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The current trends in Industrial Symbiosis and its potential implementation in Portuguese industrial parks

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Dedication

To the memory of my father

“Waste is merely raw material in the wrong place”

Frederick A. Talbot

in *Millions from Waste (1920)*

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Resumo

Os efeitos negativos do aumento das emissões de gases com efeito de estufa e do consumo de recursos têm impulsionado os países para a procura de soluções sustentáveis que promovam o crescimento económico dissociado do aumento das emissões e do aumento do consumo de recursos. Neste contexto, a simbiose industrial que consiste numa abordagem colaborativa entre diferentes entidades que envolve o uso de resíduos e subprodutos de uma empresa como matéria-prima em outra empresa, pode desempenhar um papel importante para o desenvolvimento sustentável. Com reconhecidos benefícios a nível ambiental, económico e social, esta prática tem sido aplicada um pouco por todo o mundo, quer em países desenvolvidos quer em países com economias em vias de desenvolvimento.

O principal objectivo deste trabalho é contribuir para o aumento da simbiose industrial em Portugal, proporcionando uma análise da simbiose industrial existente e estabelecendo uma série de recomendações e melhores práticas para aumentar o número de sinergias e melhorar as existentes em Portugal. Para a concretização deste objectivo principal, outros casos de simbiose industrial existentes e potenciais em todo o mundo foram compilados e analisados a fim de caracterizar as várias redes de sinergia e estudar os factores que podem inibir ou impulsionar a criação e desenvolvimento das relações de simbiose industrial.

Os resultados evidenciam o enorme potencial de aplicação da simbiose industrial em Portugal. Contudo, para o crescimento desta prática, várias barreiras políticas, culturais e económicas têm ainda que ser transpostas e várias medidas têm que ser implementadas.

Palavras-chave

Simbiose industrial; Caso de estudo; Simbiose industrial potencial; Método; Indicador; Simbiose industrial e urbana; Parques eco-industriais; Economia circular; Sustentabilidade.

Abstract

The negative effects of rising greenhouse gas emissions and resource consumption have driven countries to seek sustainable solutions that promote economic growth decoupled from rising emissions and rising resource consumption. In this context, industrial symbiosis, which consists of a collaborative approach between different entities involving the use of waste and by-products from one company as raw material in another company, can play an important role for sustainable development. With recognized environmental, economic and social benefits, this practice has been applied around the world, both in developed countries and in countries with developing economies.

The main objective of this work is to contribute to the increase of the industrial symbiosis in Portugal, providing an analysis of the existing industrial symbiosis and establishing a series of recommendations and best practices to increase the number of synergies and improve those existing in Portugal. To achieve this main objective, other existing and potential cases of industrial symbiosis around the world have been compiled and analyzed in order to characterize the various synergy networks and to study factors that may inhibit or drive the creation and development of industrial symbiosis relationships.

The results demonstrate the enormous potential of application of industrial symbiosis in Portugal. However, for the growth of this practice, various political, cultural and economic barriers have to be overcome and various measures have to be implemented.

Keywords

Industrial symbiosis; Case study; Potential industrial symbiosis; Method; Indicator; Industrial and urban symbiosis; Eco-industrial parks; Circular Economy; Sustainability.

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List of Acronyms and Abbreviations

BATTER	Best Available Techniques for a Territory
BCSD	Business Council for Sustainable Development
CML	Centrum Milieukunde Leiden
EPD	Environmental Product Declaration
EWC	European Waste Catalogue
GHG	Greenhouse gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
GWP	Global Warming Potential
I.C.	Intermunicipal Community
INE	Instituto Nacional de Estatística. Statistics Portugal
IPCC	Intergovernmental Panel on Climate Change
IS	Industrial Symbiosis
ISIC	International Standard Industrial Classification of All Economic Activities
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
M.A.	Metropolitan Area
MFA	Material Flow Analysis
MIND	Method for analysis of Industrial energy systems
NACE	European Classification of Economic Activities
NE	Number of Enterprises
SNA	Social Network Analysis
SWOT	Strengths, Weaknesses, Opportunities and Threats

Chapter 1

Introduction

1. Background and motivation

Earth's surface temperature has been rising over the past three decades [1] and if no significant action is taken, it is expected that this rise will continue in the coming years [1,2]. The most visible consequences of this increase have been the recent climate-related extremes, such as heat waves, floods, droughts, cyclones and wildfires. These extremes have many impacts, such as alteration of ecosystems, disruption of food production and water supply, damage to infrastructures and settlements, morbidity and mortality, consequences for human well-being, among others [3]. According to the Report of the Intergovernmental Panel on Climate Change (IPCC) the dominant cause of the observed warming since the mid-20 century is the increase of the anthropogenic greenhouse gas emissions that have driven large increases in the atmospheric concentrations of carbon dioxide, methane, chlorofluorocarbons and nitrous oxide [1]. This increase is mainly driven by the intensive use of resources, population size, economic activity, lifestyle, energy use, land use patterns and climate policy [4–7].

International agreements that have been established, from the United Nations Framework Convention on Climate Change in 1992, currently ratified by 195 countries, to the most recent agreement established in December 2015 and currently ratified by 185 countries, the Paris Agreement, have greatly contributed to raising the world's population's awareness of climate change issues and finding sustainable solutions. In the latter agreement, the aim was to strengthen countries' capacity to respond to climate change and to set a limit to the global temperature increase in this century, setting it well below 2˚C above pre-industrial levels and to drive efforts to limit this temperature rise to 1.5˚C [8]. The issue of climate change is also part of the goals set in the formal declaration adopted by United Nations members, the 2030 Agenda. This declaration, with the main objective of sustainable development, is a comprehensive action plan aimed at ending poverty, ensuring prosperity, protecting the planet and strengthening universal peace through the establishment of 17 Sustainable Development Goals and 169 targets [9], whose implementation by each country depends on their circumstances and depends on the priority level given to each of the goals [9,10]. To achieve this sustainable development, the three dimensions, economic, environmental and social, need to be integrated and balanced [9] in solutions that address social and environmental issues without compromising economic growth. This commitment necessarily involves more efficient consumption of resources and reduction of waste generation, being transversal to several goals and explicitly addressed in sustainable development goal 12, “responsible consumption and production” [9]. And although in the last five years, the resource productivity, defined as gross domestic product divided by domestic material consumption, has grown at a rate of 1.5% per year, the waste generated, excluding major mineral wastes, dredging spoils and contaminated soils, has grown at a rate of 0.8% per year over the last four years [2].

Therefore, solutions must be found to decouple economic growth from increased carbon dioxide emissions and resource consumption. Industrial symbiosis, a subfield of industrial ecology, has contributed to this aim by enabling businesses, the environment and populations to achieve a host of environmental, economic and social benefits.

The designation of industrial symbiosis has its genesis in biology in which symbiosis represents the "association of individuals of different species in a relationship where there is mutual benefit" [11]. In industrial symbiosis, also companies that traditionally operate separately, cooperate with each other, thus obtaining greater benefits than those that would achieve alone, involving the exchange of materials, by-products, energy and water [12]. Often referred to as the incorporation of one company's waste as a raw material in another company's production process [13], industrial symbiosis, in addition to involving this exchange of resources, also includes the sharing of utilities and infrastructure and the joint provision of services [14]. Posteriorly, industrial symbiosis was also identified as "a business opportunity and tool for eco-innovation" [15].

There are numerous factors that drive the creation of industrial symbiosis relationships and different forms of organization. For example, in some cases the symbiosis results from the initiative of some companies, often motivated by economic factors, such as the reduction of taxes and costs with the disposal and treatment of waste [16], which come together in a self-organized way to create synergies. An example of this type of symbiosis activity is the case of Kalundborg, Denmark, where companies in the region came together to solve the problem of water scarcity. In other cases the existence of policies to encourage, disseminate and facilitate synergies has led to increased symbiosis between companies [17–19]. This can be done by defining concerted plans and programs to support the creation and development of symbiosis relationships, such as the National Industrial Symbiosis Programme in the United Kingdom [20], the National Eco-Industrial Park Development Program in South Korea [21], and the Japan's Eco-Town Program in Japan [22]. In addition to these, several actions can be taken to facilitate the creation of synergy networks, such as the creation of taxes that penalize waste management options that are more costly to the environment, such as landfills and incineration, financially support businesses that promote eco-efficiency activities, provide training and assist companies so that they can efficiently manage their waste.

The European Commission has also played an important role in this regard as it has been developing a set of programs, directives and communications comprising a number of recommendations to Member States encouraging more efficient use of resources and waste reduction [23–25]. The Communication from the European Commission "Roadmap to a Resource Efficient Europe", which without sacrificing economic growth, proposed a framework for action to ensure sustainable management of all resources [26] and the Communication "Closing the loop - An EU action plan for the Circular Economy" which stressed the importance of industrial symbiosis and proposed to facilitate this practice through cooperation with Member States and through guaranteed funding through policy funds of cohesion and through the research and innovation framework program, Horizon 2020 [27], are some of the examples of the various initiatives taken by Europe with a view to more sustainable use of all resources and waste.

An example of European directive published in this area is the Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste [28] whose main objective is to prevent and reduce the adverse impacts of the generation and management of waste. Although the Directive has prioritized waste prevention and preparation for reuse as a general principle of waste prevention and management legislation, there is no clear reference to the use of industrial symbiosis to promote the efficient resource management. However, at the end of May 2018, with the signing of a new Directive on waste (Directive 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste), the way industrial symbiosis was seen has changed. This new directive, besides reinforce the importance of improving waste management, also states that it should be transformed into sustainable material management, i.e. “ensuring that waste is valued as a resource” [29], in order to ensure improvements in the environment and human health.

In addition to these recommendations and directives, the European Commission has developed programs of financial support for companies wishing to develop projects in the area of industrial symbiosis, such as the “Moving towards a circular economy through industrial symbiosis” program [24]. And the LIFE program, which began in 1992 to finance projects to promote the “implementation, updating and development of EU environmental and climate policy and legislation” [30], including in its action plan, set for 2018 to 2020, projects in the area of industrial symbiosis.

There are many successful cases of industrial symbiosis. One of the best known and most cited examples in the literature is the case of Kalundborg in Denmark. This synergy network emerged in the 1960s and 1970s, as a result of private conversations between some local business managers and was driven by water scarcity [31]. Since then, and with the aim of reducing costs associated with increasingly stringent environmental regulatory requirements and achieving economic benefits from by-products [32], the number of symbioses has been increasing among local authorities, businesses and industries [33] that have resulted in the development of the region with benefits for the companies involved, the environment and the population [34].

Since then, there have been numerous cases of industrial symbiosis with great diversity in terms of network size, entities and economic activities involved, as well as geographical location. In Europe there are several cases spread across different areas, with a predominance of case studies published in the North and Northwest. The United Kingdom is the country in Europe with the most cases reported in the literature and these are distributed in different locations. Grangemouth [35], Humber [20], West Midlands [36], Bristol [37] are some of these examples. In addition, there are cases of industrial symbiosis in Sweden [38–40], Netherlands [37,41,42], France [43,44], and Italy [45,46]. Also in Asia there are numerous cases, especially in China [47–49], which is the country with the most published cases of industrial symbiosis. Also in Japan [22,50,51] and South Korea [52–54] are several cases of industrial symbiosis. In North America [55–57], South America [58], Oceania [59,60] and North Africa [37] there are also several cases of synergy networks.

Reduction of carbon dioxide emissions [40,61–63], reduction of resource consumption [62–65], reduction of the cost with tax, waste treatment and disposal [39,65,66], increased economic benefits from the entities involved [34,40,65,67] and job creation [40] are some of the benefits that have been achieved with the practice of industrial symbiosis.

In China, the development of industrial symbiosis in the Xinfa Group has reduced carbon emissions by 10.84% compared to a non-symbiosis scenario [61]. In Songmudao chemical industrial park in Dalian, China, the sharing of by-products allowed the environmental benefits to reach 13.63 thousand TJ of primary energy and 1218 thousand tCO_2e of greenhouse gas [63]. Also in China, at Midong chemical industrial park the 32 industrial symbiosis activities resulted in a total annual material exchange volume of 4.74 million tons, with an economic benefit of about 62.29 million US dollar related to the cost savings with the purchase of raw materials, cost reduction with the deposition of waste, and waste sales revenues and and a total environmental benefit due to reduced resource consumption and waste emissions reduction of about 5.86 million tons per year [65]. At Kawasaki, Japan, the 4 symbiotic connections in the iron and steel industry allowed a total by-product/waste exchange volume of about 500 kton/y with an economic gain of over 54 million USD [67]. In Sotenäs, Sweden and even though the synergy network was at an early stage it was possible to achieve a range of socio-economic benefits such as the retention and creation of 20 jobs and the creation of 5 new companies [40].

With these environmental, economic and social benefits, the reasons for the various entities to engage in industrial symbiosis networks are immense. However, the spread of this practice is not the same in all regions and there are a number of economic, social and political constraints that arise when creating industrial symbiosis relations. Thus, it is important to investigate the existing cases of industrial symbiosis around the world and to analyze their characteristics and the main barriers and drivers to their implementation. In Portugal, although there is a great potential for the application of industrial symbiosis, there are still few cases [68–71]. Thus the research conducted in this thesis is framed in the study of the application of industrial symbiosis to real cases. The issues to be studied are related to the analysis of several existing and potential case studies and with a special focus on the analysis of the situation of industrial symbiosis in Portugal with the study of existing cases, main barriers to the dissemination of this practice and the factors that can drive its development.

2. Review of research trends

The number of articles published on industrial symbiosis has been growing exponentially in recent years, especially since 2007, revealing the growing interest of the scientific community on this subject. In terms of content, the theoretical and conceptual articles and those using models from mathematical functions, that is, modeling and simulation are the most published. This is followed by publications whose content is case studies and publications that study the potential application of industrial symbiosis in a given geographical location. Review articles are those with fewer publications.

The research topics that have been studied in the various publications have a very wide and distinct scope, ranging from the most general to the most specific, and have addressed various issues such as: *(i)* the identification of research trends and possible evolutions [72,73]; *(ii)* barriers and drivers for the creation and development of synergies [74–76]; *(iii)* the influence of policy instruments [77,78] and programs [79]; *(iv)* the evolution of industrial symbiosis [75,80–83]; *(v)* the identification of future symbiosis [84,85]; *(vi)* methods and indicators [86–88]; *(vii)* the assessment of the environmental [89–105], economic [100,101,106–110] and social impact [90,111] of industrial symbiosis; *(viii)* the analysis of symbiosis networks [112–125]; *(ix)* the study of collaboration and information sharing platforms to facilitate the creation of synergies [126,127] and *(x)* the industrial and urban symbiosis [99,100,108,128–138].

Many of these articles have mentioned the importance of case study analysis as a way of fostering the development of industrial symbiosis, not only because it can be an important tool for stakeholders to verify that there are synergy networks with innumerable possibilities in terms of size, industries and waste exchanged and that they can transpose these cases into their reality. Moreover, this analysis is also a crucial tool in order to increase the knowledge about industrial symbiosis and serve to elucidate and draw lessons for future improvements. However, when analyzing the various articles on industrial symbiosis, it was identified that there was a research gap regarding the analysis and compilation of different case studies. And while there are several publications that have compiled and analyzed the various case studies [72,73,139–145], they have some limitations regarding the number of cases covered and the geographic location. Moreover, an analysis of the cases of industrial symbiosis with potential to come to fruition was also missing. And in relation to Portugal, the existing studies of industrial symbiosis are few in number, both in the analysis of existing cases and in the analysis of barriers and better ways to increase the application of industrial symbiosis.

3. Research objectives

The increasing number of published articles in recent years, the growing number of industrial symbioses and the increasing reference to this practice in European Communications show the importance of industrial symbiosis for increasing sustainability development and for meeting European and international targets for reducing greenhouse gases. Thus, the overall goal of this work is to contribute to the increase of the industrial symbiosis in Portugal, providing an analysis of the existing industrial symbiosis and establishing a series of recommendations and best practices to increase the number of synergies and improve those existing in Portugal. For the realization of this main objective, a number of other objectives have been defined. Thus, the research is divided into three main parts, each referring to a specific scale, starting from the most comprehensive to the most specific.

The first objective is to compile the various cases of industrial symbiosis in the world and to analyse the location, types of economic activities involved in the synergies and the methods employed in the various studies. This analysis, besides comparing different characteristics, also aims to framing them in the different realities underlying each case, not only to outline future research paths, but also to improve understanding of industrial symbiosis and increase its usage.

The second objective is to compile the publications that studied and evaluated the creation of new industrial symbiosis networks in real context and with this survey to map this potential characterizing and analysing it as to the location, the number and type of entities involved in symbiosis, the type of waste and by-products, the type of utilities and facilities sharing, the main economic, environmental and social benefits and the main methods used in their analysis. Based on these cases, it is also intended to point out the main drivers and barriers that may arise in the creation of industrial symbiosis relations.

The third aim is to map and characterize the existing cases of industrial symbiosis in Portugal and to analyze the current state and legislative framework of Portugal in the context of industrial symbiosis. It is also intended to analyze the main barriers to the growth of synergy relations and outline new paths for the development of industrial symbiosis in Portugal, based on the best practices and success factors of the numerous examples of industrial symbiosis cases around the world, adapting them to the specific circumstances of the country.

4. Thesis outline

This thesis comprises four main parts. The first corresponds to chapters 2 and 3 and aims to review the literature and provide a comprehensive overview of industrial symbiosis case studies and the main methods and indicators employed in the different analyzes. The second part analyzes the potential application of industrial symbiosis and the main barriers and drivers to its realization. The third part, composed of chapters 5 and 6, aims to analyze cases of industrial symbiosis in a specific context, first in a larger one and later in a narrower one. Finally, recommendations for future research and key findings are given in chapter 7. Each of these chapters is detailed in the following paragraphs.

Chapter 2 presents a review of research trends, which analyzes the evolution of publications on industrial symbiosis, the contribution of various journals, and the distribution of publications by article type and content type. In addition, a compilation and analysis is made of the published industrial symbiosis case studies regarding geographic distribution, the type of industries involved in synergy networks and the methods employed in the analysis. An analysis is also made of cases of industrial and urban symbiosis. Reference is also made to the main needs that underlie industrial symbiosis and how they were materialized.

Chapter 3 describes the main methods and indicators that are used to assess the environmental, economic and social impact of industrial symbiosis. An analysis of the most used methods is performed and the main advantages and disadvantages of each one are pointed out.

Chapter 4 presents a compilation and analysis of potential cases of industrial symbiosis. The geographical distribution, the industries involved, the types of waste streams, the type of utility sharing, infrastructure and services, the methods employed in the analyzes and the potential environmental, economic and social benefits are analyzed. In addition, potential uses of industrial symbiosis to manufacture different products and use different wastes are also analyzed. Finally, the main barriers and drivers to the realization of potential industrial symbiosis are also analyzed.

Chapter 5 looks at industrial symbiosis in North America, focusing on the type of industrial units, type of study, and location. Key trends and initiatives are also analyzed.

Chapter 6 analyzes the industrial symbiosis in Portugal, compiling the existing cases, and analyzing the current state of Portugal and the legislative framework in the context of industrial symbiosis. Current development, challenges and future prospects are also analyzed.

Finally in chapter 7 the main research conclusions are pointed out and some paths for future research are indicated.

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Chapter 2

A Comprehensive Review of Industrial Symbiosis

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Review

A comprehensive review of industrial symbiosis

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A B S T R A C T

Industrial symbiosis, which allows entities and companies that traditionally be separated, to cooperate among them in the sharing of resources, contributes to the increase of sustainability with environmental, economic and social benefits. Examples of industrial symbiosis have grown over the years with increasing geographic dispersion. Thus, through a comprehensive review of previous studies, this work aims to trace the trend of industrial symbiosis research and to map the existing case studies around the world, with a critical analysis of its impact. The analysis of the 584 selected publications allowed tracing the evolution of these according to their content and the type of article, as well as its distribution by journals. Based on the literature review, the main lines for research in industrial symbiosis are assessed, as well as an updated study of the published case studies is provided with emphasis on the location, type of industry and employed methodologies. Several challenges are then identified for future research. The results reveal the number of articles on industrial symbiosis has greatly increased since 2007 and China is the country with the largest number of publications and cases of industrial symbiosis, followed by the United States. The methods for quantifying impacts and analysing industrial symbiosis networks were the most widely used. The analysis of the published case studies allowed an overview of the industrial symbiosis in the world and showed that the potential for application is enormous, both in developed countries and in countries with developing economies, and although the most present economic activities in the synergies are associated with the manufacturing sector, the possibilities of industrial symbiosis are not restricted to these activities nor to the number of entities involved. The symbioses between industry and the surrounding community also have great potential for development with numerous advantages for both parties.

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1. Introduction

The rise in industrialization and urbanization over recent years has led to an increase in carbon dioxide emissions (Dong et al., 2019; Liu and Bae, 2018), which are largely responsible for greenhouse gases. This increase has led to global warming, with adverse consequences for the environment and human health, as has been mentioned in the Intergovernmental Panel on Climate Change reports (IPCC, 2014). The increase in industrial and municipal solid waste and the increasing consumption of resources have also been highlighted as a consequence of the growth of industrialization and urbanization (Guan et al., 2019b, 2019a; Luzi et al., 2015; Minelgaitė and Liobikienė, 2019). However, the important role of industrialization for long-term economic growth has been recognized (Haraguchi et al., 2019). Thus, it is essential to find solutions which allow for the reduction of these negative effects, without jeopardizing economic growth.

The international agreements that have been established, ranging from the United Nations Framework Convention on Climate Change in 1992, currently ratified by 195 countries, to the most recent agreement reached in December 2015, the Paris Agreement, have greatly contributed to raising awareness of climate change issues and the search for sustainable solutions. These solutions are indispensable towards maintaining carbon dioxide emissions below the limits set in international agreements but also for the increasingly efficient use of resources. Industrial symbiosis has been shown to be a strong ally for the achievement of these objectives, without causing damage to the economic growth of the parties involved (Daddi et al., 2017; L. Dong et al., 2014; Fan et al., 2017; Martin and Harris, 2018), a fact also recognized by the European Commission, which has published several directives and communications mentioning the importance of industrial symbiosis (European Commission, 2018a, 2018b; 2018c).

The designation of industrial symbiosis has its genesis in biology in which symbiosis represents the "association of individuals of different species in a relationship where there is mutual benefit" (Schwarz and Steininger, 1997). This definition has been transposed to industries in which industrial symbiosis "engages traditionally separate entities in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and by-products" (Chertow, 2000). This definition is widely disseminated in the developing industrial ecological environment and research community (Albino et al., 2013). Posteriorly, industrial symbiosis was also identified as "a business opportunity and tool for eco-innovation" (Lombardi and Laybourn, 2012). Producing more without spending more energy or resources through cooperation is the ultimate objective pursued by the industrial symbiosis: companies that use by-products or waste from other companies. It is an effective method of “locking” the matter cycle and, therefore, to obtain a zero level of waste (Mantese and Amaral, 2018).

Often this concept appears associated with eco-industrial parks, because the concept of these parks is associated to the existence of a communities of companies, in which there is a sharing of resources, such as materials, energy, information, among others, with the aim of achieving economic, environmental and social gains (B. B. Huang et al., 2019; Liu et al., 2018b). The concept of industrial symbiosis is related to this definition, and it is not surprising that many of the existing eco-industrial parks have industrial symbiosis between firms. However, eco-industrial parks involve other characteristics besides industrial symbiosis, such as the use of renewable energies, the design of green buildings, among others, and in addition, when there are industrial symbiosis, they are almost always confined to the space of the park, and indeed industrial symbiosis can be triggered without the demand of the geographic proximity between the participants (Lombardi and Laybourn, 2012; Shi et al., 2010). Although proximity is a factor that facilitates the creation of synergies and reduces waste transportation costs, the reality is that there are examples in which symbiosis occur between more distant enterprises, such as in Tianjin, China (Shi et al., 2010; Yu et al., 2014b) and Choctaw in United States of America (Zhang et al., 2013).

Industrial symbiosis relationships have been fostered through a number of factors, such as saving resources, obtaining economic benefits, meeting environmental requirements such as reducing greenhouse gas emissions, scarcity of natural resources and reduction of waste that would otherwise stop at landfills and incinerators (Chertow and Ehrenfeld, 2012; Domenech et al., 2019; Mortensen and Kørnøv, 2019). Therefore, in order to meet these needs, industrial symbiosis has spread throughout the world with positive economic, environmental and social results (Geng et al., 2014; Guo et al., 2016; Martin and Harris, 2018; Park and Behera, 2015; F. Yu et al., 2015a, 2015b; Zhang et al., 2017). For example, in Sotenäs, Sweden, and even at an early stage, the industrial symbiosis network has allowed for the retention or creation of 20 jobs, the creation of 5 new companies as well as a reduction of approximately 59 million kg CO_2-eq emissions annually through resource sharing (Martin and Harris, 2018). In Kalundborg, Denmark with the replacement of groundwater with surface water, all symbiosis industries reduced the use of more than 30 million m^3 of groundwater, and in the period 1990–2002 due to the industrial symbiosis between the power plant and the refinery, of more than 7.6 million m^3 of surface water (Jacobsen, 2006). The implementation of urban industrial symbiosis in Guiyang, China allowed for a reduction of the urban carbon footprint by about 1090 thousand tCO_2 annually (Fang et al., 2017).

Since the earliest publications reporting on the case of Kalundborg in Denmark (Lowe and Evans, 1995; Schwarz, 1996; Schwarz and Steininger, 1997), one of the most successful cases of the application of industrial symbiosis and the most cited in literature, much research has been done not only to evaluate the impact that industrial symbiosis has had on the environment, the economy and society, but also on ways to increase the propagation of this practice and to understand and find solutions towards solving its vulnerabilities. Many of these studies have a practical application base, supported by their application to case studies. These are a crucial tool in order to increase the knowledge about industrial symbiosis, not only to validate proposed methods and structures, but also to analyse and serve to elucidate and draw lessons for future improvements (Eisenhardt, 1989; Yin, 2014).

Cases of industrial symbiosis have been growing over recent years and are scattered all over the world, whether in developed regions such as the United Kingdom, the United States of America and Japan, or in countries with developing economies, such as Thailand, Morocco and Algeria. In addition to diversity in terms of location, the case studies reported in literature also reflect the enormous variety in the size and types of activity involved in symbiosis. The two cases of industrial symbiosis studied in Västra Götaland in Sweden (Patricio et al., 2018) are examples of cases having few companies and little diversity, where one of the symbioses is developed between growers of mushrooms and farmers and the other between brewers and breeders. The case of Tianjin, China (Shi et al., 2010; Zhang et al., 2013) is one of the most varied of activities, involving a synergy of water and wastewater companies, thermal power plants, farms, pharmaceutical, paper, cement, automobiles and machinery industries, among others.

Given this wide variety of case studies, some publications have appeared with the aim of compiling and extracting lessons about the characteristics, the methodology, and the weaknesses of the network, among others and to use them as a basis for theories. In the same way, Chertow (2000) used twelve cases of industrial symbiosis to illustrate the proposed taxonomy of five different material exchange types. Zhang et al. (2015a) also used some examples of industrial symbiosis cases to illustrate proposed theories and types of industrial parks based on these theories. Herczeg et al. (2018) with the aim of improving the understanding of supply chain collaboration in industrial symbiosis networks, combined the analysis of fifteen case studies with theoretical perspectives. Chertow and Ehrenfeld (2012) focused the study on the self-organizing industrial symbiosis using ten existing cases categorized according to the spatial scale where they were organized. Mathews and Tan (2011) described and compared nine case studies of industrial symbiosis to study their evolution and identify which are the drivers and inhibitors of the various synergy initiatives. Zhu and Ruth (2014) analysed the growth of the industrial symbiosis networks of sixteen cases, by characterizing them in terms of the number of companies involved, clusters and their institutional settings and analysed the impact of the promotional institutions. Also in the article by Kastner et al. (2015) some case studies were listed and classified according to the existing exchange. Chertow and Park (2011), by analysing the types of waste reused and the industries involved in these synergies in thirteen distinct cases of industrial symbiosis, proceeded to identify and categorize waste materials and types of industries with the potential to generate and use the various types of waste. Through this list it was possible to identify which categories of waste had the greatest links across different industries and therefore provide more potential for development. More recently, a study has been published which compiled the various cases of industrial symbiosis in Europe and through this mapping and the interviews conducted, analysed the main characteristics of the symbioses in Europe and the main drivers that lead companies to create such synergies (Domenech et al., 2019).

In spite of the existence of all these publications that somehow compiled and characterized the various cases of industrial symbiosis, the number of cases analysed in each article was reduced and in the publication where the number of cases was much higher, these were confined to a particular area. As a result, there was still a need for a publication that was more comprehensive and that compiled in a single article all published case studies without any restriction of characteristics or location.

In order to fill this gap in research, this article has as its main objective to compile the various cases of industrial symbiosis in the world and to perform an analysis concerning the location, types of economic activities involved in the synergies and the methods employed in the various studies. This analysis, besides comparing different characteristics, also has the objective of framing them in the different realities underlying each case, not only to trace future research paths, but also to improve the understanding of industrial symbiosis and to increase its usage. In addition, this article also aims to serve as a guide for the creation of new synergies, since this has been recognized by some authors (Grant et al., 2010; Patricio et al., 2018) highlighting the importance of the dissemination of cases of industrial symbiosis as a way to identify and promote new symbiosis opportunities, called relationship mimicking. In addition to these objectives, the article also intends to provide a quantitative view of the publications on industrial symbiosis and to trace the evolution of research on this theme, explaining its distribution by journals, content and type of article. Although there were some studies with quantitative evaluations, these were related to articles published until 2012 (Yu et al., 2014a), 2014 (Chertow and Park, 2016) and 2016 (M. M. Huang et al., 2019), and are therefore not currently up to date.

The remainder of this article is organized as follows. Section 2 presents the methodology that was adopted for the research and selection of publications, as well as how the objectives of the article guided the subsequent content analysis. In Section 3 the trend of research on industrial symbiosis is described and analysed. In addition to the analysis of the evolution of the number of publications, the distribution through journals and type of article is also presented and examined. The study of the distribution of publications by type of content and the analysis of published case studies involving their geographical distribution, type of industries involved in the symbiosis and methods used is performed in Section 4. Finally, in Section 5, a discussion about the material presented in the previous sections, as well as the limitations of the study carried out. The main conclusions and recommendations for future research are made in Section 6.

2. Methodology

To carry out the main purpose of this paper in providing a comprehensive review of previous studies on industrial symbiosis, several steps were conducted. As shown in Fig. 1, these can be summarized in three main ones, research, selection and analysis of the several articles, directly related to the objectives of a literature review, such as "identifying, evaluating, and synthesizing the existing body of completed and recorded work produced by researchers, scholars, and practitioners" (Fink, 1998). These steps were conducted in order to answer, on the one hand, the way in which the works published in this theme have evolved and how they are classified in the various aspects, and on the other hand, the distribution of case studies of industrial symbiosis around the world, their characteristics and the methods used.

For the accomplishment of the research of articles, it was necessary the establishment of the keywords and the choice of the academic databases. Thus, in order to identify the largest number of publications, the keyword used for the research was "industrial symbiosis" and no time interval was imposed. For the research of the various publications, the academic databases that comprise the publishers with the greatest number of articles published in this

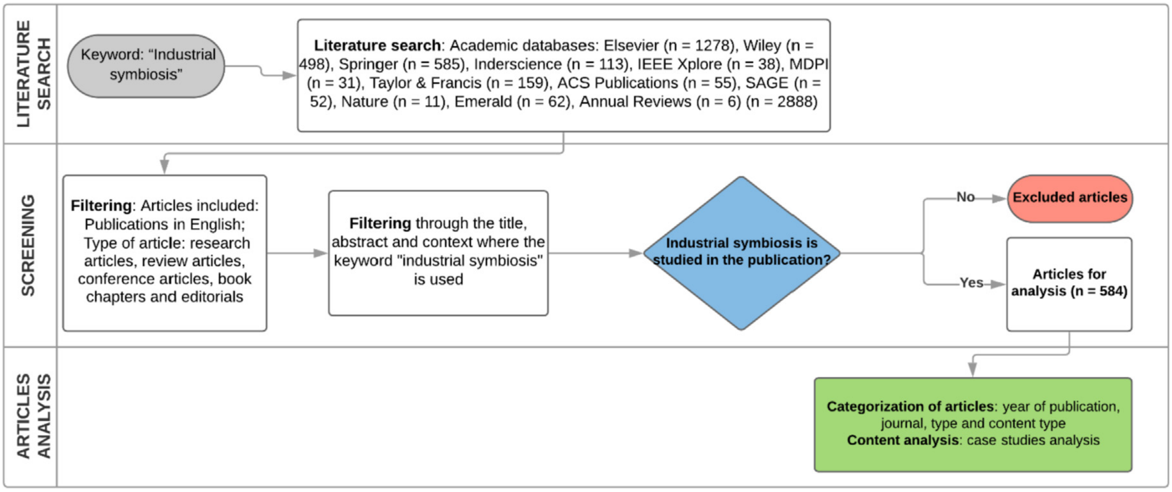

Fig. 1. Flow diagram of literature search and respective screening.

area were used, such as Elsevier, Wiley Online Library, Springer, Inderscience Online, IEEE Xplore, MDPI, Taylor & Francis Online, ACS Publications, SAGE Journals, Nature Research, Emerald Insight and Annual Reviews. The choice of using these publishers instead of the most usual databases, such as the Web of Science and Scopus, was due to the fact that after comparing the initial results of the research, it was concluded that some of the articles were not included in these. Also the number of publications obtained through the publishers was greater than in these two databases. The search resulted in 761 publications from Web of Science, 907 from Scopus and the total of publications obtained through the publishers was 2888, as shown in Fig. 1.

Included in this study were research articles, review articles, conference articles, book chapters and editorials. Although some of these publications were not peer-reviewed, they provided more information about existing industrial symbiosis cases that were not reported in peer-reviewed publications. The only exclusion criterion, in this first phase of research, was all articles that were not written in English.

The next step comprised the selection of the articles. Titles, abstracts and keywords were read in a first stage to analyse whether the article concerned with the theme of industrial symbiosis. If, after this reading, some doubts remained as to the inclusion of the articles for later content analysis, then the text was examined. This included not only the counting of the number of times the term industrial symbiosis appeared, but also reading the context in which they were inserted. That is, all articles those referred only to industrial symbiosis as an example, or mentioned only in the introduction to contextualize another concept or to distinguish concepts, without the study of this practice, were eliminated. The snowballing method (Bakker, 2010) was used to obtain additional articles, that is, the references cited in the papers analysed were used to search for more relevant publications, however, few emerged from this analysis, which may be indicative of the effectiveness of the initial research. A total of 584 articles resulted in the end of the entire research and screening process.

In order to obtain a quantitative representation of the distribution of publications and their evolution, the main data of the selected articles, such as the year of publication, the journal and the type of article (research, review, conference, book chapter and editorial) were collected. To map the industrial symbiosis and characterize the main activities and methods used in the various studies, the publications were analysed in two distinct phases. The first one consisted in categorizing the selected publications in terms of content type and the second consisted in a content analysis of all case studies in order to characterize and map the various initiatives of industrial symbiosis in the world. In the first phase of categorization, the publications were classified into three types: Theoretical, Review and Case Studies. However, during the analysis of the articles, it was concluded that many of the studies carried out looked at the potential of applying industrial symbiosis in new places and what the environmental and economic advantages could result from its application. Thus, these cases were not covered in the case studies, because although they related to a specific location and existing industries, they were not yet realized. Therefore, a new category, Potential Industrial Symbiosis was defined, in order to encompass these publications. In the Theoretical category are included theoretical and conceptual articles, as well as those that use models from mathematical functions, that is, modelling and simulation. The publications in which qualitative data was used, such as interviews, to study a case of existing industrial symbiosis were classified as Case Studies.

3. Review of research trends

3.1. Evolution of the number of published articles

After the research and application of the selection criteria set forth in the previous Section, the main data of the 584 articles selected were extracted in order to draw conclusions about the trend of research on industrial symbiosis. Fig. 2 shows the evolution of the number of articles published since 1995. It can be seen from the analysis of the figure that the number of articles has grown exponentially, revealing an increasing interest of the scientific community in this subject. This growth can be divided into two distinct periods, the first between 1995 and 2006, in which in the first years the number of articles remained almost constant, beginning to increase from 2004, however in this period the increase in the number of articles published was not very significant. In the second period between 2007 and the present year, there is a clear increase in the number of articles, from 20 in 2007 to 78 in 2018, reaching a maximum of 86 publications in 2017. And although in some years there has been a decrease in the number of publications, it is negligible compared to the considerable increase in the number of articles in subsequent years, reaching in 2014 and 2017 growth rates over the previous year of 88% and 72% respectively. It should be noted that the value of 2019 is provisional, since it refers to the first five months of the year, however given the large number

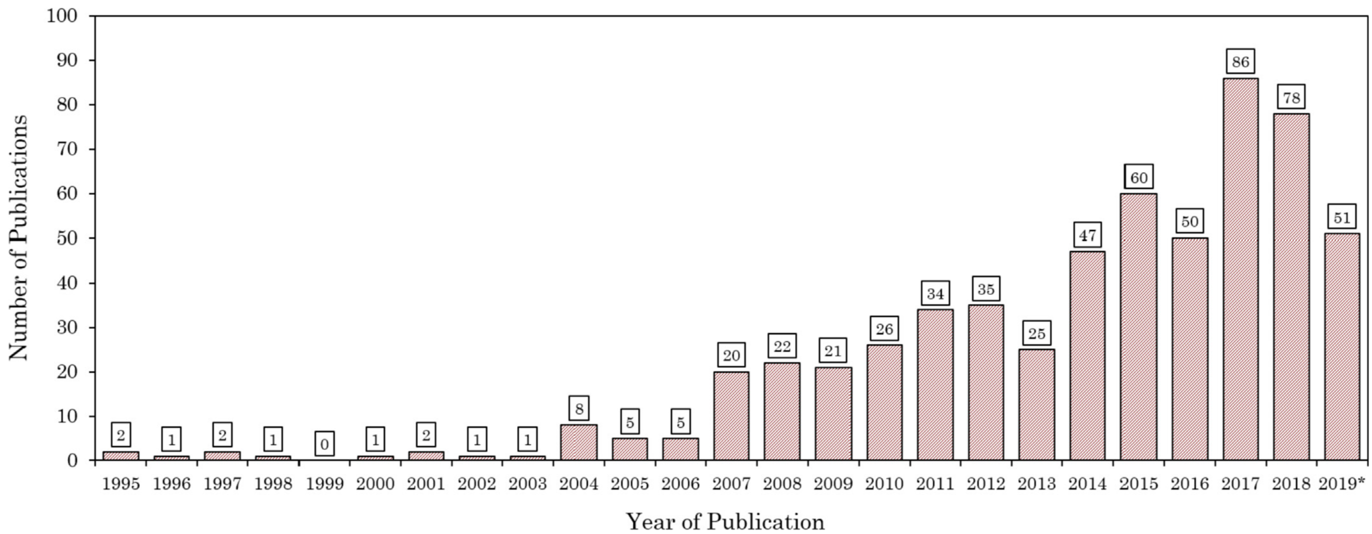

Fig. 2. Number of publications per year.

of publications already verified; it is likely that by the end of the year the number of articles will exceed the value of the previous year.

This increase in the number of publications may be related with the development of European, national and regional programs and policies that have encouraged the practice of industrial symbiosis, as corroborated in the study by Chertow and Park (2016). The successful example of Kalundborg, so often cited in the literature (Domenech and Davies, 2011; Ehrenfeld and Gertler, 1997; Jacobsen, 2006; Valentine, 2016), may also be an important factor in the growing interest in industrial symbiosis and the consequent growth in the number of publications. As an example of success since 1972 and allied to the many studies that have demonstrated the numerous economic, environmental, and social benefits to companies and the surrounding community, it may have increased the interest in studying this practice.

3.2. Contribution of journals in the evolution of published articles

Selected articles were collected from 183 different sources, including journals, books and conference proceedings. However, as can be seen in Fig. 3, the distribution by journals is not uniform. In this figure it is possible to observe the distribution of articles by journals with the highest number of publications, at least 5, in the area of industrial symbiosis.

From Fig. 3, we can observe that the journals with the most publications are the Journal of Cleaner Production, with 121 articles, followed by the Journal of Industrial Ecology with 77 articles. In the universe of 183 sources, these 16 journals illustrated in the figure, corresponding to approximately 9% of the total, are responsible for 59% of all publications. While the two main journals, equivalent to 1.1% of all journals, books and conference proceedings, are responsible for 33.9% of the total articles, of which 20.7% are published in the Journal of Cleaner Production and 13.2% in the Journal of Industrial Ecology.

