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Economic evaluation framework for Industrial Symbiosis through network lenses: a systematic literature review

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Abstract

Current economic and productive systems, characterized by huge resource consumption, cause significant environmental and social impacts, underlining their intrinsic unsustainability. This research explored circular economy models, in particular Industrial Symbiosis (IS) process, involving materials, energy, water and by-products exchange among different entities. Although the economic aspect is often considered of paramount importance, IS costs and benefits proved to be scarcely identified and properly quantified in the existing literature, since methodologies lack an organized structure to link economic outcomes to specific activities that generate value, which, in turn, remains assumed at a merely descriptive level if there's no quantification approach alternative to market value estimation. Therefore, through a systematic literature review literature (2019-2023), 61 articles were analyzed, with the objective of filling the knowledge gap by means of systematization of recent scientific evidence on IS economic aspect, pinpointing areas of potential economic advantage or disadvantage, for the final construction of an innovative and detailed IS economic evaluation framework, including revenues and costs items, calculation methodologies and specific performance KPIs. This research contributes to the broad comprehension of economic benefits, bolstering sustainable practices and network business model adoption.

Keywords: industrial symbiosis, economic evaluation, networking, industrial ecology, circular economy

1. Introduction

The current economic and productive systems, based on a large and growing resource consumption, entail significant footprints, in terms of environmental and social impacts, proving their intrinsic unsustainability; therefore, the need to find innovative sustainable business models (Bocken et al., 2014), that can minimize negative effects and positively influence the way value is generated and distributed. Among them, the circular economy business model, aiming at creating value from waste management, transformation and recovery (Sadraei et al., 2023) represents a source of competitive advantage, combining the generation of profit from differentiated products with a conscious perspective on environmental impacts (Costanza, 2020). This business model often translates into Industrial Symbiosis (IS) processes, engaging "traditionally separate entities in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and by-products" (Chertow, 2000), and distinguishing itself from other types of mutual interaction because, according to some authors, it associates at least three distinct entities in the exchange of two, or more, different resources (Albino et al., 2016; Chertow, 2007). Case-study analysis (Neves et al., 2020) underlines the development and wide adoption of symbiosis practices, involving a variety of industries (Lombardi & Laybourn, 2012), mainly from the manufacturing sector. Scientific literature emphasizes, as peculiar features and keys of success, cooperation and synergistic possibilities provided by geographical proximity (Boons et al., 2017; Chertow, 2000, 2007): for those reasons, the symbiotic process generally takes place inside the so-called eco-industrial parks, defined as communities of businesses that cooperate to gain economic, environmental and social advantages from the efficient share of resources (Chertow, 2000). In fact, IS models fully took shape within the eco-industrial park of Kalundborg, Denmark, although many scholars do not consider spatial proximity as a necessary or sufficient pre-condition (Neves et al., 2020; Zhang et al., 2015), exploring other possibilities for non-localized exchanges, as knowledge networks, intended to eco-innovation and efficient resource use (Lombardi & Laybourn, 2012). Indeed, by investigating temporal evolution (Mallawaarachchi et al., 2020), it can be noticed that IS definition has been enlarged, to embrace intangible exchanges, besides sharing of services and infrastructure. Moreover, three specific dimensions have been progressively integrated and deepened: willingness for network cooperation, structural and sociocultural context, and externalities linked to exchanges' sustainability and consequential economic and environmental gains. Scientific research regarding IS framed it into the field of Industrial Ecology (IE) (Baldassarre et al., 2019; Lybæk et al., 2021), that discipline considering industrial systems similar to ecosystems, with the aim of reducing environmental impacts and closing energy and resource loops. Recently, the analysis has been broadened to the domain of Circular Economy (CE), an umbrella concept that promotes the transition towards circular models for recycling, reusing, and waste valorization, combining environmental and economic goals (MacArthur, 2013). Businesses are at the forefront of transition, and peculiar partnerships that develop within an IS are a driving force for enterprises' shift towards production systems oriented to circularity (Costanza, 2020). The CE-focused definition certainly receives more validation at the political level, in particular from European policy landscape, which acknowledges IS as a strategic key for circularity of industrial and economic systems, within the scope of policies and programs such as the Circular Economy Action Plan (Lybæk et al., 2021; Neves et al., 2020; Wadström et al., 2021). Even if both disciplines are built on close-loops theories, CE addresses IS both as a critical dimension to evaluate circularity (Piontek et al., 2021). and as a business model in which its principles take

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shape (Ranjbari et al., 2021), clarifying the economic rationale and operative functioning, and integrating IE perspective, which provides a good understanding of IS as a sociotechnical process and its development over time (Baldassarre et al., 2019).

Focus on economic aspects can be found since the starting point of IS processes: scientific literature identifies costs reductions (Colpo et al., 2022b; Lybæk et al., 2021) and search for private advantages (Chertow, 2000, 2007) as the main *raison d'être* for symbiotic exchanges, while the acknowledgment of environmental benefits as a positive consequence of resource flows happens at a later time (Boons et al., 2017; Wadström et al., 2021). In fact, even if circularity offers a concrete manner to reduce emissions and environmental impacts linked to the use of materials along the whole value chain, it should also represent a more attractive production system for companies from an economic point of view (Piontek et al., 2021). The strategic opportunity for financial gains, often resulting from scarce raw material availability (Chertow, 2007; Faria et al., 2021), makes a spontaneous triggering of IS (Boons et al., 2017; Neves et al., 2020): researchers highlight the need to "*uncover*" (Chertow, 2007) symbiosis dynamics and their social structures, in order to incentivize exchanges and spread knowledge with the support of specific policies (Boons et al., 2017; Chertow, 2007; Lybæk et al., 2021), aiming at overcoming major operative, technological, economic-financial, knowledge and sociocultural barriers (Colpo et al., 2022b; Kosmol & Otto, 2020; Re et al., 2023; Taqi et al., 2022), and their associated risks (Henriques et al., 2020). However, even if the economic aspect is one of the most investigated, because of its primary relevance, scholars pinpoint the need to identify and properly measure economic implications, enlarging the scope of research by including quantified IS economic costs and benefits, more than merely descriptive outcomes. (Wadström et al., 2021). In fact, current analytical schemes are able to estimate economic advantages and disadvantages only through means of existing associated market value, pointing out the lack of specific frameworks for the identification and integration of all kinds of value, essential for a comprehensive evaluation of IS feasibility, beyond the market one, outlining furthermore a structured model to link outcomes to specific activities generating value. Consequently, this study was motivated to fill this knowledge gap by a systematic review of recent literature (2019-2023) in the field of IS economic analysis, from business' point of view, in order to ascertain research trends through a bibliometric analysis, in addition to outlining most cited areas of potential advantage/disadvantages. Consequently, the research conducted was oriented to answer the following questions:

RQ1: What is the research trend in the field of IS economic analysis?

RQ2: What are the most relevant areas of potential economic costs/benefits?

