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Systematic Review

Business Models for Industrial Symbiosis: A Literature Review

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Abstract: In recent years, companies have tried to implement various strategies focused on sustainability that impact the way they do business. This is how industrial symbiosis, which is a collaborative approach that favors the exchange of material, infrastructure, and energy resources that create economic and environmental benefits, arises. The implementation of industrial symbiosis is complex and requires collaboration and knowledge. Although there are empirical studies in countries where it has been developed, thus far, there has been no study integrating the advances in knowledge about industrial symbiosis. The main objective of this study is to become familiar with the current state-of-the-art industrial symbiosis and its business models in order to identify areas of opportunity and knowledge gaps. Through a bibliometric analysis and a systematic review of the literature, a codification of the dimensions and categories of the literature was carried out, identifying various tools, as well as theoretical models, simulation models, and business models designed to implement and evaluate a transition toward industrial symbiosis. The results indicate that the most studied variables are the material flow and the possible strategies that companies can adopt to move toward industrial symbiosis. However, there is still a need to go deeper into the study of cultural transformation, the ideal mechanisms to record and exchange information, and what negotiations are required to encourage collaboration.

Keywords: industrial symbiosis; sustainable business models; analytical tools; circular economy; material flow; collaboration; literary review

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1. Introduction

According to Osterwalder and Pigneur [1] (p. 14), a business model "*describes the rationale of how an organization creates, delivers and captures value.*" With this tool, companies can generate strategies, manage collaborative activities, and include technological tools to trigger innovation while configuring their businesses models to create competitive advantages and obtain economic benefits [2]. Sustainable innovations also require tools that facilitate the transition to a sustainable business strategy by adopting a business model perspective. Bocken et al. [3] (p. 44) define business model innovations for sustainability as "*Innovations that create significant positive and/or significantly reduced negative impacts for the environment and/or society, through changes in the way the organization and its value-network create, deliver and capture value or change their value propositions.*" The proper use of infrastructure, material, and energy resources, as well as waste reduction, are needs that companies have identified to create strategic advantages that are focused on sustainability and are impacting the way they do business. This is how concepts such as the following arise: (a) the circular economy, preserving goods and supplies for as long as possible through multiple cycles of production and consumption [4]; (b) circular ecology, which uses natural principles in industrial systems to minimize their impact on the environment [5]; and (c) industrial symbiosis, as defined by Agudo et al. [6] (p. 198) as "*the economic exchange of material flow, resources and residual waste in a multiple, collaborative network facilitated by trust, available information and existing stimuli.*" Fraccascia et al. [7] affirm that companies can follow the industrial symbiosis perspective by implementing various business models; however, selecting the best will be determined by technical, economic, and strategic factors. Industrial symbiosis has been proven to create a possible competitive advantage for companies, but the time spent and the costs associated with the implementation and long-term development are perceived as more complex than the impact created once it is translated into economic and environmental benefits. This has limited its application.

The business model allows companies to generate innovation strategies to create value for their customers. If we also intend to generate sustainable innovations, there is a wide literature focus on circular economy; however, due to the fact that industrial symbiosis requires collaboration between companies for this to be triggered, it is important that they understand their business model in order to later identify opportunities for collaboration with other companies that will allow them to move toward industrial symbiosis and create shared value. However, this is not the only aspect to consider, because, by including digital information as a result of strategic changes, business processes can be influenced [8] to identify actions in order to modify and improve services based on the information obtained, making them more resilient to unforeseen changes [9]. By offering new services, participants in symbiotic chains find new ways to co-create value by gaining new competitive advantages, and, not only that, but this new information can help to clarify production and supply chain problems [10] and favor the exchange of waste, such as equivalence problems and dependency between companies. Since we are conducting a bibliometric analysis and a literature review, through this research we want to provide a description of the existing literature on industrial symbiosis and its business models in an integrated way in order to obtain a global vision and discover how industrial symbiosis evolves and adapts to the needs of the environment where it is implemented. Given its relevance, and the fact that it is a new area of study with few empirical cases, there is a need for a document that synthesizes both the state-of-the-art industrial symbiosis and the many gaps to be addressed from business models for industrial symbiosis.

The main objective of this study is to identify what tools have been developed to facilitate the transition toward industrial symbiosis, their design and implementation, and what results have been reported, thus consolidating the set of existing knowledge on the subject. For academics, this research may inspire us to study other processes that are relevant to the implementation of industrial symbiosis from other perspectives, such as (a) the types of incentives and collaborative activities that motivate companies to create innovation in a value chain through industrial symbiosis; (b) what the best way to disseminate knowledge and interest in industrial symbiosis is; and (c) how to ensure the inclusion of different industries by increasing resilience. Practitioners can use the findings to choose among the different tools, strategies, and business models depending on their objectives, needs, and partners' profiles, facilitating their transition toward industrial symbiosis.

This document is structured into five sections. Section 1 presents the research context. Section 2 explains how the literature and processes were examined for analysis. Section 3 shows how the studies were classified from the codification that was performed. Section 4 discusses the findings, and Section 5 shares the conclusions and contributions to this area of study.

2. Framework for the Systematic Literature Review

Systematic literature reviews are used to aggregate, organize, and evaluate existing scientific production and, when they are combined with bibliometric analysis, this allows for the measurement, evaluation, and analysis of the impact of studies in collaborative networks [11].

In order to expand our knowledge of a specific topic or concept, it is necessary to review the previous work, as well as the depth of the studies carried out. To make this possible, we used the systematic review process that was proposed by Xiao and Watson [12] and the bibliometric analysis proposed by Donthu et al. [11], Ikpaaqhindi [13], and Arencibia-Jorge et al. [14], which is described in Figure 1.

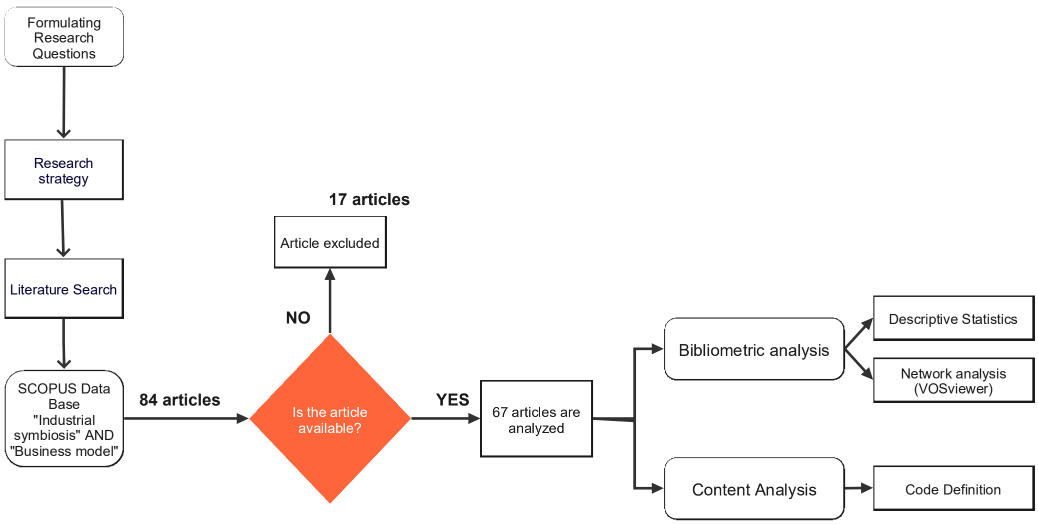


Figure 1. Systematic Literature Review and bibliometric analysis Process.

Research Questions:

RQ1. What are the main research topics, authors, and journals?

RQ2. What other concepts related to industrial symbiosis and business models have been analyzed?

RQ3. What methodologies and types of research are used most often?

RQ4. Who are the most analyzed study subjects?