3.3. Distribution of publications by article type

The publications that resulted from the research and selection were grouped by article type, that is, research articles, review articles, conference articles, book chapters, and editorials, as illustrated in Fig. 4.

Comparing the different types of publications, the research articles are those that stand out with a great difference compared to the other types, with a total of 411 articles. This is followed by conference articles with a total of 77, book chapters with 59, review articles with 21 and editorials with 16 publications in total.

Fig. 5 shows the evolution of the number of publications according to the type of articles. It is possible to analyse from the figure that, although the research articles are always preponderant over the other types, not always the proportion of the various types of articles in each year remains constant.

Until 2003, and due to the small number of articles published, almost every year the research articles were the only ones to be published. Since 2004, the type of articles has become more diverse, nevertheless research articles continued to predominate over the others, with an average annual weight of 74.1% compared to the total published annually.

Regarding the maximum values obtained by the main types of articles, these have been verified in recent years, which illustrate the growing interest in industrial symbiosis. The research articles, as stated above, present the highest value of publications, reaching a maximum of 58 in 2017. Also in this year the conference articles reached a maximum of 17 and editorials a maximum of 3, while the other types of publications, reached the maximum values in dissimilar years. In 2018 book chapters peaked at 12 and review articles reached 4 publications in consecutive years from 2014 to 2016.

4. Analysis of case studies on industrial symbiosis

The next two sections focus on the analysis of content made to the various publications. In the first section, a broader analysis is carried out regarding the distribution and evolution of publications by content type. The following is an analysis of the various cases studies of industrial symbiosis found in the literature, where a characterization of the geographical distribution and type of activities involved in the symbiosis was carried out, as well as the methods that were used in the several studies.

4.1. Distribution of publications by content type

During the detailed study of the selected articles on industrial symbiosis and with the aim of analysing the evolution of the

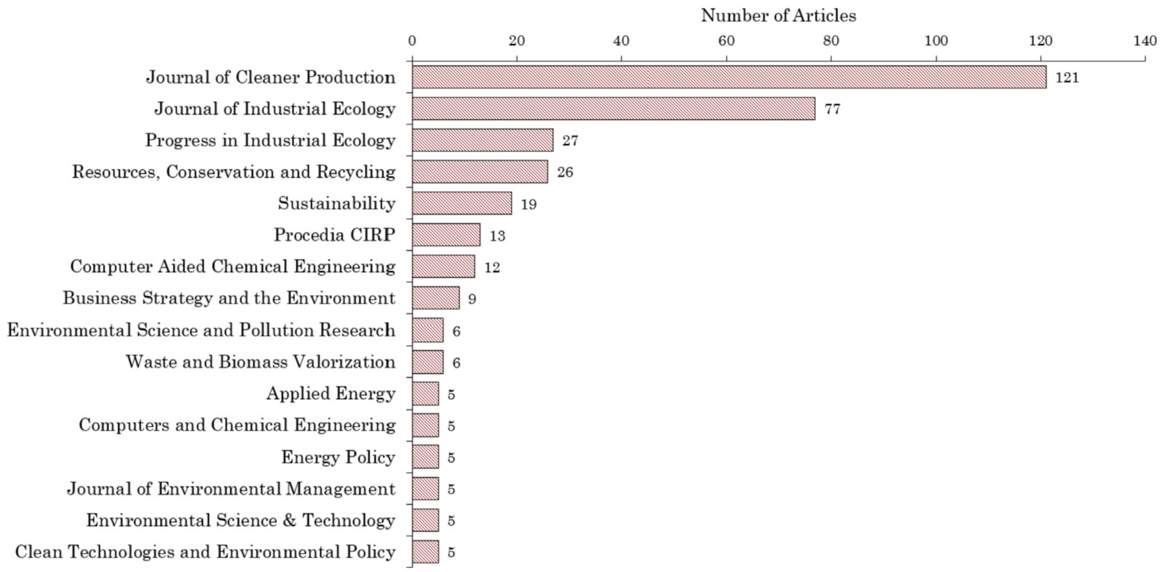

Fig. 3. List of journals with the highest number of articles published (at least 5 articles).

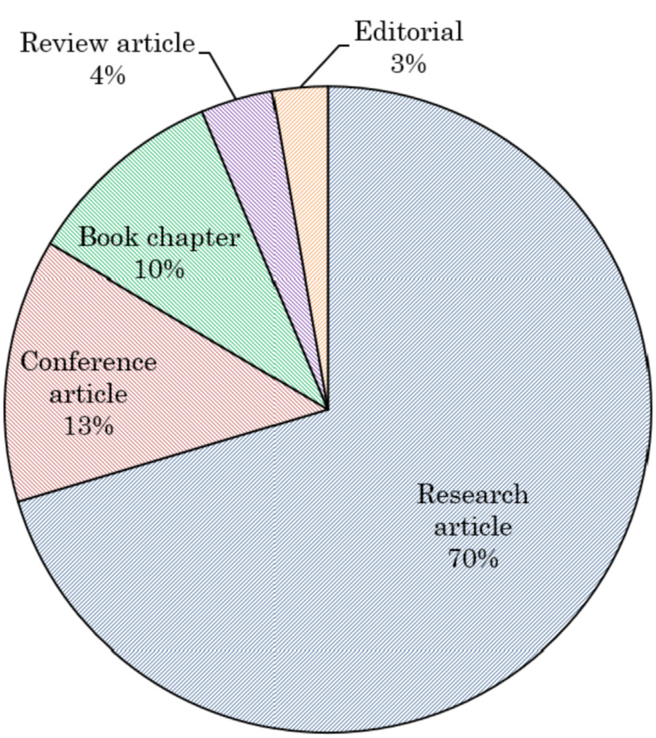

Fig. 4. Distribution of the number of publications by article type.

research regarding the content of the publications, these were classified according to the content type. The categorization of selected publications was initially conducted according to three types of content: Review, Theoretical and Case Studies. However, during the analysis of the articles it was concluded that many of them were not included in any of these categories, and although they reported to a study of industrial symbiosis in a given location, they did not fit within the scope of the case studies. Thus, a new category, Potential Industrial Symbiosis was defined, with the aim of clarifying the division between content types and including all publications whose main focus was the analysis and description of potential industrial symbiosis.

4.1.1. Distribution and evolution of publications by content type

The selected articles on industrial symbiosis were carefully analysed and classified according to the type of content, whose distribution by categories, Review (R), Theoretical (T), Case Studies (CS) and Potential Industrial Symbiosis (PIS), is shown in Fig. 6.

From the analysis of the figure it is possible to conclude that the distribution of the publications by content type is quite different. Publications whose content is theoretical occupy the largest part of the universe of publications on industrial symbiosis. Of this category, a total of 279 articles were published, with a very wide and distinct scope. Some examples are the articles that dealt with methods (Valero et al., 2013), indicators (Couto Mantese and Capaldo Amaral, 2017; Felicio et al., 2016), approaches to quantify environmental performance (Martin et al., 2015) and analysis of symbiosis networks (Zeng et al., 2013). The study for the creation and development of industrial symbiosis was also the focus of many articles in this category. Articles in which quantification tools were developed to identify the best scenario for the implementation of industrial symbiosis (Brondi et al., 2018), in which platforms for collaboration and information sharing were studied and developed to facilitate the creation of synergies (Fraccascia and Yazan, 2018; Low et al., 2018), as well as the study of the best network configuration (Somoza-Tornos et al., 2018), are some of the examples.

The second content type most approached in industrial symbiosis publications are case studies, with 179 articles. The variety of these articles with regard to location, type of activities, methods used and formation and development of symbiosis is vast. Section 4.2 will provide a more detailed explanation of the case studies.

The potential industrial symbiosis corresponds to the third most published content in this area, with 102 articles. Although the core of this new category is the study of the industrial symbiosis that can be carried out, the scope of the publications included in this category is quite broad. Thus, publications with a narrower scope which focused on the study of new uses of by-products or waste in order to enhance industrial symbiosis were included. Examples of these publications were the study conducted for the potential recovery of platinum from waste thermocouples (Charles et al., 2018), and the study of the use of grape marc for the development of a bio-adsorbent used for the removal of copper sulphate from water (Bustos et al., 2018). Publications with a broader scope were also

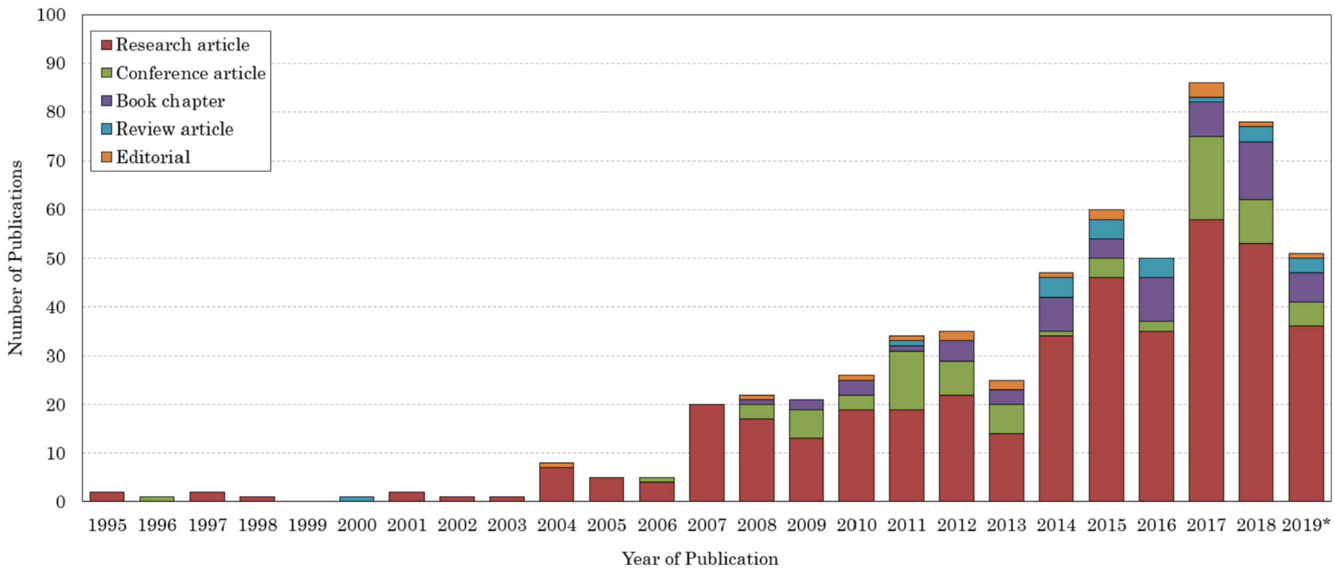

Fig. 5. Evolution of the number of publications by article type per year.

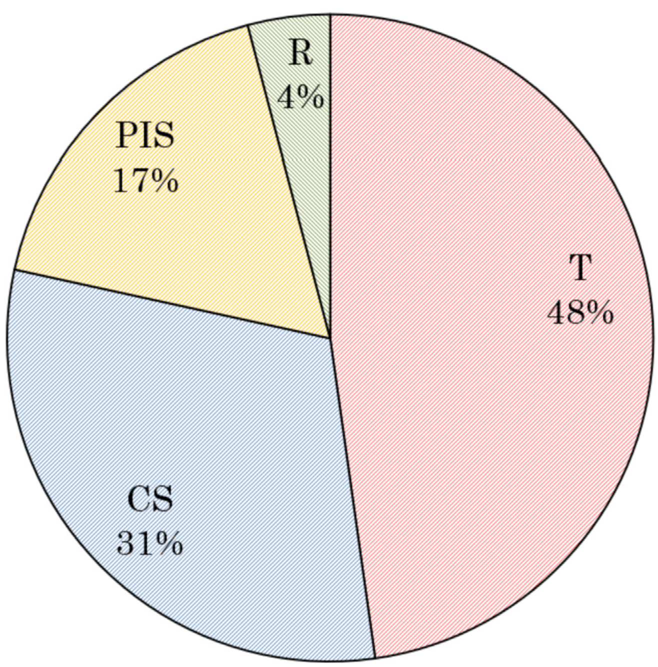

Fig. 6. Distribution of the publications by content type.

included in this category, from publications that have studied the possibility of creating and developing industrial symbiosis around a specific industry, usually responsible for the production of a large number of wastes and by-products and therefore more attractive for the development of industrial symbiosis, to those who studied the potential transformation of an industrial park into an eco-industrial park with a major focus on industrial symbiosis. Examples of these publications are studies that have been developed to identify and evaluate industries capable of creating industrial symbiosis around nuclear plants in France (Leurent et al., 2018) and rubber industries in Kedah, Malaysia (Sharib and Halog, 2017), and the studies done in the industrial park of Salaise-Sablons in France (Ribeiro et al., 2018) and in the industrial city of Borg El-Arab in Egypt (ElMassah, 2018), which involved various types of industries with the aim of transforming the park where they are inserted into an eco-industrial park with various industrial symbiosis.

The lowest number of publications, 24 articles, is in the review content category. The subjects covered in these review publications are very diverse, ranging from the most comprehensive, in which a thorough study of previous publications is done, and from that analysis they establish categorization systems, identify the trends of the research carried out, as well as the possible evolutions (Chertow, 2000; Zhang et al., 2015a), to the most restricted in which although a thorough study of previous publications is done, it is more confined to the subject under analysis. Review articles that focus on a given region (Maes et al., 2011; Park et al., 2016) or waste (Gopinath et al., 2018), or methods and indicators (Neves et al., 2019a) or that study the role of policies for the development of industrial symbiosis (Jiao and Boons, 2014), or that study the role of information systems (van Capelleveen et al., 2018) and online social networks (Ghali et al., 2016) for the formation of new synergies are some of the examples of publications whose content is more focused.

The evolution of publications taking into account the content type is not always constant according to the evolution of the total publications, as shown in Fig. 7.

Until 2003, the number of existing publications was very small and articles whose content is theoretical were predominant, representing until that year 73% of all publications. With the increase in the number of articles published on industrial symbiosis since 2004, the diversity of contents began to be noticed, but with few exceptions, publications whose content is theoretical dominated the annual publications, almost always accounting for about 50% of all publications. Articles whose contents are case studies accounted for a considerable portion of the total number of publications over the years, often occupying second place in annual publications. Furthermore, in 2007, 2011 and 2015 were the most published type of article. Since 2004, papers dealing with potential industrial symbiosis have been published regularly, and although their weight has varied over the years, there has been a clear increase since 2015. Of all content types, the ones that presented the greatest interregnum between publications were the review articles. However, since 2014 they have been published more regularly, reflecting the need to identify and analyse research trends.

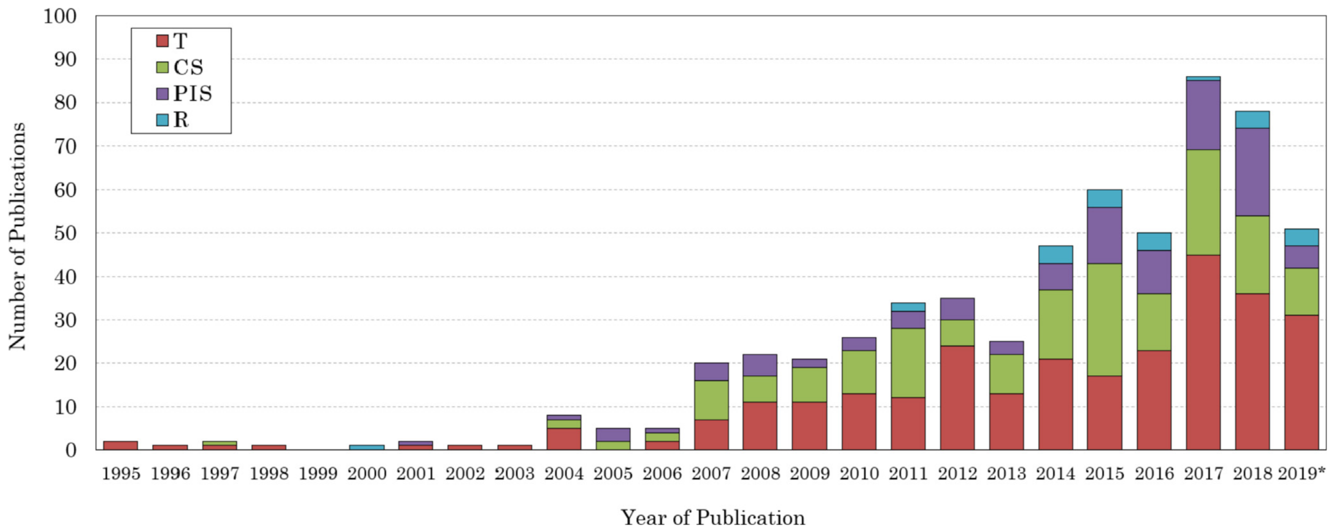

Fig. 7. Evolution of the number of publications by content type per year.

4.2. *Analysis of case studies*

In order to map the existing industrial symbiosis case studies as well as the methods employed in the respective studies, the various publications were analysed. From this analysis it was possible to verify the enormous variety of cases of industrial symbiosis, not only in terms of location, but also in the size and industries involved, as illustrated, in a summarized form, in Table 1 where all these data were compiled. In Table A.1, in Appendix A, all this information is set out in more detail.

The case studies of industrial symbiosis reported in the literature cover several areas, such as, Europe, North America, Asia, Oceania, North Africa and South America. The order in which the various areas are organized refers to the year of publication, being sorted from the oldest to the most recent. Within each area, the regions were also organized in ascending order of publication year of the articles.

With the objectives of making the table more concise and analysing the economic activities present in the various cases of industrial symbiosis, it was decided to group the various activities into sections, defined according to the International Standard Industrial Classification of All Economic Activities, Revision 4 (ISIC, Rev.4). Recognized as an International reference classification, according to this, economic activities are subdivided into four levels in a hierarchical structure. However, in the table below the economic activities are established by the classification into sections, more comprehensive, belonging to the highest level and collected in alphabetical order. Of the 21 sections defined in the ISIC, 14 are present in the various cases of industrial symbiosis studied, being chosen to put in the table a more concise designation to enunciate the various sections. Thus, sections A: Agriculture, forestry and fishing, B: Mining and quarrying, C: Manufacturing, D: Electricity, gas, steam and air conditioning supply, E: Water supply; sewerage, waste management and remediation activities, F: Construction, G: Wholesale and retail trade; repair of motor vehicles and motorcycles, H: Transportation and storage, I: Accommodation and food service activities, L: Real estate activities, M: Professional, scientific and technical activities, N: Administrative and support service activities, O: Public administration and defence; compulsory social security and R: Arts, entertainment and recreation are included in the case studies.

4.2.1. *Geographic distribution*

Case studies of industrial symbiosis are scattered throughout the world, but this distribution is quite disparate, as illustrated in Fig. 8, where the distribution of the number of case study publications by country is represented. In addition to this asymmetry in the number of publications, the number of industrial symbiosis cases in each country, represented by the different divisions in each bar, is also indicative of the disparity between them.

The area with the largest number of published case studies on industrial symbiosis is Asia with 102 studies corresponding to 49.0% of the total case study, followed by Europe with 78 studies and North America with 19 studies, corresponding to 37.5% and 9.1%, respectively. Oceania, North Africa and South America hold the remaining 4.4% of the total case study.

As shown in Fig. 8, China is the country with the largest number of case studies on industrial symbiosis accounting for 34% of all publications, value much higher than in the other countries and accounting for 70% of the total number of case studies published in Asia. It is also the country with the most cases of industrial symbiosis reported in the literature, with a total of 36. The number of studies on industrial symbiosis in China began to increase from 2014, peaking in 2017, a year in which the maximum value of publications on industrial symbiosis was also verified. The large number of industrial symbiosis and their dispersion across the country is greatly justified by the policies and plans that China has been implementing over the years. As a country with rapid economic growth, this has resulted in increased primary energy consumption, increased resource consumption and increased greenhouse gas emissions such as carbon dioxide, CO_2 (Fang et al., 2007; Liu et al., 2017). And since these emissions are much higher than those in other countries and with greenhouse gas emissions limitations set by the international community (Pao and Chen, 2019), China needed to implement policies and measures to counter this increase. Thus, over the years, China has implemented various measures, policies, research incentives, financial incentives, among others, that have been instrumental in the development of industrial symbiosis (Tao et al., 2015; Q. Wang et al., 2017). And although the plans that were established did not have the industrial symbiosis as the main objective, the fact of guiding the various measures for the circular economy and the development of eco-industrial parks, have made industrial symbiosis develop and China has thus played a key role in increasing synergies between

Table 1
Industrial symbiosis application and analysis studies.

Country	Region	N. Enterprises	Activity	Method	Publication Year	Reference
Europe						
Denmark	Kalundborg	6/18	Energy supply, Manufacturing, Agriculture, Water and waste and Public administration	On-site visits and interviews. Interdependencies analysis. Environmental and economic analysis. Social network analysis (SNA) and core-periphery structure analytical methods. Centrality indicators, centralization measures and small-world and scale-free effects. Disruptive scenarios and cascading effects. Input-output inoperability model, Fuzzy approach. Dependency and influence gain indexes. Stability analysis	1997/2019	(Branson, 2016; Chopra and Khanna, 2014; Domenech and Davies, 2011; Ehrenfeld and Gertler, 1997; Jacobsen, 2006; Kuznetsova et al., 2017; Valentine, 2016; Zhang and Chai, 2019; Zhang et al., 2013)
United Kingdom	Grangemouth		Manufacturing, Energy supply and Water and waste	Technology transfer model adapted	2004	Harris and Pritchard, (2004)
	Forth Valley		Manufacturing, Energy supply and Water and waste			
	Humber		Energy supply, Manufacturing, Agriculture and Water and waste	Direct observations, interviews and SNA	2004/2016	(Mirata, 2004; Velenturf, 2016)
	West Midlands	167	Manufacturing, Food service and Professional and scientific activities	Direct observations and interviews and conversations	2004/2012	(Mirata, 2004; Paquin and Howard-Grenville, 2012)
	England/Scotland/Wales			Geographic Information Systems software package	2011	Jensen et al., (2011)
	Bristol		Manufacturing	On-site visits and interviews	2014	Cerceau et al., (2014)
	Wissington		Manufacturing	Interviews	2014	Short et al., (2014)
			Transportation and storage	Interviews	2015	Leigh and Li, (2015)
			Manufacturing, Water and waste and Professional and scientific activities	Interviews	2018	de Abreu and Ceglia, (2018)
Sweden	Landskrona	>20	Manufacturing, Water and waste, Agriculture, Transportation and storage and Public administration	Interviews	2005	Mirata and Emtairah, (2005)
	Southern Sweden		Manufacturing and Energy supply	Interviews	2007	Wolf et al., (2007)
	Sundsvall-Timrå		Manufacturing and Public administration	On-site observation and interviews	2007	Wolf and Petersson, (2007)
	Mönsterås		Manufacturing and Public administration			
	Östergötland		Manufacturing and Energy supply	Planned and unplanned IS activities analysis	2011	Baas, (2011)
	Händelö	3	Agriculture, Manufacturing, Energy supply, Water and waste and Public administration	Visits and interviews. Material and energy flows. Life cycle assessment (LCA), EPD 2008, energy allocation, system expansion and the 50/50 methods	2011/2015	(Martin, 2015; Martin et al., 2014; Martin and Eklund, 2011)
	Västra Götaland	11	Agriculture and Manufacturing	On-site visits and interviews	2018	Patricio et al., (2018)
	Stenungsund		Manufacturing	LCA and CML 2001 method. Cost-effectiveness analysis	2018	Røyne et al., (2018)
	Sotenäs	10	Manufacturing, Agriculture and Water and waste	Interviews, consultation, LCA and socio-economic assessments	2018	Martin and Harris, (2018)
Netherlands	Rotterdam		Manufacturing, Agriculture, Sale and repair, Energy supply, residential areas and port	On-site visits and interviews. Role of organizations. Analysis of embeddedness and capabilities. Historical background and development analysis. Planned and unplanned IS analysis	2007/2014	(Baas, 2011; Baas and Boons, 2007; Baas and Huisingh, 2008; Baas and Korevaar, 2010a; Cerceau et al., 2014)
	Canal Zone of Zeeland		Agriculture, Manufacturing, Water and waste and regional port authority	Interviews and event sequence analysis	2013/2014	(Boons et al., 2014; Spekkink, 2013)
	Zeeland		Agriculture and Manufacturing	On-site visits and interviews	2014	Cerceau et al., (2014)
	Sloe Area and Canal Zone		Agriculture, Manufacturing and Water and waste	Interviews and event sequence analysis	2015	Spekkink, (2015)
	South of the Netherlands		Agriculture, Manufacturing, Public administration and Professional and scientific activities	Interviews, brainstorming sessions, comparative analysis and visual analysis	2019	Baldassarre et al., (2019)
France	Mèze		Agriculture and Water and waste	On-site visits and interviews	2007	Gibbs and Deutz, (2007)
	Marseille-Fos		Energy supply	On-site visits and interviews	2014	Cerceau et al., (2014)
	Bazancourt-Pomacle		Manufacturing	Interviews	2015	Schieb et al., (2015)

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Table 1 (*continued*)

Country	Region	N. Enterprises	Activity	Method	Publication Year	Reference
	Dunkirk	14	Manufacturing, Energy supply, Water and waste, Agriculture and Construction	Site visits and interviews. Geographical system dynamics method and Causal Loop Diagrams	2019	Morales and Diemer, (2019)
			Water and waste and local companies	Site visits, interviews, qualitative and quantitative model of the stakeholder value network approach	2017	Hein et al., (2017)
Russia	Kola Peninsula	9	Mining and quarrying	Interviews, counterfactual method, eco-efficiency indicators and material flow analysis	2007	Salmi, (2007)
Finland	Kuusankoski		Manufacturing, Energy supply and Water and waste	Quantifiable indicators for the analysis of sustainability	2010	Pakarinen et al., (2010)
	Kymenlaakso		Manufacturing, Energy supply and Water and waste	On-site survey. Process, hybrid and input-output life cycle assessment approaches and LCIA-RECIPE method. LCA	2010/2011	(Mattila et al., 2010; Sokka et al., 2011b)
	Kouvola	9	Manufacturing, Energy supply and Water and waste	Interviews and LCA	2011	(Lehtoranta et al., 2011; Sokka et al., 2011a)
Portugal	Chamusca		Water and waste, Manufacturing and Agriculture	Interviews, on-site visits and middle-out approach	2010	Costa and Ferrão, (2010)
	Lisbon	44	Manufacturing, Sale and repair, Construction, Energy supply and Agriculture	Material Flow Analysis	2015	Patrício et al., (2015)
			Manufacturing	Interviews, indicators and radar chart graph. Comparative analysis	2019	Ferreira et al., (2019)
Austria	Styria		Manufacturing, Sale and repair, Water and waste, Mining and quarrying, Energy supply and Public administration	SNA and core-periphery structure analytical methods	2013	Zhang et al., (2013)
Italy	Taranto	>15	Manufacturing, Agriculture and Energy supply	Questionnaires	2014/2016	(Notarnicola et al., 2016, 2014)
	Venice, Veneto		Manufacturing	Surveys data	2015	Mannino et al., (2015)
	Prato, Tuscany		Manufacturing	Interviews	2015	Daddi et al., (2015)
	Ponterosso, Friuli-Venezia Giulia		Manufacturing			
	Ancona, Marche		Manufacturing, Sale and repair, Professional and scientific activities, Food service and Administrative and support service			
	Abruzzo		Manufacturing	On-site survey and questionnaires	2017	Taddeo et al., (2017)
	S.Croce sull'Arno, Tuscany		Manufacturing	LCA	2017	Daddi et al., (2017)
Spain	Galicia		Port-based industrial complexes	On-site visits and interviews	2014	Cerceau et al., (2014)
			Manufacturing	Interviews, indicators and radar chart graph. Comparative analysis	2019	Ferreira et al., (2019)
Belgium	Antwerp		Manufacturing and city	On-site visits and interviews	2014	Cerceau et al., (2014)
	Brussels		Port-based industrial complexes			
	Koekhoven		Energy supply, Agriculture, Professional and scientific activities, Manufacturing, Sale and repair, and Water and waste	Interviews, observations, field visits and dual-perspective framework application	2016	Verguts et al., (2016)
Germany			Manufacturing	Simplified life cycle assessment model	2015	Ammenberg et al., (2015)
Latvia			Manufacturing, Agriculture and Energy supply	Interviews. Integrated method for evaluation of the quality of industrial synergies	2015	Rosa and Beloborodko, (2015)
			Manufacturing and Agriculture			
Denmark/UK/ Portugal/ Switzerland				Interviews and quantitative and qualitative descriptors	2010	Costa et al., (2010)
North America						
United States of America	Guayama, Puerto Rico		Energy supply, Water and waste, Manufacturing and Construction	Field research, interviews, questionnaires and material flow analyses	2005/2008	(Chertow et al., 2008; Chertow and Lombardi, 2005)
	Barceloneta, Puerto Rico	15	Manufacturing, Agriculture and Water and waste	Field research and interviews. Material flow analyses. SNA. Congruence method	2008/2011	(Ashton, 2008, 2011; 2009; Chertow et al., 2008)
	Pennsylvania			Environmental assessment using the life cycle inventory databases of GREET and Ecoinvent	2009	Eckelman and Chertow, (2009)
	Honolulu	11	Energy supply, Manufacturing, Water and waste, Mining and quarrying and Arts, entertainment and recreation	Interviews. Quantification of environmental and economic benefits. LCA	2010/2013	(Chertow and Miyata, 2010; Eckelman and Chertow, 2013)

Table 1 (*continued*)

Country	Region	N. Enterprises	Activity	Method	Publication Year	Reference
	Kansas City	9	Manufacturing, Water and waste and Energy supply	Material flow network and mixed integer programming model	2011	Cimren et al., (2011)
	Choctaw		Manufacturing, Water and waste and Agriculture	SNA and core-periphery structure analytical methods	2013	Zhang et al., (2013)
	New York/New Jersey		Port-based industrial complexes	On-site visits and interviews	2014	Cerceau et al., (2014)
	Long Beach		Ports and marinas	On-site visits and interviews	2014	Cerceau et al., (2014)
	North Dakota		Manufacturing and Energy supply	Interviews and surveys. Stochastic mixed integer linear programming model and energy efficiency analysis	2015	Gonela et al., (2015)
	Upper Valley	2	Manufacturing and Water and waste	Interviews	2017	Krones, (2017)
	Chicago		Manufacturing, Agriculture, Real estate activities, Professional and scientific activities and Water and waste	Measurements on-site and off-site, interviews, questionnaires and material flow analysis	2018	Chance et al., (2018)
Canada	Sarnia-Lambton		Manufacturing, Agriculture and Energy supply	Interviews	2009	Bansal and Mcknight, (2009)
Mexico	Altamira-Tampico	15	Manufacturing	Interviews and on-site visits	2019	Morales et al., (2019)
Asia						
South Korea	Ulsan	2/21/41	Manufacturing, Water and waste, Energy supply, Sale and repair, metropolitan city and port-based industrial complexes	On-site visits and interviews. Analysis of the development of IS. Eco-efficiency evaluation. Eco-production strategy analysis. Assessment of economic, social and environmental benefits. GHG emissions based on the GHG protocol and LCA. Cut-off, avoidance impact, and 50/50 methods	2006/2018	(Behera et al., 2012; Cerceau et al., 2014; Kim et al., 2018b; Park and Behera, 2015, 2014; Park et al., 2008; Park and Park, 2014; Won et al., 2006)
	Yeosu	27	Manufacturing and Energy supply	Interviews, questionnaires and waste heat utilization network model	2010	Chae et al., (2010)
	Banwol-Sihwa		Manufacturing, Energy supply, and residential areas	Fieldwork and interviews	2018	Yoon and Nadvi, (2018)
		596		Network analysis. Economic and environmental benefits analysis	2019	Park et al., (2019)
China	Guigang		Manufacturing, Water and waste, Energy supply and Agriculture	Interviews. SNA and core-periphery structure analytical methods. Robustness analysis and optimization of the network. Assessment of the vulnerability of symbiosis network based on the automatic control theory. Material flow analysis and comparative analysis	2007/2018	(Fang et al., 2007; Guo and Hu, 2011; Shi and Chertow, 2017; Q. Wang et al., 2018b, 2018b; Zhang et al., 2013; Zhu et al., 2007)
	Wudi County, Shandong province	8/21	Manufacturing, Mining and quarrying, Agriculture, Water and waste, Energy supply and living area	Eco-industrial development analysis. Environmental and economic analysis. SNA and core-periphery structure analytical methods. Centrality indicators, centralization measures and small-world and scale-free effects. Stability analysis. Ecological network analysis	2007/2019	(Fang et al., 2007; Guo and Hu, 2011; Wang et al., 2010; Zhang and Chai, 2019; Zhang et al., 2015b, 2013)
	Guiyang		Manufacturing, Energy supply, Agriculture and urban areas	Eco-industrial development analysis. Hybrid model integrating an input-output approach and process-based inventory analysis. Carbon emissions analysis	2007/2017	(Fang et al., 2017, 2007)
	Nanning, Guangxi		Manufacturing	On-site survey and Material flow analysis	2008	(Jianhua and Zhaohua, 2008; Yang and Feng, 2008)
	Dafeng	5	Agriculture and Manufacturing	Environmental and economic benefits analysis	2010	Wang et al., (2010)
	Guangdong	13	Manufacturing and Energy supply			
	Tianjin		Water and waste, Energy supply, Construction, Manufacturing, Agriculture, Administrative and support service, industrial, commercial and residential users and port-based industrial complexes	On-site visits and interviews. SNA and core-periphery structure analytical methods. Process analysis. Multicriteria decision analysis	2010/2015	(Cerceau et al., 2014; Qi and Wang, 2011; Shi et al., 2010; Yu et al., 2015a,b,c,e,f, 2014b; Zhang et al., 2013)

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Table 1 (*continued*)

Country	Region	N. Enterprises	Activity	Method	Publication Year	Reference
	Tianjin Binhai		Energy supply, Water and waste and Manufacturing	Interviews and Transition course analysis	2011/2017	(Li, 2011; Q. Wang et al., 2017b)
	Suzhou		Manufacturing, Water and waste and Energy supply	Field study and interviews. Energy-related GHG emissions using IPCC guidelines method. Substance flow analysis and resource productivity indicator	2012/2015	(L. Liu et al., 2012; Wen and Meng, 2015)
	Weifang	2/11	Mining and quarrying, Manufacturing, Energy supply, Water and waste and residential zone	Field research and interviews. Three-level approach. System dynamics method. Method of scenario analysis	2012/2018	(Cui et al., 2018; C. Liu et al., 2012; Liu et al., 2015)
	Liuzhou	3	Manufacturing and urban community	Surveys data. Hybrid physical input and monetary output model, co-benefit indicators and calculation of CO_2 emissions. Material flow analysis	2013/2014	(Dong et al., 2013a, 2013b; L. Dong et al., 2014)
	Jinan	6	Manufacturing and urban community	Questionnaire surveys and interviews. Material flow analysis and CO_2 emission reduction	2013/2014	(Dong et al., 2013b; L. Dong et al., 2014)
	Changsha Huangxing		Manufacturing, Agriculture and Water and waste	SNA, network connectedness analysis and core-periphery structure analytical methods	2013	Zhang et al., (2013)
	Shihezi		Manufacturing, Agriculture and Water and waste			
	Wujing		Manufacturing			
	Liaocheng	16/27	Manufacturing, Energy supply, Water and waste and Mining and quarrying	Laboratory data, field investigation and interviews. Energy-saving and financial indexes. Substance flow analysis. Carbon accounting methods. LCA. Network analysis method and SNA	2014/2017	(Han et al., 2017; Li et al., 2015; F. Yu et al., 2015a, 2015b)
	Shenyang		Energy supply and Manufacturing	Interviews and meetings. Emergy analysis method and logarithmic mean divisia index method	2014/2018	(Dong et al., 2018; Geng et al., 2014)
	Ningbo		Manufacturing	On-site visits and interviews	2014	Cerceau et al., (2014)
	Rizhao	94	Manufacturing	Questionnaires and interviews	2015	(F. Yu et al., 2015c)
	Jiangsu	86	Manufacturing and Energy supply	Interviews. Geographical information systems. Interconnected network model based on complex network theory	2015	Li and Shi, (2015)
	Dalian	7	Water and waste, Manufacturing and Energy supply	Field research. Multicriteria decision analysis and process analysis approach. Emergy analysis and index decomposition analysis. LCA	2015/2017	(Yu et al., 2015a,b,c,e,f; Zhang et al., 2017; Zhe et al., 2016)
	Jiayuguan	26	Manufacturing	Backward approach, substance flow analysis and substitution analysis method	2016	Wu et al. (2016a)
	Midong	18	Manufacturing, Energy supply and Mining and quarrying	Interviews, questionnaires, material flow analysis and evaluation of benefits of IS	2016	Guo et al., (2016)
	Shanghai Caohejing	10	Manufacturing	Site investigations	2016	Huang et al., (2016)
	Gansu	12	Manufacturing	Bow-tie and risk index methods	2017	Wu et al. (2017b)
	Hefei		Energy supply and Manufacturing	On-site survey, interviews and emergy analysis	2017	Fan et al., (2017)
	Qijiang	17	Manufacturing	Interviews, field trips, questionnaire-and simulation analysis on the cascading failure mode	2017	(Li et al., 2017; Sun et al., 2017b)
	Wu'an		Manufacturing, Energy supply, Mining and quarrying and Water and waste	On-site investigations, material flow analysis, CO_2 emission inventory and economic analysis	2017	Cao et al., (2017)
	Yulin/Ordos/Jining		Manufacturing	Field research, cascading failure model, network performance indicators, simulation and comparative analysis	2017	(D. Wang et al., 2017a)
	Ordos		Manufacturing	Lotka-Volterra population ecology model and interpolation fitting method	2018	(D. Wang et al., 2018)
	Gujiao	38	Mining and quarrying, Manufacturing, Water and waste and Energy supply	SNA	2018	Song et al., (2018)
	Bohai Bay		Energy supply, Manufacturing and Water and waste	Field surveys, interviews and meetings	2018	Liu et al. (2018a)
			Manufacturing		2018	Wu et al., (2018)

Table 1 (*continued*)

Country	Region	N. Enterprises	Activity	Method	Publication Year	Reference
	Northwestern China			Interviews, exergy analysis, life cycle GHG emissions assessment and water footprint analyses		
	Daqing		Manufacturing and Energy supply	Questionnaires and field visit. Grey correlation analysis method. Eco-efficiency, economic, environmental and network indicators	2019	Wang et al., (2019)
			Manufacturing	Interviews and substitution analysis method	2015	Yu et al., (2015a,b,c,e,f)
			Manufacturing and Energy supply	Exergy analysis. Energy and exergy efficiency, CO_2 emissions and overall performance indicators	2016	Wu et al. (2016b)
			Manufacturing and Water and waste	Environmental, fracture and redundancy indexes, stability analysis method and probability method	2017	Wu et al. (2017a)
Japan	Kawasaki	5	Manufacturing, Water and waste, community and port-based industrial complexes	Site visit and interviews. Material flow analysis. Life cycle CO_2 analysis method. Environmental and economic indicators. Hybrid life cycle assessment, material carbon footprint method, input-output analysis and emission coefficient. Emergy methods	2009/2017	(Cerceau et al., 2014; H. Dong et al., 2014; Dong et al., 2013b; Hashimoto et al., 2010; Ohnishi et al., 2017; Van Berkel et al., 2009a)
	23 cities		Eco-town	Questionnaires, influencing factors and performance indicators	2012	Chen et al., (2012)
	Kitakyushu		Manufacturing and Water and waste	SNA and core-periphery structure analytical methods	2013	Zhang et al., (2013)
	Osaka		Energy supply, Manufacturing, Public administration and ports	On-site visits and interviews	2014	Cerceau et al., (2014)
India	Nanjangud	12/>14	Manufacturing and Agriculture	Field surveys and interviews. Material flow analysis. SNA and statistical network correlation analyses	2009/2012	(Ashton and Bain, 2012; Bain et al., 2010, 2009)
	Tamil Nadu		Manufacturing, Agriculture and Water and waste	Multi-objective mixed integer linear programming model and sensitivity analysis	2019	Vimal et al., (2019)
Bangladesh	Sitakunda-Bhatiary		Water and waste	Interviews	2011	Gregson et al., (2011)
Thailand	Map Ta Phut		Port-based industrial complexes	On-site visits and interviews	2014	Cerceau et al., (2014)
Singapore	Jurong Island		Manufacturing, Transportation and storage and Energy supply	Online maps, workshop and survey	2019	Yin and Lee, (2019)
	Ulu Pandan, and Clementi		Water and waste and domestic and commercial buildings			
	Tuas, Tuas South, and Senoko		Public administration and Water and waste			
			Food service and Manufacturing			
			Water and waste, Manufacturing, Energy supply, Agriculture, Construction and Arts, entertainment and recreation			
Oceania						
Australia	Kwinana	35	Manufacturing, Agriculture, Energy supply, Construction, Water and waste and Mining and quarrying	Interviews. Integrated research programme and framework to facilitate IS	2007/2013	(Harris, 2007; MacLachlan, 2013; Van Beers et al., 2007)
	Gladstone	7/>8	Manufacturing, Energy supply, Agriculture and Water and waste	Interviews and field survey. Qualitative tool for analysis of IS barriers	2007/2015	(Golev et al., 2015, 2014; Van Beers et al., 2007)
North Africa						
Morocco	Jorf Lasfar		Port-based industrial complexes	On-site visits and interviews	2014	Cerceau et al., (2014)
Algeria	Bejaïa		Manufacturing			
South America						
Brazil	South-East		Construction and Manufacturing	Indicators of quantitative data analysis and SWOT analysis	2017	Freitas and Magrini, (2017)

enterprises. One of the measures that indirectly promoted the creation and development of industrial symbiosis and considered pioneering to change the paradigm of linear economy for the circular was the creation of a program, the National Pilot Circular Economy Zone Program, launched by the State Environmental Protection Administration in 2001, which considered the circular economy as fundamental to China's development (Mathews and Tan, 2011; Zhang et al., 2010). Another measure that had a major impact on the creation and development of industrial symbiosis was the China National Eco-industrial Park Demonstration Program launched in 2000 by the State Environmental Protection Administration (Shi et al., 2010), which developed the largest national network of eco-industrial parks and whose main objectives were to promote industrial symbiosis among companies, boost

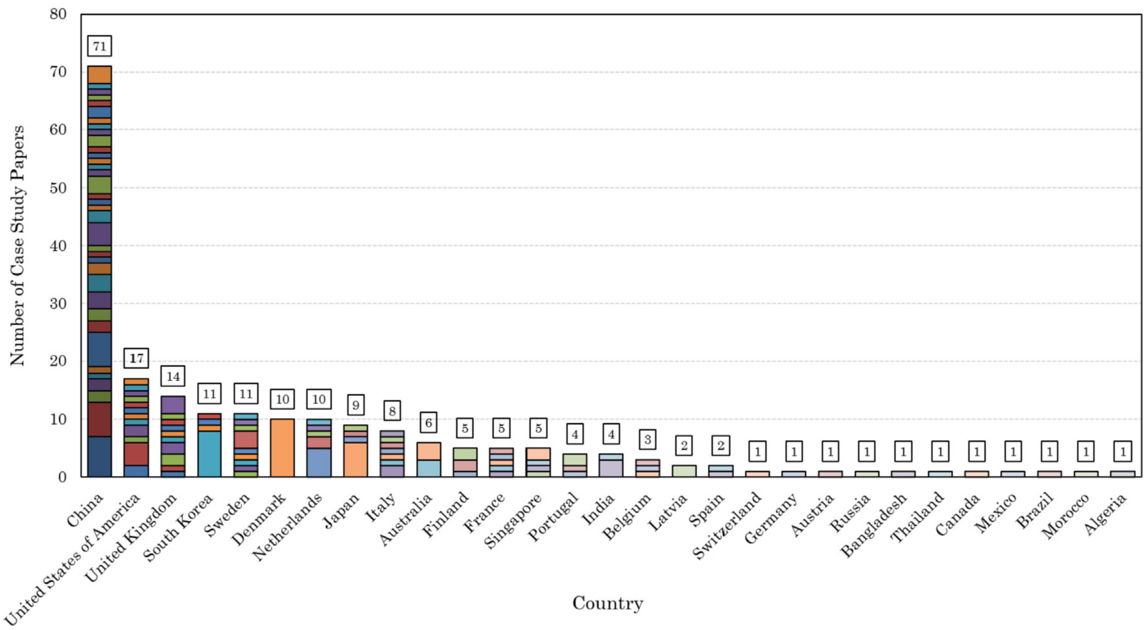

Fig. 8. Distribution of the number of case study publications by country.

environmental management and encourage cleaner industrial practices in industrial parks (Shi et al., 2012; Yu et al., (2015a,b,c,e,f)). The number of approved parks has grown exponentially since its implementation. By November 2011, a total of 60 National Trial Eco-Industrials Parks had been evaluated and approved, being distributed in 15 National Demonstration Eco-Industrials Parks and 45 National Trial Eco-Industrials Parks (Shi et al., 2012; Zhang et al., 2010) and by 2017, 108 eco-industrial park projects had been approved by the Ministry of Environmental Protection of People's Republic of China for construction (Liu et al., 2017).