From the examination of 61 scientific articles, assessed on the basis of a dedicated review protocol, papers' metadata and content data were extracted about industrial sectors involved, economic evaluation and the methodology implemented. Final objective consisted in the construction of a detailed framework, innovative and different from all others because of clear specification of all cost and revenue items and their quantification methodologies, useful to consider in an IS project economic feasibility study because of their recurrence in scientific literature. In a context of growing interest in IS as a powerful tool to achieve triple sustainability goals (Neves et al., 2020), this research contributes to the systematization of recent evidence in the field of analysis, which constitutes the theoretical basis of the framework, which proves practically useful for weighing benefits

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and disadvantages that may affect firms in overall evaluation of IS projects. Further relevance of this study is confirmed by its helpfulness in overcoming economic barriers and incentivizing the adoption of IS practices and network business models.
The structure of this paper is as follows: Section 2 delineates methodological steps in conducting systematic literature review, Section 3 presents the main bibliometric results and findings useful to construct economic framework of analysis, developed in Section 4, also devoted to general discussion. Section 5 draws conclusions, limitations of the study and recommendations for future research development.

2. Methodology of Research

Systematic literature review could be defined as "a systematic, explicit, [comprehensive,] and reproducible method for identifying, evaluating, and synthesizing the existing body of completed and recorded work produced by researchers, scholars, and practitioners" (Fink, 2019). This means that the analysis, to be called scientific, must be "systematic in following a methodological approach, explicit in explaining the procedures by which it was conducted, comprehensive in its scope of including all relevant material, and, hence, reproducible by others who would follow the same approach in reviewing the topic" (Okoli, 2015)

This approach was deemed the most appropriate to provide an in-depth summary of existent evidence on the state of the art for Industrial Symbiosis, particularly focused on benefits and disadvantages involved in economic feasibility assessment. To pursue this aim, the presented analysis adapted systematic literature review (SLR) methodology outlined by Okoli (2015), following a replicable, scientific and transparent approach based on an eight-step guide:

1. Identify the purpose: to be clear and explicit with the audience, the purpose of this study was to fill a knowledge gap by providing a deep understanding of the most up-to-date state-of-the-art on economic feasibility of Industrial Symbiosis. Generally speaking, this analysis was conducted to systematize progress in field of inquiry, develop a framework based on latest scientific evidence and make recommendations for future research;

2. Draft protocol and train the team: a written protocol document, as a road map to conduct the review, provided details and training for both reviewers, in order to guarantee consistency and uniformity of analysis;

3. Apply practical screen: in order to critically select sources for scientific evidence, screening for inclusion involved three filter criteria:

- *Publication language*: English, the one both reviewers could read;
- *Range of publication*: last five years (2019-2023), to focus on the most up-to-date progress in the field of inquiry and to uncover potential research avenues;
- *Document type*: article, to ensure peer-reviewed quality paper excluding reviews of literature.

No filter for Journal or Subject area was considered, in order to make the review as more comprehensive as possible, taking into account interdisciplinarity in analysis;

4. Search for literature: literature search was performed on Scopus and Web of Science platforms (Pranckutė, 2021).

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Frequently used by researchers across social sciences and disciplines, these databases were selected because they ensure a holistic and multidisciplinary vision of the research theme, including high-impact articles on aspects ranging from environmental engineering to sustainable development and circular economy, essential for an integrated analysis. Search string was built on concepts directly related to the research questions. In order to reach the largest number of relevant articles in the most scientific manner, a preliminary keyword pattern analysis was carried out using VOSviewer. A small representative sample of articles analyzing economical aspects of Industrial Symbiosis was used to extrapolate keywords most appropriate and cited by scholars in the field of research. Performing a brief first analysis of databases' results, researchers opted to maintain keywords combining the two criteria of breadth and specificity. On the one hand, selected keywords provided the highest number of results; on the other hand, coherence with the research theme was evaluated in order to guarantee as focused analysis as possible, excluding circular practices beyond the definition of Industrial Symbiosis (Chertow, 2000a). Moreover, the use of Boolean operators among selected terms let the researchers take advantage of database search power. This strategy led to a search string where the term "Industrial Symbiosis" was combined with synonyms identifying economic implications. In particular, the search string ("industrial symbiosis" AND ("effect" OR "economic* aspect*" OR "benefit" OR "economic* analysis" OR "cost")) was performed on databases, searching within "Article title, Abstract and Keywords". Asterisks were used because they represent any number of characters. The procedure was deemed effective to answer the research questions because it let researchers be as specific as possible, excluding circular practices beyond the boundaries of Industrial Symbiosis, aligning with the objective of constructing an economic evaluation framework as detailed as possible on specific peculiarities of symbiotic exchanges. Records identified through searching on Web of Science and Scopus were filtered according to criteria for practical screening; then, the removal of duplicates (n= 127) and not accessible (n= 8) articles led to a preliminary total of n= 323 papers for eligibility;

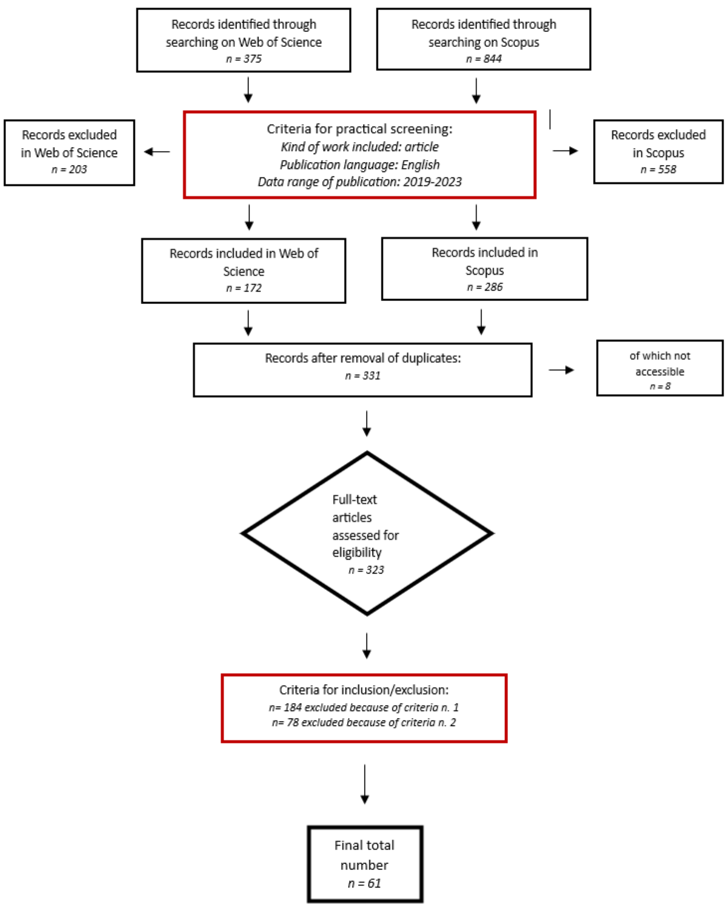
5. Extract data: this step involved the gathering of information that serves as raw material for answering research questions, analyzing and discussing results. In particular, the following data were extracted:

- *Keywords, Journal and year of publication*: to perform bibliometric analysis and assess evolution patterns in scientific literature;
- *Economical cost/benefit*: to give a direct answer to research question, upon which building economic assessment framework for Industrial Symbiosis;
- *Industries involved in symbiotic exchanges*: to understand what economic sectors could be interested as potential users of the framework;
- *Methodology for quantifying costs/benefits*: to comprehend what applicable calculation methodologies are for the practical implementation of the framework.

