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and by-products. The keys to Industrial Symbiosis are collaboration and the synergistic possibilities [often] offered by geographic proximity*". Lombardi and Laybourn (2012) presented a renewed definition of Industrial Symbiosis, which the Journal of Industrial Ecology accepted. This definition was summarized by Domenech et al. (2019) as follows: "*Industrial Symbiosis (IS) is a systems approach to a more sustainable and integrated industrial system, which identifies business opportunities that leverage underutilized resources (such as materials, energy, water, capacity, expertise, assets etc.)*." Explaining this definition further, Domenech et al. (2019) state that *"Industrial Symbiosis involves organizations operating in different sectors of activity that engage in mutually beneficial transactions to reuse waste and by-products, finding innovative ways to source inputs and optimize the value of the residues of their processes, for instance by using waste or by-products from one activity as an input for another activity."*

However, different EU research and innovation projects and EU policy departments, known as Directorates-General (DGs), define IS differently. Only recently, in 2018, the European Committee for Standardisation (CEN) (2018) initiated the process to address the need to define Industrial Symbiosis. During the 2018 workshop, an agreement on Industrial Symbiosis was reached, defining Industrial Symbiosis as *the use by one company or sector of underutilized resources broadly defined (including wastes, by-products, residues, energy, water, logistics, capacity, expertise, equipment and materials) from another, with the result of keeping resources in productive use for longer*. However, this process is still ongoing, and CEN plans a series of consultations and standardization dialogues to shape the roadmap for Industrial Symbiosis standardization in 2025.

1.3. Report objectives

Due to technical and non-technical barriers, the implementation of IS practices around the globe is lagging and still needs to be expanded. Over the last two decades, extensive literature on identifying these barriers has emerged since the seminal paper of Chertow (2000). This report aims to provide an overview of the identified barriers to the implementation of IS, assess their impact on the implementation of IS, identify potential solutions to overcome the barriers and propose recommendations to the IS practitioners.

1.4. Barriers - what are they?

Golev et al. (2014: 142) note that despite the comprehensive citation of IS barriers, "*there is still a lack of real cases describing the process of investigation and overcoming these barriers, and no methodology has been reported for analysis of the barriers in a consistent manner.*"

Although there are different definitions and authors' opinions of what is considered a particular barrier, the most common and critical types of barriers, described according to the literature review, are:

- Technological barriers are related to technological changes or adaptations that must be made in the IS-related industries. Some industries must undergo transitional stages and adaptations. They also include a need for more technical expertise and infrastructure and a lack of utilizing advanced equipment and machinery (Herath et al., 2023). Waste quality issues are also considered technological barriers.
- Geographic proximity is also essential because it can impede product exchange due to the unavailability of low-cost transport systems (Rahman et al., 2016).
- Economic barriers are related to different costs (adaptation, logistical, transaction, initiation, transport costs) and insufficient financial resources (Herath et al., 2023).
- Informational barriers include a lack of information about other companies' by-products and waste flow (Rahman et al., 2016), technical and training information, operational information management, information-sharing mechanisms, and job roles and responsibilities (Herath et al., 2023). They also mention poor awareness of the IS concept and a lack of information on synergistic possibilities.
- Organizational barriers, or as Rahman et al. (2016) call them, "Absence of trust among organizations" include competition among similar industries, lack of environmental concerns and management support, resistance to change, lack of collaboration due to isolation, lack of institutional support, trust, power, status, time and spatial facilities, lack of knowledge on IS concept, lack of employee engagement on new processes and conflicting participant (Rahman et al., 2016; Herath et al. 2023).

Herath et al. (2023) mention risk barriers as a risk and uncertainty of investments, system performance, outcomes, risk of interdependence, and risk of changes in demand and supply by participants.

Regulatory barriers are related to conflicting regulations, restrictive regulations for establishment and operation, lack of regulatory incentives, and complex approval processes (Herath et al., 2023). Professional and scientific literature and various reports highlight the problem of regulatory barriers as one of the most important. Regulatory barriers are related to restrictive or unclear legislation and a lack of guidance on compliance criteria (Södergren & Palm, 2021), uncertainties in environmental legislation, difficulties in obtaining approvals for waste reuse projects from the regulatory authorities (Golev et al., 2015), conflicting regulations, restrictive regulations for establishment and operation, lack of regulatory incentives, complex approval processes (Herath et al. 2023). It should be emphasized that the literature often mentions that "Laws and regulation can be both good and bad for uncovering industrial symbiosis" (Rahman et al., 2016:17) and that "compulsory legal requirements to recycle specific materials, higher taxes for waste disposal, and so on, are the drivers for synergy projects" (Golev et al., 2014: 142).

1.5. Scope and limitations

The literature has identified a wide range of technical and non-technical barriers. However, the barriers to IS implementation may diversify significantly across countries, regions, industries, and individual cases.

In this report, we draw these out—it is, however, valuable to recall the coin analogy. Factors given as enablers might operate as barriers depending on the context and how they are managed. Therefore, although we have identified the barriers to date, there will be other barriers the reader may identify by reflecting upon the enablers.

2. Methodology

The research methods used in this study included literature review, surveys, in-person workshops, and assessment of case studies.

The barriers considered in this report include financial, technical/technological, social, economic, regulatory, policy, management, informational and geographical barriers, but also, among others, absence of trust among organizations (organizational barrier), emotional barriers, risk and uncertainty and cultural barriers, commitment to sustainable development, cooperation barriers, community awareness barriers (Domenech Aparisi 2010; Golev et al. 2014; Rahman et al. 2016; Järvenpää et al. 2018). "Hard one relates to technical or economic issues, and soft ones relate to institutional and regulatory or social and cultural factors" (Järvenpää et al., 2018:78).

The IS barriers were divided into the following: 1) technical barriers (challenging barriers) and 2) non-technical barriers (soft barriers), according to (Golev et al., 2014; Järvenpää et al., 2018:78).

This work has been carried out as part of the LIASE COST Action CA22110 - Cooperation, development and cross-border transfer of Industrial Symbiosis among industry and stakeholders. With 257 members from 39 countries, LIAISE COST Action aims to create synergies between stakeholders to promote IS implementation by identifying barriers relevant to various countries, sectors and stakeholders and designing guidelines to mitigate these barriers. To this end, WG1 (Industrial Symbiosis Technical Synergies) and WG2 (Industrial Symbiosis Business Model) jointly identified the barriers emphasized in the literature and surveyed LIAISE members to assess and rank the most prevalent barriers to implementing industrial symbiosis in different countries. The broad categorization of barriers to the implementation of industrial symbiosis refers to technical obstacles - such as lack of technical experience and knowledge within the company, low levels of technological readiness for industrial symbiosis solutions or inadequate infrastructure, and non-technical barriers - which can include a lack of financial motivation, incentives and financing opportunities, lack of awareness/knowledge about the implementation of industrial symbiosis or inadequate regulatory framework to support the implementation of industrial symbiosis.

The survey was designed with closed and open-ended questions to capture professionals' perceptions from various professional backgrounds and countries and identify the key technical and non-technical barriers to implementing industrial symbiosis in their countries. The closed questions were designed to obtain a specific ranking of the most relevant technical and non-technical barriers to implementing industrial symbiosis in the respondents' countries, asking them to rank the technical and non-technical barriers separately on a scale from 1 (least relevant) to 10 (most relevant). On the other hand, the open-ended questions allowed respondents to identify barriers that they considered appropriate to implementing industrial symbiosis in their countries. Still, these were not listed as an option in the survey. It was conducted between July and September 2024, using the Google Forms platform, enabling effective collection and subsequent data analysis.

To ensure clarity of the questions and the process of completing the survey, the survey included a pilot and a primary survey dissemination. The pilot survey was conducted at the fifth virtual meeting of the WG2, which took place in July 2024 via the ZOOM platform. The content of the survey and the procedure for its correct completion were clearly explained at the meeting. After a successful pilot survey, the central survey dissemination was performed. The primary dissemination of the survey was carried out by sending the link via email to all COST Action 22110 LIAISE members, along with a guide with detailed instructions on completing the survey correctly.

As a final part of the preparation of this report, a survey was conducted to evaluate the barriers that influence different IS implementation phases. Both surveys (see Annex 1 and Annex 2) had one question in which participants evaluated the influence of the identified technical and non-technical barriers. The survey was sent to the COST LIAISE action WG1 and WG2 members - 212 members. The survey was conducted from March 8 until April 1, 2025. Forty-six participants answered questions about technical barriers, making a response rate of 21.2%, and 29 answered questions about non-technical barriers, making a response rate of 12.7%.

3. Survey on barriers of WG1 and WG2

Fifty-three respondents from 28 countries across Europe, South America, Africa and beyond participated. Of the 257 COST Action LIAISE members, 53 participants completed the survey, resulting in a response rate of 20.6%. Regarding the country of origin of the respondents, Türkiye and Spain have been represented most by respectively constituting 17% and 13.2% of all respondents, followed by Estonia, North Macedonia and Portugal, each having 5.7%, and Albania, Austria, Croatia, Italy, and the United Kingdom, each having 3,8% share. The remaining respondents are evenly distributed to the other countries (Argentina, Belgium, Czechia, Ethiopia, Finland, Greece, Kenya, Latvia, Lithuania, Luxembourg, Malta, Montenegro, Netherlands, Norway, Poland, Romania, Serbia, Slovakia, and Slovenia), each having 1,9%. Moreover, it is observed that 83% of all respondents have an occupation in Academia/Research, while Industry, NGOs and public entities are minorly represented by 4%, 2% and 2%, respectively. The remaining 9% of respondents reported occupations in other entities such as consultancy, chamber of commerce or cluster organizations.

After collecting the survey data, a descriptive analysis was performed on the closed-ended questions to identify the most significant technical and non-technical barriers to properly implementing industrial symbiosis in different countries based on the respondents' opinions and experiences. The analysis revealed that the companies' lack of technical expertise and knowledge is the most significant technical barrier. In contrast, lack of financial motivation, incentives and funding opportunities is identified as the highest-ranked non-technical barrier by receiving the highest score in the survey, i.e., an average of 5.7 and 6.9, respectively, out of 10. The ranking of other barriers in both categories is listed, with average points provided in parentheses.

Ranking of Technical Barriers:

1. Lack of technical expertise and knowledge within the company (5.7)
2. Lack of technological compatibility between different systems and difficulties in process integration / inadequate infrastructure (5.4)
3. Low level of technology readiness for industrial symbiosis solutions/Lack of technical solutions for a given problem/Low recovery efficiency (5.3)
4. Lack of information/data on resource mapping/available resources and synergies for potential symbiosis (4.9)
5. Lack of tools for supporting waste-to-resource matchmaking to identify IS opportunities (4.5)
6. Low quality and quantity of required resources/materials (4.1)
7. Environmental challenges (e.g., waste management) (3.5)
8. Occupational health and safety-related challenges (2.5)

Ranking of Non-Technical Barriers:

1. Lack of financial motivation, incentives and funding opportunities (6.9)
2. Investment barriers related to high initial costs and risks (6.7)

3. Lack of awareness/knowledge on IS implementation (6.6)
4. Lack of/Inadequate regulatory framework to support industrial symbiosis implementation (6.2)
5. Organizational barriers: resistance of management towards change, lack of inter-organizational communication, lack of internal capacity (e.g., labor capacity, time constraints) (6.0)
6. Lack of awareness of the economic and environmental benefits of industrial symbiosis (5.8)
7. Bureaucratic hurdles (5.2)
8. Lack of knowledge sharing and trust in collaboration due to competition, confidentiality and intellectual property concerns (5.1)
9. Geographical constraints (e.g., location proximity) and supply-chain issues (e.g., lack of a business model for cost-effective transportation) (3.4)
10. Lack of knowledge sharing and trust in collaboration due to cultural factors (society/country) (3.2)

The geographical distribution of the barriers with the highest ranking is as follows. When technical barriers are concerned, "Lack of technical expertise and knowledge within the company" ranked highest in Finland, Turkiye, Malta, United Kingdom, Czech Republic, Spain, "Lack of information/data on resource mapping/available resources and synergies for potential symbiosis" ranked highest in Ghana, Portugal, Argentina, Kenya, Albania, Austria and "Low level of technology readiness for industrial symbiosis solutions/Lack of technical solutions for a given problem/Low recovery efficiency" in Serbia, Italy, Latvia, North Macedonia, Croatia. Moreover, within the non-technical barriers, "Investment barriers related to high initial costs and risks" ranked highest in Türkiye, Ghana, Belgium, Serbia, and Estonia, "Lack of financial motivation, incentives and funding opportunities" in Italy, UK, Czech Republic, Portugal, and "Lack of/Inadequate regulatory framework to support IS implementation" in Spain, North Macedonia, Albania, Slovenia.

The following parts of this report will deal with the technical and non-technical barriers based on the survey results and the ranking of barriers.

4. Technical barriers and strategies for their overcoming

4.1. Infrastructure and Technology

IS requires specific infrastructure to facilitate the exchange of resources, such as energy, materials, and inventory, between two or more production systems. The implementation of IS involves both physical and digital infrastructure components. IS requires specific physical infrastructure to enable companies to exchange resources and by-products. This infrastructure plays a crucial role in facilitating the successful implementation of IS initiatives. The infrastructure can be between two companies or three or more companies. The providing company would realize the required infrastructure, so digital infrastructure is based on information systems and servers to share information standards for all interested parties and monitor the whole exchange process.

The primary physical infrastructure for IS includes pipelines, equipment, transportation networks, and shared resource exchange and processing facilities. Technical barriers include IS synergies, like utility, supply chain, service, and gaseous synergies (Biswas & John, 2022).

The physical infrastructure required for IS to exchange energy sources includes energy recovery systems like cogeneration systems, ORC, distribution networks such as hot or cold utility pipeline networks, heat storage systems, heat exchanger networks, internal electricity grids (for industrial parks), different types of batteries, systems for hydrogen production and storage, and potentially digital systems for management and optimization. However, it is important to note that the lack of technology and infrastructure readiness is often cited as a significant barrier to implementing IS, particularly in emerging economies (Hossain et al., 2024). Therefore, careful planning and investment in appropriate infrastructure are crucial for successful energy-based IS.

In material exchange systems, many different equipment may be required as infrastructure for the creation and functioning of IS. There is a need for transportation equipment (different for solid, liquid and gaseous materials), reservoirs for materials with various characteristics, wastewater treatment systems with all standard construction and, in some cases, additional specific types of equipment, and different separation systems for waste or by-product modification (adsorption, distillation, sieves, extraction, etc.).

Inventory exchange infrastructure contains supply chain and service synergies related to the normal functioning of IS. This is shown in the study of IS design in the Humber region in Northeast England (Bailey & Gadd, 2016). That study highlighted the importance of significant capital investment in infrastructure projects to support IS initiatives. The most critical infrastructure that must be done by the local government and local community is building roads (or/and railways), access points for the industrial park between all companies for secure collaboration, and parking places for cars, trucks and buses if they are used as standard service systems, fuel stations, charging stations.