The first industrial park to be considered by the State Environmental Protection Administration of China as a national demonstration eco-industrial park was the Guitang Group, located in Guigang in 2001 (Guo and Hu, 2011; Liu et al., 2017). This group established by the state in the 50's is responsible for one of the largest sugar refineries in the country, and even before it was chosen as a demonstration park, industrial symbiosis was already common practice between the sugar refinery and the surrounding companies (Shi and Chertow, 2017; Zhu et al., 2007). For these reasons, it is not surprising that it is the third case most studied in the literature. In addition to this case, the Tianjin Economic-Technological Development Area in Tianjin was also the subject of these programs, being called as national pilot industrial area for circular economy in 2005 (Yu et al., 2014b) and was one of the first three national demonstration eco-industrial park (Shi et al., 2010; Yu et al., (2015a,b,c,e,f)). However, the proposals for industrial symbiosis creation date back to 2002, and in 2008, there were identified 81 symbiotic exchanges between companies located inside and outside Tianjin industrial area (Shi et al., 2010). For these reasons, it is not surprising that this area is the second region of China with more published case studies. The Lubei Group located in Wudi County, Shandong province, is also part of the national demonstration eco-industrial park, having been approved as such in 2003 (Guo and Hu, 2011) and is also one of the regions with the most published case studies.

In addition to these examples, there are others in China that are also included in the examples with the largest number of published case studies on industrial symbiosis, such as the examples of Xinfa Group in Liaocheng (Li et al., 2015; F. Yu et al., 2015a), the industrial city of Liuzhou (Dong et al., 2013b; L. Dong et al., 2014), and the Dalian Economic and Technological Development Area in Dalian (Yu et al., (2015a,b,c,e,f); Zhe et al., 2016).

Apart from China, South Korea also occupies an important place in the number of industrial symbiosis case publications. Of the 11 cases published, 8 concern Ulsan Metropolitan City, which accounts for 73% of the total and among the various case studies analysed, is the second region with the most publications. This position is justified by the strong incentive of the government to conduct measures for the development of industrial symbiosis. These were accomplished through the National Eco-Industrial Park Development Program, designed for 15 years, to be developed in three distinct phases, beginning in 2005 that aimed to transform industrial parks into eco-industrial parks with a strong component in the development of industrial symbiosis (Behera et al., 2012; Park et al., 2008). This program was effectively determinant for the creation and development of industrial symbiosis, with at the end of 2014, 107 symbiosis projects in operation (Park et al., 2019). The industrial complexes of Mipo and Onsan, located in Ulsan, were chosen to be part of this program (Park and Behera, 2015; Park and Won, 2007), and are among the most advanced (Mathews and Tan, 2011), which also justifies the number of case studies in this region. However, even before the implementation of this program, Ulsan was already considered an important focus for Korea's industrial development. It contained in its industrial complex a huge number of companies, some of them of a very significant size, existing even before the program implementation, some already established synergy relations (Mathews and Tan, 2011).

Also in Japan, efforts have been made to reduce and manage waste more efficiently. In addition to the implemented recycling-oriented legislative framework, the Eco-Town program was set up in 1997 to reduce the amount of waste sent to landfills and to revitalize local industries (H. Dong et al., 2014; Van Berkel et al., 2009b). To this end, the government has provided funds to support projects that promote the achievement of these objectives. 26 Eco-Town Plans were approved during the ten years of operation (Chen et al., 2012; Van Berkel et al., 2009b). This program, together with the entry into force of legislation to promote recycling, and the provision of technology resources from the private sector, has enabled the development of industrial symbiosis and interaction between the industrial and urban areas, facilitated by the proximity between these two areas (Chen et al., 2012; Van Berkel et al., 2009b, 2009a).

India, despite showing significant growth in gross domestic product, still has many social problems, with high poverty rates and a very significant portion of the population without access to basic conditions, as well as population growth and rapid urbanization (Falebita and Koul, 2018; Gupta et al., 2019). The various initiatives that have been made to develop industrial symbiosis have proved fruitless, despite being a resource-scarce country (Bain et al., 2010). The lack of economic incentives and tax benefits, the lack of environmental legislation, the lack of financial resources and infrastructure are some of the barriers pointed to the development of circular practices and industrial symbiosis (Singh et al., 2018). However, in order to take advantage of the various resources, some relationships of industrial symbiosis that have emerged among self-organizing companies have been reported, such as the case of the Nanjangud Industrial Area (Bain et al., 2010).

Europe, as mentioned above, ranks second in the areas with more cases studies on industrial symbiosis. The European Union has played a very important role, both politically and practically, in enhancing practices that lead to sustainable development (Szopik-Depczyńska et al., 2017). The concept of circular economy in Europe dates from the 1970s, and since then several countries have adopted the concept (Bassi and Dias, 2019). The application of circular practices has been driven by various measures taken by the European Commission, which have been achieved through the publication of strategic documents, policies and programs with the provision of monetary support (Colombo et al., 2019; Fura et al., 2017; Szopik-Depczyńska et al., 2017). Industrial symbiosis has been mentioned in several communications and in the most recent publication of Directive (2018)/851 on waste as important for more efficient use of resources and in which it encourages Member States to take measures to facilitate the application of this practice (European Commission, 2018b, 2015).

However, despite these incentives, the development of industrial symbiosis has proved to be disparate in the various countries of Europe, as a result of their economic development, but also the policies adopted in each country. The countries of North and North-West Europe account for the majority of published studies, corresponding to 72% of the total European studies. Leading the case studies is the United Kingdom with 14 studies, followed by Sweden, Denmark and the Netherlands with 11, 10 and 10 case studies, respectively. Most of these countries in northern and north-western Europe have been precursors in implementing policies that are in line with a more circular economy (Bassi and Dias, 2019), which has facilitated the spread of industrial symbiosis. In addition, existing economic conditions and the resilience to maintain sustainable development patterns even in the face of economic hardship, such as the major economic crisis in 2007–2008, have helped to drive the adoption of more sustainable practices (Domenech et al., 2019; Szopik-Depczyńska et al., 2017). In the United Kingdom, the increase in cases of industrial symbiosis is related to the policies and measures that have been implemented to encourage the development of industrial symbioses. Examples of these measures were the creation of more waste-oriented instruments, such as the Landfill Tax and the Waste Protocols Project, and the voluntary program launched by the United Kingdom government, the National Industrial Symbiosis Programme, to help companies find partners who could use their waste as raw materials, which made synergies between companies grow (Costa et al., 2010; de Abreu and Ceglia, 2018). In addition to this program, there have been others in Europe that have facilitated the development of industrial symbiosis, such as those in Italy, Finland, France, Denmark and Belgium (Domenech et al., 2019).

However, the existence of plans for the occurrence of industrial symbiosis relations is not essential. In many cases these arise spontaneously from a company initiative. The most published case study with 10 references in Kalundborg, Denmark is one such example. This emerged spontaneously in the 1960s between the four major industries and some companies outside the industrial area (Ehrenfeld and Gertler, 1997; Zhang and Chai, 2019). Over time, industrial symbiosis has developed not only to respond to the scarcity of resources, but also because of the economic and environmental benefits obtained by the companies involved in the synergies (Jacobsen, 2006; Valentine, 2016).

Some southern European countries, such as Portugal and Spain, while not having many reported cases of industrial symbiosis, have made an effort to promote more sustainable practices and to adopt programs for the promotion of industrial symbiosis (Costa and Ferrão, 2010; Ferreira et al., 2019). In the case of Portugal, in addition to the legislative amendment to transpose Directive 2008/98/EC on waste, a number of national plans have been established, in which not only the importance of industrial symbiosis is emphasized but also some measures to increase its implementation are defined (Neves et al., 2019b).

Initiatives to promote the creation of eco-industrial parks with the practice of industrial symbiosis in the United States date back to 1994, with funds available for the development of such projects (Chertow, 2000). And while some publications mention the creation of several eco-industrial parks in the United States (Chertow, 2000; Sakr et al., 2011), and that there are cases of industrial symbiosis scattered throughout the country (Chertow, 2000), publications on industrial symbiosis are few in number and most are not very recent. Some reasons have been cited as inhibitors of further development of industrial symbiosis (Neves et al., 2019c). The strong presence and involvement of the government was one of the reasons given for companies' reticence to start eco-industrial park projects (Heeres et al., 2004). Another reason is associated with existing regulations that make it difficult to create the industrial symbiosis relationship, especially the US Resource Conservation and Recovery Act where many wastes are defined as hazardous wastes (Gibbs and Deutz, 2007). The existing industrial symbioses are located in different regions. The largest number of studies were carried out in Barceloneta, Puerto Rico, an unincorporated territory of the United States, where the first industrial symbiosis date back to the end of the 1970s (Ashton, 2011, 2009), being the pharmaceutical companies, present in great number, the great responsible for the development of synergies between the different companies. The regions with the second largest number of case studies are Guayama in Puerto Rico and Honolulu where the existing industrial symbiosis are driven by the coal-fired power plant (Chertow and Miyata, 2010; Chertow and Lombardi, 2005), often considered as anchor tenant insofar as they are crucial for the creation and stimulation of the industrial symbiosis between the various companies.

In the case of Brazil, although the potential for applying industrial symbiosis has been recognized (Ometto et al., 2007; Santos and Magrini, 2018), practices associated with the circular economy and consequently with industrial symbiosis are still poorly developed (Oliveira et al., 2018). In addition, most of the waste produced is disposed of in landfills and although municipalities have high waste management expenditure, there has been no concern from them to correct this and invest in ways to reuse waste (da Silva, 2018).

4.2.2. Type of industries involved in industrial symbiosis

From the analysis of Table 1 and Table A.1, it is possible to

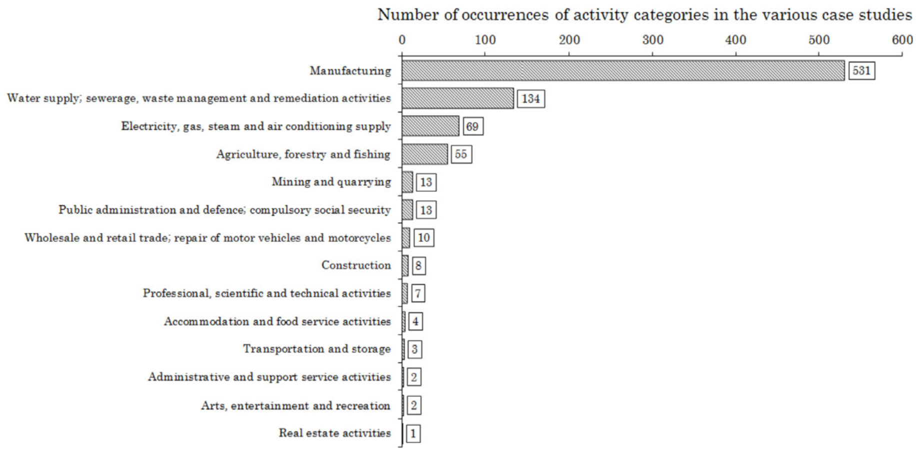

Fig. 9. Number of occurrences of economic activities categories in the various case studies.

conclude that the types of economic activities present in the industrial symbiosis are very disparate, which illustrates the immense possibilities of this type of practice. However, as shown in Fig. 9, the one which has a markedly higher weight is the manufacture, which according to ISIC is the section which comprises the activities involving the transformation of materials into new products.

It should be noted that Fig. 9 does not reflect the total number of companies involved in the symbiosis, because although the activities are listed in the publications, the number of companies involved and their distribution by type of activity is rarely mentioned. Thus the figure intends to illustrate the type of activities and the frequency with which they appear in the several industrial symbiosis case studies.

The high presence of the manufacturing industries is justified by the volume of waste generated during their economic activity, but also by the capacity to absorb wastes and by-products and to incorporate them as raw material in their production processes. Within this section, the activities that are most often present in the industrial symbiosis are the chemical, cement, pulp and paper, and steel and iron industries and refineries. The first four industries are characterized by high energy consumption (Dong et al., 2013a; Man et al., 2018), thus representing great potential for measures to reduce resource consumption. The activities related to waste and water management and recycling also occupy a prominent place in cases of industrial symbiosis not only to establish the link between industries but also as an active part in the chain of transformation of waste into new products. The primary sector, in particular agriculture-related activities, is also often found in case studies, not only those directly related to crops, but also those associated with raising and breeding of animals.

Although the manufacturing section is the predominant one in most countries, as shown in Fig. 10, the weight of each activity varies depending on the case, also reflecting the economic reality characteristic of each country. With the exception of countries with few published case studies in the literature, such as Morocco, Algeria and Mexico, in which all companies belong to the manufacturing section, most countries have industrial symbiosis participants belonging to various types of activities. However, there is no direct relationship between the existence of many case studies in one country and the variety of sections. An example of this is China, which although it is the country with the largest number of cases, is not the one with a wider range of sections. The United States of America and Singapore with 12 and 4 distinct cases of

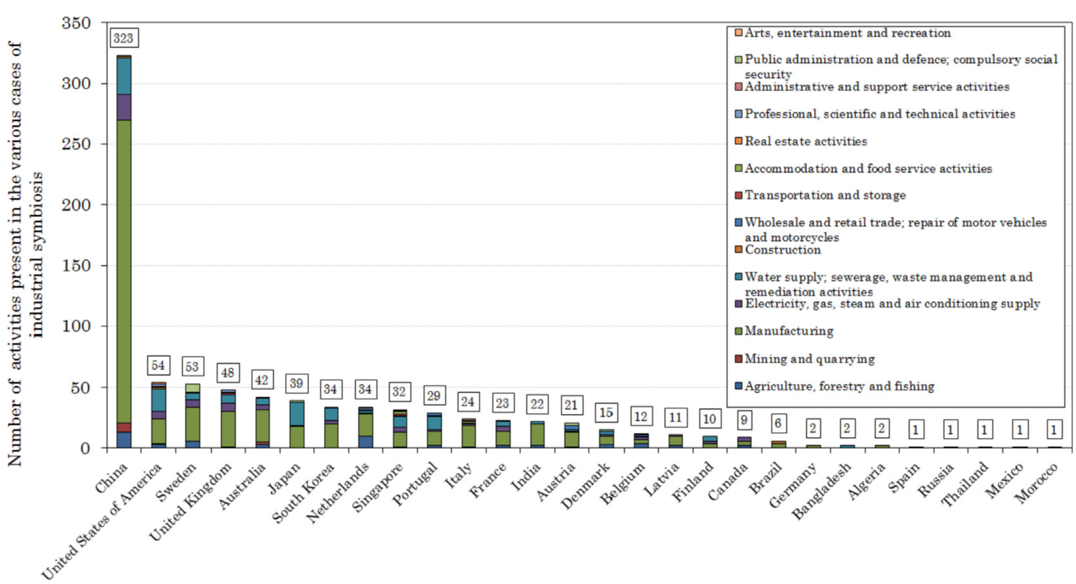

Fig. 10. Distribution of the categories of economic activities existing in cases of industrial symbiosis by country.

industrial symbiosis, respectively, are those that present a greater diversity of economic activity classes, having participants in the synergies belonging to 9 different sections. It follows China with activities belonging to 7 distinct sections and in Europe with equal numbers, the United Kingdom, the Netherlands and Italy.

The chemical industries are among the most present in the various cases of industrial symbiosis, having played a key role in cases scattered throughout Europe, Asia, Australia and North America. The weight of these in the network of synergies varies greatly depending on the location. For example, in Grangemouth, in the United Kingdom, a region with a strong presence of the chemical and petrochemical industries (Harris and Pritchard, 2004), these have played a key role in boosting and creating industrial symbiosis. In other cases, although they have a less significant presence, they do play an important role in increasing sustainability. Thus, they have contributed to the reduction of wastes, as in the case of Kalundborg where the chemical company started to supply sludge and yeast slurry to farms (Branson, 2016), for the reduction of consumption of resources such as in Finland where chemical companies receive combustion gases and purified water from pulp and paper mill (Pakarinen et al., 2010) and for the substitution of petroleum products with others obtained from waste oils generated by the chemical and petrochemical industries, such as the Ulsan case (Behera et al., 2012).

The cement and steel and iron industries are of great importance in China and have contributed to the country's economic growth, but are both resource intensive and responsible for serious environmental problems such as greenhouse gas emissions (Cao et al., 2017; Gao et al., 2017; Zhu et al., 2019). Thus, it is not surprising that they are the target of many of the measures implemented to meet international requirements for the reduction of gas emissions, such as industrial symbiosis. Thus, by analysing the published case studies, most of the industrial symbiosis where these industries participate are located in China being scattered across several regions (Dong et al., 2018; Shi and Chertow, 2017; Q. Wang et al., 2018a; Wu et al., 2016a). The industrial symbiosis with this type of industries also occurs in other areas; however they have little expression compared with the case studies verified in China. In some parts of Europe, there are some examples where cement industries are part of the synergies, such as Kalundborg in Denmark (Domenech and Davies, 2011; Ehrenfeld and Gertler, 1997; Jacobsen, 2006), Rotterdam in the Netherlands (Baas and Boons, 2007; Baas and Korevaar, 2010b), Taranto in Italy (Notarnicola et al., 2016, 2014), among others. As for the steel and iron industry, it is much more concentrated in China, with fewer examples in other regions. However in Italy (Notarnicola et al., 2016, 2014), Japan (Dong et al., 2013b; Van Berkel et al., 2009a) and South Korea (Behera et al., 2012; Park and Behera, 2015), there are some of these cases.

The predominance of the paper industry in the case studies analysed also occurs in countries in Asia, such as China (Guo et al., 2016; Shi et al., 2010; Q. Wang et al., 2018a, 2018b; F. Yu et al., 2015c; Zhu et al., 2007), Japan (H. Dong et al., 2014; Dong et al., 2013b; Ohnishi et al., 2017; Van Berkel et al., 2009a) and South Korea (Behera et al., 2012; Park and Behera, 2015, 2014; Park et al., 2008), with the highest incidence in China. However, it is in Finland, a country with a long tradition in the pulp and paper industry, that it plays an essential role in the development of industrial symbiosis, around which all synergies with other companies are developed (Pakarinen et al., 2010; Sokka et al., 2011b).

One of the activities with the highest incidence in the case studies of industrial symbiosis are the power plants. Many authors have verified that this type of activity has the capacity to mobilize companies to create industrial symbiosis, functioning as an anchor (Chertow and Miyata, 2010; Korhonen, 2001). This concept, which is not unique to power plants, is referred to as anchor tenant (Chertow, 1998; Lowe, 1997), and has been widely used in the literature on industrial symbiosis, from the 1990s to the present day. It is based on the idea of a company capable of attracting and anchoring a network of companies not only for the supply of materials but also for the reuse of waste (Chertow, 2000, 1998; Lowe, 1997; Yoon and Nadvi, 2018). In the case studies analysed on industrial symbiosis, this concept was applied to different industries. Thus, the anchor tenants considered in the various case studies were a power plant in Honolulu, United States (Chertow and Miyata, 2010), a cement company in Kawasaki in Japan (Hashimoto et al., 2010), mining firms in Gujiao, China (Song et al., 2018), a pulp and paper mill in the region of Kymenlaakso in Finland (Lehtoranta et al., 2011; Pakarinen et al., 2010), and a combined heat and power plant in Händelö, Sweden (Martin and Eklund, 2011). However, in the development of industrial symbiosis, new anchor tenants may emerge, such as Guigang's example in China, in which the sugar manufacturing chain was initially the only driver of industrial symbiosis, and later the pulp and paper and combined heat and power units joined the network also as anchors (Shi and Chertow, 2017).

The diversity of industries in a given region can be seen as facilitating the creation of synergies (Mortensen and Kørnøv, 2019; Yu et al., 2014b). In the case studies analysed, the range of industries is very varied, and the diversity in each case study is very large. Thus, there are examples in which the diversity of industries involved in industrial symbiosis is reduced, such as the Västra Götaland Region of Sweden, where the industrial symbiosis are centred on two industries, beer production and mushroom farming (Patricio et al., 2018) and the case of North Dakota in the United States with the symbiosis between 1st generation bioethanol and combined heat and power plants (Gonela et al., 2015). And on the other hand, we have industrial symbiosis that are developed among a wide variety of industries, such as the example of Liaocheng in China where synergies occur between a wide variety of chemical and material production industries (Han et al., 2017; Li et al., 2015; F. Yu et al., 2015a, 2015b), the case of Kawasaki in Japan where there are symbiosis between the steel and iron, cement and paper industries together with different recycling companies (H. Dong et al., 2014; Hashimoto et al., 2010; Ohnishi et al., 2017; Van Berkel et al., 2009a), and the case of Ulsan in South Korea with synergies among chemical industries, steel industries, paper mill company, waste treatment companies, among others (Behera et al., 2012; Park and Behera, 2015, 2014; Park et al., 2008).

4.2.3. Methods used in the analysis of case studies

From the analysis of Table 1 and Table A.1, it is possible to verify that the methods used in the analysis of the case studies are very diverse and have been applied with very different objectives, such as quantification of environmental, economic and social impacts, analysis of the stability of the industrial symbiosis network, analysis of barriers to industrial symbiosis, evaluation of operational performance, among others.

4.2.3.1. Data collection. The first step in any analysis of a case study is the collection of relevant information and data for further analysis. Thus, various strategies were conducted to achieve this goal, such as interviews (de Abreu and Ceglia, 2018; Morales et al., 2019; Patricio et al., 2018), site visits with investigations, data collection and research (Cerceau et al., 2014; Wu et al., 2018; Yu et al., (2015a,b,c,e,f)), questionnaires (Han et al., 2017; Qi and Wang, 2011; Wen and Meng, 2015), and meetings with experts, companies, government departments, and local stakeholders, conducted mostly in an informal way (Branson, 2016; Dong et al., 2018;

Liu et al., 2018a). Of all these strategies, the semi-structured interviews were the most used (Hein et al., 2017; Lehtoranta et al., 2011; Velenturf, 2016), since they allow the interviewer to get answers to their questions and to validate their hypotheses, but also to discuss the subject more broadly.

4.2.3.2. Qualitative analysis. In many of the case studies analysed, the collection of data and information on industrial symbiosis preceded the application of other methods, such as those used to quantify environmental and economic impacts (Gonela et al., 2015; Guo et al., 2016; L. Liu et al., 2012). However, in some cases, the approach to the case studies was more qualitative and only the methods related to the research and the obtaining of information and data on the industrial symbiosis were used. There are several examples of these case studies in the literature, as shown in Table 1, with very different objectives. One of the most common objectives is the study of industrial symbiosis in order to find the best ways to create and develop synergies between companies and maximize the benefits not only economic but also environmental. Thus the identification of barriers and drivers for the creation and development of synergies (Patricio et al., 2018; Valentine, 2016; Van Beers et al., 2007), the influence of policy instruments (Lehtoranta et al., 2011; Park et al., 2008) and programs (Mirata, 2004) in the development of industrial symbiosis and the development of approaches that would allow the evolution of an industrial symbiosis network (Wolf et al., 2007), are some of these examples. Also the evolution of industrial symbiosis (Mannino et al., 2015; Morales et al., 2019; Paquin and Howard-Grenville, 2012; Taddeo et al., 2017; Van Beers et al., 2007), the identification of future symbiosis (Notarnicola et al., 2016, 2014) and the comparative study between measures implemented in different case studies (Liu et al., 2018a) have been analysed in several publications.

One of the factors that may affect the creation and assessment of industrial symbiosis is the reluctance of some companies to provide quantitative information regarding their production process and waste generated since they are afraid of compromising their confidentiality. Thus, with the objective of overcoming this barrier, several studies have emerged that allow evaluating the industrial symbiosis in a qualitative way. One of these studies defined "exchange quality" evaluated through assessment categories such as geographic proximity, quality of environmental performance and quality of economic performance (Rosa and Beloborodko, 2015).

4.2.3.3. Environmental, economic and social analysis. Many of the methods applied in the analysis of the case studies are related to the evaluation of the industrial symbiosis either at the environmental, economic or social level in order to assess the true impact of these practices on the participating companies, the population and the environment. To meet this objective, a number of methods and indicators have been used, some of which have a very broad field of application and not only industrial symbiosis (Eckelman and Chertow, 2013; Fan et al., 2017; L. Liu et al., 2012; Sokka et al., 2011a), while others have been developed specifically to evaluate this practice (Felicio et al., 2016; Rosa and Beloborodko, 2015; Trokanas et al., 2015). The dissemination of the benefits obtained by the industrial symbiosis can serve as a lever for the development of this practice, not only for companies but also for municipalities so that they create plans to encourage the creation and development of synergies. In the case studies analysed, the environmental impact was of all dimensions of sustainability, the most quantified, followed by the economic and social impact. The social dimension is the most difficult to quantify (Valenzuela-Venegas et al., 2016), which justifies being the dimension of sustainability less analysed in case studies of industrial symbiosis.

Several methods and indicators were used to quantify the environmental impact. The most used method was life cycle assessment, which allows quantifying potential environmental impacts throughout the life cycle (Daddi et al., 2017; Martin, 2015; Martin and Harris, 2018). In the various studies where it was used, it was possible to assess the environmental advantages of industrial symbiosis in comparison to non-symbiosis reference scenarios, such as the case centred on a pulp and paper manufacturing in Kymenlaakso, Finland (Sokka et al., 2011b), or the industrial cluster involving 11 companies in Honolulu County, Hawaii (Eckelman and Chertow, 2013) or in comparison with scenarios with various stages of development of industrial symbiosis such as the one performed at the Italian tannery cluster located in Tuscany (Daddi et al., 2017) or the one centred on the biofuel industry in Händelö, Sweden (Martin et al., 2014).

In addition to this method, the emergy analysis method was also used, which allows taking into account the contribution of the natural ecosystem to the development of synergies. There were several case studies where this method was employed (Dong et al., 2018; Fan et al., 2017; Geng et al., 2014). Two of the examples were carried out in Shenyang, China, where it was intended to analyse changes in environmental performance (Dong et al., 2018) and to evaluate the overall performance of industrial symbiosis, proposing various industrial symbiosis emergy indicators, such as absolute emergy savings, relative emergy savings from different resources, and emdollar values of total emergy savings (Geng et al., 2014).

Material flow analysis was also one of the most used methods in the case studies (Bain et al., 2010, 2009; Chance et al., 2018; Dong et al., 2013b; Guo et al., 2016; Hashimoto et al., 2010), with the main objective of analysing flows and stocks of materials, by-products, wastes, and resources. The exergy analysis method was also another of those used in industrial symbiosis cases (Wu et al., 2018, 2016b).

Due to the harmful effects of increasing greenhouse gases, the international community has imposed limitations on emissions of these gases by countries. Thus, many of the papers published on the quantification of environmental benefits of industrial symbiosis have focused on the quantification of greenhouse gas emissions (Cao et al., 2017; L. Dong et al., 2014; Fang et al., 2017; Jacobsen, 2006; Wu et al., 2016b; F. Yu et al., 2015a). China, where this issue is very relevant given the large volume of greenhouse gas emissions (Fang et al., 2007; Liu et al., 2017), has been the subject of several studies in which carbon emissions have been quantified. One of these studies used the methods based on the IPCC 2006 and the Greenhouse Gas Emission Accounting Methods and Reporting Guidelines (Trial) to account for carbon emissions (F. Yu et al., 2015a). Another example was the carbon footprint analysis in Guiyang, China (Fang et al., 2017) and its evolution over the years following the implementation of government programs. For this purpose a hybrid model was used that integrated the input-output approach and process-based inventory analysis. In Kawasaki, Japan, the reduction of carbon dioxide emissions was estimated by calculating annual CO_2 emissions, whose value depends on various parameters such as CO_2 emissions from the transport of raw materials, industrial and municipal waste to be recycled and to be disposed of, CO_2 emissions from cement production and CO_2 emissions due to the deposition of waste (Hashimoto et al., 2010).

In some case studies and in order to overcome some limitations inherent in the methods and improve the results obtained, some methods were combined. One of the examples was the study done in Kawasaki, Japan, in which the method for calculating carbon footprint was based on the hybrid model (H. Dong et al., 2014), from which the total lifecycle carbon footprint of an industrial park was calculated from six carbon footprints. Also in Kawasaki, a combination of the methods of material flow analysis, carbon footprint and emergy was used to evaluate the environmental consequences of industrial and urban symbiosis (Ohnishi et al., 2017).

In addition to the methods mentioned, indicators were also used to assess the impacts of industrial symbiosis. In order to evaluate the environmental impacts, the indicators used in the case study analyses were diverse, such as, for example, resource consumption reduction and waste emission reduction (Guo et al., 2016). In addition to these indicators, others have been proposed in the analysis of industrial symbiosis, such as "environmental gains", defined as the consumption or emission that a company can avoid with industrial symbiosis (Dong et al., 2013b), and indicators involving the quantification of energy consumption, exergy consumption and carbon dioxide emissions for the purpose of assessing the overall performance of a steel and iron industry network (Wu et al., 2016b).

Besides the environmental impact assessment, the economic consequences of industrial symbiosis were also evaluated in several case studies (Cao et al., 2017; Chertow and Miyata, 2010; Dong et al., 2013b; Guo et al., 2016; Jacobsen, 2006; Park et al., 2019; Wang et al., 2010), although the number of publications was smaller compared to environmental assessments. These evaluations were conducted in different ways. The use of indicators, such as cost saving of raw material purchase, cost saving of waste disposal, and sales income of waste (Chertow and Miyata, 2010; Guo et al., 2016), the combination of several parameters (reduction of direct costs, real investments and estimated return times) as a way of estimating the economic aspects of industrial symbiosis (Jacobsen, 2006), and the assessment of economic efficiency through the calculation of the gross benefit and dynamic investment payback period (Cao et al., 2017) were some of the forms used in case studies to quantify the economic consequences of industrial symbiosis. In addition to these, indicators have also been proposed in some publications, such as "economic gains", which are expressed in the revenue or costs avoided by a given company due to the reduction of raw materials, reduction of waste generation or the use of these (Dong et al., 2013b).

In the case studies analysed, most environmental and economic evaluations are carried out separately, but in one of the publications an eco-efficiency indicator was established to evaluate the performance of the industrial symbiosis located in Ulsan, South Korea (Park and Behera, 2014), which includes one economic indicator and three environmental indicators. In another publication and with the aim of also evaluating the industrial symbiosis in Ulsan, the environmental, economic and social benefits were estimated by calculating the payback period used to evaluate the economic component, the reduction of greenhouse gas emissions used to assess environmental benefits, and the increased employment and environmental quality as synonymous with social benefits (Park and Behera, 2015).

Another case study that analysed the social and economic component was carried out in the Sotenäs region of Sweden, where quantitative and qualitative/semi-quantitative analyses were carried out to evaluate the social and economic dimensions (Martin and Harris, 2018). In the quantitative analysis, socioeconomic indicators were used, such as job retention or creation, number of new companies, potential revenue of sales of the network, visitors to the region due to the network, and savings on waste disposal transport. In qualitative/semi-quantitative analysis, some of the indicators used were improvement and strengthening of the local skill basis, impact on research and development, impact on sales values, and impact on operational efficiency (Martin and Harris, 2018).

4.2.3.4. Network analysis. The study of the industrial symbiosis network was also one of the topics most approached in the case studies analysed. This issue is of great importance, mainly because the companies involved in the symbiosis have to create a trustful link, since the operation of companies that receive waste depends in part on the flows of the issuing companies and their supply in sufficient quality and quantity. When there is a failure in this supply, it may compromise the operation of a company or the entire industrial symbiosis network (Chopra and Khanna, 2014; Q. Wang et al., 2018a). On the other hand, it is also important to understand the network structure of industrial symbiosis and how the interaction between the various actors takes place, because it has implications in the results of synergies, both in economic and environmental aspects (Domenech and Davies, 2011, 2009). In this way, by characterizing the network and its interactions, it is also possible to optimize them in order to improve the economic and environmental performance of the entire network. This optimization was done in a case study in Kansas City, Missouri (Cimren et al., 2011), in which using mathematical programming techniques it was possible to determine the ideal network in order to minimize the total cost or environmental impacts. And the optimization that was based on the profit maximization of the system was the one that allowed achieving greater benefits both in the reduction of the total cost, in the reduction of carbon dioxide emissions and reduction in wastes for landfill (Cimren et al., 2011). Knowledge of the network of synergies and their arrangement in the network, that is to say more central or in the periphery, also allows to improve symbiosis relations and to study ways to make it more stable over time (Zhang et al., 2013).

The most used method in the case studies to understand the network of industrial symbiosis was social network analysis (Ashton, 2008; Ashton and Bain, 2012; Domenech and Davies, 2011; Han et al., 2017; Shi and Chertow, 2017; Song et al., 2018; Velenturf, 2016; Zhang et al., 2013), whereby several associated concepts such as density, degree centrality, degree distribution, betweenness centrality, closeness centrality, compactness and degree of connectedness were determined. In addition to the symbiosis network characterization, some case studies analysed the behaviour of this network in the presence of some perturbations. Among them are studies that allowed the study of the resilience (Chopra and Khanna, 2014) and the robustness (Q. Wang et al., 2018a) of the network in the face of disruptive scenarios and the cascade effect that these could provoke. The vulnerability of the industrial symbiosis network was also evaluated based on the automatic control theory, a mathematical analysis method (Q. Wang et al., 2018b) and based on indicators, namely the vulnerability of an industrial symbiosis network and node betweenness (Li et al., 2017). However, the vulnerability of an industrial symbiosis network can also be affected by economic fluctuations. One of the case studies analysed this vulnerability, applying it to a symbiosis industrial coal network (D. Wang et al., 2017), and establishing for this purpose a cascade failure model with a weighted target network and design five network performance indicators.

4.2.3.5. Other methods. In addition to the methods mentioned in the previous sections, which comprise the most used in the analysis of industrial symbiosis, there are other methods and tools that were used. Among them, a qualitative tool that was proposed and applied to the case study in Gladstone, Australia (Golev et al., 2015), with the aim of analysing the barriers of industrial symbiosis, called industrial symbiosis maturity grid. In Japan, to evaluate the eco-town program, an environmental performance indicator and an operational performance indicator, the operating rate, which relates the amount of wastes treated with the planned ones (Chen et al., 2012) were calculated. Another example was the study carried out in the Suzhou region of China to evaluate the contribution of industrial symbiosis to the development of the circular economy, being used for this study the substance flow analysis with the resource productivity indicator (Wen and Meng, 2015).

4.2.4. Industrial and urban symbiosis

Although the main focus of this review is the industrial part and the synergies that exist between the companies, this cannot be dissociated from the urban part that by proximity is often affected by the negative aspects of industrial zones, such as pollution. However, both the industrial and urban parts share some concerns with regard to sustainability, such as high resource consumption, increased greenhouse gas emissions, increased waste and cost of waste treatment (Dong et al., 2016; Simboli et al., 2017; Lu Sun et al., 2017). Thus, if in addition to the symbiosis between companies, these can be extended to the urban part, this can bring benefits to both parties and there is potential for the mitigation of some of the problems verified in the industrial and urban part. In the last years a number of scientific articles have been published which have focused on the symbiosis between industries and cities (Dong et al., 2017; Kim et al., 2018a; Ohnishi et al., 2017), with a more pronounced growth in recent years.

Some authors have used the term Urban Symbiosis (Ness and Xing, 2017; Van Berkel et al., 2009b, 2009a), referring to the use of waste produced in cities by adjacent industries in their industrial operations, either as an alternative to raw materials or as a source of energy, facilitated by the geographical proximity between them (Van Berkel et al., 2009b). This process differs from recycling, because the companies that receive these wastes are not the usual waste treatment and recycling centres, that is, they are companies that normally would not receive this type of waste nor would use it as raw material in their process productive. The term Industrial and Urban Symbiosis (also called Urban and Industrial Symbiosis) has also appeared in several publications when the symbiosis comprises the industrial symbiosis and synergies between the industrial and urban zone (Kurdve et al., 2018; Van Berkel et al., 2009b). In other publications, this term has been used when waste generated by the urban area is used by industries as alternative raw materials or source of energy and in turn the industries provide the urban areas with heat wastes resulting from their operation (Dou et al., 2018; Fang et al., 2017).