6. Appraise quality: screening in full-text for exclusion led to articles scored on the basis of qualitative quality appraisal that did not involve methodology evaluation but appropriateness in answering the research question. To ensure articles met this criterion, a preliminary review was implemented on a total of n= 323 papers, accurately reading titles and abstracts; from this step, n= 184 articles were excluded. Then, a refined assessment based on full-text was manually performed. This last step led to a final total number of n= 61 articles included in systematic literature review. In each evaluation step, researchers have always confronted each other on doubts of interpretation;

7. **Synthesize studies**: charts and tables, presented in *Result* section, were drafted to map at best the extracted data and to structure the systematic literature review;

Figure 1[1]. Systematic literature review – methodological process



Source: Authors own elaboration from Okoli, C. (2015). A guide to Conducting a Standalone Systematic Literature Review.

[1] Criteria of selection are specified as follows:

- *Criteria n. 1: first preliminary title and abstract evaluation about relevance and usefulness in answering research questions;*
- *Criteria n. 2: integral paper analysis to evaluate relevance and usefulness in answering research questions.*

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8. Write the review: final step involving paper writing; in particular, a framework for economic assessment of Industrial Symbiosis was built upon analyzed literature and presented in *Discussion* section. This represented the practical implication of the study carried out, proving its usefulness especially for companies that want to test economic sustainability of industrial symbiosis projects.

Figure 1 illustrates the above-mentioned process of search, selection and screening, with the detailed number of articles involved in each phase.

3. Results

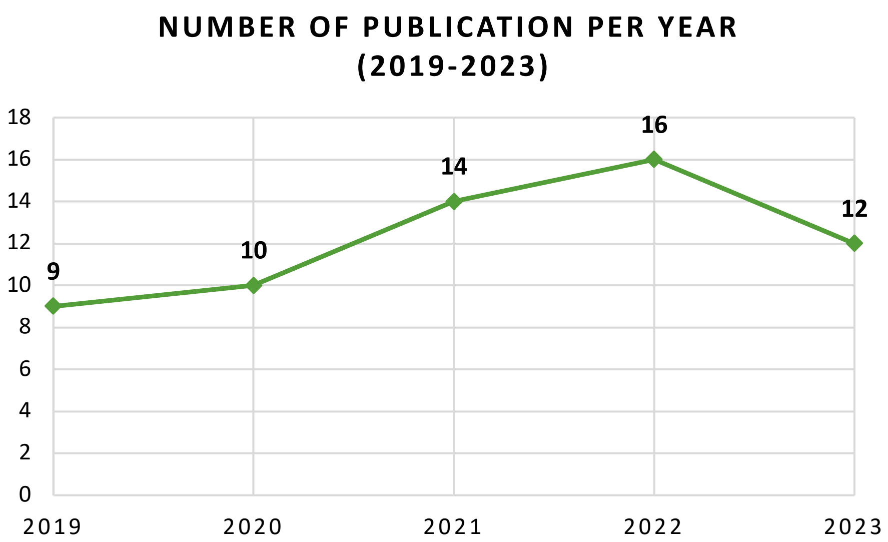
3.1 Review of Research Trends

This section is devoted to description and discussion of results emerging from bibliometric analysis of selected articles, especially useful to give an answer to the first research question, identifying evolution trends and evaluating research progress in the field of Industrial Symbiosis economic analysis. In particular, after the application of selection criteria exposed in Methodological section, the main articles' data were extracted, concerning journal and year of publication, in order to draw conclusions about the trend of research. Finally, a keywords co-occurrence analysis was conducted to deeply understand semantic relations and emerging issues, to better direct future investigations.

The following analysis comprises 61 articles included in the systematic literature review, related to economic analysis of Industrial Symbiosis and published from 2019 up to 2023. The records analyzed were written by 243 different authors, for a total of 1.069 citations.

Figure 2 illustrates publication evolution over time, starting from 2019 up to 2023.

Figure 2. Publication evolution over time, 2019-2023



Source: Authors own elaboration

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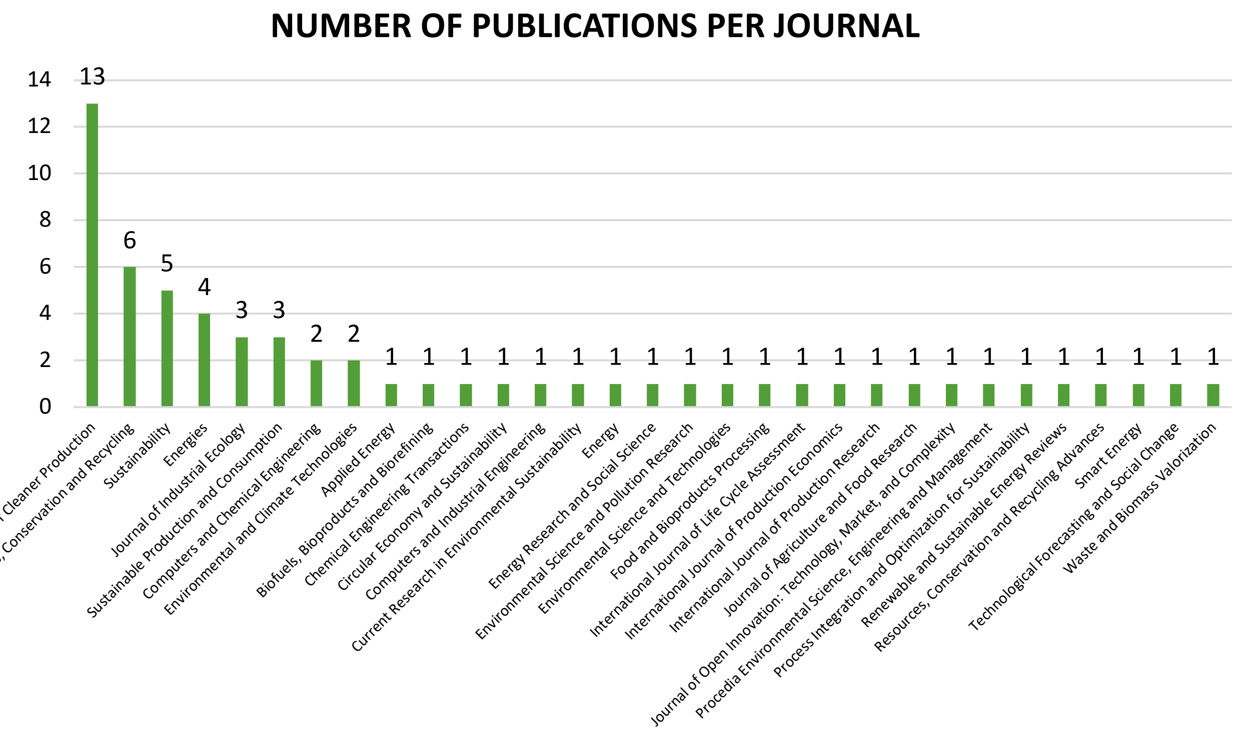
As can be seen, 2022 was the year with the highest number of articles published (16), while 2019 records the minimum of publications (9). Generally speaking, it can be noticed that the number of articles has grown steadily, reflecting an increasing interest of the scientific community that may be related to the ever-rising attention to sustainability issues and transition towards more circular production models, backed by Industrial Symbiosis within the scope of Circular Economy (Yazan & Fraccascia, 2020), for which it is relevant to assess economic feasibility, besides environmental and social implications. The growing centrality of economic issues regarding Industrial Symbiosis provides a rationale for the comprehensive recent literature systematization, conducted in this study.