RQ5. Which industries are most researched?

RQ6. From what perspectives have industrial symbiosis and its business models been approached?

RQ7. What is the geographical focus of the literature?

RQ8. What are the main barriers and facilitating factors for the implementation of industrial symbiosis?

Develop and Validate the Review Protocol

The defined methodology for conducting this study was bibliometric and content analysis using the SCOPUS database and the VOSviewer V. 1.6.18 and Atlas.ti software V. 23.1.1.

Literature Search

The search criteria were the title, abstract, keywords, as follows: "industrial symbiosis" AND "business model" [TITLE-ABS-KEY ("business model" AND "industrial symbiosis")]. No chronological restriction was included. The search resulted in 84 articles that were published in 38 journals between 2014 and May 2023.

Criteria for Inclusion/exclusion

After an initial examination, 16 articles were excluded because they were conference memoirs or were not available, which left 66 for review, identifying 274 authors. A list of the documents analyzed is available in Supplementary Materials.

Extracting Data

Bibliometric analysis consists of a series of techniques to describe the written information process and the most prolific authors related to specific topics [13]. First, we carried out an analysis of the evolution of the publications by year, which facilitated the identification of the journals in which they were published, the years with the most research, and their distribution over time. In the next step, we made a list of the authors whose articles were the most cited, the journals where they were published, the subject of analysis, the number of times cited, and their country of affiliation.

Analyzing and Synthesizing Data

To assess the impact of the articles, we included a network analysis using the VOSviewer software V. 1.6.18 from the exported SCOPUS database, including all bibliographic data. The networks that were analyzed were as follows: (a) a network of co-occurrence of keywords among articles; (b) the co-occurrence of keywords in the abstract of the article and the most-cited authors; (c) a network of co-authorship based on country and citation; and last, (d) co-citation among documents indicating the degree of similarity in the references used in the articles. These analysis techniques allowed us to evaluate the evolution of knowledge and its relationship among concepts [14].

For the content analysis, the articles included in the sample were registered on the Atlas.ti software V. 23.1.1. Our first analysis was for the co-occurrence of words with a minimum count of one thousand per document, including only adjectives, verbs, and nouns as the selection criteria. To visualize the information and analyze the degree of similarity among variables, we applied the dendrogram method [15], using Bibliometrix software [16], for the analysis of the documents based on the titles from the literature. Multiple correspondence analysis with the five-cluster method parameters have been adopted for analysis. The next step was to classify the publications according to an adaptation of the methodology used by Carvalho et al. [17] and Homrich et al. [18] for the codification of content analysis, generating the following four major classifications: research method, level of analysis, perspective, and focus. Table 1 shows the codes that were used to classify the articles, and Table A1 shows how the articles were classified according to this code. Two subclassifications were made, with the first referring to conceptual research, which in turn was divided into a literature review for those articles that only focused on the concepts or theoretical frameworks and the simulation or theoretical models for those articles that presented a theoretical–practical proposal or a simulation of scenarios. The second classification focused on the information collection method, i.e., whether the selected method was a survey, case study, or interview.

Table 1. Codification of the dimensions and categories analyzed.

Research Method	Focus	Perspective	Level of Analysis
Conceptual Research	E1—Strategy and Business	P1—Knowledge and Information	L1—Micro
CR1—Literature Review	E2—Diagnosis and Assessment	P2—From the Consumer	L2—Meso
CR2—Simulation or Theoretical Models	E3—Transformation and Implementation	P3—Material Flow	L3—Macro
Empirical Research	E4—Information Technology	P4—Policies and Fiscal Strategies	
ER1—Survey			
ER2—Case Study		P5—Systemic Vision	
ER3—Interview			

For the classification of the approach, the following was determined: (1) the strategy and business for those articles that included successful factors in the implementation of industrial symbiosis; (2) the diagnosis and evaluation for research focused on tools for obtaining data and information; (3) the transformation and implementation for case studies that evolved in their processes or business models; and (4) information technologies for studies that involved access and exchange of data through software and hardware.

The perspective classification was used to determine what the object of study was, selecting the following five options: knowledge and information, the consumer's point of view, the material flow, the fiscal policies and strategies, and the systemic vision.

The last classification, level of analysis, was based on the theoretical context of the three levels of Nikolau and Tsagarakis [19]. The first level, micro, refers to a company in particular. The meso level refers to collaboration between companies, and the last level, macro, implies collaboration at a regional, city, or country level. The results of the classification of the articles are concentrated in Appendix A, which makes it easier to visualize the object and the study method.

Once the articles were classified based on the generated codification, we compared the contribution of each author who proposed theoretical models, simulation models, or tools to be developed, implemented, or to represent industrial symbiosis mechanisms and their business models, including the purpose for which they were created (Table 2). The case studies were also analyzed in order to identify the types of industries that were most studied, the countries in which the research was carried out, and the topics of analysis.

Table 2. Authors with the Most Publications on Industrial Symbiosis and Business Models.

Authors	Number of Publications	Country	Title
Fraccascia	3	Italy	The industrial symbiosis approach: A classification of business models [20]. Business model for industrial symbiosis: A guide of firms [7]. Business model for industrial symbiosis: A taxonomy focused on the form of governance [21].
Aid	2	Sweden	Looplocal—a heuristic visualization tool to support the strategic facilitation of industrial symbiosis [22]. Expanding roles for the Swedish waste management sector in inter-organizational resource management [23].
Angelis-Dimakis	2	Greece–UK	SWAN platform (a digital Solid Waste reuse plAtformfor BalkaN): A web-based tool to support the development of industrial solid waste reuse business models [24]. Waste management and the circular economy in Cyprus—The case of the SWAN project [25].
Koreevar	2	The Netherlands	Re-organise: Game-Based Learning of Circular Business Model Innovation [26]. Industrial Symbiosis: towards a design process for eco-industrial clusters by integrating Circular Economy and Industrial Ecology perspectives [5].

3. Outcomes

3.1. Main Topics of Research, Authors, and Journals

To answer the first research question, Figure 2 shows the evolution of the number of publications per year, with 2014 having the oldest publication in SCOPUS and 2022 being the year with the highest number of publications. It is important to highlight that 73% of the sample was published from 2018 to 2022, which speaks of a substantial increase in interest in the specific topic of the business model for industrial symbiosis, since both of these constructs were first published in 1968 and 1965, respectively. The journals with the highest number of publications are the *Journal of Cleaner Production*, with 11 publications, and *Sustainability* from Switzerland, with 8 publications, which represents 28.36% of the information that was analyzed. These are followed by *Procedia Environmental Science, Engineering, and Management* (Procedia ESEM), with 5.97%; the *Journal of Industrial Ecology; Procedia Resources; Conservation and Recycling* (Procedia CIRP); *Sustainable Production and Consumption*; and *Resources, Conservation, and Recycling*, all with 4.47%. These journals are focused on environmental and sustainability issues, rather than on business and/or entrepreneurship, in general (Figure 3).