The performance of the industrial and urban symbiosis has been studied by several authors (Dong et al., 2013b; Ohnishi et al., 2017; Van Berkel et al., 2009a) with the objective of evaluating the real impact of this practice in industry and in the cities and if its application proves to be an effective measure to achieve environmental and economic advantages. From the studies carried out it was possible to conclude that this practice has provided economic benefits (Afshari et al., 2018; Dong et al., 2013b) and environmental benefits such as saving of resources and raw materials (Dong et al., 2013b; Ohnishi et al., 2017), the reduction of carbon dioxide emissions (Dong et al., 2016; Ohnishi et al., 2017), and the reduction of wastes sent to landfills and incineration (Cao et al., 2017; H. Dong et al., 2014; Van Berkel et al., 2009a). And although in some cases the costs of creating symbiosis are high, for example in the exchange of waste heat and energy between industries and communities that requires the construction of necessary infrastructure, and in addition to these costs there is also the uncertainty of supplying these wastes in sufficient quantity and quality to meet the needs of communities, which may lead some industries and the community to retreat, but according to some studies (Afshari et al., 2018; Fang et al., 2017) the final balance is positive, with environmental and economic benefits. Some of the advantages listed are crucial for some countries, such as for China, as allied to highly industrialized areas and industries with high energy consumption and large carbon dioxide emissions, such as the iron and steel industry and the cement industry (Dong et al., 2013a; L. Dong et al., 2014), also has areas with a lot of population (Cao et al., 2017; Dong et al., 2017) which greatly increases the amount of household waste. In this case, the possibility of creating a symbiosis between these industrial sectors and the urban zone can mitigate some of the problems characteristic of highly industrialized and populated areas.

One of the examples of the studies carried out to evaluate the impacts of industrial and urban symbiosis was the case of Guiyang, China, where several synergies were measured. Regarding industrial and urban symbiosis, this was characterized by two types of flows, solid and energy waste. That is, municipal solid waste was used as a source of energy by the steel and iron industry and this provided residual heat to urban areas (Fang et al., 2017). In addition to resource saving, these synergies have led to the reduction of carbon footprint and reduction of urban waste disposal in landfills and incinerators (Fang et al., 2017). Jinan, also located in China, was another example that allowed the achievement of these environmental benefits by the steel and iron industry and adjacent community (Dong et al., 2013b; L. Dong et al., 2014). In this industrial and urban symbiosis, the steel and iron industry received, in its production process, waste steel and waste water from the urban zone and provided surplus steam to the community.

Japan was one of the countries that invested in the creation of industrial symbiosis and industrial and urban symbiosis, creating the Japan's Eco-Town Program applied to 26 cities that were designated as national eco-towns. Initiated in 1997, its main objective was to use industrial, municipal and commercial waste in industrial applications and arose from the need to boost the economy and reduce waste disposal, since the area available for this purpose was reduced to the amount of waste deposited at the launch of this program (Van Berkel et al., 2009b). One of the cities included in this program was Kawasaki City, whose formal approval of Eco-Town Status occurred at the launch of the program in 1997, being one of the first four cities to be approved with this statute (Van Berkel et al., 2009b, 2009a). With the participation of nine companies, municipal waste collection and wastewater treatment centres and a group of industrial and commercial waste management companies, it was possible to conduct wastes generated by communities and industries to be incorporated into productive processes of various industries, used either as alternative fuels or as alternatives to raw materials, removing a considerable amount of waste from refuse and incineration (H. Dong et al., 2014; Dong et al., 2013b; Van Berkel et al., 2009a). In addition to this environmental advantage, others were obtained due to these synergies, such as saving resources and raw materials, reducing carbon emissions, and economic gains (H. Dong et al., 2014; Dong et al., 2013b; Ohnishi et al., 2017).

Although much of these examples are more recent, industrial and urban symbiosis has been taking place for a number of years. An example is the municipality of Köping, Sweden, where the symbiosis network dates back to the 1980s, where excess heat produced by local industries was used for district heating, and this power grid has recently been extended to three municipalities in the Västra Mälardalen region (Kurdve et al., 2018).

In addition to the existing examples, there is great potential for the growth of these symbiosis, and many studies have been published with the aim of assessing the feasibility and the impact that new industrial and urban symbiosis have in the industries and communities. One of the examples was the assessment of the environmental impacts that the expansion of industrial and urban symbiosis would have in Liuzhou, China (Dong et al., 2017; Lu Sun et al., 2017). With this study, as in the case of existing symbiosis, it was possible to conclude that the new synergies would enable reductions in carbon dioxide emissions, consumption of raw materials and waste disposal. Another of the examples was the study carried out in Ulsan, South Korea, to evaluate the environmental and economic benefits that could be obtained through industrial and urban symbiosis based on the demand and supply of high and low-grade waste heat by the industrial area and/or urban area (Kim et al., 2018a).

5. Discussion

Through an extensive review of the existing literature on industrial symbiosis, this article aimed to reach two main objectives, to trace the tendency of the evolution of the publications about this practice and to map the case studies characterizing them as to the main activities involved in the symbiosis and methods used in the analyses. Based on the research and selection of publications, it was possible to verify the growing importance of this theme, due to its contribution to increasing sustainability in its three dimensions, environmental, economic and social, bringing innumerable advantages to companies and communities, such as reduction of the consumption of raw materials, energy and natural resources, reduction of greenhouse gas emissions, reduction of waste sent to landfills and incinerators, reduction of costs with the purchase of raw materials, reduction of landfill costs and treatment of waste, revenue from the sale of waste and creation of jobs. These results can be interpreted as opportunities for decision-makers in companies and governments to continue their efforts to create and develop industrial symbiosis. From the analysis to the various cases of industrial symbiosis reported in the literature, it was possible to conclude that the drivers for the development and creation of synergies can be several, as illustrated by some concrete examples in Table 2. The economic motives are the most frequent ones in the initiatives taken by the companies for the creation of industrial symbiosis relations. Whether on its own initiative or through associations organized by companies that support the search for partners for synergy networks, the reasons why companies are driven to achieve symbiosis relationships are economic profits or increased competitiveness or on the other hand they are intended to avoid costs with taxes or waste treatment and disposal. Environmental and social reasons are most often found as driving the action of governments to promote industrial symbiosis. Reducing waste, reducing greenhouse gas emissions and increasing job creation are some of the reasons why governments have created plans and measures to encourage the creation and development of synergies and to apply additional taxes to penalize companies that do not implement sustainability measures and to dissuade them from sending waste to landfills and incinerators.

Whether in creating synergies or in its operation or expansion, a number of challenges are put to companies so that the industrial symbiosis develops successfully and provides benefits to all parties. When creating new symbiosis, companies have to develop a trust bond so that the supply of waste and resources is assured in sufficient quantity and quality for the operation of the receiving companies. Often this confidence is facilitated by the closeness of companies, as happened in Kalundborg (Domenech and Davies, 2011). However, the challenge for companies increases substantially when symbiosis involves the sharing of utilities, such as water and heat, in which, in addition to the large initial investment in infrastructures, the risk of supply variability is greater in these cases with a greater impact on the functioning of companies, so it is not surprising that from the case studies analysed the sharing of waste is more frequent than the sharing of utilities. Furthermore, the way the symbiosis network is built can also cause some problems for companies, especially if there is a failure of a supply. And this impact is greater the more central, with greater responsibility for the synergies and with greater number of connections is the company in which the failure occurs, as was studied for Kalundborg (Chopra and Khanna, 2014) and Guigang (Q. Wang et al., 2018a). For these cases, and in order to minimize the impact of these failures, the introduction of new symbiosis may prove to be an excellent opportunity to increase the economic benefits and reduce the vulnerability of the symbiosis network. For example, through the study of the evolution of the network of industrial symbiosis in Kalundborg, it was concluded that the increase of synergies by different industries with similar exchanges had allowed the reduction of vulnerability of the network, since if any node were removed, the network had the capacity to adapt since there were alternatives to this synergy (Chopra and Khanna, 2014). The inclusion of a company and the synergies developed between it and non-core nodes proved to be fundamental to increase the robustness of an existing industrial symbiosis network in Guigang, China, since it allowed to reduce dependence on the network and to reduce the possibility of collapse if the company considered nuclear failed (Q. Wang et al., 2018a).

The case studies on industrial symbiosis represent a considerable part of the publications on this subject, revealing the pertinence of this type of article to the knowledge of industrial symbiosis, not only to validate proposed methods and frameworks, but also to be analysed and serve to elucidate and draw lessons for future improvements. The review of publications on industrial symbiosis showed the huge diversity of case studies, in terms of location, industries involved in the synergies, and in the methods employed. From the analysis done to the case studies, it was possible to conclude that there are cases spread all over the world, with China having the highest incidence of studies on industrial symbiosis, justified by the growing concern about the reduction of greenhouse gases, due to the strong presence of industries characterized by high energy consumption and large carbon dioxide emissions and due to the limitations of emissions set by the international community. And while there is a greater tradition of implementing sustainability promotion measures in Europe, China has made an effort to contain greenhouse gas emissions by implementing a number of policies and programs that curb the negative effects of rapid industrialization and urbanization that have occurred in recent years. In addition, China being a developing economy country, presents a lower economic and social level, and it is therefore imperative to become more efficient, which has resulted in several programs to accelerate growth and to use resources efficiently, such as those to stimulate the circular economy and consequently industrial symbiosis. Although China, Brazil, India and South Africa are all developing countries, the number of industrial symbiosis in China is undoubtedly higher than in other countries. How countries are organized can contribute to this difference, while China has a more centralized planning, the other countries present more heterogeneous, disorganized and more unstable social scenarios.

As for the type of industry, it is concluded that the chemical industry, cement industry, paper industry, steel and iron industry, power plant, and refineries are those that appear most frequently in industrial symbiosis. The fact that the refineries, iron and steel, pulp and paper, and chemicals industries are most involved in industrial symbiosis can be explained by the high overall industrial final energy consumption of these industries, as well as being responsible for a large proportion of carbon dioxide emissions (Napp et al., 2014), which encourages measures to make them more efficient and to reduce the negative effects of the process.

The study by Jensen (2016) and more recently the study by Domenech et al. (2019) have revealed that the diversity of industries is a crucial factor in the development of industrial symbiosis. However, in addition to cases where there is great diversity, for example in Landskrona, Sweden (Mirata and Emtairah, 2005) and Kwinana in Australia (Van Beers et al., 2007), symbiosis has

Table 2
Needs that triggered the creation of industrial symbiosis and how they were materialized.

Region/Needs that triggered industrial symbiosis	How was materialized	References
Västra Götaland, Sweden - Increase economic gains - Creation of new business opportunity - Improve environmental performance - Avoid/reduce disposal costs - Reduce cost for virgin material - Marketing reasons	The industrial symbiosis was initiated by several micro, small and medium enterprises dedicated to the mushrooms production and beer production, which without the help of external institutions, sought the potential users of their residues. In the case of mushroom production the main by-products were used as fertilizers by the producers or local farmers. In brewing, the spent grains were used by animal breeders and the waste yeast is used as horse feed	Patricio et al., (2018)
Kalundborg, Denmark - Saving water resources due to the region's large groundwater deficit	Since the 1960s several industrial symbiosis projects involving cooperation between the various water consuming industries have been developed. The strategies have been to replace groundwater by surface water in the most water-consuming industries, to diversify external water sources and reduce internal water consumption in industries and to improve surface water to drinking water quality and to import groundwater from adjacent regions to the Kalundborg region	(Domenech and Davies, 2011; Ehrenfeld and Gertler, 1997; Jacobsen, 2006)
Kuusankoski, Finland - Increase economic growth - Increase production so as to respond to export growth, driven by increased demand for paper, which began in 1874	Between 1872 and 1913 the symbiosis began to be developed between hydropower plant, forest ecosystem and pulp and paper mill, with linear flows of material and energy. Subsequently the symbiosis expanded, the numbers of participants increased and have developed an industrial symbiosis composed of power plants, chemical manufacturing plants, waste management facilities and sewage treatment plants operate around a pulp and paper mill, considered as an anchor tenant	Pakarinen et al., (2010)
Grangemouth, United Kingdom - Improving the competitiveness of the local chemical industry - Creating further jobs - Reduction of waste volumes - Increased sustainability due to public and community pressure	Company attraction for the region, by the organization that exists in the region formed by major companies at Grangemouth, the Local Enterprise Council, Forth Ports, and Falkirk District Council, offering for this brownfield sites, which have water, electricity and steam utilities, waste management, storage and emergency services, and employee training centre for sustainability	Harris and Pritchard, (2004)
Dunkirk, France - Mitigate the negative effects of industrialization, especially air pollution - Improvement of the quality of life	A shared territorial action plan which promoted the implementation of industrial symbiosis	Morales and Diemer, (2019)
South of the Netherlands - Create space for new greenhouses - Creation of a cluster that would contribute to the sustainable development of the region by creating new jobs and by reducing emissions and local waterways	The industrial symbiosis was initiated by the local government, represented by a coalition between the Local Province, Local Municipality and the Local Port Authority. Subsequently joined an existing large industrial company in the zone to create a small company to manage the cluster of industrial symbiosis. It operates the infrastructure that collects and distributes waste heat and CO2 from the industrial company to greenhouse farming in nearby areas	Baldassarre et al., (2019)
Kawasaki, Japan - Need to boost economy and revitalize local industries - Reducing waste deposition, since the area available for this purpose was reduced to the amount of waste deposited	Through a national initiative, inaugurated in 1997, the Japan's Eco-Town Program was created and applied to 26 cities that were designated as national eco-towns, where the creation of industrial symbiosis and industrial and urban symbiosis was promoted. Kawasaki was one of the first cities included in this program. With the participation of nine companies, municipal waste collection and wastewater treatment centres and a group of industrial and commercial waste management companies, it was possible to conduct wastes generated by communities and industries to be incorporated into productive processes of various industries, used as alternative fuels or as alternatives to raw materials, removing a considerable amount of waste from landfill and incineration.	(H. Dong et al., 2014; Van Berkel et al., 2009b, 2009a)

also been found in many places where diversity is reduced, for example in Västra Götaland in Sweden (Patricio et al., 2018) and North Dakota in the United States (Gonela et al., 2015). It was also concluded that the predominance of a particular type of industry could enhance the initiation of synergies, for example the pulp and paper industry in Kymenlaakso in Finland (Sokka et al., 2011b) and the chemical and petrochemical industries in Grangemouth, in the United Kingdom (Harris and Pritchard, 2004).

The methods used to quantify the impacts of industrial symbiosis were the most widely used and were very diverse, being the life cycle assessment the most used in these assessments, and the environmental dimension was the most analysed, followed by the economic one. The predominance of environmental impact assessment can be explained by growing concerns about climate change, the urgency of reducing greenhouse gas emissions, the need to conserve natural resources and the consequent increase in environmental policies that have been applied. Interest in the assessment of economic impacts can be justified by the fact that companies are often driven to create synergies because of the economic benefits they can derive from them and are therefore an important impact to be assessed.

This literature review presents some limitations, associated with the methodology used for the research of publications. By limiting the search to articles written solely in English, some relevant publications may have been omitted. Another limitation relates to the data source used, that is, only research articles, conference articles, book chapters and editorials obtained through publishers have been used, however there must be more cases of industrial symbiosis scattered around the world that are not reported in this manner such as reports or public documents. Subsequently a more extensive research, such as an online survey or research with facilitators of industrial symbiosis could have provided more case studies.

6. Conclusions

Finding solutions that limit resource consumption and greenhouse gas emissions is essential to ensure sustainable economic growth. Industrial symbiosis has proved to be a strong ally for the achievement of environmental, economic and social objectives, evidenced by the growing number of publications on this subject, especially since 2007. From the analysis of the 584 published articles, it was possible to conclude that most of them were concerned with the analysis of industrial symbiosis case studies, whether were already implemented or with potential to be developed. Thus, one of the objectives of this extended review of industrial symbiosis was to map the existing case studies, with analysis of the location, type of activity and methods used in the analyses, in order to serve as a guide to foster new symbiosis opportunities. In Europe and Asia, notably China, it was where there was a higher prevalence of industrial symbiosis, justified by the implementation of public policies. However, in North America, Oceania, North Africa and South America it was possible to find cases of symbiosis. The manufacturing sector was the one that presented the highest prevalence in the industrial symbiosis relations, due to the wastes generated but also in the capacity of integrating wastes and by-products into the production cycle. Within this section, the chemical, cement, paper and steel and iron industries and the refineries are the most present. Power plants and waste and wastewater companies were also part of a large number of industrial symbiosis cases. Although the diversity of economic activities does not cease in these statements, there are many more present in the various cases. However, there was no direct link between the existence of many case studies in one country and the variety of sections of economic activity.

The review also emphasized that the methods used to quantify the impacts and to analyse the network of industrial symbiosis were the most used in the analysis of the case studies. The methods used to quantify the impacts of industrial symbiosis were very diverse, being the life cycle assessment the most used in these assessments, and the environmental dimension was the most analysed, followed by the economic one. Another of the conclusions drawn from the analysis of the case studies concerns the growth of studies conducted on industrial and urban symbiosis. Although some synergies between industries and cities date back to the 1980s, it has only been in recent years that the number of publications has expanded further. However, this type of synergy has great potential for growth, because with urban development, populations are closer to industrial areas and need to increase sustainability due to high energy consumption and waste production with significant increases in landfills and incinerators.

As previously mentioned, knowledge of the existing cases of industrial symbiosis can foster new synergies through relationship mimicking, that is, knowledge of success cases can lead to similar organizations applying the same concept. Although this article has contributed to an increase in the knowledge of existing cases in the world by compiling into one single publication the various published case studies, it does have some limitations, as stated in the previous section. Thus, one of the recommendations for future work would be to provide greater knowledge of existing cases. For this purpose, it would be important to use other types of sources, not only scientific publications in order to collect more information about cases of industrial symbiosis. In this sense, online research and research with local authorities, industrial associations, and associations that coordinate industrial symbiosis could provide a better understanding of existing cases.

Although the industrial symbiosis is spread all over the world, in some regions the number of cases reported in the publications is very small, for example in Canada, Mexico, Brazil, among others. Thus, future research could deepen the knowledge about the industrial symbiosis in these places. On the one hand investigate whether there are more cases of symbiosis, and on the other hand evaluate the potential of new synergies, i.e. to assess local reality in terms of existing industries, legislation, and other constraints, and to study the best ways of disseminating these practices in those locations. Future research is also needed to make a greater comparison of case studies in different countries with industrial symbiosis with different levels of development, in order to draw conclusions about the reasons for this development and the surrounding reality of each one and how this translates into drivers and barriers to development.

The case studies reported in literature, whether confined to a small number of stakeholders or those involving hundreds of entities, are mostly success stories. These can, therefore, be translated into a greater or lesser benefit for the environmental and economic results having a variable impact on the companies involved. However, even though these studies are essential for assessing the impact of industrial symbiosis and for collecting very important lessons in order to foster new synergies and develop existing ones, the lessons that can be drawn from failed cases are equally important. Understanding if there were external constraints, such as the economic situation of the region or country where the industrial symbiosis develops or if the failure was in the network itself and to understand the reasons for this failure, can be a very valuable source of information to better understand symbiosis and eventually prevent similar situations in other networks. Thus, there is a great potential for research in this field, and although a study has been carried out to analyse the reasons that led to the decline of symbiosis in Porto Marghera, Italy (Mannino et al., 2015), this is still insufficient.

The expansion of industrial symbiosis to the surrounding communities has also revealed a strong ally for the reduction of carbon dioxide emissions and the amount of waste sent to landfills and incinerators. However, the published studies are still small in view of the great potential of these synergies. Thus, future research on industrial and urban symbiosis is essential, not only to quantify the impacts and improve existing synergies, but also to foster the creation of new symbioses. Thus, the economic viability of the construction of structures for the industry to supply the urban part of residual heat or studies to evaluate the integration of urban waste in the productive process of several industries, are some of these examples.

Contrary to environmental and economic indicators, social indicators are translated by some subjectivity and complexity, and data for their quantification are more difficult to obtain (Hutchins et al., 2019; Ibáñez-Forés et al., 2019; Kühnen and Hahn, 2018). Moreover, another barrier that can be placed in determining the social impact of industrial symbiosis is to dissociate the effects of this practice with other measures that may be taken in the community and also increase the social benefit. As for example the improvement of the quality of the air can be boosted by the industrial symbiosis but also could have occurred other measures that have contributed to this improvement. Thus, it is not surprising that in the case studies analysed, the social component is the least studied. However, this component may be very important for the development of industrial symbiosis, since if the surrounding community and regional governments are aware of the advantages of these synergies, they can become active agents in the development of industrial symbiosis. Thus, future research is needed to study the impacts on society derived from this practice. For example, quality of life, translated by better social and economic conditions, spending on health, employment and income, improvement of roads and accesses can be developed to assess the impacts of industrial symbiosis in the surrounding communities. In addition, research should also focus on ways to measure them and how to decouple the effects of industrial symbiosis from other measures that are taken to increase sustainability and it would also be important to assess which factors are most valued by the surrounding populations.

Another future active area of research would be the development of indicators or methods, aimed at industrial symbiosis, which would allow quantifying the impacts of the three dimensions of sustainability, environmental, economic and social. Although there are several studies that have encompassed these three dimensions, they are not aimed at industrial symbiosis. In addition, encompassing the environmental, economic and social components has entailed some difficulties, such as the integration of qualitative and quantitative indicators in the same evaluation framework (Schoubroeck et al., 2018), the possibility of considering several objective functions simultaneously in the optimization studies (Boix et al., 2015), and the difficulty of integrating the social component with the other dimensions, since it is more related to the practices of an organization and not to the unit processes (Petit et al., 2018). Thus, future research would be necessary to overcome these barriers and to define a specific indicator for industrial symbiosis that would allow to quantify the total impact of this practice on companies, the environment and society and that allows the comparison of industrial symbiosis in different realities, that is, different characteristics of the network and taking into account the particularities of the region where it develops. Future research is also need to develop the integration of these indicators or methods with decision-making methods in order to serve as a tool in the final decision-making process.

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Intellectual property

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

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Appendix A

Table A.1
Industrial symbiosis application and analysis studies.

Country	Region	N. of Enterprises	Activity	Method	Publication Year	Reference
Europe						
Denmark	Kalundborg		Coal-fired power plant, oil refinery, maker of pharmaceuticals and enzymes, plasterboard manufacturer, district heating, fish farms, neighbouring farms, and cement and road aggregate producers	Evolution and interdependencies analysis	1997	Ehrenfeld and Gertler, (1997)
Denmark	Kalundborg		Power plant, oil refinery, biotech and pharmaceutical company, producer of plasterboard, soil remediation company, fish farm, public wastewater treatment, fertilizer company, municipality, farmers, and cement industry	Qualitative key-informant interviews, environmental effects analysis, cogeneration effect, net reduction of emissions, and economic benefits estimation	2006	Jacobsen, (2006)
Denmark	Kalundborg		Power station, two major chemical companies, plaster board manufacturer, soil remediation company, refinery, the municipality, farmers, fishing factory, cement companies, and some material recycling companies	Site-visit, face-to-face interviews, and short communications. Social Network Analysis	2011	Domenech and Davies, (2011)
Denmark	Kalundborg		Liquid fertilizer, refinery, fish farm, power plant, gypsum board plant, cement plant, biopharmaceutical plant, Kalundborg City, recovered nickel and vanadium, farm, and specialist in remediation of soil contaminated	Social network analysis and network connectedness analysis. Degree of connectedness and sub-network relationships. Density and core-periphery structure analytical methods	2013	Zhang et al., (2013)
Denmark	Kalundborg	6	Power plants, oil refinery, pharmaceutical company, the district municipality, and fish farm	Network analysis; network metrics: degree centrality, betweenness centrality, stress centrality and network efficiency; hypothetical disruptive scenarios; cascading effects; social network analysis and visualization software	2014	Chopra and Khanna, (2014)
Denmark	Kalundborg				2016	Branson, (2016)

Table A.1 (*continued*)

Country	Region	N. of Enterprises	Activity	Method	Publication Year	Reference
			Power station, two major chemical companies, plasterboard manufacturer, soil remediation company, refinery, municipality, farmers, fishing factory, waste water treatment, cement company, and some material recycling companies	On-site visits, interviews and meetings with experts		
Denmark	Kalundborg		Insulin production, enzymes production, oil refinery, coal-fired power plant, wallboard manufacture, biofuel producer, Kalundborg's municipal waterworks, soil remediation and recovery company, fertilizer industry, waste management company, cement industry, wastewater treatment, nickel industry, purification plant, farms, fish farms, and pig farms	On-site visits, interviews, and follow-up enquiries	2016	Valentine, (2016)
Denmark	Kalundborg		Refinery, power plant, biotech and pharmaceutical company, producer of plasterboards, biotechnology company, soil remediation and recovery company, waste treatment company, fertilizer industry, cement industry, fish farms, farms and Kalundborg municipality	Questionnaire for experts, input-output inoperability model, Fuzzy approach, dependency index, and influence gain index	2017	Kuznetsova et al., (2017)
Denmark	Kalundborg	18	Biomass refinery, refinery, fertilizer industry, plasterboards manufacturer, waste management company, energy company, farms, fish farms, cement industry, nickel-vanadium industry, pig farms, pharmaceutical and biotechnology company, fresh water provider, district heating distribution and wastewater treatment company, purification plant, and wastewater treatment company	Social network analysis. Densities. Centrality indicators: degree and relative degree centrality, betweenness and relative betweenness centrality, and closeness and relative closeness centrality. Centralization measures: degree, betweenness, and closeness centralization. Small-world and scale-free effects: average clustering coefficient, average path length, and power law distribution of degree. Stability analysis: network fragmentation degree. Comparative analysis	2019	Zhang and Chai, (2019)
United Kingdom	Grangemouth		Biotechnology company, active ingredient manufacture, refinery, gas supplier, water effluent treatment, de-watering/drying company, combined heat and power plant, petrochemical company, plastics and rubber industry, chemical industry, and plastics-chemical industry	Technology transfer model adapted with the idea of industrial ecology as a learning process	2004	Harris and Pritchard, (2004)
	Forth Valley		Energy company, refinery, chemical industry, paper mill, oil and gas company, cement manufacturer, and waste processor			
United Kingdom	Humber		Bioenergy sector: fuel producer, energy intensive company, farmers, specialist recycler, and steam producer	Semi-structured interviews and Social network analysis	2016	Velenturf, (2016)
United Kingdom	Humber		Bio-Diesel production, plaster board manufacturer, chemical industry, refineries, water treatment chemicals, food and fish processing, wastewater treatment, local farms, pet food, and furniture production	Direct observations, and in-person and telephone interviews	2004	Mirata, (2004)
	West Midlands		Local food processors and restaurants, bio-fuel production, automotive industry, and horticultural research institute			
United Kingdom	West Midlands	167		In-depth interviews, informal conversations, and observations in field	2012	Paquin and Howard-Grenville, (2012)
United Kingdom	England/Scotland/Wales			Geographic Information Systems software package	2011	Jensen et al., (2011)
United Kingdom	Bristol		Port-based industrial complexes	On-site visits, and individual or collective interviews performed on site	2014	Cerceau et al., (2014)
United Kingdom	Wissington		Sugar factory, liquefaction facility, bio refinery and an animal feed production facility	Semi structured interviews	2014	Short et al., (2014)
					2015	Leigh and Li, (2015)

(*continued on next page*)

Table A.1 (*continued*)

Country	Region	N. of Enterprises	Activity	Method	Publication Year	Reference
United Kingdom			Distributor of timber and building materials to trade	Face-to-face interviews with open-ended questions		
United Kingdom			Dairy, anaerobic digestion plant, consulting firm for food and agriculture, waste, water and energy management services company, and automotive and aerospace components industry	Semi-structured interviews	2018	de Abreu and Ceglia, (2018)
Sweden	Landskrona	>20	Chemicals, waste management, metals processing and recycling, various types of printing and printed packaging, motor vehicle components, agricultural seeds, transport and logistics companies and public organizations	Interviews	2005	Mirata and Emtairah, (2005)
Sweden	Southern Sweden		Sawmill, paper processing industries, paper mill, and energy service company	Interviews	2007	Wolf et al., (2007)
Sweden	Sundsvall-Timrå		Two sawmills, paper mill, pulp mill, two integrated pulp and paper mills and the municipalities of Sundsvall, Timrå, Härnösand and Bollstabruk	On-site observation and open-ended interviews	2007	Wolf and Petersson, (2007)
	Mönsterås		Chemical pulp mill, sawmill, pellet production facility and the municipality of Mönsterås			
Sweden	Östergötland		Forest industry, pulp mill, pellet production plant, slaughterhouse, biogas production facility, renewable energy companies, combined heat and power plant, and ethanol plant	Planned and unplanned IS activities analysis	2011	Baas, (2011)
Sweden	Händelö		Energy, recycling, forestry and biofuel production plants	Visits, interviews and material and energy flows	2011	Martin and Eklund, (2011)
Sweden	Händelö		Integrated ethanol and biogas plants, combined heat and power plant, forestry, municipality, and regional farmers	Direct inquiry to the companies, life cycle assessment, EPD 2008 method, energy allocation method and system expansion method	2014	Martin et al., (2014)
Sweden	Händelö	3	Combined heat and power, ethanol and biogas plants	Life cycle assessment, EPD 2008 method, energy allocation method, system expansion method and the 50/50 method	2015	Martin, (2015)
Sweden	Västra Götaland	4 (mushroom) 7 (beer)	Mushroom and beer production	On-site visits and semi-structured interviews	2018	Patricio et al., (2018)
Sweden	Stenungsund		Chemical industry cluster: industrial and specialty gas products and services; paints and coatings; polyolefins, base chemicals and fertilizers production; chemical; and specialty chemicals products companies	Life cycle assessment and CML 2001 method. Cost-effectiveness analysis: Indicator: ratio between investment cost and reduced global warming potential	2018	Røyne et al., (2018)
Sweden	Sotenäs	10	Fish/food industry, algae production, salmon farming, waste treatment and energy and plastic recycling	Interviews, consultation with key experts, life cycle assessment and socio-economic assessments	2018	Martin and Harris, (2018)
Netherlands	Rotterdam		Air supplier; organic chemical, inorganic chemical, aluminium-processing, cement, chemical and metal-working companies, and residential areas	Role of organizations in the cluster based on Sustainability capabilities	2007	Baas and Boons, (2007)
Netherlands	Rotterdam		Refinery, greenhouse companies, residential area, port, and shrimp farm	Analysis of the synergistic role of embeddedness and capabilities in industrial symbiosis	2008	Baas and Huisingh, (2008)
Netherlands	Rotterdam		Air supplier, organic chemical company, inorganic chemical company, aluminium-processing company, cement company, residential areas, greenhouse horticulture, port authority, and shrimp farm	Historical background and development analysis	2010	Baas and Korevaar (2010a)
Netherlands	Rotterdam		Refineries, city, greenhouse companies, chemical company, truck cleaning company, and power plant	Planned and unplanned IS activities analysis	2011	Baas, (2011)
Netherlands	Rotterdam		Port and city	On-site visits, and individual or collective interviews performed on site	2014	Cerceau et al., (2014)
Netherlands	Canal Zone of Zeeland		Four greenhouses; alcohol factory; fertilizer, agricultural, waste processing, and chemical companies	Interviews and event sequence analysis	2013	Spekkink, (2013)
Netherlands	Canal Zone of Zeeland		Agricultural industry, process industry, greenhouses, regional port authority, and chemical company	Event sequence analysis	2014	Boons et al., (2014)

Table A.1 (*continued*)

Country	Region	N. of Enterprises	Activity	Method	Publication Year	Reference
Netherlands	Zeeland		Agricultural and horticultural greenhouse complex and fertilizer plant	On-site visits, and individual or collective interviews performed on site	2014	Cerceau et al., (2014)
Netherlands	Sloe Area and Canal Zone		Food industry, greenhouse horticulture zone, alcohol factory, fertilizer industry, and waste processing	Interviews and event sequence analysis	2015	Spekkink, (2015)
Netherlands	South of the Netherlands		Industrial company, greenhouse farming, local government (Local province/Local Municipality/Local Port Authority) and management company	Interviews with the operating and financial managers, brainstorming sessions with academic experts, comparative analysis, visual analysis and strategic design co-creation workshop	2019	Baldassarre et al., (2019)
France	Mèze		Sewage treatment plant, and marine micro-algae production	In-depth, semi-structured interviews, and on-site visits	2007	Gibbs and Deutz, (2007)
France	Marseille-Fos		Energy intensive companies and liquefied natural gas terminal	On-site visits, and individual or collective interviews performed on site	2014	Cerceau et al., (2014)
France	Bazancourt-Pomacle		Sugar factory, starch and glucose processing plant, producer of molecules for cosmetic use, producer of plant-sourced succinic acid, bioethanol producer, and recovery and processing plant for CO_2	Interviews	2015	Schieb et al., (2015)
France	Dunkirk	14	Steel industry, power plant, central heat power plant, cement grinding centre, cement factory, cement subsidiary, steel slag treatment company, agricultural market, brick manufacturer, construction company, crude still mill production and dust recycling company	Interviews conducted with expert analysts and researchers, site visits and collaborations with local organizations. Geographical system dynamics method. Causal Loop Diagrams	2019	Morales and Diemer, (2019)
France			Waste incinerator steam network symbiosis and local companies	Semi-structured interviews, site visits, and qualitative and quantitative model of the stakeholder value network approach	2017	Hein et al., (2017)
Russia	Kola Peninsula	9	Mining industry	Stakeholder interviews, counterfactual method, eco-efficiency indicators based on input-output analyses, and material flow analysis	2007	Salmi, (2007)
Finland	Kuusankoski		Pulp and paper mill, three chemical plants (chlorine dioxide, hydrogen peroxide and calcium carbonate plants), a power plant, a water purification plant, two sewage plants and a landfill	Quantifiable indicators for each of the conditions of The Natural Step System Conditions for the analysis of sustainability	2010	Pakarinen et al., (2010)
Finland	Kymenlaakso		Pulp and paper mill, chlorine dioxide, calcium carbonate, and hydrogen peroxide plants, power plant, local electricity, municipal sewage treatment plant, and landfill	Process, hybrid and input-output life cycle assessment approaches, and LCIA-RECIPE method	2010	Mattila et al., (2010)
Finland	Kymenlaakso		Pulp and paper mill, three chemical plants (chlorine dioxide, hydrogen peroxide and calcium carbonate plants), a power plant, a water purification plant, two sewage plants, a landfill, and a regional energy supplier	On-site survey; life-cycle inventory methodology of life-cycle assessment	2011	Sokka et al. (2011b)
Finland	Kouvola		Pulp and paper mill; calcium carbonate, hydrogen peroxide, chlorine dioxide, municipal wastewater treatment, and power plants	Life cycle assessment	2011	Sokka et al. (2011a)
Finland	Kouvola	9	Pulp and paper mill, three chemical plants, power plant, energy distributor, water purification plant, wastewater treatment plant, and a landfill	Semi-structured interviews	2011	Lehtoranta et al., (2011)
Portugal	Chamusca		Integrated recovery, treatment and elimination centre for hazardous wastes, municipal waste management, non-hazardous industrial waste landfill, wastewater treatment facilities, plastics recycler, dismantlers of end of life vehicles, biomass processers, fertilizer producers, metal reclamation projects, container refurbishment, aluminium slag	Unstructured interviews, on-site visits, and middle-out approach	2010	Costa and Ferrão, (2010)

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Table A.1 (*continued*)

Country	Region	N. of Enterprises	Activity	Method	Publication Year	Reference
			processor, battery recycler, paper pulp producer, and local farms			
Portugal	Lisbon	44	Manufacturer of pulp, repair and maintenance of ships and boats, construction of railways and underground railways, wholesale of waste and scrap, manufacturer of doors and windows of metal, manufacturer of other fabricated metal products, shaping and processing of flat glass, production of electricity, logging, manufacturer of cement, manufacturer of household and sanitary goods and of toilet requisites, aluminium production; manufacturer of plastic plates, sheets, tubes and profiles; manufacturer of basic iron and steel and of ferro-alloys, and manufacture of flat glass	Material Flow Analysis	2015	Patrício et al., (2015)
Portugal			Pulp and Paper Industry	Unstructured interviews with members and interviews with two experts from a paper industry association. Eco-efficiency, reuse and industrial symbiosis indicators. Comparative analysis method. Comparative index. Radar chart graph	2019	Ferreira et al., (2019)
Austria	Styria		Paper producing industries, pressboard plant, scrap material dealer, wastewater treatment plant, mining company, wastepaper dealer, textile plants, chemical plant, saw mill, iron scrap dealer, construction materials plants, power plants, region of Voitsberg, stone and ceramic industries, cement plants, region of Graz, iron manufacturing industry, used tire dealers, plastics plant, colour industry, and fuel producer	Social network analysis and network connectedness analysis. Degree of connectedness and sub-network relationships. Density and core-periphery structure analytical methods	2013	Zhang et al., (2013)
Italy	Taranto		Cement factory, steelworks factory, power plants, refinery, construction material producing companies, distilleries, and wine companies	Questionnaires	2014	Notarnicola et al., (2014)
Italy	Taranto	>15	Steelworks, refinery, cement, food sector, construction and construction materials production industries, agricultural firms and power stations	Collection and analysis of data and questionnaires surveys	2016	Notarnicola et al., (2016)
Italy	Industrial area of Venice, Veneto region		Chemical industry	Surveys data	2015	Mannino et al., (2015)
Italy	Prato, Tuscany Ponterosso, Friuli-Venezia Giulia Ancona, Marche		Textile industry Chemicals, food, glass, machinery and components production companies Maritime activities such as shipbuilding, mechanical repairs, electrical systems, nautical decor, food supplies, logistics, shipping agencies and seafood processing	Data collected directly from managers and telephone interviews	2015	Daddi et al., (2015)
Italy	Abruzzo		Chemical/automotive/agri-food	On-site survey and questionnaires	2017	Taddeo et al., (2017)
Italy	S.Croce sull'Arno, Tuscany		Tannery industry	Life cycle assessment	2017	Daddi et al., (2017)
Spain	Galicia		Port-based industrial complexes	On-site visits, and individual or collective interviews performed on site	2014	Cerceau et al., (2014)
Spain			Pulp and Paper Industry	Unstructured interviews with members and interviews with two experts from a paper industry association. Eco-efficiency, reuse and industrial symbiosis indicators. Comparative analysis method. Comparative index. Radar chart graph	2019	Ferreira et al., (2019)
Belgium	Antwerp		Petrochemical industries, chemical industries, and city	On-site visits, and individual or collective interviews performed on site	2014	Cerceau et al., (2014)
Belgium	Brussels		Port-based industrial complexes			
Belgium	Koekhoven				2016	

Table A.1 (*continued*)