Figure 3 illustrates the number of publications by journal. The 61 selected articles were collected from 31 different journals, but most appear in a few key journals.

Figure 3. Number of publications by journal



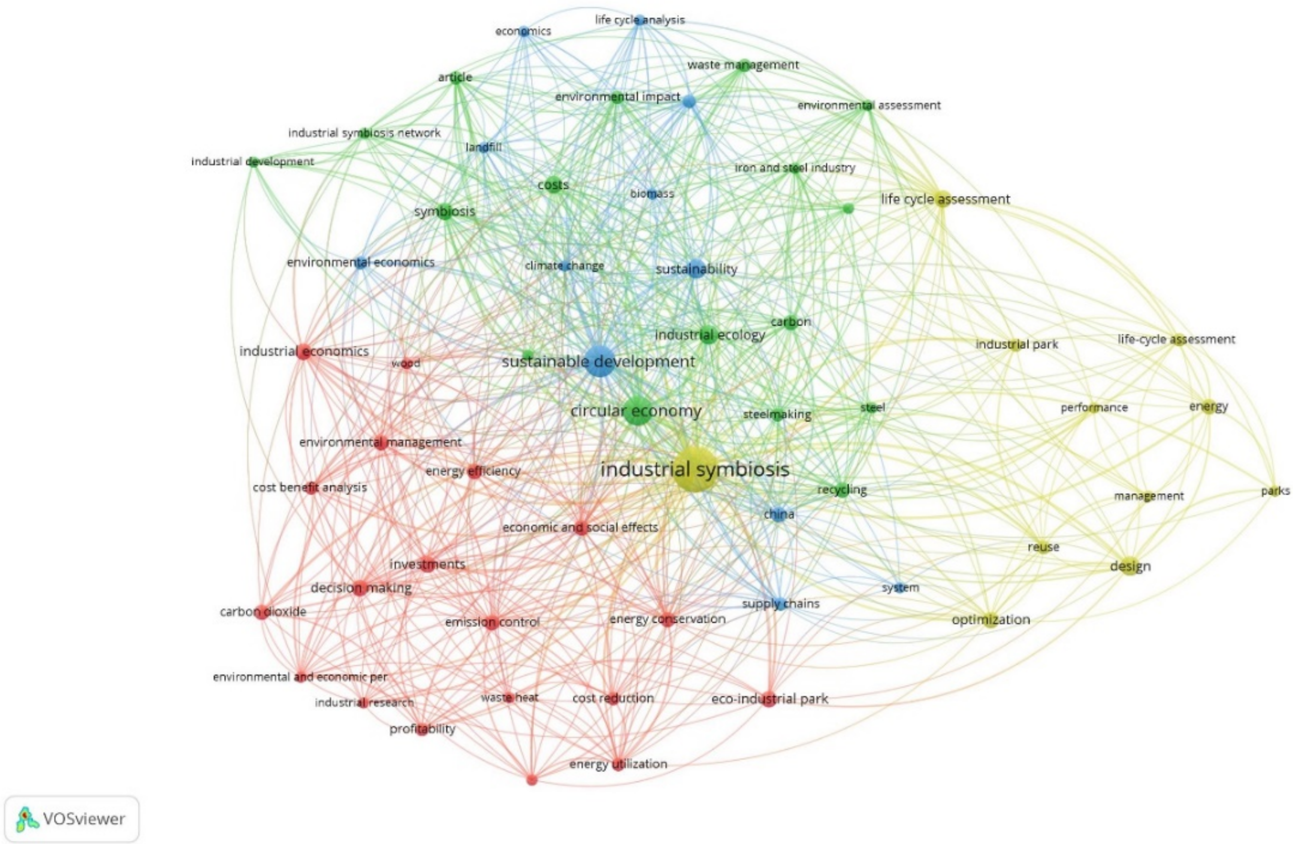
Source: Authors own elaboration

As can be seen, the distribution is not uniform: in particular, *Journal of Cleaner Production* is the most influential research journal, with 13 articles on the investigated topic, while the top 5 gather a considerable percentage of publications (nearly 51%), proving they are of special importance in Industrial Symbiosis research related to economic aspects. In conclusion, the presence of influential journals in the field of waste management, energy engineering, innovation and technology proves the interdisciplinary point of view adopted by scholars in examining Industrial Symbiosis.

VOSviewer software was then used to perform a keywords co-occurrence analysis, with the aim of enlightening hotspots and revealing most popular themes in the topic of interest. Keywords' cluster evaluation could help in the reconnaissance of semantics used for the topic, in order to understand past trends and advances in the field, and to give direction to future research. Correlations among clusters can reveal border-crossing themes and future possible links to different disciplines and research fields.

The network visualization provided by VOSviewer was created applying the "full counting" method and keeping the keywords which appeared, at least, 3 times (for a total of 59 keywords).

Figure 4. Keywords co-occurrence analysis - network visualization from VOSviewer



Source: Authors own elaboration from VosViewer

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The three most relevant keywords, linked with *Industrial Symbiosis* (number of occurrences: 45), are *Sustainable Development (*number of occurrences: 21), *Circular Economy* (number of occurrences: 19), *Industrial Ecology* (number of occurrences: 8), resulting in 2 clusters.