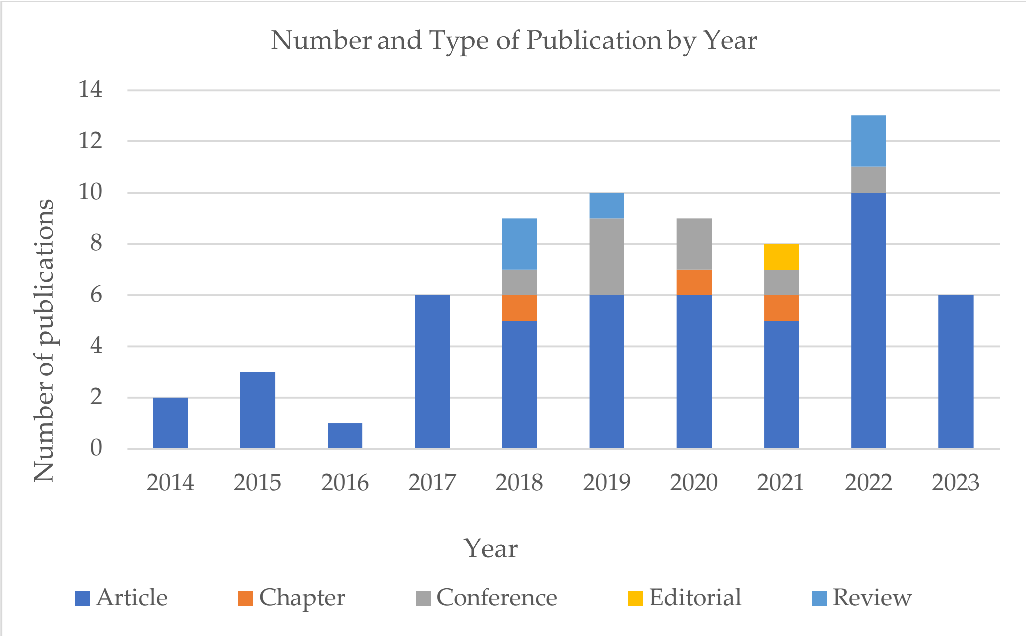


Figure 2. Number and Type of Publication by Year.

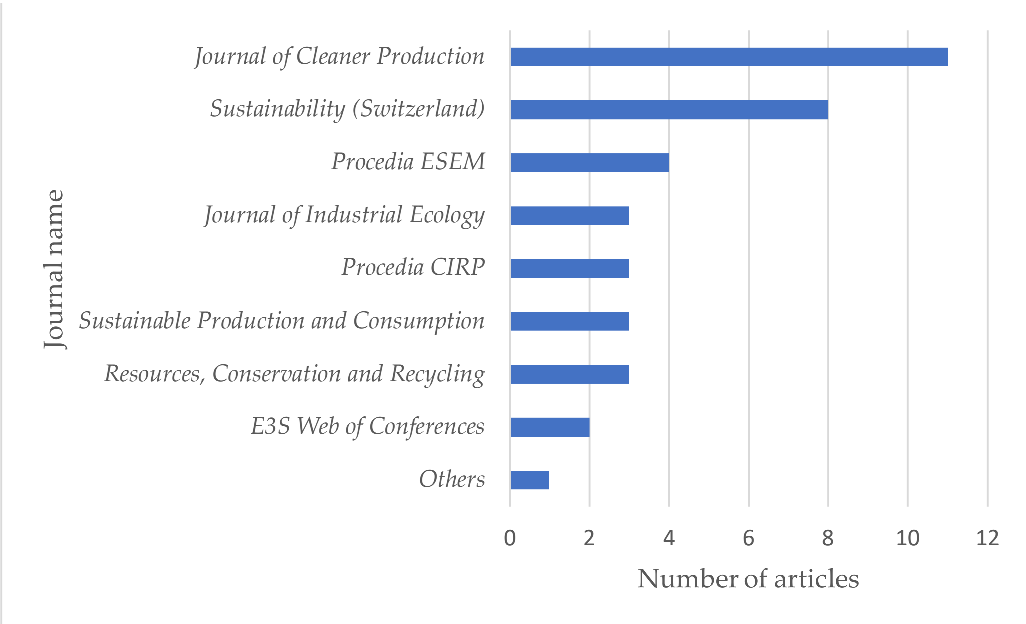


Figure 3. Number of Articles by Scientific Journal.

The author with the highest number of publications is Fraccascia L. [7,20,21] of Italy, who established a classification of business models that companies can adopt to implement industrial symbiosis, obtaining economic benefits and creating value from a business or systemic perspective. Aid G. [22,23] from Sweden, Angelis-Dimakis A. [24,25] from Greece and the United Kingdom, and Koreevar [5,26] from The Netherlands are in second place among the authors with the highest number of publications on the subject. Aid G. [22] developed a tool to strategically facilitate the implementation of industrial symbiosis, identifying the best possibilities for creating networks, exchanging flows, and informational needs, as well as the main obstacles and opportunities for a successful transition while exploring new business models [23]. Angelis-Dimakis A. [24] created a platform to assess the possible opportunities for industrial symbiosis from industrial solid waste, as well as its classification and exchange options, presenting a case study that identified and evaluated business models for the implementation of symbiotic chains between four countries [25]. This confirms that most related studies have been conducted in Europe (Table 2).

The most cited article is Merli et al. [27], with 565 citations, which broached the subject of the state-of-the-art of circular economy. Next is Homrich et al. [18], with 347 citations, which presented a general panorama of the circular economy, its evolution, and the existing gaps. The definition of symbiosis from the perspective of a circular economy and industrial ecology, with 158 citations, belongs to Baldassarre et al. [5]. Short et al. [28] established new proposals of value, starting from industrial symbiosis, and Walmsley et al. [29] proposed a multidisciplinary approach for the creation of innovative business models that included the circularity of flows in industrial processes. Each of these were cited 87 times. On the other hand, Kim et al. [30], with 78 citations, presented a case study on industrial symbiosis and the importance of representing the potential of economic and environmental benefits in the business model. Table 3 includes a summary of the authors and their contributions to science. The network of collaboration for the creation of scientific articles among countries was carried out through an analysis of co-authorship by countries with at least one article and one citation. Italy remains the most important.

Table 3. Most-Cited Authors and Their Contributions to Science.

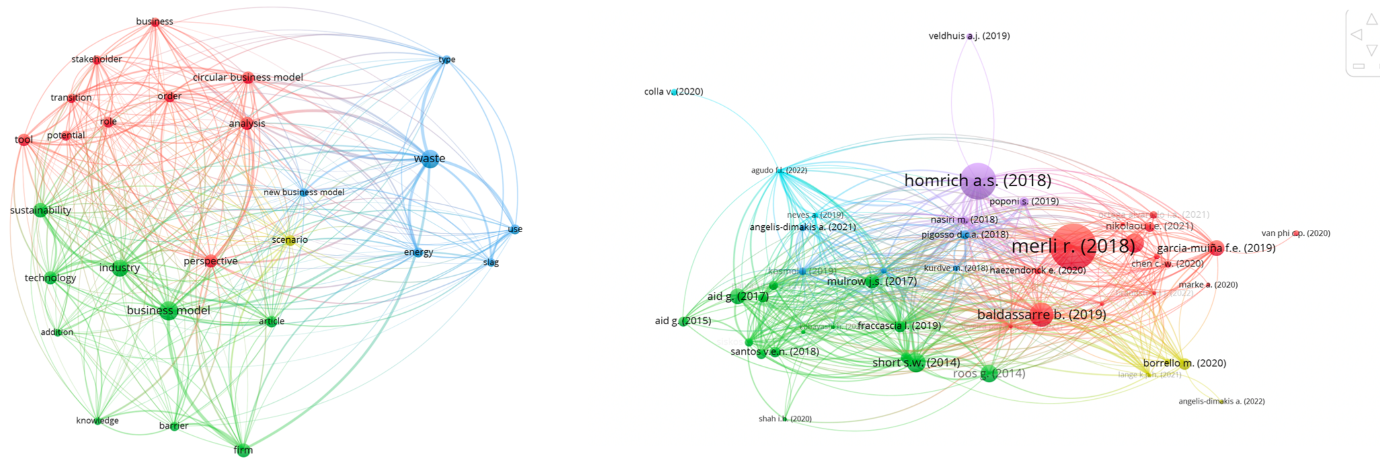
Title	Authors	Times Cited	Contribution
How do scholars approach the circular economy? A systematic literature review.	Merli et al. [27]	565	This article analyzes the literature on the circular economy in order to discover its state, concluding that it is an evolving concept that has not yet been defined, where most of the studies recommend tools and methods for implementation and the proposed business models do not represent the totality of the creation of value that circular economy raises, such as the collaborative economy, the circularity of resources, products as services, etc.
The circular economy umbrella: Trends and gaps on integrating pathways.	Homrich et al. [18]	347	The main contribution of this article is the analysis of the different dimensions of the circular economy that have not yet been fully included in the studies that have been carried out, such as legislative, institutional, and cultural aspects, as well as the different types of business models, as a way of generating new opportunities to evolve toward a circular economy.
Industrial symbiosis: towards a design process for eco-industrial clusters by integrating circular economy and industrial ecology perspectives.	Baldassarre et al. [5]	158	This article presents the definition of industrial symbiosis from the perspective of the circular economy and industrial ecology, concluding that they are complementary, since one focuses on a business vision and the other on the triple impact generated over time, proposing a process to facilitate the strategic design of industrial symbiosis clusters.
From refining sugar to growing tomatoes: Industrial ecology and business model evolution.	Short et al. [28]	87	This article creates new value propositions from industrial symbiosis and experimentation with new business models in order to create new value propositions and accelerate the transition toward sustainability.
Circular integration of processes, industries and economies.	Walmsley et al. [29]	87	This article proposes a multidisciplinary approach for the circular integration of material flow in industrial processes, creating innovative business models.