Country	Region	N. of Enterprises	Activity	Method	Publication Year	Reference
			Biogas cogeneration firm, manure-drying farmers, farmers, greenhouses, energy firm consultant, cattle farmers, jatropha cogeneration, power grid, retail, unpack organic wastes, and garden centre	Open questions and semi-structured interviews, observations in project meetings, field visits and dual-perspective framework application		Verguts et al., (2016)
Germany			Cement industry	Simplified life cycle assessment model, CO_2 emissions from different production systems and products	2015	Ammenberg et al., (2015)
Latvia			Brewery industries, agricultural farms, bakeries (cookie production), and biogas production Wood-processing industries: plywood production, manufacture of furniture, sawmilling and wood procession, wood product transfer harbour, composite wood board production, energy recovery, pellet production, and a farm	Stakeholder interviews. Integrated method for evaluation of the quality of industrial synergies: overall evaluation score for exchange quality through three evaluation categories (environmental quality, economic quality, and geographic proximity)	2015	Rosa and Beloborodko, (2015)
Denmark/ United Kingdom/ Portugal/ Switzerland				Interviews and quantitative and qualitative descriptors	2010	Costa et al., (2010)
North America						
United States of America	Guayama, Puerto Rico		Coal-fired power plant, public wastewater treatment plant, petrochemical refinery, and waste stabilization	Interviews	2005	Chertow and Lombardi, (2005)
United States of America	Guayama, Puerto Rico		Refinery, cogeneration plant, pharmaceutical firms, industrial landfills, road construction, and wastewater treatment facility	Field research at industrial sites, in-person interviews, detailed questionnaires, empirical observation, and material flow analyses	2008	Chertow et al., (2008)
United States of America	Barceloneta, Puerto Rico		Pharmaceutical firms, hay farm, paint manufacture, energy recovery, wastewater treatment facility, and waste management firms	Field research at industrial sites, in-person interviews, detailed questionnaires, empirical observation, and material flow analyses	2008	Chertow et al., (2008)
United States of America	Barceloneta, Puerto Rico	15	Pharmaceutical manufacturing facilities, hay farm, animal feed producer, paint manufacture, energy recovery, wastewater treatment facility, and waste management firms	Interviews, social network analysis	2008	Ashton, (2008)
United States of America	Barceloneta, Puerto Rico		Pharmaceutical firms, hay farm, animal feed producer, paint manufacture, energy recovery, wastewater treatment facility, and waste management firms	In-person and telephone interviews, congruence method, and integrated framework based on economic geography, industrial ecology, and complex systems theory	2009	Ashton, (2009)
United States of America	Barceloneta, Puerto Rico		Pharmaceutical manufacturing facilities, hay farm, animal feed producer, paint manufacture, energy recovery, wastewater treatment facility, and waste management firms	Open-ended interviews and in-person semi-structured interviews	2011	Ashton, (2011)
United States of America	Pennsylvania			Evaluation of the difference in environmental impacts (primary energy and emissions) between reuse and production of the substituted material using the life cycle inventory databases of GREET and Ecoinvent	2009	Eckelman and Chertow, (2009)
United States of America	Honolulu	11 (8 analysed)	Coal-fired power plant, oil refinery, city water recycling plant, concrete production company, quarry, construction and demolition waste landfill, city water agency and recycling company	Interviews. Quantification of environmental benefits (changes in consumption of natural resources, and emissions to air and water), and economic benefits (revenue streams from by-products, disposal costs avoided, reductions in raw material and transportation costs)	2010	Chertow and Miyata, (2010)
United States of America	Honolulu	11	Biosolids beneficiation company, local golf course, wastewater treatment plant, oil refineries, power plant, oil and tire recovery company, municipal water	Life cycle assessment	2013	Eckelman and Chertow, (2013)

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Table A.1 (*continued*)

Country	Region	N. of Enterprises	Activity	Method	Publication Year	Reference
			authority, cogeneration plant, cement company, and private construction and demolition waste landfill			
United States of America	Kansas City	9	Synthetic resins and plastics materials producer, long steel producer, greeting cards and gift products company, motorcycle manufacturer, solid waste treatment, electric utility company, construction materials company, organic recycling facility, and provider of by-product co-processing services	Material flow network and mixed integer programming model	2011	Cimren et al., (2011)
United States of America	Choctaw		Tire crushing, tire pyrolysis, carbon black processing, ink cartridge production and recovery, plastics, plastic products, wastewater treatment, and crushed steel recovery plants; hard rubber tire manufacturers, and greenhouse	Social network analysis and network connectedness analysis. Degree of connectedness and sub-network relationships. Density and core-periphery structure analytical methods	2013	Zhang et al., (2013)
United States of America	New York/New Jersey		Port-based industrial complexes	On-site visits, and individual or collective interviews performed on site	2014	Cerceau et al., (2014)
United States of America	Long Beach		Ports and marinas	On-site visits, and individual or collective interviews performed on site	2014	Cerceau et al., (2014)
United States of America	North Dakota		1st generation bioethanol and combined heat and power plants	Interviews, surveys, and direct observations. Stochastic mixed integer linear programming model, Sampling average approximation. Bioethanol production, economic, GHG emission, irrigation land usage, water usage, and energy efficiency analysis	2015	Gonela et al., (2015)
United States of America	Upper Valley	2	Solid waste resource management company and manufacturer	Interviews	2017	Krones, (2017)
United States of America	Chicago		Real estate developer, education, research and development, agriculture/farming, consulting, compost collection, beverage producers and food producers	Measurements of material and energy flows on-site and off-site, interviews, routine observations, questionnaires, and material flow analysis	2018	Chance et al., (2018)
Canada	Sarnia-Lambton		Fertilizer company, greenhouse operator, gas specialist company, power plant, medium-sized fine-particle manufacturer, oil refinery, chemical company, integrated energy company, and cattle farmers	Interviews	2009	Bansal and Mcknight, (2009)
Mexico	Altamira-Tampico	15	Petrochemical industry	Open and face-to-face interviews, and on-site visits	2019	Morales et al., (2019)
Asia						
South Korea	Ulsan		Automobile, oil-refinery, shipbuilding, petrochemical, chemical, non-ferrous metal smelting, and cement companies, and metropolitan city	Analysis of the development of IS	2006	Won et al., (2006)
South Korea	Ulsan		Chemical, petroleum, and petrochemical company; industrial waste treatment and disposal company; chemical companies; tank terminal business; copper smelter and refinery; non-ferrous metal smelting company; paper mill company; wastewater treatment facilities; specialty chemicals and life science products company; integrated water management enterprise; and Ulsan Metropolitan City	On-site surveys	2008	Park et al., (2008)
South Korea	Ulsan	41	Industrial and municipal waste incinerator, sewage treatment, paper mill, non-ferrous metals, chemical, petrochemical, steel, metal, non-metal, metal recovery, aluminium manufacturer, transport and oil spill restoration companies	Field survey	2012	Behera et al., (2012)
South Korea	Ulsan	21	Industrial and municipal waste incinerator facilities, municipal wastewater treatment plant, paper mill, petrochemical, zinc waste processing,	Eco-efficiency indicators: one economic indicator and three environmental indicators (raw material consumption, energy	2014	Park and Behera, (2014)

Table A.1 (*continued*)

Country	Region	N. of Enterprises	Activity	Method	Publication Year	Reference
			paint manufacturing, zinc manufacturing and chemical companies	consumption, and CO_2 emission) and eco-efficiency evaluation		
South Korea	Ulsan		Waste-to-energy incinerator and chemical plants	Economic and indirect benefits analysis	2014	Park and Park, (2014)
South Korea	Ulsan		Port-based industrial complexes	On-site visits, and individual or collective interviews performed on site	2014	Cerceau et al., (2014)
South Korea	Ulsan		Chemical, chemical manufacturer, steel, petrochemical, aluminium manufacturer, aluminium, metal, metal recovery, non-ferrous metals, automobile, non-metal, transport, paper mill, utility supplier, waste treatment, municipal waste incinerator, food waste treatment, wastewater treatment, municipal waste landfill, industrial waste incinerator, and sewage treatment facilities, and oil spill restoration company	Eco-production strategy analysis and assessment of economic, social and environmental benefits	2015	Park and Behera, (2015)
South Korea	Ulsan	2	Zinc smelter and paper mill company	Method for the assessment of total and allocated greenhouse gas emissions from IS exchanges based on the GHG protocol and life cycle assessment. LCA allocation methods: cut-off, avoidance impact, and 50/50	2018	Kim et al. (2018b)
South Korea	Yeosu	27	Refineries, power plants, and petro-chemical companies	Interviews, questionnaires, and waste heat utilization network model	2010	Chae et al., (2010)
South Korea	Banwol-Sihwa		Textiles dyeing and printing firms, cogeneration plant, residential areas, and cement manufacturing industry	Fieldwork, and semi-structured interviews	2018	Yoon and Nadvi, (2018)
South Korea		596		Network analysis (NetMiner 4.0). Economic benefits (cost savings and revenues, and total economic surplus) and environmental benefits (reduction of energy consumption, and reduction in the generation of waste, wastewater, and emissions) analysis	2019	Park et al., (2019)
China	Guigang		Sugar refinery, alcohol plant, pulp and paper mills, cement plant, compound fertilizer plant, and alkali recovery plant	Interviews	2007	Zhu et al., (2007)
China	Guigang		Sugar-making industry, alcohol-processing plant, compound-fertilizer plant, cement mill, and paper making system	Eco-industrial development analysis	2007	Fang et al., (2007)
China	Guigang		Sugar, pulp, paper, alcohol, power, fertilizer, and calcium carbonate plants; cement mill, and alkali recovery facility	Analysis of the different technological evolution trend and the diversified dynamics of the selected environment	2011	Guo and Hu, (2011)
China	Guigang		Sugar refinery, sugarcane planting system; and alcohol, pulp and paper, compound fertilizer, power, wastewater treatment, alkali recovery, cement, and light calcium plants	Social network analysis and network connectedness analysis. Degree of connectedness and sub-network relationships. Density and core-periphery structure analytical methods	2013	Zhang et al., (2013)
China	Guigang		Sugar processing and refinery, pulp, paper manufacturing, alcohol, cement mill, fertilizer, caustic soda, calcium carbonate, alkali, wastewater treatment, and water recycling facilities; combined heat and power, local and regional farmers, and road material manufacturers	Social network analysis, material flow analysis, and comparative analysis	2017	Shi and Chertow, (2017)
China	Guigang		Sugar plant, brewery, fertilizer plant, thermal power plant, pulp mill, paper mill, and cement factory	Robustness analysis under random failure and intentional disturbance, and optimization of eco-industrial symbiosis network. Node failure rate, indicator for structural robustness (natural connectivity), and indicator for performance robustness (network efficiency)	2018	(Q. Wang et al., 2018a)

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Table A.1 (*continued*)

Country	Region	N. of Enterprises	Activity	Method	Publication Year	Reference
China	Guigang		Sugar plant, brewery, chemical fertilizer plant, thermal power plant, pulp mill, paper mill, and cement factory	Assessment of the vulnerability of eco-industrial symbiosis network based on the automatic control theory	2018	(Q. Wang et al., 2018b)
China	Wudi County, Shandong province		Cement and marine chemical industries	Eco-industrial development analysis	2007	Fang et al., (2007)
China	Wudi County, Shandong province	8	Ammonium phosphate, cement, sodium hydroxide, salt, sulfuric acid, ammonia, bromine, and electric power plants	Environmental and economic benefits analysis	2010	Wang et al., (2010)
China	Wudi County, Shandong province		Salt field; chlor-alkali, ammonium phosphate, sulphate, cement and power plants	Analysis of the different technological evolution trend and the diversified dynamics of the selected environment	2011	Guo and Hu, (2011)
China	Wudi County, Shandong province		Ammonium phosphate, sulfuric acid, cement, thermal power, chlorine, aquaculture, bromine, salty gypsum production, and chlor-alkali plants; raw salt production, potassium magnesium salt production, and living area	Social network analysis and network connectedness analysis. Degree of connectedness and sub-network relationships. Density and core-periphery structure analytical methods	2013	Zhang et al., (2013)
China	Wudi County, Shandong province	8	Ammonium phosphate, sulfuric acid, cement, ammonia, thermal power, bromine, salty gypsum production; and potassium and magnesium salt production plants	Ecological network analysis	2015	Zhang et al. (2015b)
China	Wudi County, Shandong province	21	Thermal power plant, culture of special species, crude salt plant, salt field, aquaculture, sea water desalination, potassium magnesium plant, water enrichment plant, bromide plant, chlor-alkali plant, petrochemical plant, hydrochloric acid plant, titanium dioxide plant, salt gypsum plant, alumina plant, chemical fertilizer plant, ammonium phosphate plant, sulfuric acid plant, cement plant, synthetic ammonia plant, and urea plant	Social network analysis. Densities. Centrality indicators: degree and relative degree centrality, betweenness and relative betweenness centrality, and closeness and relative closeness centrality. Centralization measures: degree, betweenness, and closeness centralization. Small-world and scale-free effects: average clustering coefficient, average path length, and power law distribution of degree. Stability analysis: network fragmentation degree. Comparative analysis	2019	Zhang and Chai, (2019)
China	Guiyang		Aluminium and phosphorus chemical industries	Eco-industrial development analysis	2007	Fang et al., (2007)
China	Guiyang		Iron/steel, aluminium, phosphorous chemical, coal, and cement industries; power plant, urban areas, and agriculture sector (greenhouses)	Hybrid model integrating an input-output approach and process-based inventory analysis. Carbon emissions from a production and consumption perspectives. Indirect/direct ratio and production/consumption ratio indexes. Carbon footprint intensity and carbon footprint per person	2017	Fang et al., (2017)
China	Nanning, Guangxi		Sugar industry	On-site survey	2008	Yang and Feng, (2008)
China	Nanning, Guangxi		Sugar industry	Material flow analysis	2008	Jianhua and Zhaohua, (2008)
China	Dafeng	5	Barley field, feedstuff plant, livestock husbandry plant, beer company, and fish ponds	Environmental and economic benefits analysis	2010	Wang et al., (2010)
China	Guangdong	13	Coagulation, aluminium processing, metal smelting, synthetic fibres, plastics, activated charcoals, plastic additives, environmental protection instruments, wood planking, adhesive, ceramic, steam, and sound-proof material plants			
China	Tianjin		Public utilities and environmental infrastructures (sewage, water, and wastewater treatment plants; cogeneration, desalination, steam and hot water supply, and thermal power plants); electronics industry; food and beverage industries, pig farms, farms, coal briquette factory; biotechnology and pharmaceutical industries, eco-landscaping development company, public works company; automobile and	Field trips and interviews	2010	Shi et al., (2010)

Table A.1 (*continued*)

Country	Region	N. of Enterprises	Activity	Method	Publication Year	Reference
			machinery industries, battery products manufacturer, paper mill, and cement mill			
China	Tianjin		Metal mill and power factories	Survey questionnaires	2011	Qi and Wang, (2011)
China	Tianjin		Water treatment plant, industrial, commercial and residential users, wastewater treatment plant, construction companies, cogeneration plant, new water source company, desalination plant, resource recovery company, cast iron company, auto die makers, automatic transmission company, aluminium smelting, resource management company, stemless steel pipe maker, steel scrap contractors, refineries, chemical companies, lead recycling company, cement mill, rubber company, batteries company, and various lead acid battery users	Social network analysis and network connectedness analysis. Degree of connectedness and sub-network relationships. Density and core-periphery structure analytical methods	2013	Zhang et al., (2013)
China	Tianjin		Wastewater treatment plant, cogeneration power plant, and companies involved with packaging waste, scrap iron, and waste oil	Data collection in the field, semi-structured interviews, and process analysis	2014	Yu et al. (2014b)
China	Tianjin		Port-based industrial complexes	On-site visits, and individual or collective interviews performed on site	2014	Cerceau et al., (2014)
China	Tianjin		Wastewater recycling and cogeneration and waste recycling	On-site field research, technique for order of preference by similarity to ideal solution method (based on seven indicators divided into two subgroups) used as multicriteria decision analysis, and process analysis approach	2015	Yu et al., (2015a,b,c,e,f)
China	Tianjin Binhai		Power plant, desalination station, salt-making, chemical plant, and building materials producer	Transition course analysis	2011	Li, (2011)
China	Tianjin Binhai			Participant observation and semi-structured interviews	2017	(Q. Wang et al., 2017)
China	Suzhou		Wastewater treatment plant, sludge drying company, and power plant	Field study, face-to-face interviews, questionnaire-based surveys, and energy-related greenhouse gas emissions using IPCC guidelines method	2012	(L. Liu et al., 2012)
China	Suzhou		Companies of the main production chain of printed circuit boards, and waste treatment facilities and disposal services	Questionnaire surveys, interviews with stakeholders, and field surveys. Substance flow analysis and resource productivity indicator	2015	Wen and Meng, (2015)
China	Weifang	2	Salt field plant and soda plant	Open ended and face to face interviews, and investigation on site	2012	(C. Liu et al., 2012)
China	Weifang	11	Soda, bromine, salt field, silica, saleratus, calcium chloride, bromide, potassium sulphate, cement, thermal power plants and residential zone	Investigation on-site, survey questionnaires, open-ended interviews and three-level approach	2015	Liu et al., (2015)
China	Weifang		Salt field plant, soda plant, thermal power plant, bromine plant, calcium chloride plant, potassium sulphate plant, saleratus plant, petrochemical company, chlor-alkali colophony plant, and wastewater treatment facility	Field research and open-ended interviews with the managers, technicians and the government staff. System dynamics method. Causal loop diagram, stock—flow diagrams and numerical simulation. Method of scenario analysis	2018	Cui et al., (2018)
China	Liuzhou	3	Iron and steel, fertilizer, and cement and construction industries; and communities	Hybrid physical input and monetary output model, co-benefit indicators: CO_2 emissions reduction per unit of waste reduction, SO_2 and NO_x reduction per unit of waste reduction and economic revenue; CO_2 emissions calculated on the basis of energy consumption and inventory method	2013	Dong et al. (2013a)
China	Liuzhou			Surveys data	2013	Dong et al. (2013b)

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Country	Region	N. of Enterprises	Activity	Method	Publication Year	Reference
			Iron and steel, cement and construction, ammonia and fertilizer industries, and community			
China	Liuzhou	3	Iron and steel, fertilizer, and cement and construction industries; and urban community	Material flow analysis, CO_2 emission reduction from the avoided resource or waste	2014	(L. Dong et al., 2014)
China	Jinan		Iron and steel, aluminium, ammonia, chromium chemical, and cement and construction industries; and community	Company-level questionnaire surveys and interviews with stakeholders	2013	Dong et al. (2013b)
China	Jinan	6	Iron and steel, aluminium, ammonia, chromium chemical, carbonate production and cement and construction industries; and urban community	Company-level questionnaire surveys, interviews with stakeholders; material flow analysis, CO_2 emission reduction from the avoided resource or waste	2014	(L. Dong et al., 2014)
China	Changsha Huangxing		Camellia oil refinery, nucleic acid extraction, IC manufacturing; and food, cellulose enzyme, tea-leaf, aloe deep-processing, cosmetics, camellia oil, citrus, beverage, beer, antiviral medicine, tea cake processing, orange peel deep-processing, medicine, daily-use chemical, fertilizer, food additives, agricultural production, IC packing, purifying agent, plastics manufacturing, household appliances, air conditioner, metal recovery, wastewater treatment, rice husk, environmental protection equipment, green paint, green building materials, intelligent metals, green adhesives, plastics, ceramics, building bricks, equipment parts, and building materials plants	Social network analysis and network connectedness analysis. Degree of connectedness and sub-network relationships. Density and core-periphery structure analytical methods	2013	Zhang et al., (2013)
China	Shihezi		Achnatherum cultivation, paper-making, livestock breeding, wastewater treatment, and animal products processing systems; and eco-tourism industry			
China	Wujing		Coking, chemical, titanium white, carbon products, hydrogen peroxide, and Chlor-alkali plants			
China	Liaocheng		Chlor-alkali plant, alumina plant, lime factory, calcium carbide factory, electrolytic aluminium plant, aluminium processing factory, electric power plant, medium-density fibreboard plant, PVC plant, system of supply heating, and carbon plant	Field investigations. Energy-saving indexes (IS energy-saving index, contribution rate of energy saved through IS, fractional energy savings, and cut rate of energy consumption per gross industrial output value) and financial indexes (IS input—output ratio, static investment payback period of IS, net present value, and internal rate of return of IS)	2014	Li et al., (2015)
China	Liaocheng	16	Sewage treatment, polyvinyl chloride, alumina, electrolytic aluminium, aluminium processing, and steel plants; cogeneration system; red mud recycling system; soda ash, lime, calcium carbide, carbon, density board, brick, fertilizer and building materials factories	Data from laboratory determination, questionnaire surveys and field investigation. Substance flow analysis. Carbon accounting methods: based on IPCC 2006 and the Greenhouse Gas Emission Accounting Methods and Reporting Guidelines (Trial)	2015	(F. Yu et al., 2015a)
China	Liaocheng		Sewage treatment plant, polyvinyl chloride plant, soda ash factory, lime factory, calcium carbide factory, carbon factory, cogeneration system, alumina plant, electrolytic aluminium plant, aluminium processing plant, density board factory, brick factory, fertilizer factory, red mud recycling system, steel plant and building materials factory	Life cycle assessment	2015	(F. Yu et al., 2015b)
China	Liaocheng	27	Cogeneration system, coal mine, board fireproofing, gypsum board, extracting iron, dealkalize, rock wool, composite board, extracting bauxite, brime; ore, alumina, electrolytic aluminium, aluminium deep processing, salt, calcium carbide, PVC, chlor-alkali, PVC deep	On-site investigations, company-level questionnaires, interviews with experts and stakeholders; network analysis method, social network analysis program, and node importance indexes of the industrial symbiosis network	2017	Han et al., (2017)

Table A.1 (*continued*)

Country	Region	N. of Enterprises	Activity	Method	Publication Year	Reference
			processing, lime, fluoride salt, carbon, brick, desulfurization, red mud recycling, fertilizer, and eco-cement plants	(degree, betweenness, closeness, and eigenvector centralities)		
China	Shenyang		Cogeneration power plants; construction materials, chemical and pharmaceutical, manufacturing and electric, and metallurgy and casting enterprises	Interviews, informal meetings, emergy analysis method, industrial symbiosis emergy indicators (absolute emergy savings, relative emergy savings from different resources, and emdollar values of total emergy savings)	2014	Geng et al., (2014)
China	Shenyang		Power plant, chemical company, pharmaceutical group, construction material group, heavy industries, metal casting plant, steel manufacturing and metal casting	Key informant interviews, informal meetings, emergy analysis method and logarithmic mean divisia index method	2018	Dong et al., (2018)
China	Ningbo		Metallurgical company, and plastic and steel producers	On-site visits, and individual or collective interviews performed on site	2014	Cerceau et al., (2014)
China	Rizhao	94	Grain oil, food and beverage, machinery, pulp and paper, textile and garment, wine refining and biochemical industries	Questionnaire surveys and interviews	2015	(F. Yu et al., 2015c)
China	Jiangsu	86	Textile industry, chemical industry, electronic industry, thermal power plant, inorganic chemical company, photovoltaic production, nitrogen fertilizer production, citric acid production, organic compounds production, cement, concrete, and other building materials production, and machinery components production companies	Synthetic data acquisition method, surveys and interviews. Geographical information systems. Interconnected network model based on complex network theory. Degree centrality, edge betweenness metric, disruptions, cascade effect of failure and resilience. Response curve and the area under the curve score	2015	Li and Shi, (2015)
China	Dalian		Wastewater recycling, and solid waste recycling	On-site field research, technique for order of preference by similarity to ideal solution method (based on seven indicators divided into two subgroups) used as multicriteria decision analysis, and process analysis approach	2015	Yu et al., (2015a,b,c,e,f)
China	Dalian		Petro-chemical, equipment manufacturing, IT industry, aviation metallurgy, ocean shipping industry, and bio-medicine	Field survey; emergy analysis; impact, population, affluence, technology formula, and index decomposition analysis	2016	Zhe et al., (2016)
China	Dalian	7	Ammonia, soda, ammonium nitrate, cogeneration power, cement, wastewater treatment and a fertilizer plants	Life cycle assessment	2017	Zhang et al., (2017)
China	Jiayuguan	26	Iron and steel industry	Backward approach, substance flow analysis and substitution analysis method	2016	Wu et al. (2016a)
China	Midong	18	Chemical, cement, building material, iron and steel, concrete, copper, rubber and paper mill companies, thermal power plant and coal mines	Stakeholder interviews, questionnaire survey and material flow analysis. Evaluation of benefits of IS: resource consumption reduction, waste emission reduction, cost saving of raw material, cost saving of waste disposal and waste sales income	2016	Guo et al., (2016)
China	Shanghai Caohejing	10	Electronics and information industry	Site investigations	2016	Huang et al., (2016)
China	Gansu	12	Iron and steel industry	Bow-tie and risk index methods	2017	Wu et al. (2017b)
China	Hefei		Cogeneration power plant, manufacturing home appliances, electronic equipment, automobiles and parts, fast-moving consumer goods, electronic information, new materials and bio-pharmaceuticals industries	On-site survey, interviews, and emergy analysis	2017	Fan et al., (2017)
China	Qijiang	17	Coal production and production of aluminous products for different uses	Participant observation, interviews, questionnaire-based survey and simulation analysis on the cascading failure mode	2017	Li et al., (2017)
China	Qijiang		Aluminium and copper industry	In-depth interviews, and field trips	2017	(Sun et al., 2017a,b)
China	Wu'an		Cement, iron and steel, thermal power, new building material, iron ore mining, lime, chemical, and sewage treatment plants	On-site investigations, material flow analysis method, CO_2 emission inventory analysis, gross benefit	2017	Cao et al., (2017)

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Table A.1 (*continued*)

Country	Region	N. of Enterprises	Activity	Method	Publication Year	Reference
				and dynamic investment payback period analysis		
China	Yulin/Ordos/Jining		Coal industry	Field research, directed weighted cascading failure model based on the coupled map lattice, five network performance indicators, simulation and comparative analysis	2017	(D. Wang et al., 2017)
China	Ordos		Coal and coal-derived chemical industry	Lotka-Volterra population ecology model, simulation on the MATLABR2012a and interpolation fitting method	2018	(D. Wang et al., 2018)
China	Gujiao	38	Coal mining, coal processing, wastewater treatment, power generation, construction materials and coal-based chemicals	Social network analysis	2018	Song et al., (2018)
China	Bohai Bay		Thermoelectric power plant; food service, biopharmaceutical, electronics and communications, auto manufacturing, chemical, and new energy source industries; farming food factory, green company, organic fertilizer site, electroplating wastewater conduction plant, tailing company, steel casting, non-ferrous metals, aluminium alloy, chemical, and waste heat centre	Field surveys, key informant interviews, and informal meetings	2018	Liu et al. (2018a)
China	Northwestern China		Coking industry	Interviews with experts and officials. Measurements and data obtained on site. Exergy analysis: exergy and energy efficiencies, environmental impact factor, exergetic sustainability index, exergy conservation supply curve, and energy consumption. Life cycle greenhouse gas emissions assessment. Water footprint analyses	2018	Wu et al., (2018)
China	Daqing		Natural gas processing industry, petroleum and petrochemical equipment manufacturing industry, photovoltaic power generation industry, smart greenhouse industry, bulk logistics industry, and building materials industry	Questionnaire survey and field visit. Grey correlation analysis method. Eco-efficiency evaluation index. Economic performance, environmental benefit, material reduction cycle, and network structure indicators	2019	Wang et al., (2019)
China			Integrated Steel Mills	Expert interviews and substitution analysis method	2015	Yu et al., (2015a,b,c,e,f)
China			Iron and steel industry and thermal power plants	Exergy balance, total exergy losses, physical exergy of the material, chemical exergy of material, and total exergy. Energy efficiency and exergy efficiency. Total CO_2 emissions and equivalent CO_2 emission potentials associated with exergy losses, and due to inefficiency. Proposed indicators for measure and compare the overall performance of an industrial network: economic indicators and production capacity-related indicators	2016	Wu et al. (2016b)
China			Lead and zinc concentration plant, waste acid and water treatment station of copper company, tailing impoundment, side air blowing reducing workshop, cement plant, sintering plant and fuming and fusion system	Field investigation, asymmetric distribution coefficient, environmental risk index, integral fracture risk index, stock redundancy, scale redundancy, functional redundancy, stability analysis method and probability method	2017	Wu et al. (2017a)
Japan	Kawasaki		Stainless steel mill, integrated steel works, cement firm, chemical firm, paper mill, home appliances dismantling, fluorescent light tubes recycling, concrete formwork plant, recycling plant, commercial and industrial waste	Follow-up visits, and material flow analysis	2009	Van Berkel et al. (2009a)

Table A.1 (*continued*)

Country	Region	N. of Enterprises	Activity	Method	Publication Year	Reference
			collectors, municipal waste collector, and municipal waste water treatment plant			
Japan	Kawasaki		Cement, stainless steel, steel, concrete formwork, ammonia, paper recycling, and scrap home appliances recycling companies	Questionnaire survey, material flow analysis, and life cycle CO_2 analysis method	2010	Hashimoto et al., (2010)
Japan	Kawasaki		Iron and steel; cement, chemical, concrete framework, and paper mill industries; commercial, industrial and municipal waste collectors; home appliances plant; home appliance recycling and municipal waste water treatment facilities, and community	Site visit, questionnaire surveys and intensive interviews. Material flows analysis; proposed indicators: "environmental gains" based on a material flow analysis and "economic gains" based on the analysis of the material exchange	2013	Dong et al. (2013b)
Japan	Kawasaki		Iron and steel, cement, chemical and paper and pulp industries; automobile dismantling company, home appliance recycling company and PET rebirth	On-site survey, interviews; lifecycle carbon footprint evaluated by the hybrid life cycle assessment model; calculation of carbon emission reduction by symbiosis types: material carbon footprint method, input-output analysis method and detailed emission coefficient of blast furnace slag cement and Portland cement	2014	(H. Dong et al., 2014)
Japan	Kawasaki		Port-based industrial complexes	On-site visits, and individual or collective interviews performed on site	2014	Cerceau et al., (2014)
Japan	Kawasaki	5	Iron and steel, cement and paper industries; recycling and incineration facilities and urban sectors	Intensive interviews, questionnaire surveys; material flow analysis, carbon footprint and emergy methods	2017	Ohnishi et al., (2017)
Japan	23 cities		Eco-town	Survey questionnaires, influencing factors (project scale, recycling boundary, and type of waste) and performance indicators (virgin material savings and operating rate)	2012	Chen et al., (2012)
Japan	Kitakyushu		Car disassembly factory, home appliance recycling factory, PCB treatment facilities, composite core facility; and plastic bottle recycling, waste office equipment, construction waste treatment, fluorescent lamps, empty cans, reused computer, recreational machine, waste wood and plastics, cooking oil, styrofoam, ink cartridges, scrap car, and organic solvent and waste plastics plants	Social network analysis and network connectedness analysis. Degree of connectedness and sub-network relationships. Density and core-periphery structure analytical methods	2013	Zhang et al., (2013)
Japan	Osaka		Gas company, petrochemical plant, refinery, municipalities and ports	On-site visits, and individual or collective interviews performed on site	2014	Cerceau et al., (2014)
India	Nanjangud	13	Distilleries, sugar refinery, instant coffee and milk beverage powder manufacturer, and local farmers	Field data collection, interviews, material flow analysis, and network analysis	2009	Bain et al., (2009)
India	Nanjangud	>14	Garment, electrical insulation, and plywood manufacturers; oil extraction, granite polishing, food processing, and CO2 bottling facilities; paper mills, sugar cane refinery and distillery, distillery, alcohol bottling facility, textile mill and aromatic chemical processor	Structured interviews with managers and Material flow analysis	2010	Bain et al., (2010)
India	Nanjangud	12	Garment manufacturer, oil extraction facility, food processing facility, electrical insulation manufacturer, plywood manufacturer, paper mill, aromatic chemical processor, textile mill, granite facilities, sugar cane refinery and distillery, distillery, alcohol bottling facility, and CO_2 bottling facility	Field surveys, structured interviews, material flow analysis, social network analysis, statistical network correlation analyses, and quantitative and qualitative measures for different dimensions of social embeddedness	2012	Ashton and Bain, (2012)
India	Tamil Nadu		Sugar industry, sugarcane farms, paper manufacturing company, spirit manufacturing, waste paper recycling factory, cement manufacturing industry and wastewater treatment plant	Multi-objective mixed integer linear programming model and sensitivity analysis	2019	Vimal et al., (2019)
Bangladesh	Sitakunda-Bhatiary		Ship-breaking industry, and processing and recovery of scrap metal	Interviews	2011	Gregson et al., (2011)

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Table A.1 (*continued*)

Country	Region	N. of Enterprises	Activity	Method	Publication Year	Reference
			(reconditioned engineering products and remanufactured furniture)			
Thailand	Map Ta Phut		Port-based industrial complexes	On-site visits, and individual or collective interviews performed on site	2014	Cerceau et al., (2014)
Singapore	Jurong Island		Chemical plants, multi-utility service provider, storage and terminaling service providers, electricity pool, co-generation plant, refinery, gasification plant, and air separation plant	Online maps, workshop and survey	2019	Yin and Lee, (2019)
Singapore	Ulu Pandan, and Clementi		Wastewater treatment plant, co-digestion plant, reclamation plant, and domestic and commercial buildings			
Singapore	Tuas, Tuas South, and Senoko		Municipalities, waste-to-energy plants, and metal recovery facility			
Singapore			Hotels, food and beverage establishments, and micro-refineries			
Singapore			Recycling companies, food processing factories, dryer, co-generation plant, parks and gardens, shipyards, treatment plant, concrete plant, construction industries, steel mill, processing plant, combined heat and power plant, plants, conservatories, water treatment, wastewater treatment plant and wafer fabrication plants			
Oceania						
Australia	Kwinana	35	Alumina refinery, fused alumina and zircon producer, worm farm, cement manufacturing, industrial chemical and fertilizer producer, industrial gas producer, coal-fired power station, titanium mineral processing company, turf farm, construction company, cement mill, Blokpave producer, zirconia powder producer, water supply and treatment company, coal mine, insulation plant, chlor alkali plant, cement and lime producer, fertilizer producer, mineral processing plant, inorganic chemical producer, pig iron plant, nickel mine, composting facility, oil refinery, synthetic rutile plant, titanium dioxide producer, nickel refinery, gas fired power station, co-generation plant, distributor and producer of LPG	Interviews	2007	Van Beers et al., (2007)
Australia	Kwinana		Alumina refinery, fused alumina and zircon producer, worm farm, cement manufacturing, industrial chemical and fertilizer producer, industrial gas producer, coal-fired power station, titanium mineral processing company, turf farm, construction company, cement mill, Blokpave producer, zirconia powder producer, water supply and treatment company, coal mine, insulation plant, chlor alkali plant, cement and lime producer, fertilizer producer, mineral processing plant, inorganic chemical producer, pig iron plant, nickel mine, composting facility, oil refinery, synthetic rutile plant, titanium dioxide producer, nickel refinery, gas fired power station, co-generation plant, distributor and producer of LPG	Integrated research programme and framework to facilitate IS	2007	Harris, (2007)
Australia	Kwinana		Chemical plant, alumina refinery, oil refinery, manufacturer and supplier of chemicals and fertilisers, and industrial and medical gases producer	Key-informant interview and informal interviews	2013	MacLachlan, (2013)
Australia	Gladstone	7	Cement and lime producer, aluminium smelter, alumina refinery, coal fired power station, waste transfer facility, local sewage treatment plant, used tires collection facility, and spent solvents collection facility	Interviews	2007	Van Beers et al., (2007)

Table A.1 (*continued*)

Country	Region	N. of Enterprises	Activity	Method	Publication Year	Reference
Australia	Gladstone	>8	Alumina refineries, aluminium smelter, cement plant, ammonium nitrate and sodium cyanide producer, power station, sewage treatment plant and agricultural companies	Field survey	2014	Golev et al., (2014)
Australia	Gladstone		Alumina refineries, aluminium smelter, chemical company, coal power station, and cement producer	Interviews, and qualitative tool for analysis of IS barriers – IS maturity grid	2015	Golev et al., (2015)
North Africa						
Morocco Algeria	Jorf Lasfar Bejaïa		Port-based industrial complexes Food processing industry, and local producers of soap, paint and mastic	On-site visits, and individual or collective interviews performed on site	2014	Cerceau et al., (2014)
South America						
Brazil	South-East		Industrial construction, contractors, cement manufacturer, abrasive grains manufacturer, ceramic manufacturer, and wood processing company	Direct observations; indicators of quantitative data analysis (recycling rate, diversion rate, and rate of waste recovered through Industrial Symbiosis), and SWOT analysis	2017	Freitas and Magrini, (2017)

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Chapter 3

Environmental, Economic and Social Impact of Industrial Symbiosis: Methods and Indicators Review

This chapter consists of the following article:

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Environmental, Economic, and Social Impact of Industrial Symbiosis: Methods and Indicators Review

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1 Introduction

In the last years, the intensive use of resources and the resulting increase in greenhouse gas emissions have led the world to climate change with serious and irreversible impacts for people and ecosystems [1]. Thus, it is essential to develop solutions that lead to an increase in sustainability with improvements not only in the environmental but also in economic and social dimensions. The industrial symbiosis (IS) whose central idea is that the waste of one company becomes the raw material for another [2], has contributed to this increased sustainability bringing benefits for the companies involved and for communities [3]. The reduction of the natural resource

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consumption, waste disposal, and emissions, economic gains for companies due to cost reduction with landfills and the sale and/or purchase of waste products [4], are some examples of the numerous advantages obtained due to the IS. So, in order to increase synergies between companies and to enlarge incentive policies, which application has a strong impact on the development of IS [5], it is imperative to continue the efforts of the development of the IS and contribute to its wide application. One of the ways to boost this increase is to make the results obtained from the various cases of successful implementation of industrial symbiosis visible. For this, numerous methods and indicators have been developed with the aim of quantifying the environmental, economic, and social impact that the industrial symbiosis has triggered in the companies and surrounding communities.

The main objective of this article is to provide a comprehensive review of previous studies concerning the methods and indicators used to assess de impact of IS in the economic, environmental, and social scopes. The advantages and limitations of each one are also listed.

2 Methods and Indicators to Assess the Impact of Industrial Symbiosis

2.1 Methodology

With the aim of surveying the most cited methods and indicators used for quantifying the impacts of IS and their advantages and limitations, titles and abstracts of numerous publications were analysed and subsequently selected in accordance with the purpose of this review.

This study has been developed in several stages. The first one was to define the scope of the literature review, followed by the research of articles in several publishers, such as Elsevier, Springer, Emerald, Taylor & Francis, Wiley among others. For this search, combinations of “industrial symbiosis” or “eco-industrial park” and “method” or “quantitative assessment” were used in order to find publications that fit the objective of this literature review. After a careful analysis of the articles, through the reading of the titles, keywords, and abstracts, only those that aimed to quantify the contribution of industrial symbiosis to the achievement of sustainability in its environmental, economic, and social dimensions were selected. From the literature review was possible to understand the growth of the number of articles related to IS and the increase of studies that allow understanding the real impact of this approach.

2.2 A Comprehensive Review on Evaluation Methods and Indicators

Numerous methods, analyses and indicators have been used to evaluate the industrial symbiosis with respect to sustainability, development, performance, relations between companies, among others. Although several of them have a comprehensive application [6–8], others have been created specifically for industrial symbiosis [9–11]. Input–output analysis [12], ecological network analysis [13], lifecycle assessment [14], environmental impact assessment [15], carbon footprint analysis [7], material flow analysis [16], exergy analysis [17], emergy analysis [6], econometric analysis [18], social network analysis [19], ecological footprint analysis [20], cost-benefit analysis [21], and substance flow analysis [22] are some of the examples of methods and analyses used.

Several of these methods are used to assess the sustainability and many indicators of different dimensions are used to create a solid basis for decision-making. Indicators are numbers or measures that allow the interpretation of information about certain phenomena to be simplified and easier to understand [23, 24]. They also allow the development of an integral approach, essential to decision-making, in which they allow the understanding of the environmental, economic, and social dimensions in an isolated way, but also of the relationships between them.

The methods addressed in this review are those directly related to the assessment of the sustainability of industrial symbiosis, with respect to the environmental, economic, and social dimension and the most widely referenced. The indicators used in the various methods are also set forth, as well as the various advantages and disadvantages.

Life Cycle Assessment

Life cycle assessment (LCA) is a tool that "addresses the environmental aspects and potential environmental impacts throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e., cradle-to-grave) [25]. With the increase of greenhouse gas emissions and global warming, sustainability has become an issue that has attracted more and more interest and since the LCA is a tool that evaluates the environmental impact, it is understandable the increase of the use of this tool in the most diverse areas and the exponential growth of the number of studies published since its appearance in the 1960s [26]. Industrial symbiosis is no exception and several environmental impact studies have emerged using the LCA, even if industrial symbiosis entails some limitations in the application of this tool, such as the definition of the functional unit since the waste of one company is considered a by-product in another and the difficulty in obtaining data on the consumption and emissions of each one of the enterprises [21].

This method has contributed to highlight the role of industrial symbiosis in the improvement of sustainability, materialized by the reduction of polluting emissions, by the substitution and reduction of the consumption of resources and by the reduction of waste [27–31], being able to be applied in the decision-making and to influence companies and political decision-makers to opt for industrial symbiosis as a way to reduce environmental impacts [8, 14].

The LCA methodology is defined in two International Standards: ISO 14040 [25] and ISO 14044 [32] and its study, according to these, is developed in four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation. With this analysis, it is possible to evaluate the impact categories that should be appropriate with the goal of the study. Primary energy consumption [27, 31, 33], greenhouse gas (GHG) emission [27, 31, 33], acidification potential [27, 30, 31, 33–35], eutrophication potential [27, 30, 31, 33–35], global warming potential (GWP) [34, 35], Human toxicity air (HTA) [30, 35], total environmental impact potential (TEIP) [35], and climate change [30] are some of the impact categories used to assess industrial symbiosis. However, the assessment of greenhouse gases is clearly the most widely used, and there are articles in the literature that only contemplate the evaluation of this impact category [28, 29, 36].