The digital infrastructure necessary for IS should depend on the implementation stage. It could start with simple database repositories and specific platforms matchmaking tools to blockchain technology, digital twins, and sophisticated analytical tools to maximize resource exchange, foster collaboration, and boost efficiency. Addressing technological and infrastructural readiness is vital for implementing IS, particularly in developing economies. Consequently, establishing effective IS requires a blend of physical and digital infrastructure, supported by collaborative endeavors and strategic planning to tackle potential challenges and maximize benefits.

However, the specific infrastructure needs may vary depending on the local context and the types of industries involved in the symbiotic relationships. Overcoming infrastructure-related barriers is crucial for the successful implementation of IS initiatives.

4.1.1. Lack of technical knowledge and/or expertise

Despite its potential to enhance sustainability and economic efficiency, the operation of IS remains a complex and dynamic process requiring continual improvement. Among the numerous challenges faced in designing IS schemes, the lack of technical knowledge and expertise makes a significant barrier that slows IS practices' successful adoption and scaling. Implementing IS demands a comprehensive understanding of the complex relationships among industries, resource flows, and technological processes. Many stakeholders experience difficulties in grasping fundamental concepts of IS, such as resource capture, storage and exchange networks, process optimization, and lifecycle management. The success of IS projects is heavily contingent upon the technical and economic feasibility of proposed synergies. Insufficient technical knowledge within industries can obstruct the identification and implementation of viable solutions (Neves et al., 2019). This lack of awareness limits stakeholders' ability to identify potential opportunities and results in misaligned expectations, as IS is often perceived as abstract rather than a practical and profitable strategy. Sakr et al. (2011) noted that "the lack of local technical know-how capable of identifying and evaluating IS opportunities" represents a critical issue. Consequently, a deep understanding of the IS concept and the capability to recognize opportunities for implementation are prerequisites for initiating the process. A crucial element of IS is the analysis of by-products and waste streams to uncover viable synergies (Mangan et al., 2010). This necessitates specialized knowledge of material properties, resource efficiency and Circular Economy strategies, recycling technologies, and industrial processes. Unfortunately, many organizations lack access to this expertise, which hinders their capacity to repurpose resources effectively.

Furthermore, expertise in integrating processes across industries requires bespoke engineering solutions and a high level of technical proficiency to ensure compatibility and efficiency. Without such expertise, businesses may encounter significant challenges in customizing solutions to their unique operational needs. To facilitate the establishment of IS networks, it is imperative to gather knowledge regarding the potential participants and the quantities and types of waste or by-products available (Neves et al., 2019). Identifying consistent links—the matching score between two or more stakeholders using specific rules and algorithms—is essential for creating partnership opportunities and developing an IS model (Marconi et al., 2018).

Overcoming the barriers to understanding and knowledge regarding the relationships and integration of processes across industries necessitates a comprehensive approach rooted in cooperation and interaction. This includes forming networks for industry collaboration and establishing industrial symbiosis. An industrial symbiosis network comprises companies, public entities, and institutions collaborating to achieve shared objectives, often leveraging common resources or exchanging byproducts and surplus materials (Sellitto, 2025). This cooperative framework fosters innovation and sustainability across diverse industries by facilitating resource-sharing and expertise among various stakeholders. In addition, it is essential to create research centers dedicated to industrial symbiosis, staffed by experts from multiple fields. A critical aspect of overcoming knowledge barriers involves utilizing digital platforms and ICT tools, such as AI-powered systems that connect industries with compatible byproducts and resources. Additionally, simulation tools can be employed to visualize potential synergies between industries before implementation.

In terms of understanding the context for IS, it is vital to map local resource flows, assess firms' readiness, screen companies along with their inputs and outputs, analyze their value chains, and actively listen to their needs. Therefore, a significant technical barrier is the lack of knowledge regarding other companies that could receive or provide waste (Dong et al., 2016).

To address the existing knowledge gap regarding companies that could act as providers or receivers of waste in IS, it is vital to develop or utilize AI-driven platforms that analyze waste streams and facilitate matches between potential providers and receivers. A shared database would support companies engaged in waste management by offering comprehensive information about the types, quantities, pricing, and seasonality of available waste. Additionally, it could provide insights into essential support services, including transportation, distribution, and storage. Establishing centralized data repositories that detail industry-specific waste types and compatible resource flows can enhance business collaboration, minimize missed opportunities, and extend landfill lifetimes (Lawai et al., 2021). The primary takeaway is creating a centralized database that keeps partners continuously informed about waste offers, needs, and availability. Moreover, organizing sector-focused events will allow companies to explore potential collaboration opportunities. We can identify and capitalize on synergies by bringing together stakeholders from various industries. Furthermore, conducting tailored awareness programs for industries with high IS potential—such as manufacturing, agriculture, energy, and chemicals—will be highly beneficial.

Moreover, one of the technical issues related to engagement in IS, as articulated by Park et al. (2018), is knowledge capacity, which encompasses acquiring and effectively utilizing information about feasible symbiotic linkages. Although the availability of digital tools and platforms designed to facilitate IS is increasing, their adoption remains limited. Many businesses are unaware of these tools or find them too complex to use without the requisite skills. Identifying potential, in which a firm's needs, inputs, and outputs serve as a foundation for creating concepts and finding symbiotic partners. Tools for mapping resources, tracking waste streams, and modeling potential exchanges are frequently underutilized, and interpreting the data they generate necessitates advanced technical knowledge. This gap exacerbates the challenges associated with identifying and implementing IS opportunities.

Addressing knowledge capacity barriers in IS necessitates a comprehensive approach that focuses on acquiring, processing, and effectively utilizing information regarding potential symbiotic linkages. The significance of digital technologies is increasingly acknowledged, as digital platforms facilitate information sharing and minimize administrative costs associated with exchanges (Liu et al., 2023). By integrating digital tools, not only can the logistical aspects of material exchange be enhanced, but collaboration and trust among participants can also be fostered (Noori et al., 2023). It is essential to develop online platforms that combine case studies, policy guidelines, and best practices related to Industrial Symbiosis. Additionally, creating sector-specific databases that detail industrial by-products, potential symbiotic applications, and successful past initiatives will be beneficial. Establishing regional IS advisory teams can offer practical guidance on feasibility assessments and implementation efforts. Moreover, strengthening the connections between academia and industry will foster research and development focused on IS and support technology transfer. Finally, it is vital to encourage governments to integrate IS knowledge capacity-building into their environmental compliance training programs.

The lack of training programs focused on IS is recognized as a substantial technical barrier. In the absence of structured educational initiatives, organizations often find themselves lacking the resources needed to develop internal capabilities. Consequently, businesses frequently rely on external consultants, which elevates costs and restricts long-term sustainability. Additionally, the widespread absence of technical knowledge within organizations diminishes the likelihood of innovative solutions being proposed and implemented internally.

Developing industry specific IS courses to tackle the gap in training programs focused on feasible symbiotic linkages is crucial. Enhancing training, education, and competence validation will address insufficient expertise and raise awareness in this field. Collaborative training sessions among related companies are essential for fostering environments conducive to learning about symbiotic techniques and improving waste management practices (Daş et al., 2024). These educational initiatives help bridge the knowledge gap regarding appropriate technologies and opportunities for reuse. For example, "speed-dating" events between companies can encourage collaboration and the exchange of innovative ideas (Lybæk et al., 2021).

Furthermore, the engagement of universities and research and development institutions is vital, as they facilitate knowledge transfer, support industry initiatives, and strengthen local coordination. Collaborating with universities and technical schools to integrate IS-focused curricula into environmental engineering, business, and supply chain management programs is essential. Additionally, it is important to encourage policymakers to fund and mandate IS training programs for industries, creating national or regional hubs that provide training, workshops, and mentoring on IS.

4.1.2. Complexity of technical solutions

While increased interdependence within IS networks can contribute to the system's vulnerability, it does not necessarily enhance its resilience (Li & Shi, 2015). This contradiction highlights the complex nature of IS networks and the need for careful balance in their design. Technical issues related to IS can be solved using many developed methodologies and cutting-edge equipment. The main technical issues in IS are the system's flexibility, satisfying the required capacity (fluctuations), quality of supplies, chain-caused failures, and peak energy demand (especially for industries with batch processes).

The flexibility of IS systems is evident in their capacity to incorporate new participants, resources, and technologies over time. For instance, the Hai Hua Industrial Symbiosis case study demonstrates how different scenarios for energy consumption, solid waste utilization, and wastewater utilization can be modeled and analyzed to optimize the system's evolution (Cui et al., 2018). This adaptability allows IS networks to improve their resource efficiency and environmental performance continuously.

One approach to enhance system flexibility is using innovative modeling tools and ICT-based systems. Agent-Based System Dynamics hybrid approaches have been identified as appropriate methods for IS design and analysis (Demartini et al., 2021). These tools can help capture, investigate, and quantify the results of changes in the system, supporting strategic planning, design, implementation, and management of IS networks. ICT-web systems like SymbioSyS can facilitate networking among companies and businesses, promoting sustainable resource use through IS strategies (Álvarez & Ruiz-Puente, 2016).

The rapid growth in electricity network peak demand exerts pressure on existing infrastructure, potentially necessitating new investments that may be utilized for only a few hours annually (Smith et al., 2013). This issue is further intensified in IS networks, where enterprises are interdependent for energy exchanges. During periods of peak demand, the strain on the distribution system can result in capacity constraints and potential disruptions in symbiotic relationships.

Possible solutions for stabilizing the system during the energy peaks are increasing energy efficiency, using energy storage systems as additional energy suppliers, developing smart grids, demand side management, and integrating renewables directly into the production systems.

Fluctuations in the demand for end products produced by participating companies can disturb the IS network by changing the amount and accessibility of waste materials and by-products (Daş et al., 2023). These fluctuations can influence the steadiness of energy exchanges during peak times, which may result in shortages or surpluses that impact the network's overall efficiency. Systems face challenges related to fluctuations in exchange streams, which can impact their stability and effectiveness. To increase the resilience and adaptability of IS networks. Research suggests that increased interdependency can contribute to system vulnerability but does not necessarily improve resilience (Li & Shi, 2015). Managers and planners should focus on protecting significant components and controlling cascading failures within the network to enhance adaptability. This may involve identifying key companies, materials, and infrastructure pipes through centrality metrics and properly safeguarding these critical elements.

The quality of supplies in exchange streams is crucial for successful IS implementation. Implementing advanced treatment processes for byproduct extraction and valorization can enhance the quality of exchanged materials (Branca et al., 2021). This approach allows for better purification and refinement of waste streams, making them more suitable for other industrial processes. Water purification and energy transformation technologies can improve the quality of water and energy resources shared between industries (Branca et al., 2021). These technologies ensure that the exchanged resources meet the required standards for various industrial applications. Developing and sharing infrastructure for resource exchange and treatment can help maintain consistent quality in symbiotic relationships (Rosado & Kalmykova, 2019). This approach allows for centralized quality control and management of shared resources. Quality control can be automated by measuring and controlling instruments in cases where possible.

Most solutions in this issue use predictable methods, but forecasting is not always completely reliable. Implementing robust modeling and simulation approaches can help predict and mitigate potential chain-caused failures. Agent-Based System Dynamics hybrid approaches have been identified as appropriate methods for IS design and analysis (Demartini et al., 2021). These tools can capture, investigate, and quantify the results of changes in the IS network, supporting strategic planning and management. Developing a comprehensive understanding of the entire system, including upstream processes, is crucial. LCA studies have shown that upstream processes often make the most significant overall contribution to environmental impacts in IS systems (Sokka et al., 2010). Potential weak points in the chain can be identified and addressed by considering the entire life cycle. Emphasizing community, cooperation, and coordination among firms can help build resilience against chain-caused failures. IS models focus on strengthening synergies between humans and machines and sharing resources among different companies, which can improve overall system stability (Scafà et al., 2020).

Incorporating emerging technologies like plug-in hybrid vehicles can add difficulties for the electrical grid during high demand (Onar & Khaligh, 2010). Within an IS framework, companies that embrace these technologies might establish new peak-demand periods, stress distribution line capacities, and cause issues with harmonics and reactive power.

Another problem is the absence of strategic planning for developing companies in most industrial symbiotic networks, which frequently rely on spontaneous opportunities rather than long-term plans (Chopra & Khanna, 2014). This situation can create weaknesses in the system, especially when confronted with disruptive circumstances. The Kalundborg IS case study demonstrates that specific nodes, such as the Asnaes power plant, can turn into critical points in the system, potentially jeopardizing the network's resilience if disrupted (Chopra & Khanna, 2014).

Research on the Yixing Economic and Technological Development Zone in China illustrates that cascading failures can happen within individual networks and across different IS systems, highlighting the need to safeguard critical components and manage potential domino effects (Li & Shi, 2015). Several approaches can be employed to address these flexibility challenges. Incorporating diversity, redundancy, and multi-functionality can enhance the network's flexibility and resilience (Chopra & Khanna, 2014). Moreover, IS network managers and planners should aim to boost the systems' adaptability, protect crucial parts, and manage cascading failures (Li & Shi, 2015). The creation of collaborative platforms and decision support tools, as mentioned in the Singapore food waste case study, can also aid in overcoming information gaps and bolstering exchange network flexibility (Raabe et al., 2017).

Research in Puerto Rico demonstrated that initial cooperative ventures, notably a communal utility, did not fulfill technical standards or the community's hopes for enhanced environmental quality (Ashton, 2010). This underscores the need to thoroughly evaluate the quality and efficacy of exchanged materials and shared resources. Low-quality materials and energy exchanged between companies can cause production problems and lower quality in the production of the company receiver. That can be low-quality steam (energy) – non-saturated steam, lower temperature/pressure; low-quality materials – raw materials containing toxic components or components prohibited for specific production.

4.1.3. Need for adequate physical infrastructure, compatibility issues between different systems, and difficulties in process integration

One of the most pressing barriers to IS is insufficient physical infrastructure. Successful exchanges of materials and energy require investments in pipelines, storage facilities, transportation networks, and processing plants. For instance, in the Kwinana Industrial Area (Australia), the absence of infrastructure to facilitate material flow between industries demanded substantial capital to construct pipelines and shared facilities (Van Beers et al., 2007). Similarly, the Kalundborg Symbiosis (Denmark), often hailed as the gold standard of IS, required extensive infrastructure development for water and energy exchanges, which posed significant upfront costs (Ehrenfeld & Gertler, 1997).