Table 3. *Cont.*

Title	Authors	Times Cited	Contribution
Co-benefit potential of industrial and urban symbiosis using waste heat from industrial park in Ulsan, Korea.	Kim et al. [30]	78	This article presents a methodology to identify opportunities for industrial symbiosis that best represents the creation of value by evaluating them, beginning with the economic, environmental, and social impact, using the business model as a way to explore how to enhance the sustainability of the stakeholders involved.

3.2. Concept Analysis and Keywords

In the analysis of networks with a co-occurrence of keywords, we found that “perspective”, “business model”, and “waste” are the words that were repeated most often, allowing us to infer the importance of the impact of waste on business models (Figure 4a). The network analysis generated to identify the similarity of cited references between the articles (Figure 5) shows four main clusters that group the authors who study the same concepts [14], and how, in the complete sample studied, the research and findings made by Merli et al. [27] and Homrich et al. [18] are cited as references of the school of thought on the circular economy, similar to how Baldassarre et al. [5] and Nikolaou and Tsagarakis [19] are references on industrial symbiosis from the perspective of the circular economy and industrial ecology.



(**a**) (**b**)

Figure 4. Using the VOSviewer software V.1.6.18, we analyzed (**a**) the co-occurrence of keywords for “industrial symbiosis” and “business model” in the summary of the articles and (**b**) the co-citation among documents.

Figure 5. Number of Most Common Words in the Documents Using Atlas.ti Software V.23.1.1.

The content analysis through the word cloud (Figure 5) showed that "waste" was the most mentioned word in all of the documents in the sample, which implies that most of the studies focus their research on waste and how to take advantage of it. For this reason, the material flow and the resource perspectives were included in the codification for the classification of articles (Table 1). Other concepts, identified as "production", "process", "model", "product", "energy", "environmental", "cost", and "value", among others, are related to the industrial production processes, the use of supplies, the energy required, and its impact on the environment and on industry costs [20,24,30–36]. However, terms that could be related to the required investment or fiscal incentives, with technical aspects and required infrastructure, and above all, with organizational aspects such as knowledge, information exchange, trust, collaboration, and shared vision, were not identified. The purpose of industrial symbiosis is to make both an economic and environmental impact. However, within the word cloud and the network of co-occurrence of words in the abstract, terms related to social impact, such as the creation of jobs, social recognition, or the development of human capital.

The main objective of the dendrogram is to show the similarity between the documents [37], identifying five clusters related to the following aspects: (a) creating innovation; (b) sustainability manufacturing; (c) tools for industrial symbiosis in eco-parks; (d) a sustainable business model; and (e) waste and future opportunities (Figure 6).

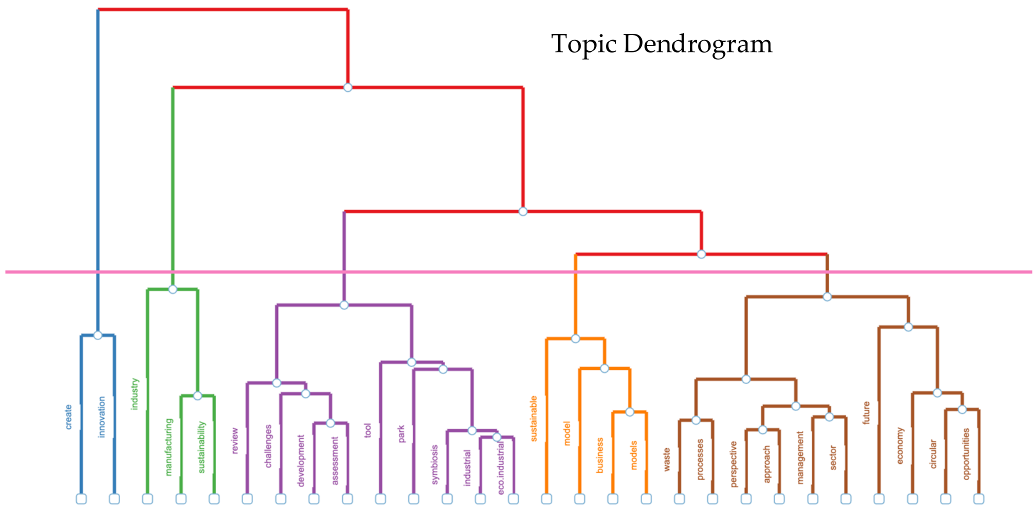


Figure 6. Dendrogram generated for the database of SCOPUS created by Bibliometrix software based on the title of the literature in "business model" AND "industrial symbiosis".

3.3. Methodologies and Types of Research

The results in this section are presented according to the codification in Table 1, describing the process of evaluating the material and the selection of categories carried out from a deductive analysis, first presenting the category selection, perspective, research methods, tools developed, and the level of analysis according to the interactions among the actors involved.

Through a review of the literature, the articles were classified according to their contribution to science. A total of 64% of the sample proposes theoretical models that try to explain the phenomenon of industrial symbiosis, 24% of the sample analyzes cases where the generated industrial symbiosis serves as a source of research on the evolution and benefits obtained from its implementation, and 20% of the sample reviews the literature comparing the different definitions [27,38,39], tendencies, and study opportunities [18]. Even though there has been research on how many studies have been carried out on industrial symbiosis from the perspectives of energy efficiency [40], the exchange of information and knowledge [41], cases in the United States [42] and in Africa [43], and studies performed on industrial symbiosis with the three levels of analysis [19] contributing new findings on the subject were also included.

The articles were analyzed according to the research methodologies that were used, finding quantitative, qualitative, and mixed research methodologies. The research approaches used were primarily case studies, interviews, and surveys. For the conceptual research, they used a review of the literature, summarizing previous publications and theoretical or simulation models, developing empirical tools to evaluate and develop industrial symbiosis and how to represent it in a business model.