Figure 4 displays the keywords network split into 4 clusters. The first and largest cluster, the red one, is related to *Industrial Symbiosis outcome assessment* and it includes words like "economic and social effect", "environmental management", "cost-benefit analysis". The existence of this cluster may be motivated by the fact that evaluating the whole impact is relevant to understanding the reasons behind the spontaneous triggering of Industrial Symbiosis and also to incentivizing its implementation. The second, the green one, encompasses *Circular Economy* themes, and it is composed of words like "costs", "recycling", "waste management". The presence of keywords linked to *Industrial Ecology* justifies a particular attention devoted to interconnections between these two research domains[2], in which Industrial Symbiosis can be placed. The third, the blue cluster, is focused on *Sustainable Development* and it involves terms like "climate change", "sustainability", "supply chains"; understanding the contribution of Industrial Symbiosis to sustainable development may be the concern that led scholars focus on this topic. Lastly, the yellow cluster, though the smaller, contains words related to *Industrial Symbiosis*, which is the central research theme of this paper: "industrial park", "reuse", "design". The often concretization of Industrial Symbiosis into eco-industrial parks can validate the presence of this specifically focused topic. It is relevant to underline the connection with domains of Circular Economy, Industrial Ecology, and methodologies of impact assessment, such as "life-cycle assessment," "cost-benefit analysis," and "environmental assessment." Still, little space is devoted to consideration of social impacts, unveiling possibilities for future deepening of the subject.

3.2 Synthesis of main results

This section is devoted to description and discussion of results coming from main articles' contents and information that were deemed useful for answering research questions and building economic evaluation framework. In particular, data were extracted about research methodologies, to comprehend what calculation methods are predominant in literature for estimation of costs and benefits, industries involved in symbiotic exchanges, to understand what economic sectors could be interested, and areas of economic costs and benefits, to give direct answer to research question.

First of all, papers examined were classified into three different categories: "*Evaluation of real case studies*", focused on comparison between pre-IS – post IS scenarios, for those analysis of already implemented IS practices; "*Evaluation of symbiosis project*", oriented to the appraisal of feasibility of designed IS and/or shared facilities in a network of enterprises; "*Application on a real case-study*", for evaluation of designed IS practices applied in a real industrial context. The majority of studies involved the second category (nearly 50% of examined papers); 27% were applications on real case studies, while the remaining were evaluations of pre-IS – post-IS scenarios. This implies that there could be some difficulties in finding studies assessing implemented IS economic contribution, the generality being analysis of costs and benefits specifically attributed to a project.

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[2] Differences and commonalities between Circular Economy and Industrial Ecology were extensively explained in the *Introduction* section.

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3.2.1 Methodologies

The first content data analyzed involved quantification methodologies used for IS project evaluation carried out in the selected studies for SLR. Understanding the estimation process allowed to create a basis upon which to build an integrated and comprehensive methodology within the framework of economic analysis. For this reason, Table I illustrates principal methodologies followed by examined literature in conducting the research and quantifying IS economic costs and benefits, with a brief description and the list of references which made use of each of them.

Table I. Research methodologies analysis

METHODOLOGY	DESCRIPTION	REFERENCES
Cash flows analysis	Estimation of monetary flows of revenues and costs incurred in a period of time, on the basis of financial market prices. Values could be discounted, if they involve future potential monetary flows.	Wijeyekoon et al., 2021
Cost-benefit analysis	Estimation of revenues obtained and costs incurred in a period of time, on the basis of financial market prices. It could consider external costs, primarily environmental and social, translated into monetary terms. Values could be discounted, if they involve future potential monetary flows.	Cervo et al., 2019 Pakere et al., 2021 Sun et al., 2020 Zabaniotou & Vaskalis, 2023
Cost savings and cost analysis	Estimation of items of cost associated with a project through monetary terms; if a project involves cost reduction, then it could be an estimation of cost savings, as the difference between pre and post financial costs. Values could be discounted, if they involve future potential monetary flows.	Ali et al., 2019 Hu et al., 2020 Li et al., 2021
Profit and Net Present Value (NPV) analysis	Calculation of profit margin as the difference between revenues obtained and costs incurred in a specific period of time. Values could be discounted, if they involve future potential economic or financial flows, to calculate a Net Present Value.	Colpo et al., 2022a De Souza & Pacca, 2023 Dong et al., 2022 Hedlund et al., 2022 Kerdlap et al., 2022 Liao et al., 2024 Sheppard et al., 2019
Life-Cycle Costing	Financial evaluation of total costs of a project, from its inception through to its disposal; the conventional c-LCC involves only economic costs, while environmental e-LCC and social s-LCC also consider externalities	Ali et al., 2020 Ansanelli et al., 2023 Diaz et al., 2021 Haq et al., 2020

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		Ruiz & Diaz, 2022 Zhang et al., 2022b
Agent-based model	Simulation framework for interaction of individual entities according to defined rules. Cost saving function is often included to model agent behaviors	Fraccascia et al., 2020 Yazan & Fraccascia, 2020
Game Theory approach	Theoretical framework analyzing strategic interactions among decision-makers, in which payoffs for each participant depend on the choices of all involved. To estimate economic outcomes, profit margin or economic benefit calculations are often used.	Ahmad Fadzil et al., 2022 Chin et al., 2021 Galvan-Cara et al., 2022 He et al., 2020
Linear and non-linear programming optimization model	Mathematical technique used to optimize a function subject to a set of linear or non-linear constraints. In the case of mixed-integer or multi-integer programming models, some variables could assume integer values. Financial cost analysis often provides the economic constraint, while the optimization goal could be a profit maximization	Al-Quradaghi et al., 2022 Asghari et al., 2023 Boix et al., 2023 Bütün et al., 2019 Chatterjee et al., 2021 Farouk & Chew, 2021 Goh et al., 2022 Misrol et al., 2022 Misrol et al., 2021 Yu et al., 2023
Singular or many-objective optimization model	Optimization framework that deals with a large number of objectives, often conflicting. Economic equations involving cash flows or cost savings analysis are used as constraints or optimization objectives.	Cao et al., 2020 Fahmy et al., 2021 Lyu et al., 2023 Teh et al., 2021 Yeşilkaya et al., 2020

Source: Authors own elaboration

For clarity of analysis, research methodologies could be clustered into four macro-categories:

- *Financial evaluation models*, adopted by the great majority of studies, aim to evaluate financial and economic flows, and they are built upon quantification through market values of revenues obtained and costs incurred and/or avoided in a specific period of time. This category includes cash flows and cost-benefit analysis, though this last could also incorporate external costs, as environmental and social ones, translated into monetary terms; cost savings and costs analysis, particularly recommendable to understand reductions and cost profiles of a project; profit analysis and net present value calculation.