Besides transportation equipment, heat exchangers and storage facilities are needed (Anastasovski, 2014). Specific infrastructure can also be needed to improve separation processes in the donor company and modify that material in an acceptable form to be immediately used by the other (receiver) company. For example, waste management systems require comprehensive planning, execution, effective operational monitoring, and infrastructure for waste collection, transportation, treatment, and final disposal infrastructure (Iqbal et al., 2023). Specific infrastructure is needed to treat and recycle produced water and includes facilities for physical, chemical, and biological treatment methods such as adsorption, flotation, sand filtration, evaporation, electrodialysis, and membrane-based processes (Choi et al., 2023). In e-waste management, infrastructure for pyrolysis, sub/supercritical water treatment, chemical dissolution, and physical treatment (e.g., ball milling, flotation, and electrostatic separation) is necessary to recover usable non-metallic materials from e-waste (Yang et al., 2024). Another example of the need for specific infrastructure heat storage is a big problem for energy synergies when waste heat temperatures differ. In that case, there is a need to design many heat storage facilities (each for the exact temperature range). That can be avoided by including cogeneration systems. Cogeneration systems can include Organic Rankine Cycle (ORC) systems. They are ideal for recovering waste heat from various sources, offering high flexibility and compatibility (Asghari et al., 2023). These systems can be strategically placed within the industrial network to maximize energy recovery and minimize infrastructure costs. ORC works with low-temperature sources in various temperatures. They convert the heat content from the source into electricity. Different sizes of ORC are produced and can be easily mounted in every industrial park.

All in all, these technical barriers are linked to issues related to the **funding** of such infrastructure, the **duration of the construction work**, which can become a deterrent, and the definition of **responsibilities regarding the maintenance** and **legal aspects** associated with these infrastructures.

To overcome these barriers, it is necessary to facilitate synergies between companies. For example, this can be achieved by subcontracting a specialized company or assigning a dedicated facilitator from within the EGM (Management and Modernization Entity of Industrial Parks). This facilitator can support communication between companies, manage data and facilitate synergies identification, manage funding applications from European, national, and local government programs or public-private funding, oversee legal matters, and supervise construction works. Regarding construction works, requesting multiple quotes, including construction time as a key requirement, and selecting a local provider for better communication and project follow-up is advisable. For legal aspects, the facilitator can also engage a legal expert specializing in infrastructure and IS projects. Finally, shared infrastructure platforms or consortia can be created among companies in the industrial park to manage the operation and maintenance of pipelines, storage facilities, treatment plants, and transportation networks, ensuring efficiency and cost-effectiveness in the long term. To address the need for specific infrastructure, the facilitator can act as a bridge between research institutions and companies, leveraging technical expertise to identify the most suitable solutions for each case. Alternatively, the facilitator may involve specialized engineers or technical consultants to design tailored infrastructure. This approach relieves companies of tasks that are often time-consuming and for which they may lack both the resources and the motivation to undertake independently.

Technological disparities between industries represent another major hurdle. **Different industries often use varied standards, equipment, and technologies,** making the seamless exchange of resources challenging. For example, in the Rotterdam Industrial Complex (The Netherlands), system compatibility issues emerged due to **differences in technological and regulatory frameworks** among participating companies, complicating the integration of processes (Boons & Janssen, 2004). Similarly, the Guitang Group (China) faced compatibility challenges in integrating sugar, paper, and cement production due to **differences in equipment and input requirements** (Zhu et al., 2007). These examples underscore the need for collaborative efforts to align technologies and establish standardized protocols, which poses the problem of process confidentiality and the fear that companies have to disclose this information and lose a competitive advantage.

To overcome these barriers, it is essential to foster trust and collaboration through formal agreements that safeguard confidentiality while enabling the exchange of technical information. Facilitators can organize technical working groups to align standards and processes, promoting joint innovation projects or pre-competitive collaborations to address compatibility issues. Additionally, adopting neutral third-party platforms or digital tools for secure data sharing can help companies identify synergies without exposing sensitive information, thus reducing concerns over competitive advantage.

Difficulties in Process Integration: Integrating processes across diverse industries require meticulous operations, logistics, and corporate policy coordination. This challenge was particularly evident in the Ulsan Eco-industrial Park (South Korea), where differing production schedules and corporate priorities among industries complicated the synchronization of processes (Park & Won, 2007). In Kalundborg, trust-building and continuous communication were essential to align operations and maintain the smooth exchange of resources (Ehrenfeld & Gertler, 1997). The complexity of aligning such diverse systems often delays realizing IS benefits. Limited technical expertise may also deter the integration of processes for IS.

For electricity exchange, a key component is the integration of innovative technologies and blockchain, enabling secure, transparent, and automated energy management across multiple industrial entities in an industrial symbiotic network (Chin et al. 2024). This would require smart meters, sensors, and communication devices to facilitate real-time data exchange and transactions when the generated electricity covers the industrial park's electricity needs, infrastructure transfers and stabilizes the produced electricity. However, when only a part of the produced electricity can be used, the rest is often shared with the national electricity grid. In that case, a distribution company and electricity storage or conversion into fuel must be included. Different types of batteries can be used for electricity storage when the amount needed is smaller. If a large amount of electricity must be stored, an extra amount can be used to generate hydrogen (water electrolysis process). After that, produced hydrogen can be easily stored in reservoirs as part of a hybrid battery-hydrogen storage system concept (Goh et al., 2023). This suggests that energy storage equipment, such as batteries and hydrogen storage systems, may be necessary for effective electricity exchange, especially when dealing with intermittent renewable energy sources. Another option is to convert excess electricity into a form that is easily stored due to the existing mature technologies. Accordingly, there are various energy storage systems, such as pumped hydro energy storage (Rehman et al., 2015), compressed air energy storage (Budt et al., 2016), advanced adiabatic compressed energy storage (Bai et al., 2021), liquid air energy storage (Borri et al., 2021), thermal energy storage (Zhang et al., 2025), and gravity energy storage (Kavoosi & Tarafdar Hagh, 2025).

Effective resource sharing and collaboration in IS networks require a well-developed physical and digital infrastructure for managing inventory exchanges and supply chains. Digital infrastructure (see section 4.2) and cutting-edge technological solutions and communication systems are essential to implementing IS successfully. In recent years, digital twins have emerged as a valuable tool for enhancing sustainability in operations and supply chain management within IS ecosystems (Liu et al., 2023). These virtual models enable the simulation and optimization of resource flows, leading to improved decision-making and coordination among participating entities. Implementing IS requires collaboration, knowledge sharing, and technological readiness (Hossain et al., 2024; Renteria Núñez & Perez-Castillo, 2023).

4.1.4. Difficulties in resource management: matching and optimization

Identifying and quantifying available resources, particularly waste and by-products, is a significant challenge in IS. Industries produce various waste streams, including solid waste (e.g., metal scraps, plastic residues), liquid waste (e.g., wastewater, chemical solutions), gaseous emissions, and heat or energy waste. The diversity of these streams makes it challenging to create a comprehensive inventory of resources that can be matched with potential users. Adding to this complexity is the variability in waste composition, which can change significantly due to fluctuations in production processes, variations in raw materials, or even seasonal shifts in industrial activity. Such inconsistencies make it challenging to ensure that waste streams are consistently suitable for reuse (Kowalski et al., 2023).

One project that has already addressed such difficulties in resource management is the Sharedbox project. The SHAREBOX project addresses key challenges in resource management, focusing on the complexities of matching and optimizing resource flows in industrial ecosystems. Difficulties include identifying compatible by-products, ensuring transparency in resource availability, and fostering trust among businesses wary of data-sharing confidentiality. Additionally, the absence of real-time information and standardized resource-sharing procedures often hinders efficient exchanges (European Union, 2019). SHAREBOX developed a secure, cloud-based platform powered by AI and data analytics to mitigate these issues. This platform supports real-time matching and optimization by analyzing various parameters such as resource types, availability, and geographical proximity. Advanced algorithms streamline decision-making while maintaining data confidentiality and encouraging industrial collaboration. The platform fosters a Circular Economy by enabling seamless exchanges, reducing waste and promoting sustainability. This holistic approach can transform how businesses manage resources, ensuring scalability, accessibility, and long-term environmental impact (European Union, 2019).

Another initiative is the Baltic Industrial Symbiosis Project, which promotes sustainable development in the Baltic Sea Region by fostering IS. This involves connecting companies to reuse waste resources like energy or materials as inputs for other businesses. The project establishes peer-to-peer exchanges for IS practitioners, develops new business and financial models, and creates the BSR Industrial Symbiosis Council as a dialogue and policy learning platform. The initiative offers three main work packages to achieve its goals. These focus on identifying underutilized resource streams, building capacity among practitioners through training programs and peer-to-peer exchanges, and testing innovative solutions in real-world contexts around Europe. It also maps existing policies, supports policy learning, and uses tools like the Baltic Industrial Symbiosis Roadshow to inspire municipalities and regions to adopt IS practices. The project aims to improve resource efficiency, foster regional cooperation, and advance sustainable industrial development in the Baltic Sea Region. The initiative that the Dansk Symbiose Center created has since 2019 been continued by Kalundborg Symbiose (Baltic Industrial Symbiosis Center, n.d.)

This project has also been named an outstanding example by Sommer (2020), who reviewed 28 projects across various sectors funded by the Directorate-General for Research and Innovation and shows how these projects support sustainability and a Circular Economy. They use a “symbiosis readiness level” (SRL) to measure these projects' technological, business, environment, and management development. It identifies challenges like low awareness, trust issues, legal hurdles, and the need for infrastructure. To solve these, it suggests better coordination, tools for sharing data, and financial support. The study recommends more research funding, creating IS hubs, and teaching these ideas in schools and universities (Sommer, 2020).

Blockchain technology (BCT) promises to enhance collaboration and data sharing among IS organizations. By providing a robust infrastructure for information management, BCT can address trust issues between organizations by ensuring data immutability and traceability (Gonçalves et al., 2022). Smart contracts on BCT platforms can improve IS network transparency, communication, awareness, and security (Bruel & Godina, 2023). They also enable the automatic execution of waste exchanges, creating a comprehensive transaction record that includes quantity, value, and quality.

This detailed information can be used to optimize IS operations by developing cross-organizational systems (Böckel et al., 2021). Unlike traditional centralized systems, which are vulnerable to manipulation or failure, BCT offers a decentralized structure that reduces the risk of system failure. Its cryptographic signature architecture enhances data security and reliability (Kouhizadeh et al., 2019).

4.1.5. Quality and quantity of resources

Another factor hindering the adoption of IS is the variability and quality of resources. Issues related to lack of, insufficient, or inconsistent material supplies are well documented in the literature (Albino et al., 2016) and emphasize that a significant challenge in IS lies in the uncertainty of waste production, particularly for material-based synergies.

A prime example involves the construction industry. Technological advancements in the construction industry have introduced innovative material processing techniques that enable the reuse of construction waste. For instance, construction debris, mainly limestone, can be combined with furnace slag and fly ash to produce alkali-activated cement (Xie et al., 2023). **However, a significant challenge facing many corporations is the lack of standardized processes for recycling materials, which results in significant variabilities in the final product or introduces significant obstacles to the capability of their efficient use.** Indeed, in the Netherlands, companies are hesitant to adopt or produce construction material from recycled waste, such as reused limestone-based cement. This reluctance stems from insurance companies' unwillingness to cover buildings utilizing such materials due to the absence of established quality assessment standards (Chen et al., 2022).

Challenges also arise when dealing with **energy cascade IS synergies**, primarily because waste energy is typically in t**hermal energy, which is difficult to transport and store.** Additionally, the **potential consumers of the recycled resource are often located far apart, leading to significant transmission losses** (Atienza-Márquez et al., 2020; Chen et al., 2022). Another challenge in energy-based synergies is the **fluctuation in waste energy supply** or continuity in demand, often caused by **seasonal product variations, technical failures, or shifting market dynamics.** This issue is further exacerbated in **batch processes, where production occurs discontinuously**, as is common in fine chemicals, pharmaceuticals, semiconductors, and food production sectors. These industries require flexibility to manufacture varying quantities of specialized products, making stable energy recovery and utilization more complex (Fraccascia et al., 2021; Meyers, 2001; Parker & Svantemark, 2019).

It is often suggested that to mitigate the mismatch between waste supply and demand, companies should stockpile waste materials for later use. However, this solution is less feasible in energy cascade synergies due to the economic limitations of energy storage technologies (Andrews & Pearce, 2011; Kikuchi et al., 2016). One solution for energy storage applications is real-time energy trading, which offers a solution for managing supply-demand mismatches in energy cascade synergies. By establishing local or regional energy-sharing networks, excess energy can be redistributed in real-time to nearby users, reducing waste and improving system efficiency. This approach leverages digital platforms and smart grid technologies to match surplus energy with demand, ensuring optimal utilization dynamically. Nonetheless, such synergies are highly influenced by disruptions caused by imbalances in energy supply and demand which may still hinder IS adoption (Wang et al., 2017; Wang et al., 2017).

A study by Couto Mantese and Amaral (2016), which focused on performance indicators for IS adoption, highlighted another major issue. Substantial inconsistencies emerged across companies when developing a "By-product and Waste Recycling Rate" indicator. For instance, a company might split its waste among multiple recipients or send it to one entity, leading to challenges in determining waste allocation. This uncertainty complicates IS adoption, as companies cannot reliably predict the waste products they will receive.

In summary, several issues relating to the quality and quantity of resources have yet to be addressed for IS to be extensively adopted across several sectors. Thus, it is clear that there exists a need for standards and regulations to guide companies in addressing IS issues. Such frameworks should consider sector-specific nuances, as a one-size-fits-all approach is unlikely to be effective (Xavier et al., 2023; Zhang et al., 2023).

4.2 Data Management and Information Sharing

Technology plays a significant role in advancing IS. Where this is missing, or there are shortfalls in infrastructure readiness, sustainable by-product exchanges become more difficult (Bacudio et al., 2016). Related to the finding above, another critical barrier is the paucity or poor quality of data on waste (Felicio et al., 2016). The volumes, quality and types of data, and the different locations where the data is generated mean that a significant proportion is challenging to collect and process economically (Holgado et al., 2018; Song et al., 2017). Other authors point out the need for an initial firm or an intermediary to precipitate the analysis to understand which others are potential candidates for symbiotic resource exchanges (Holgado et al., 2018).

4.2.1. Data collection and analysis challenges, lack of data/information, and insufficient knowledge about available resources/synergies for potential symbiosis

For industrial symbiotic relationships to develop, it is necessary to have information about potential suppliers or recipients of waste. Knowing the companies, their location, and the desired quality and quantity of resources is essential to realize potential synergies. It is therefore not surprising that there have been numerous studies on this subject (e.g., Cecelja et al., 2015; Fraccascia & Yazan, 2018; Halstenberg et al., 2017; Kosmol & Leyh, 2021; Maqbool et al., 2018; Song et al., 2017). However, this information is not always available or easily accessible, in addition to confidentiality and data sensitivity issues that often condition the implementation of IS (Tseng et al., 2018). Information asymmetry between the parties involved (Moser & Rodin, 2021), poor data quality (incomplete or outdated data), and lack of access to IT platforms or tools can also be barriers to implementing IS.