3.4. Objects of Study

Given that the largest number of investigations are focused on the study of material flow and waste, different tools and models were identified with the purpose of analyzing and evaluating the quality and quantity of possibilities of the exchange of flows from one entity to another in order to increase and slow down circularity. Brändström and Eriksson [44] proposed a measurement to assess the efficiency of material flow with different impacts on the business model. Agudo et al. [6] developed a tool to diagnose the preparation for industrial symbiosis. Angelis-Dimakis et al. [24], using a technological platform, identified possibilities for industrial symbiosis between companies and/or regions, recommending innovative business models and evaluating financial viability and technical feasibility. Mochalova and Sokolova [45] focused on the use of waste from the mining industry. Kim et al. [30] developed a methodology to evaluate alternatives to material flow exchange and steam in industrial parks, Santos and Magrini [46] performed this in a refinery, and Aid et al. [22] identified the potential of a certain region. Baglio et al. [47] presented a process to recover heavy and precious metals to be sold in the future. Kobayashi et al. [48] proposed a methodology to calculate the lifecycle of flows, and Garcia-Muiña et al. [49] used eco-design to create symbiotic supply chains.

One of the benefits of industrial symbiosis is the generation of economic returns. There are different tools to determine them. Giunta et al. [31] developed a tool to find the optimum break-even point at which the cost of managing, transporting, and recovering materials would imply a minimum energy consumption and CO_2 output, matching the income from the sale of the products. Another tool that allows us to identify the optimal combination of economic benefits and cost savings based on different scenarios of collaboration and resource sharing using the business model as a persuasion tool and negotiation between companies was created by Tan Yue Dian et al. [32]. Mulrow et al. [34] presented exclusive plans of shared facility services that help with the success of industrial symbiosis.

Implementing industrial symbiosis is a difficult task, even more so when how to integrate it into the business model is unknown. To remedy this shortcoming, Fraccascia et al. [7] proposed a guide to identify possible business models depending on the needs of the companies, proposing strategies that can be implemented—from the waste generated—to replace supplies or for the generation of new products [20], in addition to taking into account the role that they have in the system.

Oliveira Pavan et al. [33] proposed two business models focused on the generation of energy, while Marke et al. [50] suggested how to utilize electronic waste. Lange et al. [35] presented a dynamic model to identify a symbiotic network with greater possibilities of success. Braun et al. [51] adapted the Canvas business model to include the circular economy as a strategic design tool and decision making as options.

The combination of different disciplines, such as industrial ecology, processes, and the circular economy, served as inspiration for Walmsley et al. [29] to create a circular integration tool to find the best solutions available that minimize the consumption of resources and energy.

Figure 7 shows the approach that companies might select. These tools and simulation models provide different possibilities to companies that are interested in evolving toward industrial symbiosis, since it allows them, from different points of view, to integrate the aspects to be considered, how to evaluate them in terms of their economic viability or environmental impact, and how it affects the business model and the different stakeholders. Table 4 presents a summary of the tools, and Table 5 presents the theoretical and simulation models identified here.

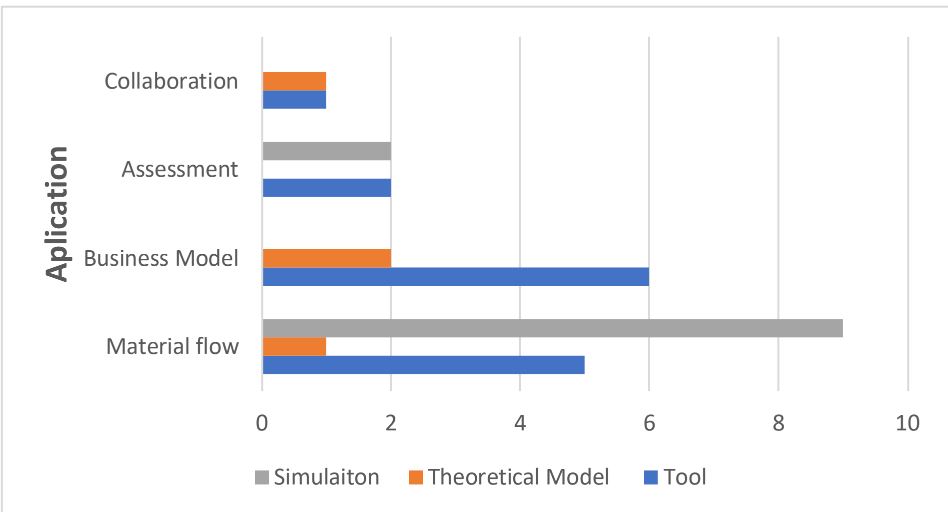


Figure 7. Types of Tools and Theoretical or Simulation Models.

Table 4. Main Tools Oriented toward Industrial Symbiosis.

Tool	Application	Methodological Focus
Material Flow	Tool that helps measure the circularity of material flow, its longevity, and its efficiency using different business strategies [44].	Metric based on material flow (Quantitative)
Material Flow	Tool that identifies the possibilities of industrial symbiosis and its representation of business models evaluating the financial viability and technical feasibility from industrial waste [24].	SWAN Platform (Mixed)
Material Flow	Tool that assesses symbiotic supply chain alternatives [49].	Eco-Design Impact Assessment (Mixed)
Material Flow	Tool that analyzes and identifies the combination of industrial waste with the lowest recovery cost, lowest environmental impact, and greatest economic benefit to be used in the generation of energy and/or in the creation of new business models [31].	Evaluation and classification of industrial waste (Mixed).
Material Flow	Tool used to analyze the potential of a region to establish symbiotic relationships between companies through the exchange of material flow and energy [22].	Looplocal Tool (Quantitative)
Assessment	Checklist that evaluates a company's readiness level to begin industrial symbiosis practices [6].	Symbiotic Readiness Checklist (Mixed)
Assessment	Tool used to measure the environmental impact generated by a symbiosis model [36].	Impact Assessment (ISO 14044) and methodology 2002 (Quantitative)
Collaboration	Roadmap for the development and regional implementation of industrial symbiosis and the required commitment of each stakeholder to achieve it [52].	Matrix for the development of industrial symbiosis (Mixed)
Business Model	Business model template that includes different strategies for the circular economy and industrial symbiosis, relating them to other blocks of the business model to easily identify new proposals [51].	Template to develop circular business models (Quantitative)
Business Model	Tool used to create different business models from electronic waste and the barriers and enablers of its implementation [50].	Circular business models for electronic waste (Quantitative)
Business Model	Strategies focused on implementing business models from the perspective of industrial symbiosis at the company level [7].	Business models for industrial symbiosis (Mixed)
Business Model	Tool to quantify the creation and capture of value among companies that implement industrial symbiosis, proposing a classification and strategies to develop business models from the system's perspective [21].	Business models for industrial symbiosis: system perspective (Quantitative)
Business Model	Strategies focused on implementing business models for industrial symbiosis in companies that produce or use waste, generating economic benefits [20].	Business models for industrial symbiosis (Qualitative)
Business Model	Survey that facilitates innovation in business models through circular value chains [53].	Guide to innovation in business models (Qualitative)

Table 5. Main theoretical and simulation models oriented toward industrial symbiosis.

Theoretical or Simulation Model	Application	Methodological Focus
Assessment	Simulation model that evaluates the best circular business models within a symbiotic network with the highest chance of long-term success and economic viability [35].	Agent-based dynamic simulation model (Quantitative)
Assessment	Simulation model that determines the optimal combination of transportation, resource sharing, collaboration, and business model with the greatest economic value for those involved [32].	Integrated collaboration model (Quantitative)
Business Model	Theoretical model of business models from the industrial symbiosis perspective to generate energy [33].	Business model to generate energy through industrial symbiosis (Mixed)
Material Flow	Eco-industrial symbiosis management model based on material flow [45].	Waste management model for the mining industry (Qualitative)
Material Flow	Simulation model used to calculate material flow to improve connected lifecycle systems [48].	Hybrid simulation architecture (Quantitative)
Business Model	Holistic methodology for the design of sustainable solutions [29].	Circular integration framework for the design of sustainable systems (Mixed).
Material Flow	Simulation model that evaluates material flow and steam heat as an energy alternative in industrial parks and their economic and environmental benefits [30].	Urban industrial symbiosis methodology (Quantitative)
Material Flow	Industrial symbiosis network simulation model at a refinery [46].	Regional bioperspective (Mixed)
Collaboration	Theoretical model of industrial symbiosis where the facilities of the different actors are shared to generate a positive environmental and economic impact [34].	Industrial symbiosis of facilities (Qualitative)
Material Flow	Simulation model that analyzes hazardous waste incineration processes from different industries that allow for the recovery of heavy and precious metals for future sale [47].	Ash treatment process (Mixed)

3.5. Case Studies and Most Researched Industries

Research that utilizes a case study as a research method (Table 6) is focused on analyzing the evolution, implications, and strategies used to implement industrial symbiosis. We can find cases from the port industry [54], the sugar industry [28,55], the paper industry and heating services [56], the recycling industry and waste management [57], the construction industry [58], the mining industry [25,59], the ceramic industry [49], and the equine industry [60], among others, in regions that seek to fully use, harness, and share resources [59,61–63] and industrial parks [64].