The temporal dimension could be taken into account by discounting financial flows and building performance indexes, as Internal Rate of Return (IRR) (Colpo et al., 2022a; Sheppard et al., 2019), Profit Index (PI) (Fahmy et al., 2021; Ruiz & Diaz, 2022) or Payback Period (PP) (Falsafi et al., 2023; Sun et al., 2020), to give a synthetic overview of economic profitability;

- *Life-cycle evaluation models*: advanced technique for quantification of total economic costs incurred all along the life cycle of a project, from its inception to its disposal. As a conventional method (c-LCC), it can be used to compare cost profiles of different projects; as a full Life-cycle Impact Assessment (LCIA), comprehensive of environmental (e-LCC) and social (s-LCC) analysis, it goes beyond economic consideration, including external costs, especially linked to eco-efficiency and environmental and social impacts (Zhang et al., 2022b), quantified by way of emission factors and technical coefficients (Ali et al., 2020; Ruiz & Diaz, 2022);
- *Decision models*: methodologies for agent behaviors simulation inside a broader network, for this reason often used in IS analysis and distribution of aggregated costs and benefits. In a game-theory model, outputs depend on cooperative approach and behavior of each participant, while agent-based models simulate actors' conduct according to different sets of rules. To model behaviors on economic reasoning, an economic-objective function, very often a cost (Chin et al., 2021; Fraccascia et al., 2020) or a net benefit (Ahmad Fadzil et al., 2022; Galvan-Cara et al., 2022) function, is included;
- *Optimization models*: frameworks for optimization of IS practices, often used in application research to existent or designed IS projects. Optimization aims at constrained maximization (or minimization) of different objectives, as frequently conflicting functions for environmental and economic goals (Cao et al., 2020; Yeşilkaya et al., 2020), expressed through cash flows analysis or financial costs (Asghari et al., 2023; Fahmy et al., 2021) and cost savings (Lyu et al., 2023) analysis.

As the final objective consisted of orientating economic evaluation framework to the most appropriate quantification methodology, this analysis led to the conclusion that a more financial focus, translating costs and benefits into monetary terms, integrated with models quantifying and optimizing external impacts all along the life cycle, beyond the mere financial sphere, is useful in obtaining a comprehensive evaluation of an IS project in its temporal range.

3.2.2 Economic sectors involved

From the analysis of economic sectors engaged in IS and circular processes, it could be stated that not all cases precisely defined type and destination of resources exchanged, and specific role (as a receiver or as a donor) of firms in symbiotic relationship. These elements turned out to be relevant, within a framework of analysis, to understand entity and subdivision of costs and benefits among resources exchange activities and agents in the network. For those articles clearly identifying exchange components, it could be observed that the principal destination (nearly 55% of cases) of resources shared, mainly biomasses, wastewater and waste heat and steam, involved production of any kind of energy (electricity, steam and heat for power production), that could be directed to an internal use or sold externally, either way contributing to economic benefit, lowering energy costs (Diaz et al., 2021; Sheppard et al., 2019; Wang et al., 2019) or as new source of revenues (Haq et al.,

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2020; Sun et al., 2020; Tan Yue Dian et al., 2021). Several studies (24%) focused on production of building materials, predominantly from slag residues, fly ashes, agro-industrial wastes and other scrap materials in the same industry.

Considering the whole number of articles examined, 34% of them explicitly outlined direct exchanges between two entities characterized as donor and receiver. Framing economic sectors through the use of ISIC[3] classification and the consideration of type and destination of wastes, analysis of direct exchanges showed that, again, the industries participating mainly as receivers were energy production and manufacturing of non-metallic products for building (43% for both), while major donors were industrial and agro-industrial sectors, especially for biowastes sharing, including domestic sector (Saeli et al., 2023). Flows of materials could engage the same industry (18% of examined articles): as example, chemical (Farouk & Chew, 2021; Lyu et al., 2023) and agrifood industry (Prieto-Sandoval et al., 2022; Raimondo et al., 2023; Yu et al., 2023), where biomasses could be turned into biological fertilizers.

A great percentage of studies (40%) focused on mutual exchanges inside industrial parks and ecological networks without an explicit definition of resource flows. Prominent examples are the agriculture and forestry sectors (Hu et al., 2020; Yeşilkaya et al., 2020), steel, iron, and cement industries (Xue et al., 2023; Zhang et al., 2022a). Inside a network, exchanges are not purely material: it is worth noting a particular study on sharing carbon permits, which led to increasing profits and overall network efficiency (Ahmad Fadzil et al., 2022).

Ultimately, economic sector analysis proved to be essential to understand main ways of interaction for symbiotic exchanges across different industrial contexts, each one with its own specificities, in order to improve flexibility of the framework for economic IS costs and benefits, highlighted by scientific literature and pointed out in the following section.

3.2.3 Cost-benefit analysis

Scientific evidence of IS economic costs and benefits was summarized in Figure 5, displaying a circular chart divided into four main sections:

- Cost reduction, as a source of economic advantage, identified by 45 examined articles (out of 61);
- New revenues, as a source of economic advantage, identified by 31 examined articles (out of 61);
- New costs, as a source of economic disadvantage, identified by 19 examined articles (out of 61);
- Revenues reduction, as a source of economic disadvantage, identified by 1 examined articles (out of 61).

It follows that, given the extracted data, cost reduction represents the most recognized IS economic implication, both by optimization application models and research on feasibility assessment.

Then, each main section of the chart is divided into all costs and revenues items highlighted by scientific literature; the size of each of them reflects the percentage number of mentions received relative to the total mentions in the domain of the corresponding main section.

[3] ISIC stands for International Standard Industrial Classification of All Economic Activities, a globally standardized system for classifying industries by a four-level hierarchy and for reporting of economic activities across countries.

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Figure 5. Cost-benefit analysis – circular chart

Source: Authors own elaboration

The most observed benefit was cost reduction (blue section of the circular graph), particularly for raw materials (34% of cost reduction mentions), waste management and disposal (32%), substantially avoided, and operating and utility costs, as costs for water and energy (Cortez et al., 2022; Diaz et al., 2021; Hedlund et al., 2022; Ruiz-Puente & Jato-Espino, 2020). This advantage was revealed both by comparative studies between IS – non-IS scenarios (Cervo et al., 2019; Raciti et al., 2019; Zhang et al., 2022b), and by optimization analysis of designed and/or already implemented IS (Al-Quradaghi et al., 2022; Chatterjee et al., 2021; Lyu et al., 2023), confirming evidence in literature about the main *raison d'être* of IS (Chertow, 2000, 2007; Colpo et al., 2022a; Lybæk et al., 2021). A small, though significant, presence of reduction in capital costs must be pointed out, confirmed by studies reporting a decrease in equipment costs as one of the economic benefits, though limited, cited by companies (Wahrlich & Simioni, 2019). This reduction in costs referred to all those cases for shared infrastructure: when it comes to highly centralized and coordinated partnerships, as within eco-industrial parks, enterprises could benefit from the provision of common services and maintenance (Fraccascia et al., 2019; Wahrlich & Simioni, 2019), while installing advanced production systems, otherwise economically not viable, on already existent plants (Goh et al., 2022; Wijeyekoon et al., 2021). Then, analysis of new revenues followed (orange section of the circular graph), first of all from sales of products (62% of new revenues mentions), mainly generation of electricity and other kinds of energy (Hedlund et al., 2022; Misrol et al., 2021; Ruiz & Diaz, 2022; Sun et al., 2020). Economic advantages from sale of waste were less reported (24%): many evaluations were based on free exchanges, which can represent an avoided cost, for receivers (Raciti et al., 2019); other studies, instead, underlined the reduced value of wastes, which sometimes is overshadowed by transportation (Borbon-Galvez et al., 2021;

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Domenech et al., 2019) or treatment costs for recycling and reusing (He et al., 2020; Saeli et al., 2023). Few studies mentioned enhanced productivity (Chen et al., 2022; Dong et al., 2022; Raimondo et al., 2023; Wahrlich & Simioni, 2019) and reputational gains (Fraccascia et al., 2019).