It is, therefore, important to find ways to overcome these barriers related to the difficulty of collecting and analyzing data. Organizations such as business associations, local governments and public institutions can play an important role in creating bonds of trust between companies and increasing the transparency of relationships (Moser & Rodin, 2021). In addition to helping to find potential synergies, they can also act as a conduit for information, such as publicizing success stories and studying potential benefits. All these steps are important for creating an environment conducive to sharing information and knowledge between stakeholders.

These facilitators can also be important in identifying and recording organizational waste. By doing so, they can more easily assess potential synergies and create a regional database where waste and available quantities could be listed to find partners in IS more easily. Being an external entity trusted by organizations, they could more easily access the data and show the economic and environmental advantages for the companies.

Universities can also be allies in the creation and development of IS. Not only can they develop methodologies to identify better and characterize waste, but they can also provide studies on the feasibility of new uses for waste. The development of the eco-industrial park in Chamusca is one such example where a university has helped to disseminate IS and establish synergistic relationships, thereby boosting the development of a region with few resources (Costa & Ferrão, 2010).

Providing training to empower stakeholders in using these tools/platforms, defining standards for data collection and checks on updates and data quality, and using public data repositories are additional measures that can encourage using these tools.

Although physical infrastructure plays a vital role, incorporating digital technologies can boost the effectiveness and clarity of energy transfers. Adopting digital solutions, including blockchain, can improve the coordination and productivity of energy exchanges within IS networks (Bruel & Godina, 2023; Chin et al., 2024). For instance, blockchain technology can be utilized to digitalize IS, enhancing its security and transparency (Bruel & Godina, 2023). This digital framework can operate alongside physical systems to maximize energy distribution and streamline transactions among participating firms. In the context of Industry 4.0, digital infrastructure is crucial for enabling IS. A framework of three levels has been suggested for IS, incorporating Industry 4.0 technologies. This framework highlights how digital tools can enhance collaboration and accelerate the achievement of sustainability objectives (Iyer et al., 2024). Within IS networks, digital platforms can enhance the exchange of surplus resources by facilitating matchmaking and sharing information among potential partners (Krom et al., 2022). That infrastructure is essential for the successful implementation of IS. It can address obstacles such as insufficient commitment to sustainability, lack of collaboration, and various technical and economic hurdles (Krom et al., 2022).

Safety, system resilience, and operational considerations such as maintenance must be considered when designing IS systems (Bailey & Gadd, 2016). These systems can enhance inter-company collaborations and provide better insights into the costs and benefits associated with IS. Local governments can play a vital role in addressing these challenges by offering infrastructure support and financial assistance (Södergren & Palm, 2021). The creation of information platforms is essential for successful IS implementation (Yang et al., 2022), highlighting the importance of strong technological infrastructure in supporting symbiotic industrial relationships. IS infrastructure necessitating a robust digital framework to enable collaboration, resource sharing, and sustainable practices among participating industries.

Blockchain technology significantly enhances the digitization of IS by offering improved security and transparency (Bruel & Godina, 2023). A framework for smart contract architecture utilizing Hyperledger Fabric can facilitate the adoption of blockchain in IS by addressing its key drivers and overcoming obstacles. This technology enables secure, transparent, automated energy management across various industrial entities within a symbiotic network (Chin et al., 2024).

Digital twins represent another critical component of IS's digital infrastructure. Research on user requirements for digital twins in IS networks is essential to providing intellectual support for future designs from a user perspective (Liu et al., 2023). This approach encourages developing supply chain collaboration based on digital twins within IS networks.

4.2.2 Accessibility of tools for supporting waste-to-resource matchmaking to identify IS opportunities

This challenge frequently occurs when local and regional industries explore IS opportunities but also in industrial parks, often due to insufficient collaboration among tenant companies and inadequate coordination by park management. Proposing or implementing industrial synergies becomes difficult without aligning waste streams from companies with raw material requirements. UNIDO (2021) developed the Industrial Symbiosis Identification Tool to tackle this. This tool identifies symbiosis opportunities through assessments, such as analyzing industry inputs/outputs, engaging with park management and companies, organizing opportunity identification workshops, and reviewing international examples. These approaches generate practical and actionable insights for IS within industrial parks.

An initial indicative list of IS opportunities can help engage park management and companies by highlighting potential benefits with minimal time investment. This early effort can build interest and commitment to conduct more detailed assessments. The tool supports identifying opportunities for by-product and waste exchanges between companies. It applies to existing (brownfield) and new (greenfield) industrial parks. In brownfields, it identifies connections between current operations, while in greenfield, it aids infrastructure and utility planning to enable future exchanges. The tool includes two worksheets:

- Search by By-product: This worksheet helps users identify IS opportunities based on specific by-products or wastes. For instance, it can suggest industries that might utilize gypsum as a raw material. Additionally, it provides information on similar by-product exchanges implemented globally. Users input the by-product or waste, and the results are auto populated. Users can copy and paste the generated results, although the worksheet cells cannot be modified.
- Search by Company: This worksheet identifies IS options based on a selected company type. It lists potential inputs and outputs and suggests industries that might collaborate. For example, it can provide options for reusing cement plants by-products. The by-product worksheet includes global examples and auto-populated results, which can be copied for further use.

These tools provide industrial park stakeholders valuable insights into symbiosis opportunities, fostering collaboration and innovation for sustainable development.

The creation of tools, computer software, digital platforms (Grimmel et al., 2024; Tian et al., 2024), online platforms (Fraccascia & Yazan, 2018; Halstenberg et al., 2017; Mollica et al., 2025), big data (Song et al., 2017), blueprint (Cervo et al., 2020) can also be key to supporting IS, whether experts in the field use these or are accessible by companies. Quantity and quality of waste, location of the company, identification of potential synergies, and even the potential gain from IS are data that can be available on these platforms and thus help create industrial symbiotic relationships. Platforms that use semantic web technologies, namely ontologies, can also help share knowledge and identify synergies (Cecelja et al., 2015; Kosmol, 2019; Kosmol & Esswein, 2018).

4.3. Health, safety and environmental barriers to industrial symbiosis

4.3.1. Health and safety barriers

IS involves the sharing/exchange of materials, energy, and by-products between different industrial entities. This interchange introduces complex operational and occupational health, safety and environmental (HSE) challenges due to varying safety standards across different industries, potential incompatibility of safety protocols and risk management approaches. Moreover, stringent waste disposal regulations can sometimes make reusing industrial by-products or waste streams challenging. In addition, interaction between different industrial waste streams can create unforeseen health and safety risks due to potential chemical incompatibility. Therefore, there may be regulatory compliance challenges or limitations between potential partners, driving the need to conduct rigorous risk assessments before implementing IS activities. Some risk assessment challenges associated with the transfer of materials or processes between different industrial contexts create HSE complications, comprising, among others, (i) uncertainty about material compatibility, (ii) lack of comprehensive risk profile for novel material exchanges, (iii) difficulty in predicting potential chemical interactions; (iv) inadequate historical safety data for innovative exchanges (Azevedo et al., 2021; Chertow, 2007; Taddeo et al., 2017).

The main challenging technical and operational barriers associated with environmental issues are ensuring the safety and quality of shared resources to avoid cross-contamination risks among different industrial processes and sophisticated quality control testing and monitoring to maintain consistent quality when reusing industrial by-products and wastes. Economic instability factors that may hinder the flow of materials and generate environmental issues related to human health concerns, such as demand factors that end up directly affecting the supply chain or low costs associated with waste disposal, especially in waste landfilling, both affecting the accumulation or improper disposal of unstable waste materials (Fraccascia, 2019; Henriques et al., 2021; Neves et al., 2019).

Overcoming health, safety, and environmental barriers requires a multifaceted approach that combines technological innovation with real-time safety monitoring tools, collaborative risk management, economic incentives, stakeholder engagement and regulatory flexibility (Golev et al., 2014; Oughton et al., 2023). The main stages of this multifaceted approach are detailed below

Technical solutions comprise investing in advanced characterization and purification technologies, implementing robust tracking and monitoring systems, and developing sophisticated analytical tools to assess chemical composition, potential interaction risks and environmental and health impacts. To overcome the barriers associated with the lack of available technology, governments need to increase investment in research and development of technological innovations, tools to quantify and optimize symbiotic potential, and greater involvement of research teams from universities or business associations (Dong et al., 2017; Dong et al., 2022).

Achieve *collaborative risk management* through comprehensive risk assessment frameworks specific to IS, shared protocols for detailed chemical characterization of waste streams and rigorous safety testing, continuous monitoring of resource exchanges and joint liability arrangements that distribute risk fairly among participating organizations (Chertow, 2007; Golev et al., 2014; Taddeo et al., 2017).

Implementing *policy innovation* to develop flexible environmental regulations that incentivize resource sharing, provide clear guidelines for safe by-product exchanges, offer tax benefits or grants for successful IS initiatives, create certification processes for safe and sustainable resource exchanges, and develop standardized protocols for cross-industry waste stream utilization. Finally, *economic incentives* create financial mechanisms that balance upfront investment costs while providing long-term economic benefits for resource sharing, reduce waste disposal expenses while increasing landfill fees, and develop insurance products tailored to IS risks (Fraccascia, 2019; Neves et al., 2019).

4.3.2. Environmental and waste management

Proper and effective waste management reduces environmental pollution. Recycling and reusing waste materials help conserve natural resources, reduce the environmental burden of extracting and processing raw materials, minimize emissions of greenhouse gases that contribute to global warming and help protect natural habitats. A focus on waste management supports a Circular Economy model, where products and materials are kept in use for as long as possible, reducing environmental impact.

IS and waste management are interconnected concepts that focus on using resources efficiently and minimizing waste. IS can contribute to achieving a win-win situation between industry and the environment for local and regional circular economies (Yang et al., 2022) by reducing waste by facilitating the reuse and exchange of materials between industries, while waste management ensures proper handling of any remaining waste. Together, these approaches can lead to more sustainable industrial systems.

Furthermore, Cárcamo and Peñabaena-Niebles (2022) recently highlighted that the concept of IS has emerged as a strategy for waste utilization in a productive chain, based on physical exchanges of waste and materials, which finds ways to use the waste from one industry as inputs or raw materials for the other, all supported by business collaboration. Costa et al. (2010) underlined that governmental institutions could significantly shape the context of IS development. However, many authors have recognized that various barriers can hinder the implementation of IS (Yang et al., 2022), including waste management issues. Waste management can be a technical barrier to IS, complicating the effective implementation of symbiotic exchanges. Technical barriers to waste management—such as complexity, lack of infrastructure, regulatory challenges, economic considerations, supply-demand imbalances, and trust issues—can significantly hinder its implementation. Addressing these barriers requires improved waste treatment technologies, better collaboration between industries, supportive regulatory frameworks, and financial incentives that make resource-sharing more economically attractive (Yadav & Majumdar, 2024; Chertow, 2000; Frosch & Gallopoulos, 1989; Lombardi & Laybourn, 2012; Zhang et al., 2019; Lawal et al., 2021; Bain et al., 2010; Bartl, 2014; Gibbs & Deutz, 2007; Wang et al., 2017; Baas & Huisingh, 2008). Overcoming these barriers is essential for widely adopting IS practices.

Environmental management, particularly waste management, presents both technical and non-technical (cross-sectional) barriers to IS, varying by specific challenges. Overcoming waste management barriers to IS requires addressing key challenges to exchange and utilize waste materials between industries effectively. Here are some strategies:

1. Establish standardized classifications for improved identification of usable by-products and reduced contamination to enhance waste sorting.
2. Create centralized digital platforms for businesses to share available waste materials and connect with potential users, enhancing infrastructure for waste exchange.
3. Establish collaborative networks among industries to improve communication and trust through local resource-sharing collaborations.
4. Encourage participation in waste recycling by providing tax breaks or subsidies and relaxing regulations that inhibit exchanges.
5. Invest in technologies that transform waste into valuable by-products, such as converting organic waste into biofuels.
6. Promote awareness of the benefits of waste reduction and IS through training programs to enhance waste management practices.

5. Non-technical barriers and strategies for their overcoming

5.1. Governmental, Regulatory, and Policy Barriers

5.1.1. Lack of/Inadequate regulatory framework to support IS implementation

The regulatory barriers are highlighted in literature as one of the most critical barriers hindering the potential of IS. Regulatory barriers to IS are generally defined within a restrictive, unclear, and conflictive environmental legislative framework (Södergren & Palm, 2021; Herath et al., 2023). Despite its endeavor to promote IS as a core element of the "Roadmap to Resource Efficient Europe" (EC, 2011), the literature still highlights two important regulatory barriers for the European Union:

- Lack of regulations directly targeting IS: Legislations towards promoting IS are not separated into special regulations and are generally indirectly mentioned in European Union legislations and national regulations. Most EU-wide regulations incorporate IS within resource management, waste management and environmental protection-related legislation (Rahman et al., 2016; SCALER, 2020).
- Lack of consistent and harmonized EU-wide legislative framework for IS implementation: within Member States, there are still significant differences and ambiguities in the definitions for waste, secondary material, end-of-life, and second life of materials, which significantly hampers key IS tasks such as recycling, reuse and exchange of waste among companies in different sectors (Domenech Aparisi, 2010).

In the report entitled "Cooperation Fostering Industrial Symbiosis Market Potential, Good Practice, and Policy Actions", even European Council itself highlighted "vagueness and lack of clarity in the language of legislation", "insufficient information and awareness of legislation", "insufficient framework for implementation of legislation", "unintended disincentives created through legislation", and competing priorities" as the main bottlenecks of existing EU legislations (EC, 2018: 109).

To this end, although a regulatory framework involving compulsory legal requirements to recycle materials and imposing higher taxes for waste disposal is essential to uncover the IS potential (Golev et al., 2014; Rahman et al., 2016), a well-defined EU-wide legislative framework still needs to be developed by improving existing regulations on waste management, clarifying vagueness in definitions and harmonizing national legislations of member countries and considering that IS can only be implemented by cross-sectoral cooperation (Henriques et al., 2021).

5.1.2. Uncertainty regarding international and national policies

Without a doubt, the strength of the legislative framework is directly linked to the support of the policymakers internationally and nationally. As Lybæk et al. (2021) suggested, the United Nations Environment Programme and the Organisation for Economic Cooperation and Development (OECD) have already set IS as a primary tool of Circular Economy that would support green economic growth through resource efficiency. However, these international initiatives have not yet materialized in regional or national policy setups. Even in the European Union, the need for broader and more harmonized implementation of policy support towards IS is emphasized as member countries still adopt disparate policies based on their economic development (Neves et al., 2020). Hence, there is a strong need for a comprehensive, holistic policy framework to scale up its adoption and to incentivize regulatory infrastructure among member countries despite existing EU-wide policies on reuse, repair, and recycling (SCALER, 2020).