Table 6. Summary of the articles that use a case study as a research methodology for industrial symbiosis.

Industry	Country	Case	Topic of Analysis
Different industries	Italy	Circularity.com	The evolution and implications of using a digital platform to inspire companies to adopt circular economy practices and industrial symbiosis through the experimentation of possible business models are analyzed [65].
Different industries and stakeholders	Norway	Trondelag County	Through discourse analysis, it is proven that the transition toward a circular economy can be oriented beyond economic benefit, using a shared vision that includes waste as a resource, business models focused on industrial symbiosis, and changes in consumer behavior [63].
Port industry	Belgium	Five Belgian maritime ports	Different strategies focused on the transition toward a circular economy used in five Belgian ports, establishing a framework based on similarities [54].
Different industries	United Kingdom	Humber Region	Demonstrates how using the EPOS methodology facilitates the identification of opportunities for industrial symbiosis, decision making, and the involvement of stakeholders, while reducing implementation barriers [59].
Different industries and stakeholders	The Netherlands	Industrial Symbiosis cluster	Develops a framework for the construction of industrial symbiosis clusters, the required processes, the viability of the business, and the expected impact over time [5].
Construction industry	Belgium	Greenhouses	The construction of greenhouses is studied using the principles of industrial symbiosis to generate new business models in the construction industry [58].
Recycling and waste management industries	Italy	10 B-certified companies	The importance of raising awareness of the different stakeholders to implement a circular economy and how B-certification supports this awareness [57].
Paper and waste management industry	Sweden	18 companies with excess steam	The main financial, technical, and organizational conditions that must exist for the implementation of industrial symbiosis are established as well as how this translates into innovative business models [56].
Sugar industry	United Kingdom	British Sugar	The gradual evolution of the company toward sustainability using the principles of industrial symbiosis, innovating the business model for the creation of value and venturing into new lines of business [28].
Diverse industries	Hungary	Danube Region	Proposes symbiotic collaboration schemes for the use and leveraging of the region's resources [61].
Portuguese legislation	Portugal	Policies and incentives on circular economy and industrial symbiosis	The aspects required in legal, political, social, technological, and strategic fields to promote a circular economy and industrial symbiosis in Portugal [66].
Various industries	Sweden	Västra Mälardalens	The current state of urban industrial symbiosis in the region and possible collaborations that complement and increase the symbiosis among companies and the city to achieve sustainability [62].

Table 6. *Cont.*

Industry	Country	Case	Topic of Analysis
Sugar industry	China	Guitang Group	The evolution of industrial symbiosis in the sugar industry, the alliances created, the flow of resources, and the comparison with other similar complexes in the United Kingdom, India, and China [55].
Petro-chemical/chemical industries, water treatment, paper industry	Korea	Ulsan Industrial Park	The importance of including waste recovery from different industries for its maximum use, generating economic and environmental benefits through industrial symbiosis and the impact on companies' business models [64].
Agri-food industry	Poland	Smilowo-Eco Park	The development process of an eco-industrial park covering the entire product cycle, including material flows and energy generation, highlighting the activities and strategies implemented that resulted in a positive impact on the environment, as well as cost-effective management [67].
Port industry	Denmark	Malmö Port (Sweden) Foss-Marseille (France) Biopark Terneuzen (The Netherlands)	The importance of collaborative partnerships and platforms to promote industrial symbiosis [68].

These empirical cases are relevant to understanding the benefits of using technological platforms to inspire companies to adopt industrial symbiosis practices [65]; how having a shared vision facilitates the transition to a circular economy and influences changes in consumer behavior [54]; the relevance of creating awareness to utilize waste from different stakeholders [57]; the political, legal, social, and technological aspects that are relevant to an industrial symbiosis strategy; and the evolution of alliances that are decisive for successful implementation [55]. Other important aspects that have been studied are the financial, technical, and organizational conditions that favor industrial symbiosis among companies with complementary needs [56] and shared-value strategies that remote companies can develop by establishing cooperation networks in their processes [5]. Studies have also been carried out where city services play an important role in industrial symbiosis [5,62,65]. The most studied industries are metal mechanics, heating services, sugar, industrial agriculture, and the food industry. The least studied industries are packaging and furniture production [65].

3.6. Focus, Level of Analysis, and Study Perspectives

The studies classified with a strategic business approach refer to those studies that facilitate the visualization of different strategies that companies can choose to achieve this objective; thus, we find strategies based on the business model [7,35,38,51,53], the processes through which businesses or regions can develop their strategy [23,34,46–49,59], and even the public policies that can boost this change [52]. Studies focused on diagnosing and evaluating concentrate their results on tools or theoretical and simulation models that allow the identification and evaluation of the optimal combinations of resources, material flows, infrastructure, actors, and their economic viability [6,24,31]. Finally, there are studies focused on the transition and implementation of industrial symbiosis, which mostly case studies of how this transformation occurred, how it evolved [28,40,58,62,65], the political enablers and incentives [50,66], the technology [40], and the results obtained thus far.

Considering the research perspective, 80% of the articles study the flow of materials and resources and how they are used, processed, or exchanged. A total of 13% focus on the information and knowledge required to carry out this business process and how it is shared through empirical studies and in specific cases [60,69]. Since industrial symbiosis is a collaborative mechanism among various actors, 4% of the research examines how the collaboration networks and the required key actors are created. Another 2% of the research shows the consumer's role, as well as fiscal policies and strategies for successful implementation (Figure 8).

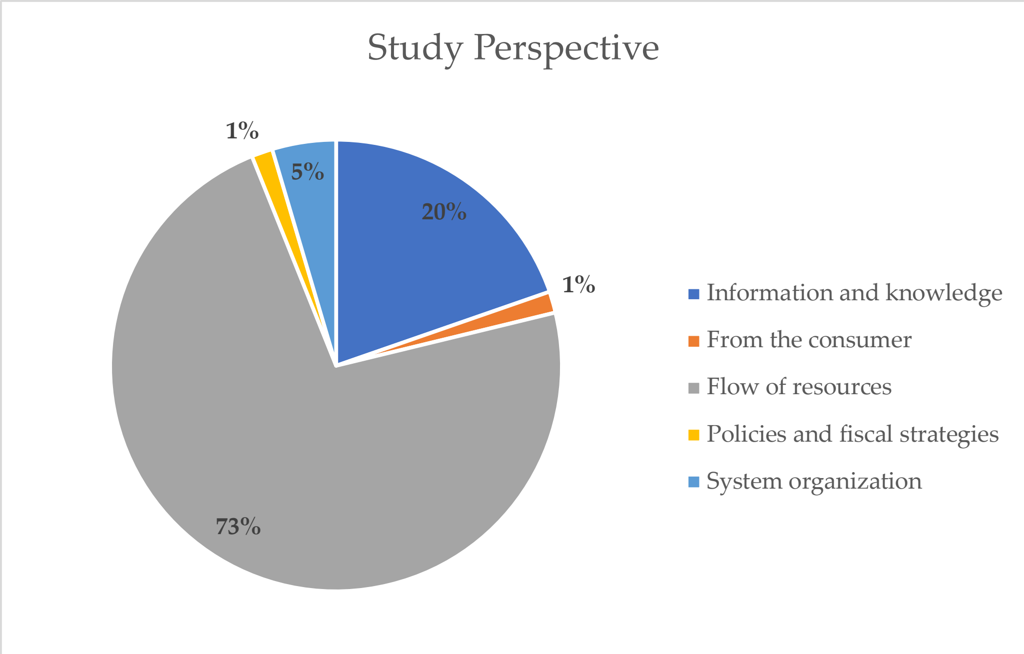


Figure 8. Main perspectives in the research sample.