Cost items (grey section of the circular graph) that could impact to a greater extent, according to examined literature, were, first and foremost, capital costs (37% of new costs mentions) for equipment and infrastructure (Chin et al., 2021; Sun et al., 2020), technologies (Bütün et al., 2019) and working capital (Colpo et al., 2022a), which reflect on manufacturing and other operating costs (repair and maintenance, 20%). If it is true that costs for required equipment and infrastructure are economically unviable for single entities (Colpo et al., 2022a), other studies also highlighted the need for institutional financial incentives to face capital costs for grand coalition, more capable of obtaining significant reduction of environmental impacts (Chin et al., 2021). On the other hand, scholars pinpointed that some technologies could entail lower costs, depending on the system they are implemented in and giving rise to the need for specific considerations about the industrial sector involved (Asghari et al., 2023), while the degree of nestedness could also results in total gains balancing capital costs (Chatterjee et al., 2021). In this regard, some studies (Fraccascia et al., 2019; Sellitto et al., 2021) emphasized the presence of transaction costs, that depend on interaction among enterprises involved.

Geographic localization is an IS aspect that should be investigated carefully: main studies reporting a reduction in transportation costs were focused on proximity exchanges of material resources (Goh et al., 2022; Raciti et al., 2019; Wijeyekoon et al., 2021), while others underline the need to broaden boundaries of symbiosis to reach variegate sources of waste, despite this could have an impact on resources' quality (Borbon-Galvez et al., 2021). Even if transportation costs depend on weight and chemical characteristics of wastes, whose marginal value is close to zero (Domenech et al., 2019), shipping carriers also play an important role (Ali et al., 2019), if treated as an endogenous variable whose optimization could eventually lead to economic benefits, looking for more sustainable transport strategies (Borbon-Galvez et al., 2021). However, the great majority of studies pointed out a rise in transportation costs (27%): besides representing a limiting factor for certain types of exchange, as heat flows (Lyu et al., 2023; Pakere et al., 2021; Sun et al., 2020), distance could affect, together with capital costs, decisions about symbiotic relationships economic convenience (Chatterjee et al., 2021), hindering opportunities for IS (Sellitto et al., 2021) or its full optimization (Lyu et al., 2023; Tan Yue Dian et al., 2021).

In conclusion, revenue reduction (yellow section of the circular graph) was observed in just one case (Cervo et al., 2019) as an economic loss for traditional suppliers and other stakeholders; nonetheless, this dimension should be deepened as an indirect consequence of symbiosis practices.

These findings confirmed the complexity of interactions, supporting the objective of building a flexible and integrated framework for IS economic evaluation, which takes into consideration, as mentioned above, the industrial sector and its peculiarities. These elements proved to have an impact on the overall cost-benefit profile of IS; in fact, according to different contexts, certain items could be recorded alternatively a cost or a benefit, as the circular graph in Figure 3.4 displays for capital, transportation, recycling, manufacturing and other operating costs, and certain revenues could not be realized, as for the case

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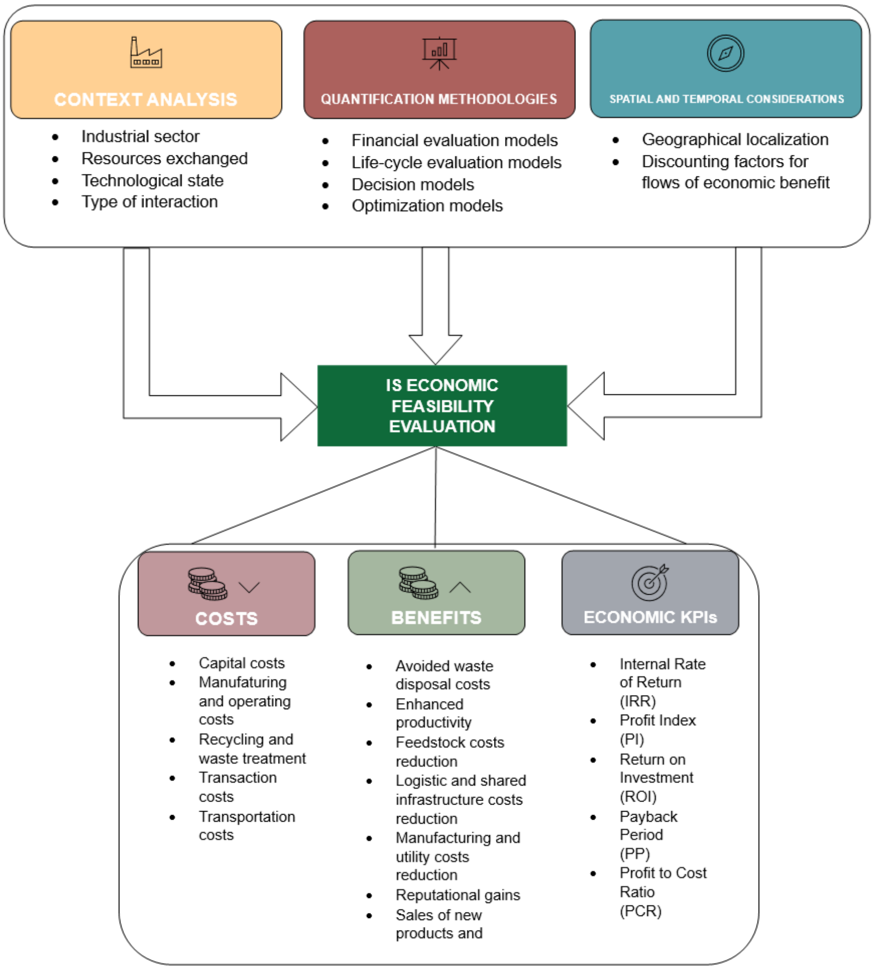
of free waste exchanges. In summary, cost-benefit evaluation must not be seen as static but rather as an evolving process influenced by externalities, exchange dynamics, and specificities of the industrial sector.

4. Discussion

Results examined in section 3.2 led to the construction of a framework for IS economic evaluation, depicted in figure 5, which implies context analysis (industrial sector and corresponding technological state, flows of resources possibly exchanged, type of interaction at the basis of symbiosis relationship), determination of proper quantification methodologies and consideration of spatial and temporal aspects, with the definition of a proper time horizon (Kerdlap et al., 2022). Economic evaluation is carried out regarding several cost and benefit items, pointed out by scientific literature, together with specific KPIs for a summative feasibility assessment and project overall vision.