Implementing IS might be difficult due to bureaucratic barriers/hurdles, even with a robust regulatory infrastructure and strong policy support. Disparities in the implementation of legislative frameworks and conflicting waste/resource codes among local and national authorities, lack of guidance on compliance criteria, and difficulties in obtaining approvals for waste reuse projects from regulatory authorities can be counted as bureaucratic barriers (Södergren & Palm, 2021). To this end, standardizing waste classifications across regional authorities (Technopolis Group, 2016) and avoiding cost-incurring bureaucratic procedures in IS projects (Sellitto et al., 2021; Taqi et al., 2022) would further promote IS implementation.

In summary, the implementation of IS faces significant challenges due to the lack of a dedicated regulatory framework and uncertainties in national, EU-wide and international policies. Current regulations, which lack clarity in definitions, particularly on waste and secondary materials, generate important barriers to materials exchange and reuse, as waste requires special permits and licenses. Furthermore, conflicting or restrictive national regulations and inconsistent enforcement across countries and sectors exacerbate these challenges. The existing policy framework remains fragmented and fails to address IS's needs comprehensively. To overcome these governmental, regulatory, and policy barriers, EU-wide harmonized regulatory and policy instruments should be developed by clarifying waste-related definitions and standards, addressing sector-specific legislation and frameworks, and simplifying bureaucratic processes during IS implementation.

Some of these instruments are listed below (European Commission, 2018: 109)

- "End-of-waste criteria: clarification and streamlined procedures,
- Definition of by-products as distinct from waste (Art. 5 of the Waste Framework Directive),
- Landfill bans and landfill diversion targets,
- Internal market for recovered materials or material flows,
- Eco-design: criteria for recyclability, use of secondary materials and consideration of the end of life,
- Standardization/homogenization of the secondary materials,
- Clarification of legislative framework for new business models (e.g., leasing),
- Better waste segregation to maintain material purity".

5.2. Economic and Financial Barriers

5.2.1. Investment barriers related to high initial costs and risks

Transitioning to a Circular Economy model often requires significant initial investments in new technologies, materials, and worker training. Economic and financial barriers, including Circular Economy practices such as IS, have consistently been recognized as critical for environmentally friendly innovation (Masi et al., 2018; Pajunen et al., 2012; Yadav & Majumdar, 2023). It is well known that substantial financial investments are needed for significant technological advancements to implement such practices in various sectors (Moors et al., 2005). Dong et al. (2017) highlighted the up-front investment requirements for infrastructure and the costs incurred due to the price of raw materials and waste for IS implementation in the case of regional eco-industrial development.

Such economic and financial barriers include the lack of funds for up-front investments (Dong et al., 2016), difficulty in acquiring external investment capital, high up-front investment costs

(Grafström & Aasma, 2021; Masi et al., 2018; Södergren & Palm, 2021), high risks associated with allocating capital to unproven technology (Moors et al., 2005; Pajunen et al., 2013), and limited access to finance (Grafström & Aasma, 2021). What complicates matters further is that major investment decisions are frequently made at the corporate level instead of the regional or national level (Grafström & Aasma, 2021), and such investments need to be economically feasible in terms of cost reduction or lower cost of waste disposal (Pajunen et al., 2012). However, another barrier is sunk investment due to the lock-in of current production technology or systems (Moors et al., 2005), which causes considerable lag in affecting modifications of new production technologies (Pajunen et al., 2012) and long-payback periods (Grafström & Aasma, 2021). Uncertainty in future policymaking, such as policy inconsistency, further increases investment risks and costs (Nemet et al., 2017).

5.2.2. Lack of financial motivation/incentives and funding opportunities

High initial investment costs, long payback periods, and uncertain returns discourage companies, particularly small and medium-sized enterprises (SMEs), from implementing IS practices. These companies are further affected by limited access to affordable financing and the perceived risks associated with eco-innovations. Inconsistent public support, such as insufficient subsidies, tax incentives, and sustainability-linked grants, further exacerbates this challenge. Moreover, traditional financial evaluation frameworks rarely consider environmental and social benefits, making Circular Economy projects less attractive to investors (Agudo et al., 2023). Overcoming these issues in an emerging economy as a case study has recently been reviewed by Hossain et al. (2024), summarizing the importance of incentives towards inter-company cooperation, thus fostering management capabilities of companies to promote their resilience. The green financing mechanisms of governments, including low-capacity loans, will help to enhance public-private partnerships. Furthermore, grants for IS-based projects from governmental and private sectoral support will cover many small-sized manufacturers and enhance their research and development capabilities by boosting the implementation of circularity, thus IS.

To mitigate these economic and financial barriers, it is imperative to highlight the long-term economic benefits of IS practices, such as reduced material costs and improved efficiency, and to seek financial incentives or support from government and industry bodies (Strahel, 2016). Moreover, from an organizational point of view, it is suggested that one "should aim to minimize the overall supply chain cost rather than their in-house cost of operations" (Yadav & Majumdar, 2023: 553). Authorities, including national IS programs, can help mitigate economic and financial barriers by providing more certainty in policy design using various policy instruments (Nemet et al., 2017), including financial policies (Valentine, 2016), and by supporting development of "funding and investment proposals for new and existing firms, guiding environmental permitting, and offering technical or production assistance" (Paquin & Howard-Grenville, 2012: 89). This should help IS by mitigating the difficulty with investment risks, and thus help IS in acquiring external investment (Pajunen et al., 2013; Södergren & Palm, 2021). It is also suggested that the role of governments is to offer "capital subsidies for investments related to sorting and recycling technologies required for IS" (Yadav & Majumdar, 2023: 553) or financial support, such as through research funds (Park et al., 2016), as financial support most often comes from public entities (Mortensen & Kørnøv, 2019; Zhu et al., 2015).

5.3. Market and Supply Chain Barriers

5.3.1. Supply chain-related barriers: Lack of cohesive logistic network and facilities, incompleteness in supply chain networks, lack of mechanisms to predict quality and quantity of exchange material along the supply chain, low fragmentation of supply chain

Geographically dispersed and poorly integrated facilities make it difficult to maintain regular material flows (Chertow, 2007). The low level of integration of the supply chain is an important factor limiting the success of IS. Ineffective supply chain networks, insufficient logistics integration and lack of infrastructure among supply chain actors make it challenging to sustain material flows regularly and predictably (Chopra & Meindl, 2001; Herczeg et al., 2018). The quality and quantity of materials used in IS are often unpredictable. This makes it challenging to plan for the reuse or recycling of by-products (Geng & Côté, 2002). Uncertainties in the quality and quantity of material flows complicate logistics and operational processes (Zhu & Sarkis, 2004). Many studies have listed the quality of returned materials among the challenges in adopting symbiosis in the industry (Brendzel-Skowera, 2021; Södergren & Palm, 2021; Fraccascia, 2019). The lack of physical infrastructure also necessitates the storage and stockpile space required for returned materials (Badhotiya et al., 2022; Erol et al., 2023). Kanda (2024) also points out the barriers related to waste and organic materials, such as the lack of predictability in waste quality and quantity, lack of technological innovation to upcycle organic waste and logistical challenges in storing organic material.

Wuni (2022) suggests that the lack of appropriate supply chain partners and collaboration among them are additional barriers to IS implementation and lack of integration. Even if fully integrated supply chain networks for IS implementation are established, stakeholders may still lack coordination (Tumpa et al., 2019). This would prevent IS opportunities from being evaluated (Lambert & Cooper, 2000). Lack of inter-business collaboration (Mishra et al., 2021; Jaeger & Upadhyay 2020), lack of institutional support for coordination and communication (Mortensen & Kørnøv, 2019; Södergren and Palm, 2021) and the lack of communication channels and information platforms among the supply chain actors (Joensuu et al., 2020; van Leeuwen et al., 2018) would lead failure in efficient and sustainable IS networks.

Hence, proper coordination between stakeholders is vital for the supply chain's on-time flow of information and materials. Without proper coordination, managing the flow of by-products and waste among stakeholders is challenging. In these networks, the timely flow of these materials and their quality are important. Lack of quality circular materials (Wuni, 2022) and uncertainty in the quality or quantity of waste and by-products (Ji et al., 2020) are among the barriers that prevent supply chains from reaching their full potential. In these closed-loop supply chains, barriers related to waste and by-products are also observed. Fuchs and Hovemann (2022) indicate that irregular flow and waste heterogeneity are among the supply chain barriers in IS networks. Moreover, as IS requires effective execution of the reverse flow of materials and wastes, uncertainty in reverse logistics operations arises as one of the main challenges (Awan & Sroufe, 2022; Jaeger & Upadhyay, 2020).

IS networks, which are closed-loop supply chains, enhance resource efficiency and environmental performance through material and information exchange (Das et al., 2024). Therefore, supply chain barriers are also closely related to informational barriers. Garcia et al. (2008) advocate that information confidentiality among stakeholders results in problems sharing training, experiences in waste reduction actions, and tools for waste mapping and monitoring techniques. Islam et al. (2016) indicate that a lack of information about other companies' by-products and waste flow is an informational barrier that avoids the establishment of self-organized IS. Kosmol and Otto (2020) and Moser and Rodin (2021) argue that confidentiality and inefficient information flow result in limited information or accessibility on resource quality and quantity, as well as collaboration methods. Apart from these barriers, lack of information-sharing mechanisms and infrastructure (Kosmol & Leyh, 2019), lack of management information systems (Kosmol & Otto, 2020), and lack of IT implementation for communication and coordination (Tumpa et al., 2019) are the challenges that limit the cooperation and coordination among supply chain partners.

Finally, high logistics/transaction costs (Gupta et al., 2020; Hossain et al., 2024; Kosmol & Otto, 2020) in supply chains appear to be another barrier. Park et al. (2016) believe high transaction costs are due to the proximity of collaborators. In this sense, proximity can be viewed as a facilitator since it reduces transportation costs and enables information flow (Paquin & Howard-Grenville, 2012). Transportation costs, product loss, and environmental impacts are the negative consequences of incomplete and poorly managed supply chains and IS networks (McKinnon, 2018).

To overcome these barriers, adequate infrastructure and logistic networks are required to realize the exchange of waste, by-products, and energy among supply chain partners. However, the complex nature of these supply chains requires optimizing these networks (Wolf & Karlsson, 2008; Yesilkaya et al., 2020; Corsini et al., 2024).

5.3.2. Market-related barriers: Low demand for recycled materials/Limited market size/ Low valuation of exchange materials

Low demand for recycled materials, limited market size, and the low valuation of exchange materials pose significant barriers to advancing the Circular Economy. Manufacturers are reluctant to use recycled materials in production due to concerns about their quality and reliability, stemming from inconsistent material properties and the absence of standardized certifications (Schultz et al., 2022). Moreover, fragmented recycling markets with limited regional infrastructure and inconsistent environmental regulations restrict cross-border trade and reduce global market opportunities (Fösterling et al., 2023). The undervaluation of recycled materials results from environmental costs being excluded from the pricing of virgin resources, reducing the competitiveness of recycled products. Promoting IS, where waste from one process becomes a valuable input for another, could help correct this imbalance by enhancing resource efficiency and creating economic value from recycled materials. These challenges require policy-driven market reforms such as mandatory recycled content standards, green public procurement initiatives, and harmonized international regulations. Establishing certification frameworks, implementing carbon pricing, introducing environmental taxes, and developing transparent digital marketplaces could enhance market confidence, stabilize material prices, and support a more competitive and sustainable recycling economy. These measures will strengthen industry trust, fostering the adoption of circular economic practices by improving market integration and ensuring more effective policy alignment (Aarikka-Stenroos et al., 2023).

5.3.3. Geographical constraints

Geographical proximity is an important constraint for an efficient and sustainable implementation of IS for several reasons (Velenturf & Jensen, 2016). Firstly, the economic feasibility of IS implementation depends heavily on the distance between the supply and demand of exchange materials due to transportation costs incurred (Henriques et al., 2021). Secondly, long-distance transportation of waste contributes to the discussion of how long distances to the environmental footprint of products are under consideration with increasing emissions (Herczeg et al., 2018). Thirdly, the remoteness of waste sources to the demand region could create technical problems in IS implementation. This is particularly true for some types of waste, such as waste heat or by-products, which might be impractical to be transported over long distances (Kusch-Brandt, 2020). Finally, as suggested by Mortensen et al. (2023), a lack of geographical proximity could cause problems in facilitating stronger relationships between companies, which are particularly important for effective coordination and solving problems. Direct social interactions between employees can explain why this is required to build trust before organizing by-products, scrap materials exchanges, and transportation (Ashton & Bain, 2012). In the same vein, Taddeo et al. (2017) discussed how long distances between companies of an IS network can stifle business innovation, as geographical proximity, due to interactive learning possibilities between members of the network, is important for facilitating the flow of knowledge that is essential for business creativity and innovation generation.

The most efficient solution to the problem of geographical remoteness in IS implementation would be to organize industrial zones/eco-industrial parks to create IS synergies. Kalundborg Industrial Park is the most successful case study of IS implementation based on the exchange of energy and resources, including heat, steam, water, gypsum, refinery gas, liquid fertilizer, biomass wastes, sludge and ash, between different companies within different sectors (Jacobsen, 2006). One of the main reasons for success is that companies are operating in the same region to form resource reuse/share pathways. Moreover, with the municipality and industrial park management building trust between companies and employees, knowledge sharing for eco-innovation has been possible.

5.4. Organizational and Management-Related Barriers

5.4.1. Lack of awareness/knowledge of IS benefits and implementation, including cognitive understanding - Lack of understanding related to IS activities

The lack of awareness of both implementation and benefits is one of the most important barriers to successfully implementing IS (Bacudio et al., 2016). Although, according to Neves et al. (2020), knowledge and awareness about IS business models within academia have been expanding over the last two decades, the level of awareness in industrial establishments is still relatively low. This is particularly true for SMEs in developing countries. Akhtar et al. (2022) observed that SMEs' lack of awareness and impulsiveness and the inconsistent supply of by-products are important barriers to such IS implementation, especially in developing countries. According to Kosmol (2019), awareness of the potential benefits of IS further hinders information sharing and trust-building between IS implementation partners.

Madsen et al. (2015) claimed that operating IS business models is crucial in enhancing the knowledge management ecosystem of potential partner companies. Namely, realizing IS exchanges of knowledge could facilitate IS by fostering awareness of the concept of IS and its benefits, awareness of the local facilitator programs (if available), and providing recommendations and guidelines for the management of the companies. These knowledge exchanges could be influenced by the availability of money and time and technical and collaborative issues. Due to the increasing number of IS cases globally, communicating the potential benefits has become easier over the last decade. Wang et al. (2017), for instance, after analyzing the IS coordination network in Tianjin Binhai New Area, proposed that local governments might play a vital role in increasing awareness among industrial enterprises by promoting relational links across different organizational divisions and governance levels. According to the authors, this would promote knowledge of IS benefits and create institutional capacity for IS development.