According to the level of analysis classification, 46% of the studies we analyzed are focused on the company level, 21% focus on studies carried out in industrial parks, and 33% focus on the analysis of different cities, regions, and countries.

3.7. Main Barriers and Facilitating Factors

The main barriers identified during the transition and implementation of industrial symbiosis at the company level focus on the economic uncertainty that implementation can create, the lack of technical knowledge or inadequate technologies, the mistrust among actors, low collaboration, commitment and environmental awareness [23], the lack of clarity in the organizational culture, and difficulties in the classification, quality, and transportation of resources [39]. Miscommunication can be avoided by establishing common goals and objectives among stakeholders [62]. The variables indicated most frequently in the studies are the exchange of resources such as water, energy, waste, and byproducts [6,48,50,69]. Information and knowledge can create controversy. Kosmol [41] considers that the exchange of knowledge requires sharing information, but not necessarily the other way around, since it depends on the people, the collaboration, and the support received. It is important to highlight that the most emblematic cases of industrial symbiosis arose spontaneously, and, as the economic, environmental, and social benefits became clear, more companies joined in proposing projects for the collaboration, valorization, and exchange of resources, even obtaining government support for research and implementation [64].

4. Discussion

In the following section we discuss our findings according to the research questions.

RQ1. What are the main research topics, authors, and journals?

Although there have been various studies on industrial symbiosis and business models, no study includes a summary of tools and methods used to implement industrial symbiosis. The studies had the greatest emphasis on analyzing material flow from different perspectives, such as through measuring their circularity [44], looking for industrial waste that might be useful for other companies [24], evaluating supply chains [49], assessing the optimal combination of waste from a cost-recovery point of view [31], and developing tools to manage material flow in specific industries [45–47]. The studies include the development of business models that serve as templates to implement strategies that companies can adopt to create industrial symbiosis [7,20,21,51,53]. The most prolific authors are from Europe, and only two journals concentrate the largest number of publications on the subject. It is necessary to identify successful cases in Latin America.

RQ2. What other concepts related to industrial symbiosis and its business models have been analyzed?

There is only one study that is part of the plan for the development and implementation of industrial symbiosis at a regional level [52] and collaboration from facilities to generate a positive environmental and economic impact [34]. Consumer behavior has been studied very little, and even less studied is its relationship with certain practices and market strategies aimed at promoting collaboration that influences the creation of contexts that favor sustainable business models as a way to obtain flows of reusable materials. It is necessary to go deeper into the studies that show how companies can face changes in the quantity and quality of waste used as supplies for another organization derived from market cycles.

RQ3. What methodologies and types of research are used most often? RQ4. Who are the most commonly analyzed study objects?

Within the literature reviewed, we found quantitative, qualitative, and mixed research methodologies. From a business model perspective, we found systematic experimentation methods for circular business models [35] and metrics to assess the circularity of materials [44]. Companies that are interested in implementing business models for industrial symbiosis can adopt the different canvases that have been developed, depending on the focus or the required needs, as well as studying their evolution process. We observed that tools and models have been developed to determine the potential of a region [46,59,62], to identify and evaluate the possible symbiotic relationships [24,25,65], and to analyze internal [55] and external [57] organizational changes. The main research approaches used were case studies and the development of empirical tools for assessing and developing industrial symbiosis based mostly on the cases studied with gaps still existing in order to be able to choose between different options according to the characteristics and environment in which the companies operate. There are assessment tools that can identify when a company is already circular; however, they cannot detect the inflection point at which a company begins to be considered circular [57]. At the meso and macro level, the focus is on how industrial symbiosis can be implemented by design, but without delving into who may lead and how the leadership of the implementation comes about [5].

RQ5. Which industries are most researched?

Most of the theoretical and simulation tools and methods that focused on the study of industrial symbiosis have been tested mainly in the primary sector industry, particularly in the chemical, mining, metal-mechanic, and sugar industries, while few studies have focused on the textile and footwear industry, which can be a niche opportunity for traceability [59] and the better use of the resources utilized in manufacturing for the recovery and use of material flow.

RQ6. From what perspectives have industrial symbiosis and its business models been approached? RQ7. What is the geographical focus of the literature? RQ8. What are the main barriers and facilitating factors for the implementation of industrial symbiosis?

In this research, the business model and industrial symbiosis constructs have been analyzed together. Industrial symbiosis is a relatively new topic that can be studied from the following two perspectives: the circular economy and industrial ecology. The first focuses on explaining it from the conception of the business, while the second focuses on evaluating its evolution and economic and environmental impact over time [5]. Perhaps this is the reason why most of the research focuses on the exchange of flows, since it implies a gradual transformation in which different actors can be incorporated as new needs are required or obstacles to its implementation are eliminated. Most of the existing studies are theorical and simulation models with few empirical cases [70] for the implementation of industrial symbiosis, the exchange of flows, and even business models; however, the study of how industrial symbiosis emerges is only just beginning [68]. There is a lack of quantitative information on the economic impact of its implementation in real cases [67].

Little has been studied about the political and social changes created by implementation, how cultural transformation has occurred in organizations, and how they overcome the barriers to implementation in terms of infrastructure and the training of staff in terms of knowledge, a sustainable mentality, and collaboration. Although there are tools that can facilitate the identification of possible collaborations based on material flow and the decision-making process, the negotiations and agreements required to facilitate this exchange have not been studied, and the fiscal and social impact that this type of decision implies for the business, cultural, and political system of the region and how the different stakeholders are impacted in their behavior toward a collective sustainability plan have not been visualized. The studies were developed mainly in Europe. Undoubtedly, cultural and political issues, as well as stricter environmental regulations, have favored collaboration between companies to adopt sustainable practices, unlike Latin America, where investment in infrastructure and education is still limited.

The willingness to do business and invest in technology were variables that were studied by Nasiri et al. [60]; however, it is not yet clear how collaborations could come about beyond economic interest and how that collaboration might be formalized. Agudo et al. [6] presented a way to evaluate the readiness of a company and how to start the implementation of industrial symbiosis without establishing how to reach that level of readiness. The role of information technologies and the importance of digitizing production processes, facilitating the understanding of their complexity, and the points of human interaction [40] as a way of visualizing the future of the industries to create a common vision and detonate the collaborative economy, are still necessary.

As a result of our research, we present our findings and the implications of industrial symbiosis as a strategy for sustainability. Although the literature on the subject is extensive, there are still gaps in the prioritization of the business models that companies can use in their transition to industrial symbiosis according to the context of the industrial ecosystem in which they operate. Many industries have been studied; however, it is still necessary to find synergies between the different types, such as the textile industry.

5. Conclusions

This paper summarizes the limits of academic knowledge related to industrial symbiosis by presenting a detailed and comprehensive review of the existing tools and simulation models to facilitate the transition to industrial symbiosis. This paper also includes an analysis of the different business models, which companies can adopt to increase efficiency and reduce cost, while obtaining economic, social, and environmental benefits.