Figure 5. IS economic evaluation framework



Source: Authors own elaboration

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Exchanges could involve different resources, material or immaterial: Ahmad Fadzil et al. (2002) proved how sharing carbon permits allowed for an efficient aggregate allocation, with cooperative solutions providing the greatest benefits (Galvan-Cara et al., 2022; Li et al., 2021). Optimal configurations imply an unequal realization of benefits and costs for each economic agent, so economic analysis should take into account the different roles, as receiver or donor, played by each IS participant.

Looking at calculation methodologies, financial approaches, better if implemented through the use of local accurate market values (Liao et al., 2024), should be complemented with life-cycle assessment, considering also external costs, such as environmental ones, that turned up to be paramount and worth of quantification, talking about IS cost reductions (Ansanelli et al., 2023; Haq et al., 2020; Pakere et al., 2021)

There are other kinds of aspects that need to be considered: among them, resource availability and supply security, relevant to IS location (Wijeyekoon et al., 2021), in particular when it comes to small flows of production (Cortez et al., 2022), and geographical proximity, which affects IS joining decision through transportation, infrastructure and investment costs (Ali et al., 2019; Cervo et al., 2019; Chatterjee et al., 2021; Galvan-Cara et al., 2022; Goh et al., 2022; Tan Yue Dian et al., 2021) and the possibility to exploit particular flows, as heat and steam (Pakere et al., 2021). Regarding logistic and transportation costs, some scholars argued that they could not impact positive IS overall benefit, while Borbon-Galvez et al. (2021) demonstrated that costs could even be lowered through sustainable means of transport and optimal shipping management.

Technological knowledge regarding waste treatment is also to be considered, as a barrier to IS joining (He et al., 2020): even if major benefits come from the leading ones (Farouk & Chew, 2021; Zhang et al., 2022b), some environmental-friendly techniques still seemed to be economically inaccessible, making the case for conflict between economic and environmental objectives (Cao et al., 2020; Chin et al., 2021; Yeşilkaya et al., 2020). Capital costs for advanced infrastructure and systems could both affect IS project profit in negative sense (Misrol et al., 2021), and be lowered by peculiar features of IS, such as proximity and sharing systems otherwise too expensive for a single participant (Bütün et al., 2019; Colpo et al., 2022a; Goh et al., 2022).

Scientific literature mentioned other IS characteristics preventing disruption risks but having an effect on economic outcomes: nestedness and flexibility, which could grow transaction and capital costs (Boix et al., 2023; Chatterjee et al., 2021; Fraccascia et al., 2020). Transaction costs resulted to be influenced also by trust and interaction approaches (Prieto-Sandoval et al., 2022; Yazan & Fraccascia, 2020).

This study also considered articles in the form of IS landscape analysis or industrial interviews (Cortez et al., 2022; Domenech et al., 2019; Prieto-Sandoval et al., 2022; Sellitto et al., 2021; Wahrlich & Simioni, 2019), enlightening barriers to IS implementation: proximity and procurement security, logistic costs, little knowledge and poor technological research investments, social reluctance, lack of adequate infrastructure and institutional support, also in the form of financial incentives, that proved to be essential, in certain cases, to face high capital costs (Chin et al., 2021; Haq et al., 2020).

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5. Conclusion

In a context of growing concern about industrial systems' unsustainability, it is paramount to assess the economic advantages of the transition towards circular models of production, as well as to incentivize more efficient solutions that could match sustainability objectives from an economic, environmental, and social point of view (Bocken et al., 2014). This study presented results of a systematic literature review for the last five years of research into IS economic feasibility. Bibliometric analysis allowed to notice an increasing interest in the topic, besides thematic connections' structure. Investigations brought out quantification methodologies, analysis of economic sectors involved and cost and benefit items, upon which an IS economic evaluation framework was built and commented in *Discussion* section. To sum up, some critical considerations about typologies of articles analyzed, in order to shape limitations and possible improvements. Main sources of costs and revenues, outlined in the framework, were deemed as the most considered in economic feasibility evaluation studies; by contrast, few studies were found on comparison between IS – non-IS scenarios (Ansanelli et al., 2023; Cervo et al., 2019; Galvan-Cara et al., 2022; Kerdlap et al., 2022; Li et al., 2021; Yu et al., 2023; Zhang et al., 2022b), most of all useful for a full comprehension of symbiosis contribute to economic benefit. Studies focused on optimization of productive models stressed out the presence of economic–environmental objectives trade-off (Cao et al., 2020; Chin et al., 2021; Fraccascia et al., 2020; Yeşilkaya et al., 2020), that could be mitigated by an integrated costs analysis, including environmental and social externalities, for a more comprehensive overview of IS economic impact. It is reiterated the need to adapt the framework to the specific industrial case and its peculiarities, from a technological, economical, sociocultural and normative point of view, though it could represent a good starting point for firms interested in economic consequences of IS cooperation.

5.1 Main contributions and practical implications

Given the lack of consideration and proper quantification of economic aspects of IS (Domenech et al., 2019; Dong et al., 2022; Wadström et al., 2021), this study contributed to filling the knowledge gap by systematizing recent literature on the topic of areas of IS economic outcomes and outlining integrated alternative methodologies for a preliminary approach to the quantification of IS impacts that result in costs and benefits beyond the mere market value sphere, providing a different perspective to evaluate financial flows of IS projects. Moreover, a dedicated support tool for IS economic viability was built, with the innovative ability to conciliate different features, from context analysis to calculation methodologies with spatial and temporal considerations, enhancing the implementation of IS activities by identification of cost and benefit items that could generate positive outcomes for companies involved. Though based on a solid and scientific protocol for literature analysis, this research constitutes a first and general step in the research field, limited by the lack of attention to environmental and social externalities' consequences and other kinds of implementation barriers that could generate an impact on IS joining decision.

5.2 Research limitations and future research agenda

Despite being accurately based on a well-structured search process, some methodological limits still exist. First, adopting Scopus and Web of Science databases for the last five years of research may restrict the potential number of articles in the

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sample. To prevent excluding relevant scientific contributions, other search databases should be used, as well as expanding the temporal range. Second, quality appraisal turns out to be inevitably afflicted by elements of subjectivity in judgment, which could be potentially lowered by more rigorous methods. Last, the use of selected keywords might restrict the scope of research conducted; a new analysis should be performed with another search string.

The economic evaluation framework is based on economic costs and benefits affecting firms directly and independently from the different roles played by participants. Future research agenda includes a wider focus on supra-enterprise network consequences, also quantifying environmental and social impacts in economic terms to find an IS cost-benefit distribution model encouraging an equal realization of benefits and costs for each economic agent and a continuous participation in an innovative business model for ecological industrial transition.

4. Conflict of Interest

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

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