5.4.2. Lack of management commitment. Resistance to change and innovation

The practical implementation of IS is hindered by numerous barriers, with the lack of management commitment, resistance to change, and barriers to innovation being among the most significant. Henriques et al. (2021) categorized the barriers related to the management process in IS under three headings: lack of resources, inadequacy in implementation, and lack of protocols/formal agreements. A significant barrier to management is the lack of qualified human and technical resources to research and develop potential waste flow and management methods. Moreover, transitioning to an IS system is a complex process that must be addressed from multiple dimensions (technical, management, geographical, etc.), requiring sustainable modifications in these areas. Consequently, deficiencies and inadequacies cause serious challenges. Additionally, the lack of formal procedures for initiating the synergistic IS planning process further slows progress. In their study, Kosmol and Otto (2020) described the organizational and managerial barriers related to IS as soft factors. As a result of their study, it was observed that approximately half of all IS-related barriers (197 barriers = 49%) included soft factors. The barriers characterized as soft factors are generally grouped under the headings of cooperation (79 barriers), management (56 barriers), information (30 barriers) and knowledge (32 barriers). The management category refers to the barriers that need to be overcome internally by the management to be ready for cooperation in the IS process. The commitment factor in this category refers to the lack of interest, involvement or behavioral change towards sustainable development and IS. The resources factor includes lack of time or available qualified personnel. The strategy factor refers to internal factors that hinder IS implementation–for example, IS policy being incompatible with company policies, the IS plan not effectively coordinated within the company, and inappropriate hierarchical organizational structures making decision-making difficult. The resistance factor includes resistance to change within the organization, such as avoidance of changing operations and processes and unwillingness to change the existing supply chain (Kosmol & Otto, 2020).

However, realizing a specific IS change within the managerial framework and developing new institutional coordination mechanisms requires a significant up-front investment, representing one of the major obstacles to development. Additionally, dependence on others and the changes and innovations introduced by IS often raise concerns for organizations. Firms tend to avoid partners with low-quality outputs or unreliable and incompetent management. Furthermore, organizational factors such as the centralized structure, lack of autonomy to cooperate with local organizations on IS, internal resistance to change, and difficulty adapting organizational routines can also create barriers (Walls & Paquin, 2015). In this context, as solutions to overcoming those challenges, the study by Henriques et al. (2021) highlighted that implementing managerial strategies for creating strong IS synergies is among the most crucial. Organizations with a strong background in IS mainly carry out these effective strategies. Such organizations possess the necessary knowledge and experience related to the development of synergies. Therefore, developing and implementing IS-related managerial strategies requires a structured process, and as the organization gains experience in this process, its IS-related efforts will yield results.

5.4.3. Lack of collaboration and communication within the organization and/or between stakeholders

According to Rodin and Moser (2021), the first step in IS is to find potential partners for cooperation. This is crucial because IS relies on voluntary collaboration between enterprises to optimize production costs and improve the environment. Collaboration and geographic proximity are key to realizing IS (Chertow 2000), but spontaneous development of such networks happens relatively rarely and requires a long time (Blam et al., 2016). In this context, barriers to collaboration, such as a lack of trust, often disrupt the flow of critical information, leading to ineffective collaboration. Managerial and social barriers, including a lack of willingness to collaborate, insufficient trust among industrial companies, and inadequate institutional support for integration, coordination, and communication (Bacudio et al., 2016; Chertow, 2007; Fichtner et al., 2005; Golev et al., 2015; Siskos & Van Wassenhove, 2017), often arise from the lack of internal alignment or inter-organizational coherence (Kosmol & Leyh, 2019; Rodin & Moser, 2021). Extensive research by Kosmol and Otto (2020) identified several cooperative challenges among companies in IS. These challenges stem from differences in corporate strategies, such as aversion to collaboration, unwillingness to engage, discontinuity in partnerships, conflicts of interest, and difficulties in multi-actor decision-making. Additional communication problems arise due to disparities in the structure and circumstances of potential partners, including existing contractual obligations, cultural differences, power dynamics variations, and company size disparities. A lack of trust—driven by competitive attitudes or social isolation—further hampers collaboration. Rodin and Moser (2021) emphasize that deeper personal trust is essential, as contractual negotiations usually follow previous bilateral and multilateral discussions. Other barriers include inadequate support tools, such as insufficient communication, coordination, and collaboration information systems, and a lack of shared understanding, reflected in inconsistent terminology or the absence of a common framework.

To overcome these barriers and enhance the willingness to cooperate, informational campaigns and training should emphasize the benefits of sustainability and inter-company collaboration (Fichtner et al., 2005). Additionally, Golev et al. (2015) highlighted that establishing a coordinating body can significantly enhance trust, willingness to cooperate, and overall collaboration. Fichtner et al. (2005) also recommend organizing regular meetings among company managers.

5.4.4. Lack of internal capacity - limited labor capacity, time constraints

Building IS is a time-consuming process (Qu et al., 2015) and requires knowledge and skills that are challenging for enterprises, particularly SMEs (Yadav & Majumdar, 2023). A lack of top management support and conflicting priorities (Södergren & Palm, 2021) have implications for internal capacity, including employee motivation (Hossain et al., 2024), their interests, and potential resistance to change (Henriques et al., 2021). Furthermore, the lack of awareness and sense of urgency (Masi et al., 2018), as well as the lack of commitment to sustainable development, can contribute to resistance to change in cases when sustainability is "a part of business strategy and practices" (Golev et al., 2015: 144). Other barriers may be informal barriers, such as lack of training (Södergren & Palm, 2021) and lack of available knowledge and information, which require time and financial resources to gain (Kosmo & Ley, 2019). The lack of human resources to recognize opportunities, including avenues for utilizing waste streams, has been identified as a management-related barrier (Henriques et al., 2021). Additionally, a lack of skills and know-how hinders the technological aspects of IS (Grafström & Aasma, 2021).

To overcome these challenges, the focus needs to be on capacity building (Wolf et al., 2005) and employee skills (Södergren & Palm, 2021), including investing time in their training and knowledge creation and exchange (Kosmo & Ley, 2019; Södergren & Palm, 2021; Valentine, 2012, 2016), at the organizational level. This will strengthen in-house solutions and knowledge (Södergren & Palm, 2021) about potential opportunities (Mortensen & Kørnøv, 2019) and ideas for new IS relationships (Yang et al., 2022), as well as reinforce the "concern for the impacts of industrial activities on the environment" (Henriques et al., 2021: 8) and how to address such issues. A successful strategy has also been establishing a sustainability-related employee training center (Neves et al., 2020). In addition, instead of focusing solely on resistance to change (Erwin & Garman, 2010; Henriques et al., 2021; Pardo del Val & Fuentes, 2003), it is relevant to shift the focus to how to gain employee acceptance of change, but an enabling factor is a clear commitment to sustainable development (Johannsdottir et al., 2015). Knowledge spillovers between SI actors may also be important based on trust between actors (Baas & Huisingh, 2009).

5.4.5. Data Protection and Confidentiality-Related Barriers: Intellectual property concerns, Information security, and Compliance with in-place data protection regulations (e.g., GDPR)

The concept of IS faces numerous barriers during its implementation, among which information sharing is considered a significant challenge. Sharing knowledge is pivotal for developing IS awareness among business ecosystems. Kosmol (2019) identified the critical gaps and the potential use of Information and Communication Technologies (ICT) for sharing knowledge. However, the complexity of this concept still presents challenges for integrating the tools within the business processes that would support businesses in joining IS activities. In this context, academic literature recognizes the lack of knowledge sharing as a barrier to IS implementation. While online platforms can enhance IS business models and highlight the importance of information sharing (Fraccascia & Yazan, 2018), the distinction between sensitive and general knowledge remains an open question. Therefore, clarifying the sensitivity of information and establishing terms for sharing is crucial.

A systematic approach to categorizing knowledge related to IS can help create frameworks for awareness and allow businesses to share general knowledge while protecting sensitive information. Information sharing could promote the sharing economy based on shared ownership of values and benefits that support the Circular Economy and sustainable manufacturing. Mandatory information sharing could help overcome this obstacle and facilitate cross-sectoral cooperation for sustainable business and societal value creation. However, Cervo et al. (2020) note that exchanging confidential data between industries remains one of the main barriers to disseminating IS. In that context, they recommend the concept of the industrial sector as a solution to overcome the challenge of sharing information. A blueprint comprises a series of profiles providing insights into the industry's key inputs and outputs regarding thermal and electrical energy, materials and services. Additionally, they present a methodology detailing a step-by-step approach for building the profiles and the required data type.

Furthermore, Akrivou et al. (2021) consider the informational gap as one of the main barriers impeding the achievement of IS actions. They find that the lack of systematic exchange of available information prevents entities from being aware of latent collaboration opportunities, regardless of their geographic proximity. The research suggests that information and communication technology (ICT) tools have been developed to overcome this challenge, particularly in identifying possible business engagements. That means the digitalization of the processes could be recognized as a facilitator of IS by utilizing a systemic approach to information sharing to promote constructive, synergistic relationships and adequate protection of sensitive data.

5.5. Cultural and Social Barriers

5.5.1. Public awareness and acceptance (Socio-cultural attitudes towards waste and resource sharing)

Socio-cultural attitudes toward waste and resources are shaped by a community's values, beliefs, practices, and norms. These attitudes significantly influence waste generation, perception, management, and how resources are consumed and conserved. A nuanced understanding of socio-cultural attitudes is crucial for designing effective policies, education programs, and initiatives that align with cultural values and drive positive waste and resource management changes. Each world region generates a different amount of waste because of its diverse population and socioeconomic background (Kaveri et al., 2020; Widyatmika & Bolia, 2023).

In the European Union, in 2022, the total waste generated in the EU by all economic activities and households amounted to 2.233 million tons or 4.991 kg per capita, while 5.0 tons of waste were generated per EU inhabitant. 40.8% of waste was recycled, and 30.2% was landfilled (Eurostat, 2024). The trend for enhancing collection and recycling is expanding in Europe, especially in the Western Balkans (Gjorshoska et al., 2023). According to the Global Recycling League Table (2024), which evaluated 48 countries worldwide, Austria, Wales, Taiwan, Germany, Belgium, Netherlands, Denmark, Slovenia, Northern Ireland and South Korea are the top ten countries with the highest recycling rates.

To address those challenges, the five-step waste hierarchy introduced by the Waste Framework Directive (Directive 98/2008/EC Article 4) provides a structured approach to waste management, focusing on (European Commission, 2008):

- "Reducing the amount of waste generated,
- Maximizing recycling and reuse,
- Limiting incineration to non-recyclable materials,
- Phasing out landfilling of non-recyclable and non-recoverable waste and
- Ensuring full implementation of the waste policy targets in all EU Member States."

According to Directive 98/2008/EC, in applying the waste hierarchy (Article 4), Member States shall take measures to encourage the options that deliver the best overall environmental outcome. This may require specific waste streams departing from the hierarchy, which is justified by life cycle thinking on the overall impacts of generating and managing such waste. Member States shall ensure that the development of waste legislation and policy is a fully transparent process, observing existing national rules about the consultation and involvement of citizens and stakeholders. Member States shall consider the general environmental protection principles of precaution and sustainability, technical feasibility and economic viability, protection of resources and the overall environmental, human health, economic and social impacts".

The Circularity Gap report (2024) highlights that high-income countries in the Global North contribute significantly to exceeding the planetary boundaries. These contributions include climate change (42%), nitrogen (27%) and phosphorus (18%) production, freshwater use (16%) and land use change (38%) while generating 43% of global emissions. Emerging countries (Southeast Asian

Countries, Latin America, and Northern Africa) account for 55% of global raw material extraction and 52% of the material footprint while housing around 37% of the global population. These countries contribute 50% of climate change, 62% of nitrogen emissions, 60% of phosphorus emissions, 53% of freshwater use, and 42% of land-use change. Less developed countries in Sub-Saharan Africa and South Asia consume 13% of the global material footprint despite accounting for nearly 50% of the global population. They contribute 20% of land-use change, 30% of freshwater use, 23% of phosphorus emissions to soil, and 11% of nitrogen emissions.

5.5.2. Cultural barriers towards collaboration and knowledge sharing

Despite the benefits of IS, there are some barriers to its implementation, which can be technological, financial, regulatory/legal, organizational and cultural (Heck et al., 2024; Hossain et al., 2024; Neves et al., 2019; Yadav & Majumdar, 2024). Cultural barriers can be associated with the characteristics and customs of each country (Agudo et al., 2024), the organizational culture of companies (Harris & Pritchard, 2004; Kirchherr et al., 2018), the unfamiliarity of entrepreneurs (Colpo et al., 2022), as well as with social relations and interactions and the policies governing the economic activities of the various players (Beaurain et al., 2023; Walls & Paquin, 2015). All these challenges can make collaboration and the flow of resources and information difficult.

To overcome these barriers, national organizations (governments, local authorities, trade and/or industrial associations, or universities) must introduce and develop IS. These organizations can facilitate relationships at different levels. Governments can offer financial incentives, such as subsidies or tax breaks, and implement environmental regulations to enhance the effect of these synergies. Furthermore, credible organizations close to companies can foster the creation of links and dissemination of information and publicize the economic, environmental, and social benefits of IS through workshops and case studies. Additionally, they can help build trust, propose new symbiotic relationships, and protect sensitive information. Digital platforms can contribute to resource matching and enhance reliability and trustworthiness. Meanwhile, universities play a key role in educating students on sustainability and the economic potential of IS for companies.

5.5.3. Social attitudes towards employment of new technology

The rapid evolution of technology has significantly transformed the landscape of people's work and lives. Therefore, it is understandable that people are concerned about new technologies, given the impact they could have on their lives and communities (Komendantova et al., 2022). Environmental, economic, and social impacts, the level of awareness and the availability of information influence social attitudes (Komendantova et al., 2022; Verhoest et al., 2022). Fear of job loss, lack of trust in technology, cultural values and misinformation are some of the social barriers to adopting new technologies (Ghali et al., 2017; Lahlou et al., 2021; Silva et al., 2017).

To address these barriers, it is crucial to identify practical solutions. In that line, knowledge is among the most important factors in accepting new technologies (Lahlou et al., 2021). Therefore, It is essential to carry out training and awareness-raising campaigns among workers and decision-makers to generate a higher acceptance rate. Governments, educational institutions and technology companies can actively contribute to demystifying the use of technology and emphasizing its many benefits. A mediator who acts as a bridge between stakeholders and has social and interpersonal skills, as highlighted in the study by Akyazi et al. (2023), can also positively contribute to the success of initiatives to employ new technologies. Encouraging dialogue between communities, technologists, and policymakers can also help break down social barriers to new technologies and can help align them with social values.