Material Flow Analysis

Similar to the previous method, the Material flow analysis (MFA) is recognized as a decision support tool, and also allows quantifying the effects of industrial symbiosis [37]. It is used in waste and environment management and through a simple material balance of inputs, outputs, wastes, and stocks, it allows to know, in an expeditious way, what wastes exist and their origins [38].

The beginning of this method goes back more than 2000 years and was postulated by Greek philosophers [38], and since then, has been widely used, individually or in conjunction with other methods that increase the scope of the analysis [7, 16, 39–41]. Even though the MFA is a simpler method that considers flows of materials and waste, sometimes its application in an industrial environment is more limited. So, in addition to combining this method with others, it is also possible to associate it with indicators that allow evaluating the evolution of the process and detecting possible weaknesses. For the MFA analysis to be complete, these indicators reflect inputs and outputs. However, outputs are more difficult to account for than indicators for input flows because input depends on materials and outputs are accounted as environmental waste and complete information in terms of mass balance is rarely available [42].

An example was the study made by Sendra et al. [39] in which two input indicators related to materials were used: direct material input and total material requirement. On the basis of these, environmental indicators were also developed to assess the amount of wastes, efficiency water, and energy.

One of the examples of the use of MFA with another methods, is the study conducted by Ohnishi et al. [7] with the aim of quantifying the effects of industrial and urban symbiosis in Kawasaki Eco-town, in which the MFA served to identify the material and inventory flows of a system and later a more intensive analysis was done using the carbon footprint and emergy method.

Emergy Method

Emergy is "the available energy of one kind (usually solar emergy joules) used up directly and indirectly to generate a service or product" [43]. This analysis, in addition to considering the economic dimension and the resources, also takes into account the

contribution of the local ecosystem. Thus, parameters that are usually not considered in other methods, in this analysis parameters as the sunlight, wind, rain, indirect support incorporated in human productive activities are taken into account [44].
Since this method was proposed in the 1980s [43], many studies have been carried out with the aim of evaluating the economic and environmental component of a process. In industrial symbiosis, this method was used to evaluate each symbiotic flow, quantifying the respective energy and mass which are subsequently converted to the same unit, as previously mentioned [6, 41, 44–54]. For this purpose, some sustainability indicators can also be established in order to evaluate various energy and environmental performances. Examples of these indicators are: emergy yield ratio that expresses the production capability of the system, emergy loading ratio that reflects the pressure of the economic activity on local eco-environment, emergy sustainability index that measures the contribution of a resource or process to the system per unit of environmental loading, emergy-to-money ratio that indicates the emergy consumed to generate per unit money and money saving due to implementing industrial symbiosis in the industrial park [49–51].

Integration of Different Methods
Some of the methods used to evaluate the sustainability of industrial symbiosis have some limitations, so in order to overcome those, several methods can be conjugated in order to promote the best of each method and to obtain a more reliable result.

Some examples are related to the Material flow analysis because, as previously mentioned, represents a simpler method of assessing inputs and outputs of materials and wastes, and it is often necessary to include indicators or complements with other methods to make the analysis more complete. This method often appears associated with emergy method. The emergy method adds to the joint analysis the assessment of the contribution of natural ecosystems and has the particularity of transforming several elements that enter into the analysis that are of different nature, such as materials, energy, services, in the same unit to evaluate sustainability [7, 40].

Emergy analysis also appears often associated with lifecycle assessment [55–58]. These methods turn out to be complementary, because LCA, as seen above, aims to quantify impact categories, such as greenhouse gas emissions, acidification potential, primary energy consumption, etc. However, this analysis, in general, does not contemplate flows that are not associated in some way to the transport of matter and energy. And, if the objective is to assess sustainability, in some cases these values may be significant. The emergy analysis does not consider the pollutant emissions, but allows counting all the resources in the same value base and allows ease of comparability with the generated product and with more knowledge, it becomes possible to decide for a more sustainable option.

Table 1 Comparison between different methods: advantages and disadvantages

Method	Advantages	Disadvantages
LCA	• as a bottom-up method, can provide more specific information to decision-makers [57] • a feasible tool for the quantification of environmental performance of IS networks in order to capture all elements of the environmental performance [14, 59]	• consumes more time and labor, due to the requirement of a large amount of detailed data [57] • the impact factors of LCA reflect the national average and not the characteristic factors of specific enterprises [31] • uncertainty of an alternative system and the difficulty of making assumptions for by-products [31]
MFA	• enables planning and decision-making [37]	• MFA alone is not a sufficient tool to assess or support engineering or management measures [38]
Emergy	• transform different kinds of inputs (materials, energy, services) in the same unit to evaluate sustainability [7] • considers the contributions of the natural ecosystem so that the IS is analyzed as a whole [7]	• gives insufficient consideration to the impacts of pollutant emission, especially for industrial systems [56]

2.3 Advantages and Disadvantages of Different Methods

The methods outlined above have inherent advantages and disadvantages in the way they determine the dimensions of sustainability. Table 1 summarizes the main advantages and disadvantages.

3 Conclusion

The number of articles concerning the methods and indicators aiming to assess the impact of IS has been increasing in the last few years. Although in many research articles the environmental, economic and social advantages of the application of IS are mentioned, most of the articles address methods and indicators that allow the quantification of the environmental effects, followed by economic impacts. All the studies provided by the application of these methods and indicators add an important contribution to the overall understanding of the importance of IS and highlights the many advantages for organizations and communities. With the intention of stimulating IS it is necessary to disseminate the results obtained by the various methods and create platforms that could enable the involvement of organizations in creating new partnerships. It could also lead to the intervention of government in order to create new incentive policies and stimulate the communities to value IS and also demand the companies to adopt new sustainable practices which could lead to several advantages for all the stakeholders.

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Chapter 4

The potential of industrial symbiosis: Case analysis and main drivers and barriers to its implementation

This chapter consists of the following article:

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The Potential of Industrial Symbiosis: Case Analysis and Main Drivers and Barriers to Its Implementation

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Abstract: Industrial symbiosis, which is characterised mainly by the reuse of waste from one company as raw material by another, has been applied worldwide with recognised environmental, economic, and social benefits. However, the potential for industrial symbiosis is not exhausted in existing cases, and there is still a wide range of opportunities for its application. Through a comprehensive literature review, this article aims to compile and analyse studies that focus on potential industrial symbiosis in real contexts, to highlight the margin of optimisation that is not being used. The cases reported in the publications identified here were characterised and analysed according to geographic location, type of economic activity, waste/by-products, main benefits, and the methods employed in the studies. From this analysis, we conclude that there is great potential for applications involving industrial symbiosis throughout the world, and especially in Europe, corresponding to 53% of the total cases analysed. Manufacturing stood out as the sector with the highest potential for establishing symbiosis relationships, and the most common types of waste streams in potential networks were organic, plastic and rubber, wood, and metallic materials. This article also discusses the main drivers and barriers to realising the potential of industrial symbiosis. The diversity of industries, geographical proximity, facilitating entities and legislation, plans, and policies are shown to be the main drivers.

Keywords: industrial symbiosis; potential industrial symbiosis; sustainability; eco-industrial parks; circular economy

1. Introduction

In recent years, resource-intensive use, rising industrialisation and urbanisation, modern lifestyles, energy-intensive use, and land use patterns have led to increased greenhouse gas emissions, with negative consequences for the environment and the population [1–3]. It is therefore urgent to find solutions that do not hinder economic development but can provide ways to reduce carbon dioxide emissions, which are largely responsible for greenhouse gases, and to use resources more efficiently. As a subfield of industrial ecology, industrial symbiosis, which is often defined as a collective approach in which one company's waste is used as raw material by another company [4], can help to address these problems without compromising economic development. This practice is similar to biological processes, in which different organisms associate in a "mutually beneficial relationship" [5], as it allows entities and companies that operate separately to come together in the physical exchange of materials, by-products, energy, and water, with competitive advantages for all participants [6]. In addition to waste/by-product exchanges, this sharing of resources also encompasses infrastructure sharing and the joint provision of services [7,8].

Some of the problems faced by industries, such as increases in waste, waste treatment costs and high resource consumption, are common in urban areas [9–11]. Thus, if cooperation between companies is extended to urban regions, there is potential for both parties to achieve environmental and economic benefits and to mitigate certain common problems. This cooperation has been referred to in several publications as Industrial and Urban Symbiosis (also called Urban and Industrial Symbiosis) and takes place when waste generated in an urban area is used as a raw material or energy source in industry or when industries provide urban areas with waste heat resulting from their operation [12,13]. However, some authors have also used the term Urban Symbiosis to refer to the use of waste from urban areas as a raw material or source of energy [14–16].

The most well-known case of industrial symbiosis, and the one most often cited in the literature, is in Kalundborg, Denmark. This network arose spontaneously from a self-organising initiative between companies to address water scarcity [4,5,17] and over the years has increased not only in terms of the number of symbioses but also the number of participants and remains a successful case to this day.

However, industrial symbiosis is not confined to the Kalundborg case, and numerous examples of synergistic networks around the world have been reported in the literature, with a wide variety in terms of the numbers of participants, types of economic activities, and how they are organised. In Europe, numerous foci of industrial symbiosis [18] are spread across different countries, and most of the cases reported in the literature are in northern and north-western Europe, with the United Kingdom reporting the highest number of cases [19]. This is due to the voluntary programme that the government has launched to help companies find partners to use their waste as raw material, called the National Industrial Symbiosis Programme [20]. Finland also has several cases of industrial symbiosis, largely arising from the strong presence of the pulp and paper industry, which has driven the creation of synergy relations [21,22]. In Asia, a number of industrial symbiosis initiatives have also been reported, with the highest number of cases in China, largely due to constraints on carbon dioxide emissions and the numerous plans and policies that have been implemented to foster circular economy practices [23–25]. In Japan, there have been cases of industrial symbiosis and industrial and urban symbiosis across several cities, driven by the Japanese Eco-Town Programme that encourages the use of industrial, municipal, and commercial waste in industrial applications, with the aim of boosting the economy and reducing waste disposal [14,15]. In North America, and particularly in the US, there have been cases of industrial symbiosis that date back to the late 1970s. The case most frequently mentioned in publications is located in Barceloneta, Puerto Rico, where the strong presence of pharmaceutical companies has spurred the creation and development of industrial symbiosis between various companies [26,27]. Several cases of industrial symbiosis have also been reported in Australia [28,29], Brazil [30], Morocco [31], and Algeria [31].

Despite the recognised benefits that these synergy cases have provided to the environment, the companies involved and the local population, the potential for industrial symbiosis is not exhausted in these existing cases, and there is still great potential for application not only in developed countries but also in countries with developing economies. Of the various articles published on industrial symbiosis, a significant proportion have focused on the best ways to foster industrial symbiosis and the most effective ways of overcoming the various obstacles, including economic, technological, legal, and social obstacles, that are faced in the creation and development of industrial symbiosis. Although some of these publications have a predominantly theoretical content e.g., [23,32,33], most present in-depth studies conducted in real contexts, that is, in a given region, with a holistic analysis of those industries, wastes and products with potential for developing industrial symbiosis e.g., [34–37]. In some of these studies, the implications of these new synergies for the environment, the economic development of companies, and the surrounding population have also been studied e.g., [36,38,39]. This article focuses on the latter type of publication, and identifies these as cases of potential industrial symbiosis. All articles that study the possibility of implementing new industrial symbiosis relationships in a given location and that indicate the types of economic activities and industrial symbiosis are included in this designation.

The various studies that have been carried out on potential cases of industrial symbiosis have a wide scope, not only in terms of the characteristics of the synergy network but also in terms of the existence or otherwise of industrial symbioses in the location under study. In places where symbiosis networks already exist, relationships of trust are already established, and there is a knowledge of the benefits of this practice that can help to facilitate the process of mobilising other companies. Studies carried out of the industrial symbiosis networks in Weifang Binhai Economic-Technological Development Area, China [40], in the Västra Götaland region of Sweden [41], and in the Taranto provincial industrial district in Italy [42] represent some of these examples. In these cases, proposals have been put forward to extend the industrial symbiosis network to other companies, with the aim of repurposing some of the waste that was not yet being shared. However, several studies have been published that have proposed the creation of industrial symbiosis relationships in areas where this practice is not yet implemented but bring together a set of characteristics that reveal the potential for establishing synergy networks. Examples include studies of the development of industrial symbiosis carried out in Perth and Kinross, Scotland [43], Botoșani and Piatra Neamţ in Romania [44], and Konia, Liberia [45].

Although the potential for the application of industrial symbiosis is high, there are a number of constraints on its implementation. A lack of trust, uncertainty about the benefits, a lack of knowledge of the concept of industrial symbiosis, and a lack of information sharing [20,33,34,46–48] are the main factors that have been identified as restraining this process. However, there are also factors that are often referred to as drivers for the creation and development of industrial symbiosis networks, such as the need to reduce raw material and waste disposal costs and the potential generation of revenue [18,34,49–51]. In addition to these aspects, existing policies and legislation have also been identified as influencing industrial symbiosis practices. Regulatory pressure and landfill tax, which drive companies to find solutions for using resources more efficiently and reducing waste disposal [50,52], are examples of these. Policies and plans that aim to foster synergy networks, such as those in China [23,25] and the United Kingdom [20], have greatly contributed to the spread of these practices. However, existing legislation can also restrict these practices, for example if it is unclear or very restrictive on the use of waste, and can thus create difficulties for companies with regard to the application of industrial symbiosis [53].

A literature review reveals that although there are many studies of the compilation and analysis of case studies relating to industrial symbiosis [18,19,23,54–58], these focus on synergies that have already been implemented. Furthermore, although a study of the evolution of industrial symbiosis was carried out by Chertow and Park [59], with an analysis of the number of articles published and the countries that were the subject of the various publications, this work only included articles published until 2014. A comprehensive analysis of the cases of potential industrial symbiosis is still absent.

This article therefore aims to compile and analyse the various cases of potential industrial symbiosis in real contexts reported in the literature, and to highlight the margin of optimisation that is not being used. It also aims to identify and discuss the main drivers and barriers to the implementation of industrial symbiosis, as well as the various strategies for overcoming these barriers. To this end, the various cases are characterised and analysed by geographical location, type of economic activity, type of waste/by-product exchange, infrastructure sharing, and joint provision of services. Moreover, the methods employed in the different cases are analysed, as are the main environmental, economic, and social benefits that would be achieved if industrial symbiosis were to be realised. The cases of potential industrial symbiosis have been separated into those concerning the symbiosis between industries and those concerning the manufacture of new products and new uses for the different wastes enhanced by industrial symbiosis.

The rest of the article is organised as follows. Section 2 describes the methodology adopted for the research, selection, and analysis of publications, as well as the inclusion and exclusion criteria.

Sections 3 and 4 contain the results and a discussion. Section 3 presents the results and an analysis of the cases of potential industrial symbiosis, in terms of the companies involved, the production of new products and new uses of waste. Section 4 discusses the main drivers, barriers, and strategies for overcoming these barriers to the creation of industrial symbiosis networks. Finally, Section 5 presents the main conclusions and discusses the limitations of this study and the scope for future research.

2. Materials and Methods

In order to fulfil the proposed objectives, a methodology was developed consisting of several stages, as illustrated in Figure 1. This methodology can be grouped into three main steps: a deep and systematic collection of the existing literature, the selection of publications and a content analysis.

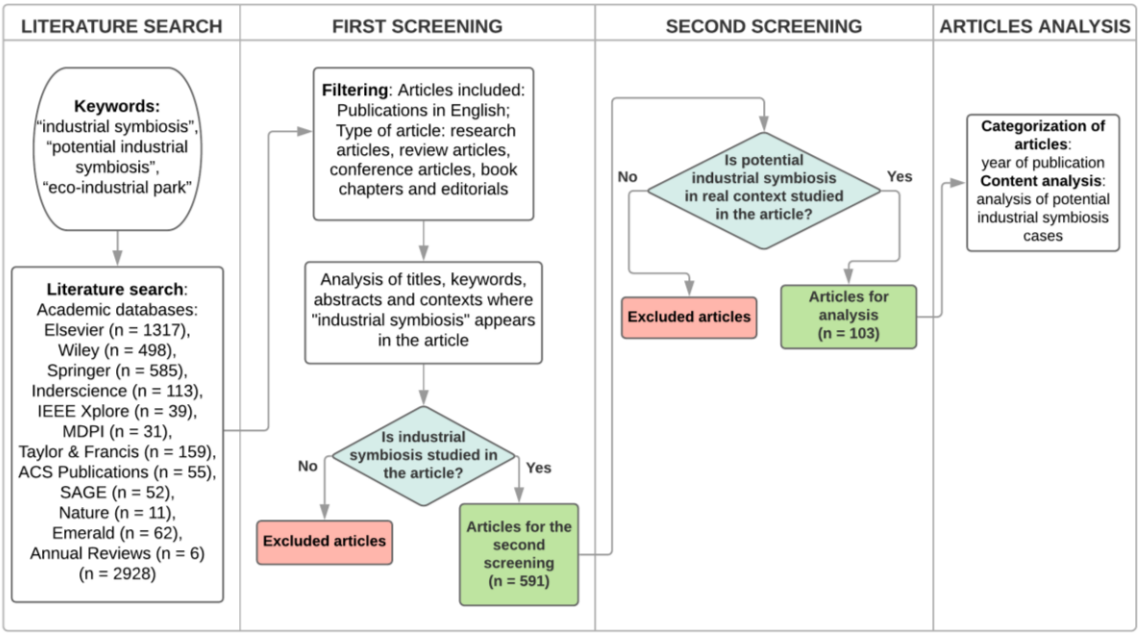

Figure 1. Flow diagram of literature search and screening.

To enable a systematic and thorough review of the existing literature, several steps were followed. The first was the choice of keywords. To avoid limiting the search and thus obtain a more comprehensive set of publications, the terms "industrial symbiosis", "potential industrial symbiosis", and "eco-industrial park" were combined. These were used to search for articles in databases with more publications in this area, such as, Elsevier, Wiley Online Library, Springer, MDPI, Inderscience Online, IEEE Xplore, Taylor & Francis Online, ACS Publications, SAGE Journals, Nature Research, Emerald Insight, and Annual Reviews. In this research, no time interval was imposed, and the only exclusions were articles that were not written in English. The publications that resulted from this initial collection were submitted to a screening process in order to select the most relevant ones for the study. Titles, keywords, and abstracts were read, with the aim of selecting articles that focused mainly or significantly on industrial symbiosis. If there were any doubts about the inclusion of the articles, we analysed the frequency with which the keywords appeared throughout the publication and the context in which they were inserted in order to verify whether industrial symbiosis was the focus of the study or whether it only appeared as an example or to contextualise other concepts. This selection resulted in 591 publications, including research articles, review articles, conference articles, book chapters, and editorials. In our analysis, the references cited in these publications were used as secondary sources; however, this resulted in only a few articles, which may indicate the wide-ranging of the initial research.

In the next step, the 591 articles on industrial symbiosis were screened with the aim of finding only the publications whose object was the study of potential industrial symbiosis in a real context. This resulted in 103 articles, and these made up the final body of articles for which a more detailed content analysis of potential industrial symbiosis was carried out. Of these 103 articles, 89 concerned industries and 14 concerned potential uses of industrial symbiosis to manufacture new products or use different wastes. A content analysis of all these articles was then conducted to gather and analyse information on potential industrial symbiosis, such as location, types of economic activities involved in potential synergies, types of waste/by-products, and the existence or otherwise of infrastructure sharing. We also analysed the methods employed in the different analyses, the main environmental, economic and social benefits, and the factors underlying the potential for creating industrial symbiosis, which may condition or favour it.

3. Potential Industrial Symbiosis

The results of the study are presented below and are structured according to the main themes that emerged from the research and analysis of publications on potential industrial symbiosis, namely its scope, evolution over time, geographical distribution, and cases of potential industrial symbiosis relating either to companies or to the production of new products or new uses of waste.

3.1. Evolution of the Number of Published Articles

Of the 591 articles on industrial symbiosis selected and analysed according to the selection criteria defined in Section 2, 103 related to potential industrial symbiosis, accounting for approximately 17% of the total. Although these articles on industrial symbiosis were published from 1995 onward, it was only around 2001 that articles on potential industrial symbiosis began to appear, as illustrated in Figure 2.

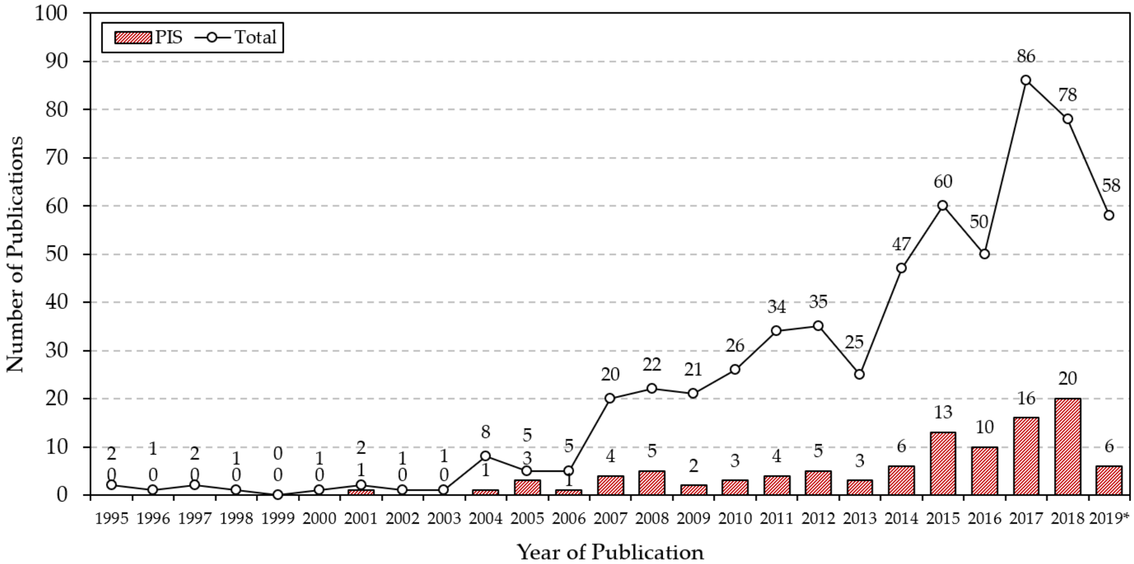

Figure 2. Number of publications on industrial symbiosis and potential industrial symbiosis (PIS) per year.

Figure 2 shows the growing evolution of the number of publications on industrial symbiosis. Although low numbers of studies were published during the early years, from 2007 onward, there was a growth in the number of publications, which continued over the following years. Despite these small numbers, publications on potential industrial symbiosis have also shown growth. The evolution of these publications essentially comprises two distinct periods. In the first, between 2001 and 2014, there was a greater oscillation between the number of publications and in which the growth of articles was not very significant. In the second, between 2015 and the current year, more pronounced growth could be seen, and whilst there was a drop in 2016, this was insignificant in light of the increase over the following years. Although this second period was shorter in terms of years, the proportion of publications was clearly higher than those in the first and accounted for 63% of the total number of publications. This increase coincided with the increase in publications on industrial symbiosis, and although it began to grow more significantly from 2007 onward, it was from 2014 onward that it began to obtain greater expression, revealing the growing scientific interest in this issue and the recognition of its potential to achieve sustainability in terms of its environmental, economic, and social aspects.

The proportion of the articles on potential industrial symbiosis in relation to the total number of publications on industrial symbiosis did not show significant variation over the years, except for 2001 and 2005, in which these articles made up 50% and 60% of the total number of publications, respectively. Three periods are of note, due to the fact that the values were very close in consecutive years—the period between 2006 and 2008, with an average of 20% of the total number of publications on potential industrial symbiosis; the period between 2009 and 2014, with an average of 12%; and the period between 2015 and 2018, with an average of 21%. Most of these 103 publications (about 84%) relate to research articles, while 12% are conference papers, and the remaining 4% are book chapters.

3.2. Geographic Distribution

The study of potential industrial symbiosis has shown great diversity with regard to geographical location; it has been studied in 31 different countries, revealing the great potential of this practice both in developed countries and in countries with emergent economies, as illustrated in Figure 3. Europe leads in terms of the number of publications on potential industrial symbiosis, with 48 articles, corresponding to approximately 53% of the total published. It is followed by Asia, with 26 publications, corresponding to 29% of the total, and North America, South America, and Oceania, with six, four, and four publications, respectively, corresponding to 7%, 4%, and 4% of the total. With three publications, equivalent to 3% of the total, Africa has the fewest studies of potential industrial symbiosis. This distribution is very different from that presented for industrial symbiosis publications [59]; here, China very significantly predominates in terms of publications, followed by the US and Australia.

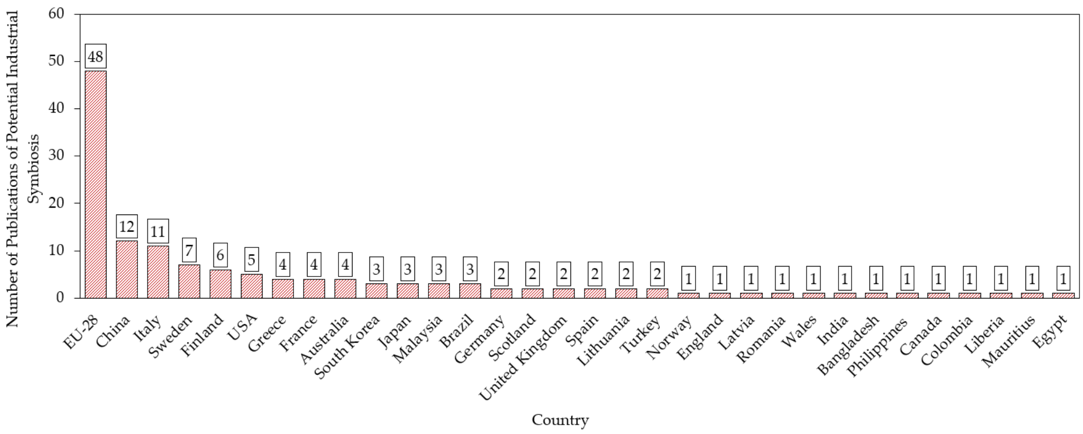

Figure 3. Distribution of the number of published studies on potential industrial symbiosis by country.

The European countries in which most case studies of potential industrial symbiosis were carried out were Italy, Sweden, and Finland, with 11, seven, and six articles, respectively. All cases in Sweden were related to the study of potential industrial symbiosis between industries, while those in Italy and Finland focused both on synergies between industries and on the investigation of waste and new products fostered by industrial symbiosis.

Of the eight countries in Asia with studies of potential industrial symbiosis, most related to China, with approximately 46% of the total for Asia.

The US occupies the fifth place on the list of countries with articles published on potential industrial symbiosis, with three articles focusing on the synergy between industries and two more on the study of new uses for waste produced by the automobile industry. This figure is still low compared to the countries with the most publications, which is also true for case studies of industrial symbiosis—although the USA occupies second place on this list, the difference between the number of articles published compared to China, which ranks first, is very significant [19]. While some incentive measures have been applied to create synergies, such as an Environmental Protection Agency–funded project to identify possible synergies in six counties in North Carolina [60], they have not had a major impact on the increase in cases of symbiosis, and even existing studies of potential industrial symbiosis between industries date back many years.

In recent years, studies have been carried out to analyse the implementation of industrial symbiosis practices in developing countries such as the Philippines, Liberia, India, Bangladesh, Colombia, Mauritius, and Egypt. While these countries have little in the way of a tradition of synergy practices between companies and the number of published case studies is still small [19], the important role of industrial symbiosis is recognised as a means to enhance the development of these regions [34,45,61].

3.3. Cases of Potential Industrial Symbiosis

Although industrial symbiosis is well established in many countries, there are still many possibilities for creating and developing new industrial symbioses. The numerous studies that have proposed and evaluated new synergy networks are examples of this. In places where there is already industrial symbiosis, the process of creating new relationships is facilitated, since there are already relationships of trust between the actors and the benefits offered by this practice are well known; however, this is not an essential factor. In places where there is no synergy, factors such as the location, the waste generated, or the nature of the industries can drive the creation of symbiosis relationships. Moreover, this potential is not bound to a particular region, country, type of activity, or number of entities (NE) involved, as proven in the many studies that have been performed to evaluate the creation of new industrial symbioses (shown in Table 1). This table summarises the main characteristics of the various cases of potential industrial symbiosis that have been published (Table A1 in Appendix A provides more details of these cases). By analysing Table A1, it is possible to verify the huge untapped potential and the huge diversity of opportunities for the development of industrial symbiosis. These cases are characterised by the location, number of entities involved (NE), type of economic activity, waste/by-product exchange, sharing of infrastructure, joint provision of services, methods used in the study, and assessment of the potential of industrial symbiosis. The various economic activities are grouped into sections, which are defined according to the International Standard Industrial Classification of All Economic Activities, Revision 4 (ISIC, Rev.4). Of the 21 sections defined in the ISIC, 16 are relevant to the various cases of potential industrial symbiosis. In Table 1, the section designations are more concisely defined. The different streams of waste exchanged in these cases are grouped into types, such as organic (e.g. food and food processing wastes, biomass, livestock and fisheries wastes); plastics and rubber; wood; metallic; non-metallic (e.g. glass, waste from construction and demolition, lime-based waste), paper, waste heat and steam; ash, water, and wastewater; chemicals; sludge; waste oil; and others (e.g. textile waste).

Table 1. Potential industrial symbiosis applications and analysis studies.

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
				Europe				
Italy	Murano		Manufacturing	Chemicals	Water treatment	BATTER tool, direct measurements	2007	[62]
	Brancaccio, Carini, and Termini Imerese		Manufacturing	Plastics and rubber		Questionnaire and interviews, life cycle assessment	2010	[63]
	Val di Sangro Industrial Area	19	Manufacturing		Collective management of scraps	Questionnaires, interviews, site visits, and focus groups	2014	[64]
	Fucino upland		Agriculture and manufacturing	Paper, plastics and rubber, and wood	Common local recycling platform	On-site survey and interviews.	2015	[65]
	Emilia-Romagna		Agriculture and manufacturing	Organic, sludge, paper, non-metallic, wood, and others		Interviews, guided collective discussion, visits to laboratories, and conferences	2015	[53]
	Catania and Siracusa districts		Agriculture, manufacturing, energy, water and waste, construction, sale and repair, transportation and storage, information and communication, professional and scientific activities, administrative and support service, education, human health and social work, and other service activities	Water and wastewater, organic, sludge, wood, metallic, waste oil, plastics and rubber, chemicals, non-metallic, and paper	Energy, equipment, expertise, and services	Invitation emails and phone calls, meeting tables	2016	[66]
	Brescia	12	Manufacturing, energy, and public administration	Metallic, wood, sludge, and waste heat and steam		SWOT analysis	2017	[67]
	Brescia	2	Agriculture and manufacturing	Chemicals		Economic model	2018	[35]
	Province of Pescara		Agriculture, manufacturing, water and waste, and construction	Organic, metallic, non-metallic, paper, plastics and rubber, waste heat and steam, and water and wastewater		Qualitative analysis and critical analysis	2017	[11]
	Marche Region	3	Manufacturing and water and waste	Plastics and rubber		Web platform, economic assessments, life cycle assessment	2018	[38]

Table 1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Sweden	Small town in southern Sweden		Manufacturing, energy, water and waste, and the municipality	Waste heat and steam, wood, organic, ash, sludge, and paper		Interviews and group discussion, direct observation and participation at the sites, mass and heat balances over the system	2005	[68]
		4	Manufacturing and energy			MIND method	2008	[69]
		4	Manufacturing and energy	Organic, waste heat and steam, and wood		MIND method. Commercial optimization solver, assessment of CO_2 emissions	2008	[70]
	Luleå, Borlänge, Finspång, Sandviken		Manufacturing and energy	Waste heat and steam and Chemicals		System perspective evaluation	2011	[71]
	All 290 municipalities		Agriculture, mining, manufacturing, energy, water and waste, and construction			Looplocal method, life cycle inventory	2015	[72]
	Västra Götaland		Agriculture, manufacturing, energy and water, and waste	Chemicals, ash, metallic, and water and wastewater		Top-down approach with three consecutive steps	2017	[73]
France	Territoire de la Côte Ouest		Agriculture and manufacturing	Organic		'Follow the Technology' method and Companion Modelling or Commod	2017	[74]
		7		Waste heat and steam		Mixed integer linear programming, direct method, key process indicators, sensitivity analysis, multi-objective model and Pareto front analysis, weighted sum method	2018	[75]
	16 regions		Manufacturing and energy	Waste heat and steam		Average energy intensity, production value, and heat consumption; spatial mapping methods and geographical information system; techno-economic model; linear programming problem	2018	[36]
	Salaise-sur-Sanne and Sablons		Manufacturing, water and waste, and urban areas	Industrial waste	Shared infrastructures	SWOT analysis	2018	[76]

Table 1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Finland	Oulu		Manufacturing	Metallic, ash, and others		Literature review	2010	[77]
			Agriculture, manufacturing, water and waste, and municipality	Sludge and organic		Interviews, collaborative research approach, replication approach	2015	[78]
			Agriculture and manufacturing	Organic		Survey	2018	[79]
Greece	Viotia		Manufacturing	Metallic		Ontology engineering approach—eSymbiosis; metrics for industrial symbiosis benefits	2015	[80]
	Pili		Manufacturing, energy, and water and waste	Wood, ash, and organic	Utility sharing	Methodology to determine the most appropriate location and bioclimatic criteria	2017	[81]
	Achaia		Manufacturing	Water and wastewater and others		Interviews and visits	2017	[82]
Germany	Rhine–Neckar				Network structure, waste software, and intranet platform	On-site surveys	2004	[83]
	Central Germany		(i) Manufacturing; (ii) manufacturing and energy; (iii) manufacturing and energy	(i) Wood; (ii) wood and organic; (iii) wood		Communications and site visits; life cycle assessment and CML 2013 method	2018	[84]
Scotland	Perth and Kinross		Manufacturing and energy	Wood		Questionnaires and focus groups	2007	[85]
	Perth and Kinross		Agriculture, manufacturing, and energy	Wood		Questionnaire survey and an attitude survey	2007	[43]
Spain	Besaya	80	Manufacturing, construction, sale and repair, and transportation and storage	Waste oil, metallic, non-metallic, plastics and rubber, wood, waste oil, paper, organic, and others	Joint waste management	Questionnaires and visits	2015	[86]
	Cartes, Cantabria autonomous community	25	Manufacturing and construction	Organic, paper, etc.	Service or infrastructure	Georeferencing, geographic information systems, and application programming interface; SymbioSyS tool	2017	[87]

Table 1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Lithuania	Jonava		Agriculture, manufacturing, water and waste, and administrative and support service	Waste heat and steam, organic, and sludge		Material flow analysis; material, energy and fuel balances; evaluation of environmental indicators and comparative analysis. Feasibility analysis	2016	[88]
			Agriculture and manufacturing	Organic		Indicators	2018	[89]
United Kingdom			Agriculture and manufacturing	Organic and others			2008	[90]
Norway	Mongstad	6	Agriculture, manufacturing, and energy	Chemicals and waste heat and steam		Mass and energy balance assessment, material and energy flow analysis, carbon and hydrogen flow analysis, CO_2 emission evaluation, and sensitivity analysis; hierarchy analysis method	2008	[91]
England	Five areas				Utilities-sharing	Habitat suitability mapping, and multi-criteria-evaluation mapping; sensitivity analysis	2012	[92]
Finland and Sweden	Gulf of Bothnia	7	Manufacturing	Metallic		Strengths and weaknesses assessment and common pool resource management analysis	2012	[93]
Latvia		2	Manufacturing and energy	Organic		Site visits, cumulative intensity indicator of a considered factor	2015	[94]
European country			Agriculture and Manufacturing	Chemicals and Water and wastewater		Concept analysis	2015	[95]
Romania	Botosani and Neamt		Agriculture, manufacturing, energy, water and waste, construction, sale and repair, accommodation and food, and administrative and support service	Chemicals	Infrastructure for utilities and supply process optimization	Interviews	2017	[44]

Table 1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
				Asia				
China	Handan		Agriculture, manufacturing, and energy	Ash, water and wastewater, plastics and rubber, waste heat and steam, metallic, and others			2009	[96]
	Shanghai City and Jiangsu Province		Manufacturing and urban areas	Plastics and rubber, organic, and others		Divisia analysis, energy demand analysis, and regression analysis	2011	[97]
	Jinqiao		Manufacturing, energy, and water and waste	Sludge and waste oil		Experiments in a laboratory, life cycle assessment, total environmental impact	2011	[98]
	Yunfu	3	Manufacturing and energy	Chemicals and waste heat and steam		Production cost and sale revenue analysis	2011	[99]
	Shenyang		Manufacturing and transportation and storage			Coefficient of industrial agglomeration degree, Space Gini coefficient and Hector Fanta coefficient, logistic model, index of competitive analysis, expert evaluation method relational degree taxis	2012	[100]
	Guiyang		Manufacturing, energy, and commercial and residential area	Metallic, plastics and rubber, ash, waste heat and steam, and others		Questionnaires, material flow analysis, environmental benefit evaluation and CO_2 emission reduction, cost reduction	2015	[39]
	Guiyang		Manufacturing, energy, and commercial and residential area	Metallic, plastics and rubber, ash, waste heat and steam, and others		Questionnaires, material/energy flow analysis, process life cycle assessment, avoided consumptions and emissions, CO_2 emission reduction, hybrid physical input and monetary output model, hybrid life cycle assessment model integrating both process life cycle assessment and input–output model, life cycle emissions change, scenario analysis	2016	[9]
	Hangu, Tanggu, and Dagang Districts		Agriculture, manufacturing, and energy	Water and wastewater and others		Satellite images analysis, geospatial data processing and analysis software, manual visual interpretation and landscape type classification system	2015	[101]

Table 1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
	Liuzhou	5	Manufacturing, energy, and communities	Plastics and rubber, ash, and others		Questionnaires, onsite survey, urban level hybrid physical input and monetary output model, hybrid evaluation model integrating process-based life cycle assessment and input-output analysis, calculation of increased or avoided consumption, trade-off emission, scenarios design	2017	[37]
	Liuzhou		Manufacturing, energy, and communities	Chemicals, waste heat and steam, plastics and rubber, and ash		Onsite survey, analytical approach integrating material flows analysis, and emergy evaluation model, avoided consumption and emissions and CO_2 emission reduction, emergy evaluation index and dilution emergy	2017	[10]
	280 proper cities and 357 county-level cities		Manufacturing, energy, and residential and commercial buildings	Waste heat and steam, ash, and metallic		Cross-sectoral symbiosis modelling; energy cascade algorithms; material-exchange algorithms; estimating reductions in fuel use, CO_2 and PM2.5 emissions, life-cycle analysis, and national-economy-wide economic input output-based life-cycle analysis; PM2.5 pollution and health benefit calculations and AERMOD atmospheric dispersion modelling system	2017	[102]
	Wuhan		Agriculture, manufacturing, and water and waste	Water and wastewater, sludge, and paper		Integrated life cycle management assessment method on the resource flows of industrial ecosystem	2019	[103]
South Korea			Manufacturing	Water and wastewater		Mathematical optimization model, general algebraic modelling system software, life cycle assessment and life cycle costing	2010	[104]
			(i) Manufacturing; (ii) manufacturing and urban area	(i) Others; (ii) wood and plastics and rubber		Interview, quantitative estimation of CO_2 emissions, uncertainty analysis	2015	[105]
	Ulsan		Manufacturing and/or urban area	Waste heat and steam		Interviews, scenarios analysis, heat load analysis procedure, CO_2 emission reductions, fuel cost reduction	2018	[106]

Table 1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Japan	Shinchi Town		Manufacturing and energy	Waste heat and steam		Technical and economic feasibility assessment, sensitivity analysis, cost-benefit assessment and spatial analysis; energy generation model; energy distribution model; energy consumption model	2014	[107]
	Shinchi Town		Manufacturing, energy, and urban area	Waste heat and steam		Model framework including energy system design, land use scenario, inventory survey and geographic analysis; district heating network design and simulation; cost-benefit assessment; sensitivity analysis;	2018	[13]
	Tanegashima		Agriculture, manufacturing, and energy	Waste heat and steam, organic, and wood		interviews; scenario analysis, energy flow analysis; greenhouse gas emissions based on life cycle analysis	2016	[108]
Malaysia		4	Manufacturing and energy	Organic		Disjunctive fuzzy optimization approach; overall degree of satisfaction, annual gross profit, net present value, and payback period of a processing plant	2014	[109]
			Manufacturing		Cooperative safety management	Interview	2014	[110]
	Kedah		Manufacturing, energy, and water and waste	Chemicals, Plastics and rubber, Water and wastewater, and Sludge	Infrastructure sharing	Questionnaires. SWOT analysis. Materials Flow Analysis and the Input-Output data based on previous Life Cycle Analysis data	2017	[111]
Turkey	Gaziantep		Manufacturing, Energy and Water and waste	Organic, Plastics and rubber, Sludge, Chemicals, Non-metallic, Waste heat and steam, and Others		Industrial symbiosis match-making platform (ESOTA®, Industrial Symbiosis Opportunity Screening Tool). Visits and workshops	2017	[112]
	Ankara	10	Manufacturing	Waste heat and steam		Tool for defining data about companies and process, cleaner production potential and costs and environmental impact graph of processes. Analysis of mass balance and all materials	2018	[113]
India	Puducherry		Manufacturing			Survey method; trend analysis, causal chain analysis, policy analysis, training needs assessment, technology needs assessment, and barrier analysis; content analysis; SWOT analysis	2015	[114]

Table 1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Bangladesh	Chittagong Export Processing Zone		Manufacturing, energy, and water and waste	Waste heat and steam, water and wastewater, and others		On-site energy audit and equipment/waste emission survey, visits, input and output analysis, feasibility analysis, business model development	2015	[115]
Philippines	Laguna					questionnaires and survey, decision making trial and evaluation laboratory	2016	[116]
North America								
USA	Six counties, North Carolina	87	Manufacturing and water and waste	Chemicals, plastics and rubber, wood, ash, metallic, non-metallic, organic, waste heat and steam, water and wastewater, and others		telephone calls, interviews and site visits, discussions and brainstorming sessions, geographic information system maps	2001	[60]
	Texas		Manufacturing and water and waste	Commercial, industrial, and municipal waste		Questionnaire survey, modified total design method	2005	[117]
	Pittsburgh		Manufacturing and construction	Ash and others		Highway density map, road density. and total highway density; optimization analysis; life cycle analysis; transportation cost analysis	2008	[118]
Canada	Ontario		Agriculture, manufacturing, and water and waste	Non-metallic, chemicals, and waste heat and steam		Inputs and outputs analysis	2009	[119]
South America								
Brazil			Agriculture and manufacturing	Organic, ash, and others		Economic evaluation, environmental and social analysis, emergy method	2007	[120]
	Norte Fluminense region	14	Agriculture, manufacturing, energy, and water and waste	Organic, chemicals, waste oil, ash, and others		Interviews and visit; scenario analysis, mass balance, synergy matrix, and material flow analysis; environmental, social, and economic indicators	2018	[121]
Colombia	15 towns	34	Agriculture, manufacturing, energy, water and waste, construction, sale and repair, accommodation and food, and administrative and support service	Wood, plastics and rubber, paper, organic, non-metallic, sludge, water and wastewater, and others	Service sharing	Workshops, observations, surveys, and interviews	2018	[34]

Table 1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Africa								
Liberia	Konia		Agriculture, manufacturing, and accommodation and food	Organic and others	Fishponds	Interviews, optimization model	2014	[45]
Mauritius			Manufacturing and water and waste	Organic, sludge, metallic, and others		Interviews and framework for adopting industrial symbiosis	2017	[122]
Egypt	Borg El-Arab		Agriculture and manufacturing	Organic, metallic, non-metallic, paper, plastics and rubber, wood, and others		Data from internal unpublished sources	2018	[61]
Oceania								
Australia	New South Wales		Mining, manufacturing, and energy	Chemicals, ash, metallic, and others		Aspen modelling	2012	[123]
	Kwinana	12	Manufacturing, energy, water and waste, and construction	Chemicals and others		Triple bottom-line perspective and preliminary sustainability assessment	2013	[124]

[1] NE: Number of enterprises

The cases compiled here are organised by region, and these are arranged into descending order based on the number of cases studied, i.e., Europe, Asia, North America, South America, Africa, and Oceania. Within each region, the various countries are also listed in descending order based on the number of cases studied, and within each country, the same process was carried out in ascending order based on the date of publication of the article.