5.1. Limitations

The limitations of this study are focused on the availability of the articles, since six studies had to be excluded because they were not available for review, having selected only scientific articles published in the SCOPUS database, leaving out the gray literature that could expand our knowledge on the topic. As a qualitative analysis, there is a certain bias of the researcher when categorizing the studies that have been analyzed.

5.2. Future Research

In future research, we recommend studying the following topics: (i) the cultural transformation of organizations immersed in this process and the importance of internal and external communication needed to facilitate the dissemination of the sustainable vision of the organization; (ii) the practices and incentives required to detonate a mentality of sustainability among collaborators and stakeholders; (iii) the development of skills and knowledge of the human resources that are directly involved in the transformation toward industrial symbiosis; (iv) regarding the flow of information and materials, what information mechanisms and technologies are most adequate to record, analyze, and determine the variations of the material flow and waste due to changes in market cycles; and (v) how to trade this information for the creation of symbiotic chains among the interested parties, emphasizing on the stages required in the negotiation processes and business agreements.

This paper contributes to academia to obtain new ideas for research, to practitioners in the search and exploration of connections involving industrial symbiosis and emerging technologies, and to regulators on how to raise awareness and drive implementation.

Supplementary Materials: The following supporting information can be downloaded at: https://www.dropbox.com/s/1xkvi80xr7s1ot2/LR%20-%20al%202023%20Final.xlsx?dl=0 (accessed on 12 April 2023).

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Appendix A

Table A1. Classification of the articles according to the codification of the dimensions and categories that were analyzed. (A) Research Method: CR1—Literature Review; CR2—Simulation or theoretical models; ER1—Survey; ER2—Case Study; ER3—Interview; (B) Focus: E1—Strategy and business; E2—Diagnostic and assessment; E3—Transformation and implementation; E4—Information Technologies; (C) Perspective: P1—Knowledge and information; P2—The consumer; P3—Material flow; P4—Policies and fiscal strategies; P5—Systemic vision; and (D) Level of analysis: L1—Micro; L2—Meso; L3—Macro.

Article	Journal	Research Method	Level of Analysis	Perspective	Focus
[22]	*Journal of Cleaner Production*	CR2	LA1	P5	E3
[23]	*Resources, Conservation and Recycling*	ER3	LA1	P3	E2
[20]	*Procedia Environmental Science, Engineering and Management*	CR2	LA1	P3	E1
[25]	*Environments—MDPI*	ER1	LA2	P3	E3
[24]	*Waste Management and Research*	CR2	LA2	P3	E3
[47]	*Procedia Environmental Science, Engineering and Management*	CR2	LA1	P3	E1
[5]	*Journal of Cleaner Production*	ER2	LA1	P3	E3
[71]	*Journal of Cleaner Production*	ER1	LA1	P2 P3	E1
[44]	*Journal of Cleaner Production*	CR2	LA1	P3	E3
[51]	*Procedia CIRP*	CR2	LA1	P3	E3
[59]	*Sustainability*	ER2	LA1	P3	E3
[39]	*Johnson Matthey Technology Review*	CR1	LA1	P3	E1
[40]	*Materiaux et Techniques*	CR1	LA3	P3	E1
[52]	*Energies*	CR2	LA1	P3	E3
[21]	*Resources, Conservation and Recycling*	CR2	LA3	P5	E3

Table A1. *Cont.*

Article	Journal	Research Method	Level of Analysis	Perspective	Focus
[49]	*Social Sciences*	CR2	LA1	P3	E1
[31]	*Procedia Environmental Science, Engineering and Management*	CR2	LA2	P3	E1
[61]	*World Sustainability Series*	ER2	LA3	P3	E3
[54]	*Sustainability*	ER2	LA3	P3	E3
[66]	*Sustainability*	ER2	LA3	P4	E3
[18]	*Journal of Cleaner Production*	CR1	LA1 LA2 LA3	P1	E1 E2 E3
[30]	*Resources, Conservation and Recycling*	CR2	LA2	P3	E2
[48]	*Procedia CIRP*	CR2	LA1	P3	E3
[41]	*Proceedings*	CR1	LA1 LA2 LA3	P1	E1 E4
[62]	*Procedia CIRP*	ER2	LA3	P5	E3
[35]	*Resources, Conservation and Recycling Advances*	CR2	LA2	P3	E3
[50]	*Asian Education and Development Studies*	CR2	LA3	P3	E1
[27]	*Journal of Cleaner Production*	CR1	LA1 LA2 LA3	P1 P2 P3 P4 P5	E1 E2 E3 E4
[45]	*E3S Web of Conferences*	CR2	LA1	P3	E2
[38]	*Environmental Challenges*	CR1	LA1	P3	E1
[34]	*Journal of Industrial Ecology*	CR2	LA1	P3	E2
[60]	*Sustainability*	ER1	LA3	P1 P3	E1
[42]	*Proceedings of 2019*	CR1	LA3	P3	E3
[19]	*Sustainable Production and Consumption*	CR1	LA1 LA2 LA3	P1	E1
[43]	*Procedia Manufacturing*	CR1	LA3	P1	E1
[33]	*Journal of Cleaner Production*	CR2	LA2	P3	E3
[63]	*Sustainable Production and Consumption*	ER2	LA3	P3	E3
[56]	*Journal of Renewable and Sustainable Energy*	ER2	LA3	P3	E3
[69]	*Sustainability*	ER1	LA2	P1	E1
[65]	*Management of Environmental Quality: An International Journal*	ER2	LA3	P3	E3
[57]	*Sustainability*	ER2	LA3	P3	E1
[58]	*IOP Conference Series*	ER2	LA3	P3	E1
[53]	*Resources*	CR2	LA1	P3	E1
[46]	*Journal of Cleaner Production*	CR2	LA1	P3	E3
[72]	*Sustainable Resources Management: Modern Approaches and Contexts*	CR2	LA1	P3	E1
[64]	*Waste Biorefinery*	ER2	LA3	P3	E3
[55]	*Sustainability*	ER2	LA3	P3	E2
[28]	*Journal of Industrial Ecology*	ER2	LA3	P3	E1
[73]	*Journal of Industrial Ecology*	ER1	LA3	P3	E2
[32]	*Chemical Engineering Transactions*	CR2	LA2	P3	E2
[73]	*Sustainability*	CR2	LA2	P3	E1
[74]	*Production Planning and Control*	ER1	LA2	P3	E1
[29]	*Renewable and Sustainable Energy Reviews*	CR2	LA3	P3	E1
[75]	*Journal of Advances in Management Research*	CR1	LA1	P1	E2
[67]	*International Journal of Environmental Research and Public Health*	ER2	LA3	P5	E1
[76]	*Journal of Cleaner Production*	CR2	LA2	P3	E2
[77]	*The International Journal of Life Cycle Assessment*	CR2	LA1	P3	E2
[70]	*Technological Forecasting & Social Change*	CR1	LA1	P1	E2
[78]	*Technological Forecasting & Social Change*	CR2	LA1	P1	E2
[68]	*International Journal of Innovation and Sustainable Development*	ER2	LA2	P1	E1
[79]	*Recycling*	CR2	LA1	P3	E1
[80]	*Inzynieria Mineralna*	CR2	LA1	P3	E2
[81]	*E3S Web of Conference*	CR2	LA1	P3	E1

Table A1. *Cont.*

Article	Journal	Research Method	Level of Analysis	Perspective	Focus
[82]	*Journal of Cleaner Production*	CR1	LA1	P1	E1
[83]	*Journal of Cleaner Production*	ER1	LA1	P1	E1
[84]	*Cleaner Logistics and Supply Chain*	CR1	LA1	P1	E1

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