6. Cross-sectional barriers

Cross-sectional barriers in IS refer to challenges that span multiple categories and affect the implementation of IS collaborations aimed at sustainable resource sharing. These barriers are interlinked and arise due to the complexity of IS systems involving different actors, technologies, and processes. The barriers can be divided into the following categories (Kosmol & Otto, 2020; Henriques et al., 2021; Yang et al., 2022):

- Hard factors: Quantifiable economic, technological, and financial challenges.
- Soft factors: Difficult-to-quantify challenges such as collaboration barriers (e.g., lack of trust or conflicts of interest), management issues (e.g., misaligned strategies or hierarchical structures), knowledge gaps (e.g., insufficient expertise or awareness), and information-related issues (e.g., lack of data sharing or confidentiality concerns).
- Contextual factors: External influences such as political/regulatory barriers (e.g., restrictive policies) and public/market dynamics (e.g., lack of market demand for sustainable practices).

In the case of cross-sectional barriers, the effects of these categories often overlap, making them particularly difficult to address. For example, collaboration issues may intersect with regulatory constraints or knowledge gaps, so holistic strategies are required to overcome them effectively (Kosmol & Otto, 2020).

During the research for this report, several cross-sectional barriers have been identified. Expertise in process integration in different industries requires customized technical solutions and a high level of technical skill to ensure compatibility and efficiency. Companies can encounter significant problems when adapting solutions to their operational requirements without this expertise. In addition, as articulated by Park et al. (2018), knowledge capacity on IS engagement would foster the ability to acquire and effectively utilize information about potential symbiotic links. The lack of training programs specifically focused on developing IS know-how capacity within the company is seen as a significant barrier. Companies often lack the resources to develop in-house capabilities without structured training initiatives. As a result, companies must often rely on external consultants, which drives costs and limits long-term sustainability. In addition, the widespread lack of technical knowledge within companies reduces the likelihood of innovative solutions being proposed and implemented internally. Hence, while know-how on process integration and system compatibility is recognized as a technical barrier, it directly leads to the economic sustainability of IS implementation, which is considered a non-technical barrier.

Besides, to facilitate the establishment of IS networks, it is essential to gather knowledge about the potential participants and the quantities and types of waste or by-products available (Neves et al., 2019). Therefore, a significant technical barrier is the lack of knowledge about other companies that could accept or provide waste (Dong et al., 2016).

The main technical issues in the IS implementation include the system's flexibility, meeting the required capacity (fluctuations), the quality of supplies, outages caused by the chain, and peak energy demand (especially in industries with batch processes). Ensuring quality and quantity of waste deliveries is a cross-cutting issue as it encompasses both technical (e.g., technical know-how in process integration and system compatibility, quality control and assessment) and non-technical (e.g., strategic planning within the firm- and supply chain-level, trust and collaboration between IS partners, confidentiality and data protection, standardization and contracts) aspects. Most IS networks lack strategic planning for business development, which often rely on spontaneous opportunities rather than long-term plans. Cross-cutting solutions/technical solutions depend on other barriers - management decisions and planning. It is not synchronized between companies.

Moreover, cascading failures can occur within individual networks and across different IS systems, emphasizing the need to protect critical components and manage potential domino effects. Similar challenges arise in the energy cascade IS synergies. Fluctuations in energy supply or continuity in demand are often caused by seasonal product demand, technical failure or changing market dynamics. To balance the mismatch between waste supply and demand, it is often suggested that companies should store waste materials for later use. However, this solution is less feasible for energy cascade synergies due to the economic limitations of energy storage technologies.

Difficulties include identifying compatible by-products, ensuring transparency in resource availability, and fostering trust between organizations that distrust the confidentiality of data exchanges. In addition, the lack of real-time information and standardized procedures for sharing resources often hinders efficient exchange. Notably, the lack of standardized procedures for recycling materials remains a major challenge many companies face, resulting in significant variations in the final product or significant barriers to using these materials efficiently.

Technology plays an important role in promoting the information society. Where this is lacking, or there are deficits in infrastructure readiness, the sustainable exchange of by-products becomes more complex (Bacudio et al., 2016). Another key barrier related to the above finding is the lack or poor quality of data on waste (Felicio et al., 2016). The quantity, quality, type of data, and the locations where it is generated mean that a significant proportion of it is difficult to collect and process economically (Holgado et al., 2018; Song et al., 2017).

The need for a more adequate physical infrastructure, compatibility issues between different systems and difficulties in process integration are related to issues of financing such infrastructure, the duration of construction work, which can act as a deterrent, as well as the definition of responsibilities in terms of maintenance and legal aspects related to these infrastructures. Another major hurdle is the technological differences between industries. Different industries often use different standards, equipment and technologies, making seamless resource exchange difficult. The examples of Rotterdam Industrial Complex (Boons & Janssen, 2004) and Guitang Group in China (Zhu et al., 2007) highlight the need for a concerted effort to align technologies and adopt standardized protocols, which raises the issue of process confidentiality and the fear that companies will have to disclose this information and lose a competitive advantage. Integrating processes across different industries requires careful coordination of operations, logistics and corporate policies. The complexity of aligning disparate systems (e.g., Ulsan Eco-Industrial Park (Park & Won, 2007), Kalundborg (Ehrenfeld & Gertler, 1997)) often delays the realization of the benefits of IS. Limited technical expertise can also be an obstacle to integrating processes for IS.

For industrial symbiotic relationships to develop, information about potential suppliers or recipients of waste must be available. However, this information is not always available or easily accessible. In addition, there are problems with confidentiality and data sensitivity, which often make IS demanding (Tseng et al., 2018). Information asymmetry between the parties involved (Moser & Rodin, 2021), poor data quality (incomplete or outdated data) and lack of access to IT platforms or tools can also be barriers to implementing IS. It is, therefore, important to find ways to overcome these barriers related to the difficulty of data collection and analysis. The introduction of digital solutions, including blockchain, can improve the coordination and productivity of energy exchanges within IS networks (Bruel & Godina, 2023; Chin et al., 2024). For example, blockchain technology can digitize IS to improve its security and transparency (Bruel & Godina, 2023). This digital framework can work alongside physical systems to maximize energy distribution and streamline company transactions. In the context of Industry 4.0, digital infrastructure is critical to enabling IS.

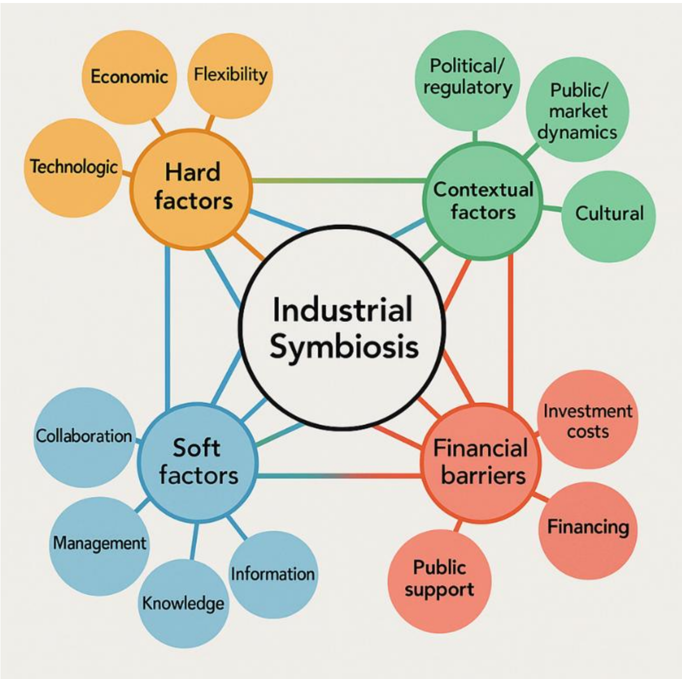
Environmental management, especially waste management, presents technical and non-technical (cross-cutting) barriers to industrial symbiosis, varying depending on the specific challenges. While processing the waste for system compatibility within IS networks could be considered a technical aspect of waste management, legislative infrastructure for defining and classifying waste streams is non-technical.

Cultural barriers can be related to the characteristics and customs of each country (Agudo et al., 2024), the organizational culture of companies (Harris & Pritchard, 2004; Kirchherr et al., 2018), the unfamiliarity of entrepreneurs (Colpo et al., 2022), and the social relationships and interactions and policies that regulate the economic activities of different actors (Beaurain et al., 2023; Walls & Paquin, 2015). All these challenges can impede collaboration and the flow of resources and information.

High initial investment costs, long payback periods, and uncertain returns discourage companies, especially small and medium-sized enterprises (SMEs), from adopting IS practices. These companies are also hampered by limited access to affordable financing and the perceived risks associated with eco-innovation. Inconsistent public support, such as insufficient subsidies, tax incentives and sustainability-related grants, exacerbate this challenge. It is also suggested that the role of governments is to offer "capital subsidies for investments related to sorting and recycling technologies required for IS" (Yadav & Majumdar, 2023: 553) or financial support, e.g., through research funds (Park et al., 2016), as financial support most often comes from public agencies (Mortensen & Kørnøv, 2019; Zhu et al., 2015).

Figure 1 visualizes the relationships among barriers to IS implementation.

Figure 1. Cross-sectional barriers relationship



The graph highlights interdependence across different barriers, showing that no single challenge exists in isolation. Within category-specific relations in technical barriers, a lack of knowledge leads to a lack of training, contributing to quality control issues and supply fluctuations. In economic barriers, high investment costs lead to uncertain returns, discouraging financial support. System compatibility influences process integration within technological barriers, which is made worse by technological differences. Trust issues and confidentiality concerns lead to a lack of collaboration, while poor data quality is connected to a lack of IT platforms, leading to information asymmetry. Lack of standardized procedures complicates legal responsibilities and is worsened by restrictive regulations. Different physical infrastructure gaps lead to extended construction times and financial challenges.

On the other hand, lack of knowledge is linked with information asymmetry, which limits effective data sharing. In contrast, a lack of standardized procedures influences data sensitivity issues and can lead to poor data quality. Gaps in physical infrastructure led to financing challenges, which made the development of the new IS projects difficult. At the same time, lack of knowledge is linked with information asymmetry, which limits effective data sharing. On the economic side, uncertain returns return financial investments due to the restrictive regulations related to IS. Data-related issues (poor quality, lack of platforms, and information asymmetry) affect technical and regulatory barriers. Trust and confidentiality concerns make collaboration more difficult, reinforcing economic and managerial challenges. Infrastructure barriers slow technological adoption and increase legal complications, delaying IS efforts.

Although many of the barriers are technical, the solution to many problems is non-technical, e.g., the need for appropriate standards and regulations. For example, no clear guidelines for a recycled product, resulting in quality variabilities, makes it difficult for companies to use recycled materials as the quality is inconsistent.

7. Case Studies

Two European case studies are described below to highlight the potential and benefits of existing IS schemes.

7.1. EcoSuBrick project

The EcoSuBrick project has been implemented in Cyprus under the responsibility of the Energy and Environmental Design of Buildings Research Lab., of the University of Cyprus. This project brought together a quarry industry, a producer of building materials and academia. The project aimed to design a new masonry brick containing limestone filler, an industrial by-product of a quarry industry, as aggregate replacement in high dosages. The most significant barriers identified under and after the implementation of the project were: a) normative requirements that minimize or ban the use of limestone filler as raw material to produce building materials, and b) the lack of knowledge and actual interest of the by-product's producers and the potential users to invest in their potential use. The organizations involved had to work at different levels to overcome these barriers. Firstly, the research organization worked individually with the private ones to inform them about the potential benefits and increase their understanding and intention to invest in a standard industrial research scheme. Then, the partners worked together to prove that using limestone fillers to produce building materials meets the market requirements regarding their characteristics, e.g., compressive strength. In addition, private organizations had to develop their profitable business models to introduce such materials on the market. Finally, the organizations worked with the policymakers and local public servants to revise the normative requirements based on the project results. The key challenge of the EcoSuBrick project was to increase the awareness of producers and potential users of the by-products and persuade them that investing and changing their common practice can be equally profitable for all. In this context, bearing in mind the limited knowledge of the private sector, the active involvement of a knowledge organization with transfer skills is significant in securing successful outcomes.

7.2. GreenBlock project

The GreenBlock project has been implemented in Cyprus under the responsibility of Domika Ylika Ledra LTD. This private enterprise is active in producing and distributing construction and building materials. This project brought together the local cement industry, a producer of building materials, a quarry industry and academia. The project aimed to develop a new block based on a designed concrete mixture that includes a significant portion of industrial by-products, cement kiln dust and limestone fillers produced by the cement and quarry industries.

The most significant barriers that were identified under and after the implementation of the project were:

1. Normative requirements that minimize or ban the use of fine materials, limestone fillers and cement kiln dust as raw material to produce building materials,
2. The lack of knowledge and actual interest of the by-product's producers and the potential users to invest in their potential use, and
3. The fluctuation of the properties of such by-products results in difficulties to introduce as raw materials in the production processes.

The participating organizations worked closely at different technical and non-technical levels to overcome these barriers. It is worth noticing that the acceleration force for the successful development of this case study was a recently implemented environmental policy that indirectly enforced the sustainable management of those by-products. These requirements force the by-product producers to work with academia and other potential by-product users to identify, study and implement sustainable solutions. To achieve that, the by-product producers, potential users, and academia worked together and investigated potential uses based on the characteristics and availability of those by-products. Then, the academia, assisted by all partners, developed prototype concrete mixtures and performed experimental tests on a laboratory scale to prove that the use of fine materials in the production of building ones ensures the meeting of the market requirements regarding their characteristics, e.g., compressive strength, workability, etc. In addition, private organizations developed profitable business models to introduce such materials on the market.

Finally, both organizations worked with policymakers and local public servants to revise the normative requirements based on the project results. The GreenBlock project's key technical challenges were overcoming the fluctuation of the by-products' properties in different batches and increasing the awareness of potential users on a business scale. In this context, bearing in mind the limited knowledge of the private sector, the active involvement of a knowledge organization at technical and non-technical levels with transfer skills is significant and secures successful outcomes.

8. Discussion

As part of the report preparation, members of the LIAISE COST Action were asked to assess the influence of technical (Table 1) and non-technical barriers (Table 2) in different IS implementation phases (Figure 2). The respondents graded the influence from 1 to 5, where 1 is the lowest and 5 is the most significant.