In the following sections, the main characteristics of the cases of potential industrial symbiosis, the methods used in the analyses and the main potential benefits of these synergies are analysed and discussed.

3.3.1. Level of Implementation

Similar to industrial ecology and the circular economy, industrial symbiosis can be implemented at three levels: the micro, meso and macro levels [40,125–128]. These are related to the boundaries at which industrial symbiosis relationships develop, i.e., at company (micro) level; between businesses with geographic proximity, such as eco-industrial parks (meso level); and activities that are carried out at regional or national level (macro level). Table 2 illustrates the diversity of potential industrial symbiosis cases, shown in Table 1, for each level of implementation.

Table 2. Distribution of potential industrial symbiosis cases by level of implementation.

Levels of Implementation	Potential Industrial Symbiosis Cases (Refs.)
Meso	Industrial park/eco-industrial park: [75,76,87,91,98,104,110,114]; business park: [81]; local industrial network: [64]; industrial districts (companies with geographical proximity): [67]; nearby companies: [35,36]; clusters: [73,107]
Macro	Region: [43,53,66,80,83,93]; region (residential, industrial, rural dimensions): [11]; city (industrial park and urban area, industrial and urban symbiosis): [9,37,39,106]; municipality: [72]; island: [74,122]; agro-industrial symbiosis: [120]; automotive sector: [63]

3.3.2. Industries Potentially Involved in Industrial Symbiosis

The diversity of economic activities with the potential to become part of an industrial symbiosis network is very wide, as illustrated in Tables 1 and A1. Manufacturing, which comprises activities involving the transformation of materials into new products, is the predominant sector in these cases of potential industrial symbiosis, as shown in Figure 4. This figure represents the distribution by country of all the economic activities involved in the various cases, grouped into sections according to the format established in the International Standard Industrial Classification of All Economic Activities, Revision 4 (ISIC, Rev.4). Of the 21 sections defined in ISIC, 16 are relevant to the various cases studied, with manufacturing accounting for 63% of the total occurrences of all sections. Sections such as agriculture, forestry and fishing, electricity and water, and waste management and recycling are also among the most frequently seen.

Within the manufacturing sector, the most frequent economic activities in the cases of potential synergy involve chemical, iron and steel, pulp and paper, construction materials, and wood and wood products. While there are cases in which manufacturing is the only sector in the synergy network, such as the study conducted in the Val di Sangro Industrial Area in Italy [64] or in Achaia in Greece [82], most of the cases involve several different industries within the manufacturing sector and other entities in the network that carry out other types of activity. This diversity of sectors has been highlighted by some authors [18,129] as being very important for the establishment of industrial symbiosis networks, as it widens the opportunities available.

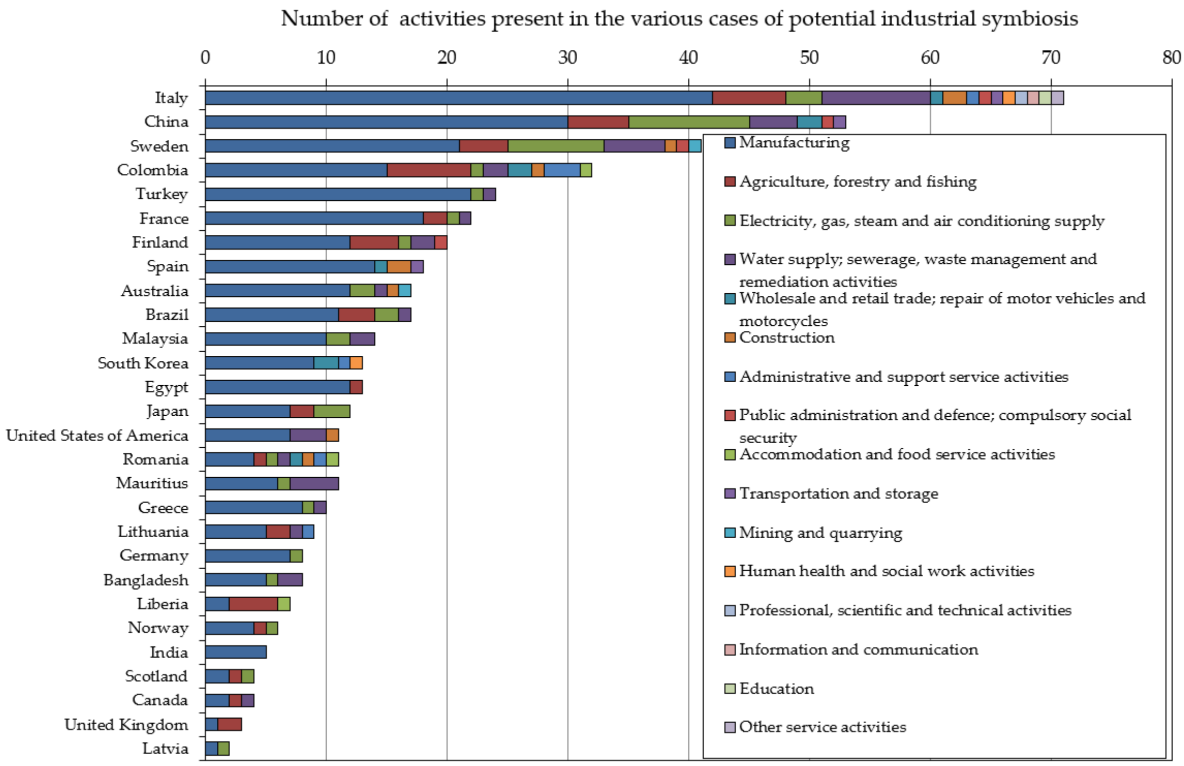

Figure 4. Distribution of the categories of economic activities existing in cases of potential industrial symbiosis by country.

3.3.3. Types of Waste/By-Product Exchange, Infrastructure Sharing, and Joint Provision of Services

The types of waste/by-product that have the potential to be used in the various cases of industrial symbiosis are very diverse, and are directly related to the nature of the economic activities that are carried out in the various networks of potential synergy. The most frequently reported wastes are organic (food and food processing wastes, biomass, livestock and fisheries wastes), plastics and rubber, wood, metallic, waste heat and steam, non-metallic (e.g. glass, waste from construction and demolition, lime-based waste), ash, water and wastewater, chemicals, sludge, and paper.

The sharing of infrastructure and the joint provision of services between companies has also been highlighted as a kind of symbiosis between entities, with potential to be developed and to provide benefits to the participants, albeit in lower numbers than for waste flow. The most frequently mentioned cases are facilities associated with the management and treatment of waste, water and recycling [34,62,64,65,86]. This type of scheme can assist companies in their waste management by freeing them of some of the costs associated with the storage and treatment of waste and by facilitating the direction of waste to various other companies. In addition to these aspects, the sharing of expertise, consultancy, equipment, logistics and transport, energy, and water supply infrastructure have also been identified as having potential to be established. Economic, environmental, and social benefits are identified as being likely to be attained if these types of sharing are established, such as cost savings in the construction of facilities [111], saving of resources used in waste treatment [62], reduction of inefficiencies [64], and job creation [65], and these can serve as drivers for the creation of new symbiosis relationships. Furthermore, the existence of shared and efficient infrastructures can foster new synergies between existing companies in the area and can also be an incentive for new companies to establish themselves in the region with the intention of being part of this symbiosis network. The sharing of services such as transport can also be an important factor in promoting symbiosis networks. Since most of the waste sold does not have a very high commercial value, any reduction in costs such as via the sharing of services can increase the potential economic benefits to the companies involved in these synergies and can foster the creation of new symbiosis relationships.

3.3.4. Methods Used in the Analysis and Assessment of Potential Industrial Symbiosis

In order to identify potential synergy relationships and assess the feasibility of implementing various cases of industrial symbiosis, several methods were used, as listed in Tables 1 and A1. The main objectives of this work were to study the best ways to establish synergy networks with regard to the most potential waste streams and the companies with the highest potential for integration and to assess the potential impacts that industrial symbiosis can have on the environment, the companies involved and the local population.

One of the first steps in the design and analysis of a potential synergy network is the collection of information and quantitative data. Various methods have been used for this, such as interviews [44,65,78,82,106], questionnaires [9,37,63,85,111], site visits [64,84,86,112], and focus groups [53,64,68,85].

To enable the realisation of industrial symbiosis networks, it is also essential to obtain knowledge not only of the possible participants but also of the numbers and types of waste/by-product available. Thus, in addition to meetings with local businesses that help foster possible relationships, as achieved in Emilia-Romagna, Italy [53], the Catania and Siracusa districts in Italy [66], and Colombia [34], the use of digital programs and platforms can also facilitate this interaction by building a common base with potential participants and waste and by optimising possible relationships. Examples of these are the development of a digital web platform for the electrical and electronic equipment sector [38], the Looplocal tool, which is useful in countries with geographically dispersed industries [72], the eSymbiosis multilingual service, implemented as an accessible web service [80], the SymbioSyS tool [87], and the ESOTA®platform, which is based on relationship mimicking [112].

One of the factors that can enhance the realisation of industrial symbiosis relationships is realisation of the potential benefits to businesses, not only the economic benefits, which are essential in encouraging companies to create synergies, but also the environmental and social benefits. While some of the studies carried out only a qualitative analysis, a significant proportion assessed at least one of these benefits. Of the three dimensions of sustainability, the environmental aspect was the most frequently discussed, and the most commonly applied method was the use of environmental indicators [10,13,39,88,105]. The reduction of carbon dioxide emissions was the most frequently addressed in the various analyses [35,36,38,63,70,73,98], followed by quantification of savings in the consumption of resources such as energy, water, raw materials and fossil fuels [9,39,63,88,95], and quantification of the reduction of waste sent to landfills [9,34,39] resulting from the potential application of industrial symbiosis. Life cycle assessment [9,38,63,84,98] was the method most commonly used to assess the environmental impact. The economic aspect, which was the second most frequently assessed, was measured using the life cycle costing method [104] and several metrics that primarily reflected reductions in raw material [39,60], fuel [13,106], energy consumption [35,36], waste disposal costs [38,39], and increased revenue [34,35,38,45,109]. Job creation [45,80,120,121] was the indicator most commonly used to assess the social benefits of realising potential industrial symbiosis relationships. The material flow analysis method [9,10,39,88,111] has also been used several times to quantitatively assess potential industrial symbiosis.

The environmental and economic components of sustainability have also been used to optimise and select the best potential symbiosis relationships. In order to compare industrial symbiosis with an equivalent system in which companies remain separate, several forms of synergy network integration have been evaluated and optimised based on their total costs [69] and carbon dioxide emissions [70] using the MIND method, an optimisation method based on mixed integer linear programming. Three models were developed using mixed integer linear programming to model and optimise waste streams in an industrial park in France with regard to cost and environmental impact [75].

SWOT analysis has also been used several times [67,76,111,114] to study the internal and external factors in the potential application of industrial symbiosis networks.

3.3.5. Potential Environmental, Economic, and Social Benefits

An analysis of the various cases of potential industrial symbiosis leads to the conclusion that most of them intend to achieve environmental, economic and social benefits through these practices. Table 3 gives some examples of this. The environmental component was most frequently measured, largely due to international constraints on reducing greenhouse gas emissions, as well as national constraints on emission reductions and the amount of waste sent to landfills and incinerators. It is therefore important to ascertain whether these practices can be effective in meeting these limitations.

The economic component, which is often cited as a determinant factor in decisions by companies to establish symbiosis relations [34,130], was the second most frequently quantified component of sustainability. However, not all cases of industrial symbiosis have the potential to provide economic benefits to all participants, such as an example of symbiosis in a chemical industrial park in the west of Urumqi City, China. In this case, one of the companies did not receive economic benefits, largely due to the fact that the price of the raw material was lower than some types of industrial solid waste that were used for the production of bricks [130]. The environmental benefits, such as reduced consumption of natural resources and greenhouse gas emissions, justify the implementation of these networks of synergy, even without economic benefits, although, in these cases, it is important that local or national governments provide economic incentives that encourage companies to create these synergies.

It can therefore be concluded that the implementation of these cases of industrial symbiosis can provide a number of environmental, economic, and social benefits that translate into an efficient use of waste and resources.

Table 3. Main environmental, economic and social benefits of potential industrial symbiosis.

Potential Industrial Symbiosis (Refs.)	Environmental Benefits	Economic Benefits	Social Benefits
[62]	Improved air quality (emissions reduced up to 65%), water quality (pollution reduced by 20–30 times), water and energy consumption and CO_2 emissions (reduced up to 60%)		
[69]		Reduction in system cost by 17.6%, increase in electricity production by 0.5%, decrease in steam discharge by 78.0%, decrease in waste heat discharge by 80.4%, and increase in bark sales in 72.8% compared to the reference case	
[85]			On-site and off-site jobs creation, contribution to the alleviation of rural fuel poverty
[63]	Reduction of resource depletion, air emissions, and landfilled wastes	Costs of secondary polypropylene are reduced up to a factor of 10, compared with virgin plastics; reduction of waste costs; reduction of 93% of supply costs	
[73]	Reduction of CO_2 emissions, reduction of the amount of waste that is currently sent to landfill, long-term storage of the CO_2, water savings, and reduction of dependence on petroleum-based materials	Increase of the production, cost reduction, and creation of new sources of income	
[36]	Industrial symbiosis complexes with two and six factories would allow to avoid equivalent CO_2 emissions of approximately 78 kteCO_2/year and 377 kteCO_2/year, respectively	Implementation of a steam exchange system between the two chemical plants and the thermal plant, with a distance of 1.8 km, could reduce the annual heat costs of the plants by approximately 15%, with a payback period ofeight8 years for recovery of infrastructure investment costs	
[34]	Twenty projects would prevent 7207 tons of waste disposal and 1126 tons of greenhouse gas emissions and would reduce energy consumption by 619,500 kWh and water consumption by 146,000 m^3 per year	It is estimated that the 20 projects can generate economic benefits in the amount of approximately $760,000 USD, considering both cost savings and additional revenue; on average, each project was estimated to generate about $38,000 USD, with a three-month payback period	

Table 3. *Cont.*

Potential Industrial Symbiosis (Refs.)	Environmental Benefits	Economic Benefits	Social Benefits
[95]	Energy reduction up to 35%, reduction in water consumption up to 50%, and reduction in greenhouse gas (GHG) emissions by 20%	Cost of waste disposal is practically eliminated	
[39]	Save raw material 2.5t and energy 12.25 GJ/t steel; 1t waste plastic could substitute 1.2 t coke; save material of clinker 500 kt/year; reduce slag by 500 kt/y; in total, resource saving and waste reduction reduce the CO_2 emissions by 1028.06 kt-CO_2/y	In terms of raw material saving, fossil fuel saving, and solid waste reduction, cost reduction is 54.14MUSD/y, 13.84MUSD/y and 4.23MUSD/y	
[106]	In the scenario for the total of industrial and urban symbioses, the CO_2 emission could be reduced to 1,108,682 ton CO_2/yr (this reduction of CO_2 emission is approximately 2% of the total CO_2 emissions in Ulsan)	The fuel cost could be reduced to $352.5 million USD/yr	
[120]	Rationalization of land use, avoidance of greenhouse gas emissions and toxic gases, and minimization of the needed inputs and equipment	Liquid present value: $10.93 million USD, economical revenue: 16.29%/year, and return time: 4.6 years	Creation of 241 jobs in the initial phase and more than 5400 in the eight months of harvest, construction of civil and social facilities
[124]	Chemical release due to dust containment avoided, avoidance of release of toxic chemicals to environment and ground water contamination, avoids $CaCl_2$ release to marine environment, less use of virgin resources and less environmental burdens by avoiding nitrogen oxide emissions	Avoid fines from dust emissions, from waste water and from emissions; savings to company and savings in the costs of using less water from other sources; revenue from $CaCl_2$, from the sale of ammonium nitrate, and from SiO_2 sales	Respiratory effects from fine dust avoided; less health risks due to reduced emissions, avoidance of long-term exposure to SiO_2, and avoidance of release of nitrogen oxides

3.4. Cases of Potential Industrial Symbiosis Applied to New Products and New Uses of Waste

Research into new uses for waste and the manufacture of new products based on industrial symbiosis is essential in order to reduce the consumption of raw materials and reduce waste sent to landfills and incineration plants. However, despite the environmental and economic benefits of this reduction, the process of moving from research to practice is not always rapid or, indeed, possible. In addition to the barriers to the creation and development of industrial symbiosis, which are often referred to in the literature, such as a lack of trust among potential collaborators [33,116], the risks and uncertainties associated with the costs and benefits of such synergies [18,131], and a lack of knowledge [34,41], there are other more specific obstacles that impede these new uses. Current legislation restricting the integration of new waste materials into productive processes [132,133] and the toxicity of some of these waste materials [134] are examples of barriers that can hinder the flow of waste materials and thus condition the development of future synergies. Thus, several studies have investigated future relationships of industrial symbiosis with a focus on the use of new waste materials and their reutilisation in the manufacture of existing or new products. Table 4 presents a summary of these studies, and in addition to the location and main characteristics of the industrial symbiosis, describes the methods used in the various studies. The different case studies are grouped into regions, i.e., Europe, Oceania, North America, and South America, which are sorted into descending order in terms of the frequency with which they appear in the studies. In cases with an equal number of articles, the ordering was carried out based on the date of publication, in ascending order.

It can be seen that, although these cases are few in number, a great variety of industries is involved in potential industrial symbiosis, and there is a wide range of different waste materials and potential uses of these in the manufacture of new or existing products. The geographical distribution is also relatively varied, with studies carried out in Europe, North America, South America, and Oceania. Although not all of these studies were contextualised with regard to a specific location, the vast majority studied the potential for using new waste materials within a given geographical context.

Table 4. Potential applications of industrial symbiosis to various products and wastes, and studies analysing these applications.

Country	Location/Region	Activity/Process	Waste/By-Products	Final Product/Use	Method	Publication Year	Refs.
Finland		Bioenergy production and forest products industry waste water treatment	Bio fly ash and bio sludge	Forest fertilizer	Laboratory scale production and test, life cycle assessment	2016	[135]
Finland	Oulu, Raahe and Kemi	Pulp and paper mill, carbon steel plant, mine, and power plant	Lime waste residues, green liquor dregs, steel ladle slags, desulphurization slag, attle rock, bottom ash, fly ash, and paper mill sludge	Soil amendment pellets, low-grade concrete, and mine filler	Life cycle assessment, CML impact assessment method, global warming potential assessment and exergy analysis method, dimensional analysis approach, primary exergy conversion efficiency of the production process	2016	[133]
Greece		Biodiesel plants, agro-industries, lignite-based power generation plant, and agricultural biomass-based combined heat and power plant	Crude glycerol and agricultural biomass	Alternative fuels production	Experiments in a laboratory scale	2016	[136]
United Kingdom	North east of England	Integrated steel mill	Vanadium-bearing steel slags		Semi-structured interviews with industry representatives, industry associations, and consultants	2017	[132]
Wales	Baglan	Foundry and research centre	Platinum from waste thermocouples	Catalytic electrodes suitable for dye-sensitized solar cell production	Synthesis and analysis of chloroplatinic acid samples, fabrication and characterization of platinized counter-electrodes, electrical impedance spectroscopy analysis, chemical analysis, supply and environmental impact analysis, cost-benefit analysis	2018	[137]

Table 4. *Cont.*

Country	Location/Region	Activity/Process	Waste/By-Products	Final Product/Use	Method	Publication Year	Refs.
Italy	S. Angeli di Rosora, Marche	Building and automotive sector	Retired lithium-ion electric vehicle batteries	Battery energy storage systems	Experimental tests, simulation of the energy system, integrated load match analysis and life cycle assessment approach, grid interaction indicators	2019	[138]
Australia	Western Australia	Nitric acid plants and fertilizer producer	By-products formed from chemical absorption of nitrogen oxide	Potassium nitrate fertilizer	Life cycle assessment and life cycle inventory; process engineering applications: stoichiometric balances, thermodynamic properties of chemical reactions. and solubility conditions; Australian Environmental Impact method; uncertainty analysis	2016	[139]
Australia	Kwinana	Phosphoric acid manufacture	Phosphogypsum	Paper and fertilizer	Life cycle assessment and life cycle inventory; economic and social analysis; Economic Analyzer software; sensitivity analysis; indicators for social implications assessment: employment opportunity, intergenerational social equity, and avoided land use	2018	[140]
USA	Southwest region	Original equipment manufacturer dealership, battery diagnostic centre, and photovoltaic industry	End of life electric vehicles lithium-ion batteries	Storage of renewable energy generated through photovoltaic technology	Avoided environmental impacts for reusing degraded electric vehicles batteries and tool for reduction and assessment of chemicals and other environmental impact	2019	[141]

Table 4. *Cont.*

Country	Location/Region	Activity/Process	Waste/By-Products	Final Product/Use	Method	Publication Year	Refs.
USA		Automobile industry and building and construction industry	Waste steel scrap	Metal facade systems for buildings' exteriors	Required capital cost and required energy consumption for making a new metal building facade product by recycling and by directly reusing waste steel scrap; potential capital cost savings and energy consumption savings by reusing waste steel scrap when compared with recycling	2019	[142]
Brazil	Quadrilátero Ferrífero, Minas Gerais	Iron mining and steel, and brick manufacturing industry	Steel slag and iron ore tailings	Solid brick	Evaluation of chemical composition of the samples by energy dispersive X-ray spectroscopy, expansibility test using the method defined in Brazilian Standard ABNT NBR NM 13, experimental procedures, visual analysis, mechanical tests, comparative evaluation, QE-CO_2 method	2018	[143]
			Wastes from laptop and photovoltaic system		Design measures and technological, environmental, and economic implications analysis	2012	[144]
		Cement industry and municipal solid waste management	Energy-from-waste air pollution control residues (fly ash and calcium or sodium salts from scrubbing of acid gases)	Blended cements	Analysis of pH-dependent leachability of pollutants from granular material and diffusion-controlled leaching from monolithic specimens; laboratory investigation of eight EfW APC residues	2014	[134]

Table 4. *Cont.*

Country	Location/Region	Activity/Process	Waste/By-Products	Final Product/Use	Method	Publication Year	Refs.
		Winery and environmental industries	Grape marc	Bioadsorbent for the desalination of water containing copper (II) sulfate	Elemental analysis, preliminary adsorption experiments, experimental design for establishing the optima conditions to remove copper(ii), quantification of copper(ii) through a spectrophotometric analysis, quantification of adsorbent capacity and percentage of copper removal, X-ray diffraction analysis, statistical analysis—response surface method, and multiple regressions using the least squares method	2018	[145]

In some cases, geographical location was not constraining, and the use of certain waste materials could be transferred to several locations. For example, waste materials from common industries and those available in most countries can be used to extend the range of application of industrial symbiosis. One example of this is a case study of the production of potential symbiosis products such as soil amelioration pellets, low-competence concrete, and mine filler from a mixture of waste materials from multiple industries, such as pulp and paper mills, carbon steel plants, mines, and power plants [133]. Although this was studied in the context of Finland, this symbiosis could be replicated in numerous different locations due to the nature of the industries available. Another example was a study of the use of wine grape pulp to produce a bio-adsorbent for the removal of copper sulphate from water [145]; this symbiosis between the winery and environmental industries could also be reproduced in several distinct locations.

In other cases, however, geographical location can condition or incentivise the use of certain waste materials in the symbiotic process. For example, the strong presence of a particular type of industry can be an enhancer for industrial symbiosis and the search for new solutions to the waste generated by the production process. One example is the pulp and paper industry, which has a long tradition in Finland and is responsible for large volumes of production [21] and consequently high levels of waste generation. One of the studies focused on the potential uses of sludge resulting from the processes of wastewater treatment in the forestry industry and of fly ash resulting from the production of bioenergy for the production of a forest fertiliser [135]. In Brazil, the steel, mining, and construction sectors have a strong presence and are responsible for large-scale generation of waste and greenhouse gas emissions, and this has boosted the search for sustainable solutions. Thus, new solutions for the use of iron and steel mining waste were studied as an example of potential symbiosis in the production of solid brick/construction blocks in the Quadrilátero Ferrífero zone [143].

Current progress and the consequent emergence of new products have created new streams of waste, and with them the need to provide solutions which promote a more sustainable end of life. If these wastes result from or are integrated into a sector or product that has a significant environmental impact over its life cycle or a certain part of it, industrial symbiosis makes it possible to reduce the environmental impact of this sector or product. One of the examples found in the literature was the potential use of end-of-life electric vehicle lithium-ion batteries as storage systems for the renewable energy produced from photovoltaic systems in the generation of electricity for buildings [138,141]. In addition to using a waste material that is expected to increase over the next few years, this potential synergy also contributes to the reduction of carbon dioxide emissions from two sectors that are responsible for high greenhouse gas emissions—buildings and the automotive sector.

The study of new solutions based on industrial symbiosis is not only due to the inherent characteristics of certain waste materials, such as their toxicity and associated value, but also to the fact that the recycling process is often expensive and a large consumer of energy, meaning that it is not a viable solution. In the case of retrieval of valuable metals such as platinum, the recovered value sometimes does not cover the costs inherent in retrieval [137] if these are present in low concentrations, and industrial symbiosis can address this limitation. One example is a case study of Baglan, South Wales, in which, due to the local proximity between the stakeholders of potential synergy, the recovery of platinum for the production of catalytic electrodes for dye-sensitised solar cells could be translated into environmental, economic, and social benefits [137]. The potential direct use of sheet metal scrap from the automobile industry in the manufacture of new facade systems for the exterior of buildings could also lead to a reduction in costs of approximately 40% and a reduction in energy consumption of approximately 67% compared to a conventional recycling process [142].

All these studies were supported by several methods with different objectives. Since the main aim of these publications was to promote the use of new waste materials or the production of new products empowered by industrial symbiosis, it is not surprising that the predominant methods were those associated with laboratory-scale experiments. These tests were carried out to study not only the characteristics of waste materials [137,138] but also the final products [135,143] in order to guarantee their functionality and suitability for these purposes. A knowledge of the potential environmental, economic and social benefits that these new uses of waste can provide is also very relevant, as these can drive realisation. In the same way as for studies of potential industrial symbiosis between companies, the environmental component was the most frequently analysed aspect [135,138–140], followed by economic factors [137,140,142,144], and finally social components [140]. The potential benefits from the use of new waste materials and the manufacture of new products based on industrial symbiosis are extremely diverse. Table 5 lists the main environmental, economic, and social benefits that could be achieved if some of these potential symbioses were put into practice.

Table 5. Main environmental, economic, and social benefits of the potential use of waste and products through industrial symbiosis.

Potential Industrial Symbiosis (Refs.)	Environmental Benefits	Economic Benefits	Social Benefits
[135]	Reduction of global warming potential (GWP) by 99%: production of 1000 kg of potential symbiosis granules would produce GWP burdens of 11.75 kg CO_2-equiv. and the existing NPK-fertilizers produced a GWP burden of 1304.92 kg CO_2-equiv.		
[139]	Reduce the overall GWP, acidification potential and eutrophication potential per kg KNO_3 produced by 7.8 kg of CO_2-e, 0.122 kg SO_2-e and 0.075 kg PO_4 -e respectively in comparison to the production of conventional KNO_3 fertilizer and could reduce GHG emissions by 45%		
[142]		Reusing the sheet metal scrap over conventional recycling of the same material would lead to a cost reduction of approximately 40% ($400 USD/ton) and savings of approximately 67% (10,000 MJ/ton) of energy consumption	
[136]	Provide a rather short-term solution to the existing environmental problem of waste glycerol, contributes to increase sustainability and reduce environmental footprint	Decrease in the cost of biodiesel production	
[132]	Removal of elements of environmental risk, such as vanadium	Income from the sale of recovered metals	
[137]	Per year, divert ~50 g of platinum from landfill, avoid up to 1400 kg of CO_2 emissions associated with primary production of an equivalent quantity of platinum, and give enough platinum to produce catalytic electrodes for ~500 m^2 of dye-sensitized solar cells, which could supply clean energy for 12 homes in the locality (South Wales)	Provide 63% materials cost savings for electrode preparation in comparison to purchasing commercially available chloroplatinic acid hydrate	Provide ~5 days employment

Table 5. *Cont.*

Potential Industrial Symbiosis (Refs.)	Environmental Benefits	Economic Benefits	Social Benefits
[140]	Reduce solid waste associated with traditional paper production, where the average amount of solid waste reduction from studied options is 0.01 kg/kg of paper, reduction of contamination of underground water sources or land from leaching of the phosphogypsum (PG) constituents	PG recycling is expected to reduce approximately 12,000 m^2 of land used for stockpiling of PG (based on the average annual operation of the plant of 25,000 tons of PG), which could be reutilized for other economic benefits such as expansion of the industrial plant or be sold for revenue generation	Employment opportunities for people in the surrounding areas; it is expected that 18 job opportunities will be needed
[143]	Reduction in GHG emissions. The construction of the 126,000 households using the T2 brick would generate a reduction of 465,588.9 tons of CO_2, when compared to the concrete block	The carbon credits related to CO_2 reduction in the simulated venture could be traded for $4.3 million USD	Access to lower-cost housing

4. Drivers and Barriers to the Realisation of Potential Industrial Symbiosis and Strategies to Overcome These Barriers

A knowledge of the drivers and barriers to the implementation of industrial symbiosis is essential in order to develop measures that enhance the application of this practice. Based on the studies of potential industrial symbiosis analysed above, this section compiles the various drivers, i.e., factors that promote and facilitate the development of industrial symbiosis, and barriers, i.e., the factors that hinder the implementation of this practice. Selected strategies for overcoming the various barriers are also highlighted, as these can create conditions for the various cases of potential industrial symbiosis to materialise.

4.1. Drivers and Enablers of the Realisation of Potential Industrial Symbiosis

An analysis of the articles on potential industrial symbiosis leads to the conclusion that there are a number of factors that play important roles in the realisation of industrial symbiosis relationships. Knowing the environmental, economic and social benefits that this practice provides is important in promoting the creation of synergy networks [146]; however, these are not always the main drivers of this practice, and many other drivers have been identified in studies of potential industrial symbiosis as being conducive for companies to participate in symbiosis networks. In most cases, it is not one factor but a set of factors that create favourable conditions for the development of symbiosis.

The economic, environmental, political, and social context of a country can be decisive in the way sustainability issues are addressed and consequently in how they can favour or condition the development of industrial symbiosis. The distribution of a number of potential industrial symbiosis articles by country, as illustrated in Figure 3, reflects the characteristic context of each country.

Existing legislation, plans and policies in each country are also repeatedly referred to as drivers of industrial symbiosis [82,101,115,118,120]. Companies are encouraged to set up synergy networks through imposing limits on emission or waste disposal through regulations and taxation, facilitating the use of waste, and allocating funds.

The higher numbers of studies of potential industrial symbiosis in Europe cannot be dissociated from the efforts that have been undertaken by European countries to reduce greenhouse gas emissions and to promote the more efficient use of resources. These efforts have been driven by the European Commission, which has established a number of directives, communications and programs with the provision of funds. One example is the "Roadmap to a Resource Efficient Europe" communication, which proposed a framework for action to ensure the sustainable management of all resources without sacrificing economic growth [147]. Another example is the communication "Closing the loop—An EU action plan for the Circular Economy". This communication underlined the importance of industrial symbiosis and proposed to facilitate this practice through cooperation with the Member States, guaranteed funding through cohesion policy funds, and the research and innovation framework program Horizon 2020 [148]. Another initiative launched by the European Commission was Directive 2018/851 on waste; in addition to highlighting the great advantages of improving the efficiency of waste management and recognising waste as a resource, this acknowledges the importance of industrial symbiosis and encourages Member States to take steps to facilitate it [149].

The European countries for which the highest numbers of cases of potential industrial symbiosis have been published are Italy, Sweden, and Finland. All of these countries have common factors that may have contributed to fostering the study of new industrial symbiosis relationships and their implementation, such as (i) a greater concern with environmental issues and the search for sustainable solutions, (ii) the established existence of cases of industrial symbiosis over several years, (iii) a considerable number of cases of self-organised symbiosis networks, (iv) the existence of facilitators through national agencies or local governments, and (v) more stringent environmental regulations [18,21,41,150,151].

The realisation of two cases of industrial symbiosis, involving the automotive [64] and agri-food [65] industries in the Italian Region of Abruzzo, is another example of the combination of several factors in realising the potential of symbiosis. In this case, good communication routes, favourable geographical positions, stakeholder involvement, and the facilitating role of the president of Consorzio Italiano Subfornitura Impresa (CISI) in the case of the automotive industry were viewed as driving factors in the development of industrial symbiosis [152].

China has the highest number of published cases of industrial symbiosis [19] and potential such cases. This may be associated with a set of measures that China has implemented over recent years, such as the implementation of policies and plans, financial incentives, and research incentives. These measures have attempted to contain the negative effects of increasing industrialisation and urbanisation in recent years [153,154], such as increased carbon dioxide emissions [153,155,156], increased amounts of industrial solid waste [154,157], and increasing resource consumption [39,97]. The National Pilot Circular Economy Zone Programme, launched by the State Environmental Protection Administration in 2001, and the laws that have been applied since 2003 to promote the circular economy, are examples of these measures. While not primarily aimed at promoting industrial symbiosis, they contribute to the spread of this practice by providing increased awareness of the importance of resource reuse and recognition of the fundamental role of the circular economy in China's development [23,24]. The China National Eco-Industrial Demonstration Programme launched in 2000 by the State Environmental Protection Administration [25] has also contributed to the increase in the number of potential industrial symbiosis cases and China's leadership in the publication of case studies [19]. This programme has enabled the development of the largest national network of eco-industrial parks, in which industrial symbiosis practices have been promoted [158,159].

The predominance of certain types of industry within countries can also be a driving factor for the creation of industrial symbiosis networks. This is particularly true if they are large consumers of resources and emitters of greenhouse gases, such as the steel and iron industry in China [97,160], and if they play a key role in economic development, such as the agri-food industry in Italy [65] and the iron, steel, and cement industries in China [160,161]. Moreover, these industries have a longstanding tradition in these countries and are located in industrially mature areas, which Jensen et al. [92] have shown to facilitate industrial symbiosis.

A diversity of industries has also frequently been highlighted as conducive to the establishment of industrial symbiosis relationships [76,114], since this opens up a range of opportunities due to the variety of wastes and the numbers of companies that produce them and have the potential to incorporate them into their processes. If there are several companies carrying out the same type of economic activity, this can be an added advantage, since it ensures a more constant flow of waste [77], while if there are no other companies nearby to ensure the incorporation of these wastes into their processes, the viability of industrial symbiosis is compromised. The fact that there are several industries carrying out the same type of economic activity may also enhance other synergies, such as infrastructure sharing and the joint provision of services.

If a company can function as an anchor tenant, this can be an important factor in driving the realisation of industrial symbiosis relationships [76,82,91,93,114]. These companies are able to attract and anchor a network of companies, not only in terms of the supply of materials but also the reuse of waste. There are some examples of such cases reported in the literature, such as a power plant in Honolulu in the US [162], mining firms in Gujiao, China [163], and a pulp and paper mill in Kouvola, Finland [164].

Although not an indispensable requirement for establishing the synergy network, geographical proximity between the potential participants in industrial symbiosis is often referred to as a facilitator [11,36,82,91]. Establishing symbiosis networks with nearby companies can increase trust in the relationship. In addition, the fact that waste is mostly of low economic value, transportation and environmental costs may no longer compensate for the symbiosis connection over long distances.

The existence of industrial symbiosis networks that have already been established in a given place can be a driving force for creating new synergy linkages and extending the network to new companies, since the internal structures [114] and trust relationships that facilitate this development [40] are already established. In addition, there is evidence that these networks can be of benefit to the parties involved, not only in terms of the reduction of waste treatment and landfill costs, but also in terms of the savings made in the acquisition of raw materials, and profits from the sales of waste. If there are entities that can support and facilitate existing on-site cases of industrial symbiosis, these can also act as enablers for the creation of new connections. This role can be played either by public entities such as local governments or by private entities such as business associations [18,41]. These entities, which are aware of the reality of the site, can more easily identify new partners for infrastructure sharing and joint provision of services, as well as new companies that may be able to use waste that is not yet in use, or that can provide waste to companies already involved in industrial symbiosis. However, in places where no synergy networks have been established, the role of these facilitators can be highly relevant, as mentioned in some of the cases analysed here [60,76,82,107]. They can provide training for companies, facilitate the exchange of information [53], foster cooperation and trust between companies [76], and coordinate and help identify possible symbiosis relationships [107].