Figure 2. IS implementation phases

Table 1. Influence of technical barriers in different IS identification phases (N=46)

	Identification	Evaluation	Selection	Realization
Lack of technical knowledge/expertise	3.9	3.8	3.6	4.0
Lack of technical solutions (for a given problem)	3.0	3.5	3.4	4.2
Need for more adequate physical infrastructure. Compatibility issues between different systems. Difficulties in process integration.	3.2	3.4	3.4	4.1
Quality and quantity of resources (lack, insufficient, variability)	3.2	3.4	3.3	4.1
Data collection and analysis challenges, lack of data/information, and insufficient knowledge about available resources/synergies for potential symbiosis.	4.0	3.7	3.5	3.2
Lack of tools for supporting waste-to-resource matchmaking to identify IS opportunities	3.9	3.6	3.2	3.3
Occupational health and safety	2.7	2.9	3.4	3.6
Environmental management (particularly waste management)	3.2	3.5	3.6	3.9
Lack of technical knowledge/expertise	3.9	3.8	3.6	4.0

Table 2. Influence of non-technical barriers in different IS identification phases (N=29)

	Identification	Evaluation	Selection	Realization
Lack of/Inadequate regulatory framework to support IS implementation	2.9	3.0	3.6	4.4
Uncertainty regarding international and national policies	2.8	3.0	3.3	3.6
Investment barriers related to high initial costs and risks	3.1	3.7	3.8	4.2
Lack of financial motivation/incentives and funding opportunities	3.2	3.3	3.5	3.6
Supply chain-related barriers: Lack of cohesive logistic network and facilities, incompleteness in supply chain networks, lack of mechanisms to predict quality and exchanged material quantity along the supply chain, low fragmentation of supply chain	2.9	3.4	4.1	4.4
Market-related barriers: Low demand for recycled materials/Limited market size/ Low valuation of exchanged material	3.2	3.6	3.7	4.0
Geographical constraints	3.0	3.0	3.3	3.6
Lack of awareness/knowledge of IS benefits and implementation incl. cognitive understanding	3.9	3.3	3.1	3.1
Lack of management commitment. Resistance to change and innovation	3.5	3.3	3.3	4.0
Lack of collaboration and communication within the organization and/or between stakeholders (e.g., networking)	3.6	3.4	3.3	3.8
Lack of internal capacity (limited labor capacity, time constraints)	2.8	3.0	3.4	4.0
Data Protection and Confidentiality-Related Barriers: Intellectual property concerns, Information security, and Compliance with in-place data protection regulations (e.g., GDPR)	2.9	3.1	3.0	3.3

Public awareness and acceptance (Socio-cultural attitudes towards waste and resource sharing	2.7	2.8	3.0	3.1
Cultural barriers towards collaboration and knowledge sharing	3.1	3.1	3.0	3.5
Social attitudes towards the employment of new technology	2.8	2.9	2.8	3.2

Based on the above tables and average grades of the technical and non-technical barriers in different phases of IS implementation, the lowest grade for technical barriers is 2.7, while the highest is 4.2. The lowest is 2.7 for the non-technical, while the highest is 4.4.

Overall, it is observed that within the technical barriers, "the lack of technical knowledge and expertise" has the most significant influence on IS implementation phases, with an average grade of 3.8. Moreover, "investment barriers related to high initial costs and risks" are the most influential within the non-technical barriers, with an average score of 3.6. Both barriers' most substantial influence is observed in the realization phase of IS implementation.

8.1. Impact of barriers on the feasibility and scalability of IS

IS stands as a transformative approach to resource efficiency and sustainability, yet its feasibility and scalability are significantly affected by various barriers. The presence of technical, economic, regulatory, and organizational challenges restricts the ability of industries to implement IS on a large scale.

Technical Barriers and Scalability

One of the most critical constraints to IS implementation is the lack of technological expertise and inadequate infrastructure. Many industries lack the knowledge and tools to identify potential synergies, leading to missed opportunities for waste-to-resource exchanges. The absence of standardized technological processes and recovered resources/products further complicates integration between industries, reducing the overall scalability of IS networks. Additionally, geographical constraints and supply chain inefficiencies limit the practical feasibility of inter-company exchanges, particularly when waste transportation costs outweigh the financial benefits of IS participation.

Economic and Financial barriers

Economic barriers such as high initial investment costs and a lack of financial incentives deter companies from adopting IS. Many firms, particularly SMEs, struggle to allocate resources for the necessary infrastructural upgrades. Furthermore, fluctuating market demand for by-products affects the stability of IS models, reducing long-term feasibility. Businesses may find IS participation financially unsustainable without well-structured economic incentives, such as subsidies or tax reductions.

Regulatory Barriers and Legal Uncertainty

Conflicting or unclear regulations pose a significant challenge to IS scalability. Industries face legal uncertainties when repurposing waste due to varying national and regional end-of-waste criteria, classification, and reuse policies. Complex approval processes and bureaucratic hurdles further slow the adoption of IS practices. Inconsistent regulatory frameworks across borders complicate multinational IS collaborations, restricting large-scale implementation.

Organizational and Informational Barriers

Lack of organizational trust, resistance to change, and insufficient communication networks hinder effective IS partnerships. Many industries operate in isolation, unaware of potential symbiotic opportunities due to poor information-sharing mechanisms. Even when synergistic opportunities are identified, industrial organizations are reluctant to take upon activities outside their main business area, which are often necessary to realize IS in practice. Therefore, the introduction of IS often requires the involvement of an additional organization providing the service, e.g., water treatment or material recovery and processing. The absence of centralized digital platforms further limits the ability to map available waste streams and identify viable partnerships.

8.2. Interrelations between different types of barriers

Economic and Technological Barriers

Economic and technological barriers are closely intertwined. The high costs of upgrading facilities and acquiring specialized knowledge often prevent industries from adopting the advanced technologies required for IS. The need to prioritize the main business activity over exploring IS opportunities, which is a long process and takes time, limits the industry's involvement. Additionally, technological limitations increase operational costs, creating a cycle where financial constraints hinder technological progress.

Regulatory and Organizational Barriers

Regulatory and organizational barriers influence each other significantly. Unclear legal frameworks discourage industries from engaging in IS due to compliance risks. Simultaneously, the absence of strong institutional support limits regulatory reforms that could facilitate IS adoption. Organizational resistance to change also impacts policy development, as industries that are hesitant to engage in IS are unlikely to advocate for regulatory improvements.

Informational and Technical Barriers

A lack of accessible information on IS opportunities prevents companies from overcoming technical barriers. Many firms are unaware of available resources, potential partners, or technological solutions that could facilitate IS implementation. The absence of data-sharing platforms further exacerbates this issue, making building the technical capacity needed for IS integration difficult.

Understanding the interconnections between different barriers is crucial for developing targeted strategies to enhance IS feasibility and scalability. By addressing these barriers through coordinated policy efforts, financial incentives, technological investments, and knowledge-sharing initiatives, IS can become a more viable and scalable model for sustainable industrial development.

9. Recommendations

Several studies state that IS needs to be influenced by different drivers and enable it to overcome the barriers to its implementation. Therefore, it is necessary to define drivers and enablers since they serve distinct but complementary functions. Drivers are the primary forces that create pressure for change or action. They directly push or motivate progression toward specific outcomes and often represent "why" change is necessary. They can be internal (organizational goals, efficiency needs) or external (market conditions, regulatory requirements) and operate as causal factors initiating movement.

On the other hand, enablers are needed for IS implementation as they are supporting elements that facilitate change without directly causing it, and they create conditions where desired changes can occur more effectively. They represent "how" change can be successfully implemented, including resources, capabilities, structures, and environmental factors, and they function as necessary but insufficient conditions for change. The key distinction lies in their relationship to change drivers and create momentum and direction while enablers to remove barriers and provide necessary support mechanisms. A helpful analogy might be that drivers are the engine pushing a vehicle forward, while enablers are the roads, fuel, and maintenance systems that allow the journey to occur efficiently. Successful change management typically requires identifying relevant drivers to create motivation and appropriate enablers to ensure feasible and sustainable implementation.

RECOMMENDATIONS FOR STRATEGIES TO OVERCOME TECHNICAL AND NON-TECHNICAL BARRIERS AND IS ENABLERS.

1. Enhancing Technical Expertise and Infrastructure

    - Establish industry-specific training programs to build technical expertise in IS.
    - Invest in digital tools and platforms for resource mapping, data analytics, and AI-powered matchmaking to facilitate waste-to-resource exchanges.
    - Develop standardized frameworks and guidelines for technological compatibility between industries to streamline process integration.
    - Promote collaborative R&D initiatives for innovative IS solutions, particularly waste valorization and material exchange.
    - Ensure open access to IS databases and matchmaking tools.

2. Facilitating Economic and Financial Support

    - Provide financial incentives such as subsidies, tax credits, and grants for companies engaging in IS practices and for IS facilitators.
    - Encourage public-private partnerships to fund infrastructure development needed for resource exchanges.
    - Develop financial models that quantify IS benefits, making a more substantial business case for investment.
    - Dedicate funds for infrastructure modernization, particularly in industrial parks.

3. Strengthening Information Sharing and Collaboration

    - Institutionalize the role of the IS facilitator as a formal job function within industrial parks and/or local authorities — ensuring the presence of dedicated, cross-disciplinary professionals capable of identifying synergies, building trust among stakeholders, and coordinating infrastructure, regulatory, and financial aspects of symbiotic exchange.

- Establish digital platforms that provide real-time data on waste availability and potential synergies.
- Encourage industry clusters and symbiosis networks to foster trust, collaboration, and resource exchange.
- Create knowledge-sharing hubs to disseminate best practices and successful case studies.
- Organize national, regional, and local events to facilitate the networking of various IS stakeholder groups and stimulate the generation of synergies and opportunities.

POLICY RECOMMENDATIONS FOR ADDRESSING REGULATORY AND ECONOMIC CHALLENGES

1. Regulatory Framework Improvements

- Simplify and harmonize regulations related to waste classification, end-of-waste criteria, and reuse to facilitate IS transactions.
- Introduce IS-specific policies that encourage waste repurpose and Circular Economy initiatives.
- Develop clear and flexible guidelines for IS compliance to ensure legal certainty for participating industries.
- EU and national regulators should establish standard IS definitions, compliance guidelines, and certification schemes.

2. Economic and Market-Based Incentives

- Implement differential pricing structures for waste disposal that promote reuse and recycling.
- Encourage the development of secondary material markets to create stable demand for IS by-products.
- Support businesses transitioning to IS models through tax incentives and innovation funding.

BEST PRACTICES FOR FOSTERING ORGANIZATIONAL CHANGE AND COLLABORATION

1. Leadership and Cultural Shift

- Promote top-down commitment by integrating IS into corporate sustainability goals.
- Encourage cross-sector collaboration and partnerships to align IS objectives with broader industrial strategies.

2. Operational Integration and Change Management

- Develop IS-specific KPIs to measure track performance and benefits.
- Establish internal IS champions within organizations to drive initiatives and foster engagement.
- Encourage inter-organizational communication through structured dialogues and formalized agreements.

PUBLIC AWARENESS AND EDUCATIONAL INITIATIVES

1. Raising Public and Industry Awareness

- Launch campaigns to highlight the economic and environmental benefits of IS.
- Showcase successful IS case studies through media, conferences, and online platforms.
- Foster community engagement through participatory workshops and IS demonstration projects.

2. Education and Capacity Building

- Integrate IS concepts into university curricula, vocational training, and professional development programs.
- Provide policymakers with specialized training on IS to enhance regulatory support and decision-making.
- Encourage knowledge exchange between academia and industry to drive innovation and research in IS.

By implementing these recommendations, IS can be effectively scaled, unlocking significant economic, environmental, and social benefits for industries and communities.

10. Conclusions

IS presents a significant opportunity to enhance sustainability and economic efficiency across various industries. However, its widespread implementation is hindered by multiple technical and non-technical barriers. This report has identified and analyzed these challenges and categorized them into technological, economic, regulatory, informational, organizational, and infrastructural barriers.

The findings highlight that the most pressing barriers are the lack of technical expertise, inadequate infrastructure, and regulatory complexities. Many industries struggle with limited knowledge about potential symbiotic opportunities, technological incompatibilities, and inefficient data-sharing mechanisms. Economic constraints, such as high initial investment costs and a lack of financial incentives, further deter companies from adopting IS practices. Additionally, geographical constraints and supply chain inefficiencies add further complexity to the feasibility of symbiotic exchanges.

Several strategic interventions have been proposed to overcome these barriers. These include enhancing technical knowledge through targeted education and training programs, developing digital platforms for improved resource mapping and data exchange, and fostering collaboration between industries. Policymakers and regulatory bodies are crucial in facilitating IS by streamlining approval processes, offering financial incentives, and setting clear regulatory guidelines to encourage waste reuse and resource optimization.

Furthermore, addressing trust and organizational barriers requires active engagement between stakeholders to establish transparent and mutually beneficial partnerships. Investing in robust infrastructure and adopting innovative technologies such as blockchain and AI-powered matchmaking platforms can significantly improve resource efficiency and industrial collaboration.

In conclusion, while IS faces considerable barriers, its sustainability, cost reduction, and resource efficiency benefits make it a vital strategy for the future of industrial operations. A concerted effort from industries, policymakers, and researchers is essential to create an enabling environment that fosters symbiotic relationships and ensures long-term success. By addressing the identified barriers through informed policy decisions and technological advancements, IS can become a cornerstone of the Circular Economy, driving economic growth and environmental sustainability.

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12. Annexes

12.1. Annex 1 - Survey questions for the impact of technical barriers in different IS implementation phases

Please choose for each technical barrier the influence on each phase of IS implementation. In the dropdown menu, you will see grades from 1 to 5, where 1 is the lowest and 5 is the most significant influence.

	Identification	Evaluation	Selection	Realization
Lack of technical knowledge/expertise				
Lack of technical solutions (for a given problem)				
Need for more adequate physical infrastructure. Compatibility issues between different systems. Difficulties in process integration.				
Quality and quantity of resources (lack, insufficient, variability)				
Data collection and analysis challenges, lack of data/information, and insufficient knowledge about available resources/synergies for potential symbiosis.				
Lack of tools for supporting waste-to-resource matchmaking to identify IS opportunities				
Occupational health and safety				
Environmental management (particularly waste management)				

12.2. Annex 2 - Survey questions for the impact of non-technical barriers in different IS implementation phases

Please choose the influence on each phase of IS implementation for each non-technical barrier. In the dropdown menu, you will see grades from 1 to 5, where 1 is the lowest and 5 is the most significant influence.

	Identification	Evaluation	Selection	Realization
Lack of/Inadequate regulatory framework to support IS implementation				
Uncertainty regarding international and national policies				
Investment barriers related to high initial costs and risks				
Lack of financial motivation/incentives and funding opportunities				
Supply chain-related barriers: Lack of cohesive logistic network and facilities, incompleteness in supply chain networks, lack of mechanisms to predict quality and quantity of exchange material along the supply chain, low fragmentation of supply chain				
Market-related barriers: Low demand for recycled materials/Limited market size/ Low valuation of exchanged material				
Geographical constraints				
Lack of awareness/knowledge of IS benefits and implementation incl. cognitive understanding				
Lack of management commitment. Resistance to change and innovation				
Lack of collaboration and communication within the organization and/or between stakeholders (e.g., networking)				

Lack of internal capacity (limited labor capacity, time constraints)				
Data Protection and Confidentiality-Related Barriers: Intellectual property concerns, Information security, and Compliance with in-place data protection regulations (e.g., GDPR)				
Public awareness and acceptance (Socio-cultural attitudes towards waste and resource sharing				
Cultural barriers towards collaboration and knowledge sharing				
Social attitudes towards the employment of new technology				