4.2. Barriers to the Realisation of Potential Industrial Symbiosis

Despite the recognised environmental, economic and social benefits that industrial symbiosis can provide, there are a number of barriers that hinder its development. The literature review shows that these barriers can be of various types, such as economic, technical, regulatory/legal, organisational, social, and cultural [18,33,47,131,165]. By analysing selected publications on potential industrial symbiosis, it was possible to identify several of these barriers.

Several studies of potential industrial symbiosis have pointed out the lack of appropriate policies as a barrier to the application of this practice [53,65,116,122]. Low taxes on landfill disposal [122], a lack of policies that encourage and regulate industrial symbiosis [116], a lack of funds to promote this practice [116], and deficient regulatory frameworks [122] are some of these barriers. In addition, existing legislation may limit the implementation of synergy relationships, especially if it is too rigid, unclear, or inconsistent. One example is Italy's regulatory system, which is referred to in studies of potential industrial symbiosis [53,65] as constraining companies with regard to the use of waste.

There are also others barriers to the creation of industrial symbiosis networks. The first is associated with the reluctance of companies to establish synergistic relationships, not only due to a lack of knowledge of the industrial symbiosis mechanism [116,122] but also due to a lack of knowledge of other companies with the potential to receive or provide waste [9,68]. In addition, a lack of trust [82,116], resistance to providing data on processes and generated waste [122], and uncertainty related to the profitability of the symbiosis network [75] and the associated costs and risks [82] were also identified as barriers to the development of symbiosis relationships.

The fact that companies are implementing measures to reduce waste generation has also been identified as a barrier to the development of industrial symbiosis [68], as there is a concern that the stream of waste involved cannot be guaranteed.

The economic component has been referred to by various authors [18,166,167] as being essential in inducing companies to take the initiative to establish an industrial symbiosis relationship. If the economic value of raw materials is very close to that of waste, there is no incentive for companies to use waste in their production processes [37]. Moreover, the price that companies are willing to pay for waste may not be economically advantageous for the company producing such waste. In this case, there is no incentive for companies to divert waste from landfills and start a symbiosis relationship [68]. In addition to these factors, the role of stakeholders in deciding whether or not to initiate symbiosis relations should be highlighted, as there is often a lack of openness [34] and willingness [116] to initiate this kind of collaboration.

For the establishment of some symbiosis relationships, such as the sharing of waste heat, the initial costs associated with infrastructure are very high, and this makes companies reluctant to establish such symbioses [75,106,107]. A lack of availability of technologies required [9,116] and the high costs of equipment [85] for the realisation of industrial symbiosis have also been identified as inhibiting the realisation of this practice.

The social and economic instability of a country can also condition the establishment of synergies, since although the issue of sustainability is recognised as being important; there may be social issues which take precedence [168]. In addition, the issue of survival is imperative in some countries with developing economies, and since the time between setting up projects and achieving results may often be long in these countries, this may constitute a barrier to the implementation of symbiosis [45].

4.3. Strategies for Overcoming the Barriers to the Realisation of Potential Industrial Symbiosis

Regulations and policies were most often referred to as being important for encouraging or limiting the establishment of industrial symbiosis relationships [85,111,122,169]. While the decision to establish a symbiosis relationship is made by a given entity, the role of policies is critical in encouraging this practice. Thus, in order for these to not function as barriers, it is necessary to provide legislation and policies that are clear, consistent, and less bureaucratic and can facilitate the process of waste use [170].

Economic incentives have also been highlighted as being important in the realisation of industrial symbiosis [9,122]. To create more efficient legislation to facilitate this practice, programmes can be coupled with the provision of funds to promote industrial symbiosis and offer monetary support for companies in terms of the construction of infrastructures or the acquisition of the equipment necessary for the realisation of these relationships [122].

However, even if there are a number of policies and programs that facilitate and encourage companies to establish symbiotic relationships, the companies themselves are often reluctant to make such connections. Thus, to drive the implementation of industrial symbiosis, it is necessary to disseminate information to companies. This can be realised through workshops, working group discussions, and other actions [116,122] that provide the necessary information to companies on industrial symbiosis and its potential benefits. A knowledge of this practice can create the willingness to cooperate, which is fundamental for the realisation of symbiosis networks [68].

The role of facilitators such as local governments and industry associations has also been highlighted as a way to overcome various barriers [34,111], including a lack of confidence, a reluctance of companies to share their data and a fear of relying on other companies. These entities can provide training to various employees on the concept of industrial symbiosis, assist in the creation of trust and cooperation relationships, and help to identify new symbiosis relationships [34,165].

Some barriers such as a lack of knowledge of companies with potential to start symbiosis relationships and lack of trust can be overcome using digital platforms and programs [87]. These tools can enable social interaction between companies and facilitate a search for companies that can provide or receive waste. In addition, where appropriate, they can facilitate the choice of the best option based on prices, distances and potential environmental and economic benefits [38,80,87].

In order to overcome the barriers associated with a lack of available technology, there is a need for increased investment by governments in research and development into technological innovations and greater involvement with research teams from university or business associations [9,37].

In the case of poorer countries with social problems such as high unemployment rates, low incomes, illiteracy, or low life expectancy, such as the cases studied in the Philippines, Liberia, India, and Bangladesh, the implementation of industrial symbiosis practices is more difficult. However, when properly supported, the implementation of this practice can make a positive contribution to the long-term sustainable development of these countries, as it makes it possible to combine environmental and economic issues with social aspects. These advantages translate into job creation, long-term links between companies and the possibility of small businesses entering the synergy network [45,61,171]. It is therefore essential to support these countries in the development of industrial symbiosis. Several authors have proposed measures for overcoming the characteristic barriers in these countries, such as (i) extending the symbiosis network to other stakeholders such as community leaders and government organisations [45], (ii) the establishment of policies that encourage symbiotic relationships between small businesses, such as small farms [45], (iii) the provision of subsidies [122], and (iv) helping to obtain international support created specifically for sustainable projects in developing countries [122].

The main drivers and barriers to achieving potential industrial symbiosis are very diverse, as illustrated in Figure 5, and overcoming the various barriers and achieving further dissemination of industrial symbiosis requires concerted action at various levels. It is therefore essential to coordinate the various entities and resources and to restructure existing regulatory systems. It is also necessary to support companies in paradigm shifting and raising awareness of the advantages of more sustainable practices, and in particular industrial symbiosis.

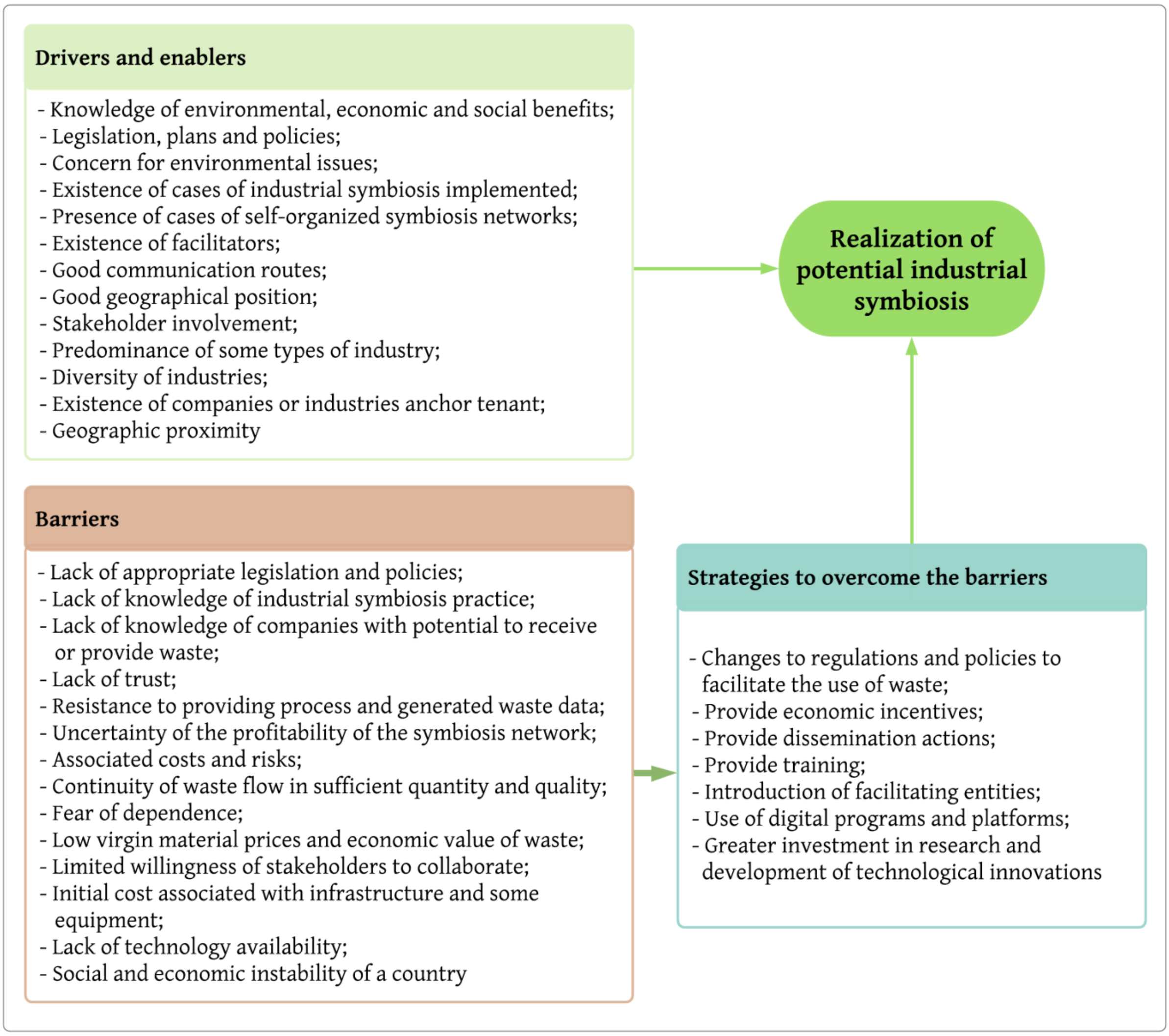

Figure 5. Key drivers, enablers, and barriers to the realisation of potential industrial symbiosis, and strategies to overcoming these barriers.

5. Conclusions

Despite the large number of existing cases of industrial symbiosis, there is still huge scope for growth, as evidenced by the various studies that have been carried out to assess the potential application of this practice. A comprehensive review of the literature reveals that there is potential for the development of new industrial symbiosis relationships around the world, with a wide diversity in terms of network size, the types of economic activities involved and the types of waste stream.

Most existing studies focus on countries where symbiosis is already widely applied, such as China, Sweden, Finland, and the US. However, the potential for industrial symbiosis has also been studied in countries where this practice has few or no existing cases, such as Egypt, the Philippines, and Colombia. Although most of these cases reproduce existing symbiosis relationships with regard to the activities and types of waste involved, there have been studies that have looked into the potential use of new waste and the manufacture of new products based on industrial symbiosis relationships. Furthermore, the potential for applying industrial symbiosis is not limited to replacing resources with waste; there are also many opportunities for other types of synergies, such as infrastructure sharing and joint provision of services.

Despite this great potential, it was only possible to verify the realisation of two of the cases of potential industrial symbiosis in the literature review. It can be inferred that there was either no interest from industry in the implementation of industrial symbiosis or, if the potential was realised, there was no follow-up that resulted in a publication. However, it is important to understand that there is interest from industry in implementing these cases. Some of the studies have a more theoretical character, and many of them resorted to interviews and site visits, which implies that industry is aware of the potential for industrial symbiosis. Thus, it is important to monitor the implementation of symbiosis in order to better understand the dynamics of implementation of this practice and the main factors enhancing its development. If potential cases of industrial symbiosis are not realised, it is relevant to analyse with companies the main barriers to this implementation.

The work carried out in this paper regarding knowledge of the potential for industrial symbiosis and the main barriers and drivers to its implementation may have theoretical implications. The characterisation of the various cases can contribute positively to the research efforts that have been developed to increase the application and diffusion of industrial symbiosis. Knowledge of the main drivers and barriers may also have implications for the development of theory, in terms of an understanding of industrial symbiosis and the main mechanisms that can drive or hinder it.

While an effort was made to ensure that the review of the bibliography was as comprehensive as possible, we limited our search to articles written in English and using only research articles, conference articles, book chapters and editorials, and this may have overlooked some cases of potential industrial symbiosis that could provide a greater understanding of this topic.

Of the various types of resource sharing available, most studies address the potential use of waste and the advantages that arise from its integration as a raw material in the production process. However, in future research, it is important to examine more case studies assessing the potential of infrastructure sharing, the joint provision of services, and the potential benefits to the companies, environment, and society. It will also be important to focus on the most favourable conditions and the factors determining implementation of symbiosis.

Future research could also assess whether various cases of potential industrial symbiosis have been implemented in order to increase our understanding of the mechanisms that drive or condition the creation of synergies and thereby promote the growth of industrial symbiosis initiatives.

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Appendix A

Table A1. Potential industrial symbiosis applications and studies analysing these applications.

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Europe								
Italy	Murano, Venetian Lagoon		Glass-based industry	Oxygen	Water treatment	BATTER tool; direct measurements at single installations, mass flow estimations, total amount of air pollutants emitted, technical options score, and evaporation treatment costs for a single water treatment plant	2007	[62]
Italy	Brancaccio, Carini, and Termini Imerese		Automotive sector and neighbouring companies	Plastic sub products and scraps		Questionnaire data survey to organizations and interviews, life cycle assessment	2010	[63]
Italy	Val di Sangro Industrial Area, Abruzzo Region	19	Motorcycle industry		Collective management of scraps: pre-treatment centre and on-site management of the end-of-life of products manufactured by the industrial network	On-site data collection, performed by using semi-structured questionnaires, direct, and e-mail interviews of the leaders, site visits, and focus groups	2014	[64]
Italy	Fucino upland, Abruzzo Region		Agri-food companies, paper mill, PVC sewer pipes producer company, pellets and plywood panels producer company	Paper and cardboard wastes, plastic wastes, and wood wastes	Common local recycling platform	On-site survey; face-to-face non-structured interviews with the head of the provincial Association of Agricultural Producers and semi-structured interviews with the technical staff by telephone or e-mail	2015	[65]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Italy	Emilia-Romagna		Agrofood sector, industries with the technologies able to transform and enhance the by-products, and companies reusing by-products	Agro-food waste, mud, packaging, waste from construction and demolition, textile waste, waste from petroleum refining and natural gas purification, waste from wood processing, and digested		Interviews with private companies and public administrators, guided collective discussion, visits to laboratories, and conferences	2015	[53]
Italy	Catania and Siracusa districts, Sicily		Agriculture, forestry and fishing, manufacturing, electricity, gas, steam and air conditioning supply, water supply; sewerage, waste management and remediation activities, construction, wholesale and retail trade, repair of motor vehicles and motorcycles, transportation and storage, information and communication, professional, scientific and technical activities, administrative and support service activities, education, human health and social work activities, and other service activities	Water, fuels, materials from agriculture, electrical and electronic compounds, municipal wastewater treatment sludge, industrial sludge, packaging, wood and wood products, metals and metal products, construction minerals, industrial minerals, mineral waste oils, plastics and plastic products, foodstuffs, inorganic chemicals, organic chemicals, products from livestock and fisheries, construction, demolition, excavation materials, paper and paperboard, sands from separation processes, glass and glass products	Energy, equipment, expertise, consultancy and services, logistics and transportation	Invitation emails and phone calls; meeting tables	2016	[66]
Italy	Brescia	12	Multi-utility company, steelmakers, cement producer, waste treatment and biomass power station, woodchips producer, car fluff treatment, asphalt producer, caviar producer, the municipality and public service facilities	Black slag, car fluff, dust, mill scales, pallets and waste wood, sludge, and energy (electrical and thermal)		SWOT analysis	2017	[67]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Italy	Brescia	2	Energy-intensive factory (with forging processes), and greenhouse horticulture installations	Carbon dioxide emissions		Economic model: increase of revenues due to the CO_2 enrichment process, savings due to the reduction of CO_2 emissions in the industrial installation, and savings due to avoided natural gas consumptions (used in traditional CO_2 enrichment methods)	2018	[35]
Italy	Province of Pescara, Abruzzo Region		Crop/vegetable production, cattle breeding, greenhouses, fish farming, industrial processing, production of pellets, urban furniture production, road works company, residential system, and waste and energy system (thermal treatment plant, composting, biofuels production, recovery and recycling activities, biomass/biogas energy plant, and wastewater treatment)	Vegetable wastes, plant waste, vegetable waste (dry fraction, e.g. from pruning, sawdust), differentiated residential waste (aluminium, steel, glass, paper, plastics), construction and demolition waste, heat waste, hot water or steam, wastewater, and industrial waste		Qualitative analysis of the scientific literature and secondary data and critical analysis	2017	[11]
Italy	Marche Region	3	Waste electrical and electronic equipment treatment centre, material recycler and a compound producer	Plastics from electrical cables insulation		Web platform. Economic assessments. Life cycle assessment methodology	2018	[38]
Sweden	Small town in southern Sweden		Sawmill, paper mill, paper processing industry, local energy service company, the municipality, ecocycle company, and local waste management company	Waste heat, sawdust, bark, woodchips, ashes, sewage sludge, organic waste materials, paper residues, and fibre residues		Conversational and open-ended interviews and group discussion, direct observation and participation at the sites, mass and heat balances over the system	2005	[68]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Sweden		4	Chemical pulp mill, sawmill, biofuel upgrading plant, and district heating system			Method for analysis of industrial energy systems (MIND method), based on mixed integer linear programming	2008	[69]
Sweden		4	Chemical pulp mill, sawmill, biofuel upgrading plant and district heating system	Bark, steam, heat, chips, and sawdust		Method for analysis of industrial energy systems (MIND method) based on mixed integer linear programming. Commercial optimization solver (CPLEX). Assessment of CO_2 emissions from biofuel and electricity for different accounting models (marginal coal, marginal new technology and average Swedish production)	2008	[70]
Sweden	Luleå, Borlänge, Finspång, Sandviken		Iron and steel industry (integrated steel plant and scrap-based steel plant), pulp and paper industries, district heating consumers, and district heating distributor	Excess heat and gasified biomass residues		System perspective evaluation	2011	[71]
Sweden	All 290 municipalities		Agriculture, forestry, and fishing; mining and quarrying; manufacturing; electricity, gas, steam and air conditioning supply; water supply; sewerage, waste management and remediation activities; and construction			Looplocal method, life cycle inventory	2015	[72]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Sweden	Västra Götaland		Waste incinerators, steel mill, cement industry, manufacture of concrete products industries, polymer industry, algae production, power stations, refineries, paper and pulp industry, municipal and industrial wastewater treatment plants, biogas upgrading plants, greenhouse operator, and methanol production unit	CO_2, fly ash, bottom ash, steel slag, municipal solid waste ash, wastewater, and hydrogen		Top-down approach with three consecutive steps: generic matrix of CO_2 sources, generic matrix of CO_2 receivers, and matching the sources with the receivers at regional level	2017	[73]
France	Territoire de la Côte Ouest, Réunion Island		Agricultural activities, fertilizer production facility, market gardeners, and complementation and granulation factory	Livestock wastes (pig manure, droppings from broiler chickens, and laying hens) and shredded green waste		'Follow the Technology' method and Companion Modelling or Commod	2017	[74]
France		7		Waste/unused energy		Mixed integer linear programming; single objective model to minimize the total cost, single objective model to minimize the total environmental impact and bi-objective model to minimize the total cost and total environmental impact; direct method to quantify the heat energy of firms; key process indicators: demand satisfaction, weighted demand satisfaction, supply utilization, and carbon tax reduction; uncertainty evaluation using sensitivity analysis; multi-objective model and Pareto front analysis; weighted sum method	2018	[75]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
France	Gravelines, Penly, Fessenheim, Tricastin, St Alban, Nogent sur Seine, Civaux, St Laurent des Eaux, Bugey, Chinon, Blayais, Chooz, Cattenom, Flamanville, Paluel, Golfech		Nuclear plants, agri-food industries (fruit and vegetables, dairy products, starch products, sugar refinery and malt production), wood, pulp and paper (wood panels, pulp and paper, card and paper and corrugated card), chemical and pharmaceutical industries (dyes and pigments, other basic organic chemicals and basic pharmaceutical products) and plastic, rubber and other elastomers (basic plastic materials and synthetic rubber)	Steam		Average energy intensity in a subsector, production value, average heat consumption of a factory in a subsector, and heat consumed by a factory in a subsector; spatial mapping methods and geographical information system; techno-economic model: energy consumption sub-model (maximum thermal power required), energy generation sub-model (infrastructure cost of a combined heat and power upgrade, required cost, and additional CO_2 emissions to compensate for power generation losses), and energy distribution sub-model (pipe diameter, heat loss assessment, pumping cost, CO_2 assessment, pipeline installation cost, and annual rental cost); linear programming problem	2018	[36]
France	Salaise-sur-Sanne and Sablons		Chemical, recycling and raw material transformation, and urban areas	Industrial waste	Shared infrastructures (for energy supply, cogeneration, solid waste treatment, reclaimed water, etc.)	SWOT analysis	2018	[76]
Finland	Oulu		Steel, pulp and paper industry, cement products manufacturer, soil amendment, soil fertilization, and pellets/ameliorants manufacturers	Granulated blast furnace slag, ashes, fibre clay, and alkaline residues		Literature review and study of a spectrum of residue-based product concepts for further research	2010	[77]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Finland			Waste management, wastewater treatment, municipality, biogas producer, crop farm, and animal farm	Sewage sludge, manure, organic household waste, and digestate		Interviews with companies, collaborative research approach, replication approach	2015	[78]
Finland			Horse industry, agriculture and pellet production industry	Horse manure		Survey sent to companies	2018	[79]
Greece	Viotia		Aluminium casting company, and companies which have capacities to buy and use aluminium waste	Aluminium waste		Ontology engineering approach—eSymbiosis. Metrics for industrial symbiosis benefits: Economic: cost savings to business, and additional sales to business; Environmental: landfill diversion, CO_2 reduction, virgin raw materials saved, hazardous waste eliminated, and water savings; Social: jobs created, and jobs saved	2015	[80]
Greece	Pili		Power plant, furniture manufactures, sewage treatment plant, concrete industry, and food industries	Sawdust, ash, whey of cheese dairies, and salad residues	Utility sharing: autonomous water supply system	Methodology proposed and implemented to determine the most appropriate location and bioclimatic criteria	2017	[81]
Greece	Achaia		Olive-oil production facility, biopolymers (PHAs) production facility, and plastics production facility	Olive mill wastewater and PHAs		Telephone interviews, visits, and face-to-face interviews	2017	[82]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Germany	Rhine–Neckar				Network structure, waste management software, waste analyser software, and intranet platform	On-site surveys	2004	[83]
Germany	Central Germany		(i) Lignocellulosic biorefinery plant, and chipping; (ii) lignocellulosic biorefinery plant, chipping, refinery plant and waste wood–fired CHP units; (iii) lignocellulosic biorefinery plant, waste wood–fired CHP units, refiner plant, chipping, bio-based resins and adhesives, wood panel production, composite manufacturing, and engineered wood products	(i) Beech wood chips from industrial residues; (ii) waste wood, bark residues, and sawmill by-products; (iii) residues from industrial wood		Communications and site visits, life cycle assessment and CML 2013 method, indicator assessment for the CML impact categories and relative advantage or disadvantage of the environmental impact	2018	[84]
Scotland	Perth and Kinross		Sawmill, pellet mill, and combined heat and power plant	Milling wood residues, sawdust, and residual wood fibre		Questionnaires to estate owners, forestry consultants, wood processors and equipment suppliers, and five focus groups with 45 residents	2007	[85]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Scotland	Perth and Kinross		Forest industry, sawmill, combined heat and power plant, and wood pellet mill	Woodchips and sawdust		Questionnaire survey of representatives from the wood fuel supply chain and an attitude survey of a sample of off-mains gas residents	2007	[43]
Spain	Besaya	80	Commerce, repair of motor vehicles and motorcycles, manufacture of basic metals and of fabricated metal products, construction, manufacture of mechanical machinery and equipment, manufacture of paper and paper products, printing and reproduction of recorded media, manufacture of other non-metallic mineral products, other manufacture activities, manufacture of food products, beverages and tobacco products, transport and storage, manufacture of chemicals and chemical products, manufacture of wood and of products of wood and cork, manufacture of rubber and plastic products, and manufacture of transport equipment	Waste oil, used metal containers, used coolants, ink slag, waste sand, rubble and waste material from construction, solid wastes (plastic, discarded tires, wood cuttings and slag from varnishes and paint), waste products from oils and grease (food, machining, hydraulics, motor, separators), lime-based waste products (plasters and slag), waste products from plastic (plastic, shavings and burns), waste products from ferrous metals (ferrous metals, ferrous metal filings and shavings, scrap metal), waste products from glass, waste products from lead batteries, waste products from used tires and slag, waste products from catalysers, waste products from wood without hazardous substances, waste products from ceramic materials (roof tiles, ceramic materials, bricks), waste products from plaster, waste products from cellulose, and waste products from food	Joint waste management: central areas for communal waste storage, shared use of waste storage space, shared transport of waste to municipal management points, joint management of waste products for sale or exchange, joint management of waste by an external agent, and shared use of waste treatment and recovery installations	Questionnaires and visits to various companies	2015	[86]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Spain	Cartes, Cantabria autonomous community	25	Automotive industry, metallurgy and manufacturing, building industry and other various manufacturing industries	Edible oil and fat, paper and cardboard packaging, etc.	Service or infrastructure: common transport and waste collection and waste treatment services	Relational database management system, georeferencing, geographic information systems, and application programming interface; SymbioSyS tool	2017	[87]
Lithuania	Jonava		Nitrogen fertilizers and chemical products manufacturer company, cattle farms, slaughterhouses, municipal wastewater treatment plant, bio-fuel production and/or solid recovered fuel production in pellet form company, administration, and special purpose facilities	Waste heat energy, biodegradable waste (manure and slurry), and sewage sludge		Material flow analysis, material and energy balances of each processes, fuel and energy balances of energy production processes, evaluation of environmental indicators (relative environmental indicators, energy savings, loss of waste heat energy and volume of carbon dioxide emissions) and comparative analysis; feasibility analysis (technical, environmental and economic evaluation)	2016	[88]
Lithuania			Nitrogen fertilizer production company, cattle farms and slaughterhouses	Biodegradable waste		Indicators: geostrategic supply risk and economic importance	2018	[89]
United Kingdom			Bio-refineries, agricultural production, and forestry	Lignocellulose and municipal solid waste (organic food and packaging)			2008	[90]
Norway	Mongstad	6	Refinery plant, coal gasification, combined heat and power plant, production of synthetic transportation fuels, carbon capture and utilization, and aquaculture	CO_2 and waste heat		Mass and energy balance assessment, material and energy flow analysis, carbon and hydrogen flow analysis, CO_2 emission evaluation, and sensitivity analysis; hierarchy analysis method	2008	[91]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
England	Thames estuary, Port of Bristol, east Birmingham, Mersey estuary, and Teesside				Utilities-sharing	Habitat Suitability Mapping: Habitat Suitability Index, Geographic Information System model, Symbiosis Suitability Index, Symbiosis Suitability Map, Symbiosis Suitability Index Variables and Variable Aggregation, and Multi-Criteria-Evaluation mapping. Sensitivity analysis	2012	[92]
Finland and Sweden	Gulf of Bothnia	7	Carbon steel mills, stainless steel mill, zinc plant, and iron regeneration plant	Iron and zinc dusts and scales, jarosite, direct reduced iron, zinc oxide, and manganese dregs		Strengths and weaknesses assessment in national and European Union waste regulation and common pool resource management analysis	2012	[93]
Latvia		2	Brewery and biogas plant	Brewer's spent grain		Site visits. Cumulative intensity indicator of a considered factor (energy consumption and CO_2 emission generation)	2015	[94]
European country			Sugar-beet production, microalgae cultivations, and agro-energy sector	CO_2 and water effluents		Concept analysis	2015	[95]
Romania	Botosani and Neamt		Manufacture of profiles and fittings from steel, manufacture of ceramic sanitary fixtures, institutions and small businesses (tourist pensions, offices, kindergartens, etc.), construction of residential and non-residential buildings, supply of steam and air conditioning, manufacture of garments, manufacture of furniture, agriculture, collection, purification and distribution of water, and retail sale of audio/video equipment in specialized stores	Hot gas	Infrastructure for utilities and supply process optimization	Interviews with the board, or the manager, of each company	2017	[44]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
				Asia				
China	Handan		Heavy chemical industry, cement industry, coal chemical industry, iron and steel industries, building materials factory, power plant, agricultural production, aquaculture, and urban heating	Fly ash, grey water, coal gangue, PVC profile processing waste, waste water, waste heat, and steel slag			2009	[96]
China	Shanghai City and Jiangsu Province		Cement and steel industries, urban areas and industrial sectors	Municipal wastes (plastics and organic wastes) and by-products from industries		Divisia analysis: total output and energy intensity of each sector and "Divisia" index approach; energy demand analysis and regression analysis: regression equations using the Vector Auto-regression model defined for forecasting gross regional product, population, energy consumption, and cement and steel production	2011	[97]
China	Jinqiao		Central heat-supplying company, waste treatment company, enterprises, and wastewater treatment plant	Sewage sludge and used oil		Experiments in a laboratory, life cycle assessment (global warming potential, acidification potential, eutrophication potential and human toxicity air), total environmental impact potential	2011	[98]
China	Yunfu	3	Sulphuric acid industry, chemical enterprise, and power plant	Sulphur acid, residue steam and heat		Production cost and sale revenue analysis	2011	[99]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
China	Shenyang		Equipment manufacturing industry and logistics industry			Coefficient of industrial agglomeration degree, Space Gini coefficient, and Hector Fanta coefficient of an industry; logistic model. Index of competitive analysis; expert evaluation method; relational degree taxis	2012	[100]
China	Guiyang		Iron/steel industry, cement industry, coal chemical industry, phosphorus chemical industry, aluminium industry, power plants, and commercial and residential area	Steel slag, slag, red mud, waste steel, waste plastics, coal gangue, coal fly ash, and waste heat		Questionnaires. Material flow analysis, environmental benefit evaluation (avoided resource consumption or avoided waste emission due to the symbiotic activity) and CO_2 emission reduction, effects of resource efficiency enhancement, cost reduction	2015	[39]
China	Guiyang		Iron/steel industry, coal chemical industry, phosphorus chemical industry, aluminium industry, cement industry, power plants, and commercial and residential area	Steel slag, slag, red mud, coal gangue, coal fly ash, waste heat, waste steel, and waste plastics		Questionnaires, material/energy flow analysis. Process life cycle assessment, avoided consumptions and emissions for a company, CO_2 emission reduction from the avoided resource or waste in a company, hybrid physical input and monetary output model hybrid life cycle assessment model integrating both process life cycle assessment and input–output model, life cycle emissions change. Scenario analysis.	2016	[9]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
China	Hangu, Tanggu, and Dagang Districts, Tianjin Municipality		Seawater desalination plant, sea salt production, mariculture, power plant cooling, Artemia culture, bromide extraction, and salt chemical industry	Clarified seawater, concentrated saline, and bittern		Satellite images analysis, geospatial data processing and analysis software, manual visual interpretation, and landscape type classification system	2015	[101]
China	Liuzhou	5	Iron and steel making, power generation, ammonia, carbonate production, cement and construction material manufacturing companies, and communities	Waste plastics recycling, scrap tire recycling, coal flying ash recycling, biomass utilization, and carbon capture by slag carbonization		Questionnaires, collaboration with national and local governmental agencies, institutes, and industrial persons; onsite survey. Research meetings and expert reviews; urban level hybrid physical input and monetary output model; hybrid evaluation model integrating process-based life cycle assessment and input-output analysis; calculation of increased or avoided consumption, and emission in the industrial symbiosis process and each related sector; trade-off emission; scenarios design	2017	[37]
China	Liuzhou		Iron and steel company, power plant, chemical company (ammonia production), hydrogen manufacturing, cement and construction material manufacturing companies, central heating for the residential sector, nearby plants and communities	Metallurgical gas, waste heat, waste plastics, scrap tires, and coal flying ash		Onsite survey, analytical approach integrating material flows analysis (includes material and energy flows analysis) and emergy evaluation model, avoided consumption and emissions for a company and CO_2 emission reduction, emergy evaluation index and dilution emergy	2017	[10]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
China	280 proper cities and 357 county-level cities		Electric power plant, cement plants, steel plants, district energy, residential and commercial buildings, food/beverage, and other low temperature industries	High-grade, medium-grade and low-grade waste heat, fly ash, and steel slag		What-If scenario modelling approach. Cross-sectoral symbiosis modelling though energy cascading and material exchange. Energy cascade algorithms. Material-exchange algorithms. Estimating reductions in fuel use, CO_2 and PM2.5 emissions at different scales, life-cycle analysis and national-economy-wide economic input output-based life-cycle analysis. PM2.5 Pollution and health benefit calculations and AERMOD atmospheric dispersion modeling system	2017	[102]
China	Wuhan		Pulp and paper industry, city greening, agriculture, paper downstream industries including printing, publishing and other corresponding industries, wastepaper collection and disposal industry, and wastewater disposal industry	Wastewater, sludge and waste paper		Integrated life cycle management assessment method on the resource flows of industrial ecosystem including the eco-environmental assessment by the life cycle assessment and the sustainable use assessment by an indicator system	2019	[103]
South Korea			Iron and steel industry: galvanized and aluminized steel sheets producer, electrolytic steel plates producer, and reinforced material producer for automobile tires	Wastewater		Mathematical optimization model. General algebraic modeling system software. Life cycle assessment and life cycle costing. Estimation of present value	2010	[104]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
South Korea			(i) magnesium plant and cement plant; (ii) magnesium plant and urban area	(i) waste slag; (ii) waste energy resources (waste wood, waste plastic and waste tire)		Interview with magnesium production-related specialists. Quantitative estimation of CO_2 emissions: CO_2 emissions from fuel combustion, CO_2 emissions from transportation, CO_2 emissions from electricity consumption and limestone calcination-related CO_2 credits. Uncertainty analysis	2015	[105]
South Korea	Ulsan		Industries, factories and companies and/or urban area (residential and non-residential buildings such as hypermarkets, department stores, office buildings and hospitals)	High and low-grade waste heat		Manager interviews. Scenarios analysis. Heat load analysis procedure (estimation of gross floor area of a building, calculation of heating and cooling area, connected heat load, and peak heat load, and estimation of heat demand quantity of the target region). CO_2 emission reductions from the avoided fuel in the company. Fuel cost reduction from the avoided fuel in the company	2018	[106]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Japan	Shinchi Town, Fukushima Prefecture		Coal-fired thermal power plants and plant factories	Waste heat		Technical and economic feasibility assessment, sensitivity analysis, cost-benefit assessment and spatial analysis. Energy generation model: influence on power generation efficiency, electricity loss for extracting heat energy, and required cost and additional CO_2 emissions to compensate for power generation losses. Energy distribution model: heat loss evaluation, pumping cost and CO_2 evaluation (energy consumption of the system, required cost, and additional CO_2 emissions in the operation of a pumping system), and pipeline installation cost (pipeline installation cost and annual rental cost with a discount rate method). Energy consumption model: estimated energy consumption due to heating in a plant factory	2014	[107]
Japan	Shinchi Town, Fukushima Prefecture		Natural gas power plant, coal-based thermal power plant, ceramic factory, chemical factory, urban area and greenhouse type plant factory	Waste heat		Model framework including energy system design, land use scenario, inventory survey and geographic analysis. District heating network design and simulation: hydraulic analysis, pipeline diameter, pressure drop, necessary pumping power and temperature drop. Cost-benefit assessment: economic costs (heat distribution cost, heat transport cost and management and maintenance cost), benefit of fuel cost reduction and CO_2 reduction. Sensitivity analysis	2018	[13]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Japan	Tanegashima		Combined heating and power plant, sugar mill, wood production industry, wood chip factory, wood pellet factory, and forestry industry	Waste heat, sugarcane bagasse, thinning residues, sawmill residues (sawdust and bark), and wood chipping residue (bark)		Interviews and discussions with the on-site experts and stakeholders. Scenario Analysis. Energy flow analysis. Greenhouse gas emissions based on life cycle analysis. Adjusted environmental load for a scenario	2016	[108]
Malaysia		4	Palm oil mill, palm oil-based biorefinery, and combined heat and power plant	Empty fruit bunches, palm mesocarp fiber, palm kernel shell, wet short fiber and dry short fiber		Disjunctive fuzzy optimization approach. Overall degree of satisfaction, annual gross profit, net present value, and payback period of a processing plant	2014	[109]
Malaysia			Various types of industries within the Halal Park		Cooperative safety management	Open-ended interview with seven industrial safety experts	2014	[110]
Malaysia	Kedah		Fertilizer industry, rubber block processor, tire producer, glove manufacturer, electricity co-generation, biomass disintegration, cement concrete industry, polymer asphalt binder industry, wastewater integrated facilities and methane recovery unit	Ammonia nitrogen waste, rubber waste, waste water from cooling system, rejected glove pieces, rubber traps, sludge and rubber woods, rubber latex waste and waste water	Co-generation unit for electricity, wastewater integration unit, methane development unit, and central storage unit	Questionnaires. SWOT analysis. Materials Flow Analysis and the Input-Output data based on previous Life Cycle Analysis data	2017	[111]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Turkey	Gaziantep		Manufacturing of textile products, food products, rubber and plastic products, leather products, chemicals and chemical products, other metallic and mineral products, ready-made clothing, furniture, fabricated metal products, paper and paper products, and wood and wood products, basic metal industry, production and distribution of electricity, gas, steam and aeration systems, and collection, disposal and recycling of wastes	Used carpets, PET wastes, animal hides, carpet and textile fibrous waste, waste polyurethane and ethylene-vinyl acetate, flax fiber residues, polyester and polyurethane based textile wastes, cotton and polypropylene fiber based textile wastes, dairy by-products, waste tyre rubber, granular and fibrous particles from a range of plastic, rubber and textile waste, wastewater treatment sludge, waste foundry sand, calcium carbonate wastes, polyvinyl chloride wastes, polyurethane foam wastes, waste polyvinyl alcohol, polypropylene-based plastic wastes, waste paint, waste glass, red mud, polypropylene-based carpet wastes, food processing wastes, dust, waste rubbers, black glass waste, acrylic butyl styrene, dried sludge, organic wastes (pistachio processing wastes, food processing wastes, etc.), synthetic shoe processing wastes, and waste heat		Industrial symbiosis match-making platform (ESOTA®, Industrial Symbiosis Opportunity Screening Tool). Assigning NACE and EWC codes to industries and wastes. Company and stakeholder visits, stakeholder analysis and workshops	2017	[112]
Turkey	Ankara	10	Machining, metals and metal processing, rubber, painting and plating sectors	Waste heat		Tool for defining data about companies and process, cleaner production potential and costs and environmental impact graph of processes. Analysis of mass balance and all materials for process work flows	2018	[113]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
India	Puducherry		Sugar, paper, galvanizing, granite, and gypsum industries, etc.			Survey method with open-ended questions. Analytical methods: trend analysis, causal chain analysis, policy analysis, training needs assessment, technology needs assessment and barrier analysis. Content analysis. SWOT analysis	2015	[114]
Bangladesh	Chittagong Export Processing Zone		Garments manufacturing company, textile mills, towel manufacturing company, shoe accessories company, power generation and distribution company, crown mills, incineration plant and purification plant	Waste heat, solid waste and wastewater		On-site energy audit and equipment/waste emission survey. Visits to companies. Input and output analysis. Feasibility analysis (techno-economics and environmental feasibilities assessment). Business model development	2015	[115]
Philippines	Laguna					Questionnaires and survey with ten participants from different sectors of the industrial park. Decision Making Trial and Evaluation Laboratory	2016	[116]
North America								
USA	Johnston, Chatham, Lee, Orange, Durham and Wake Counties, North Carolina	87	Pharmaceutical, computer, telecommunication equipment manufacturers, resin manufacturer, amino acids manufacturing, and tool manufacturing industries and municipal wastewater treatment plant	Acetone, carbon, desiccant, hydrochloric acid, methanol, packaging materials, plastic bags, sawdust, sodium hydroxide, wood ash, wood chips, wood fluff, absorbents, blasting media, coal ash, conveyor belts, copper, drums, electricity, ethanol, fiberglass, floppy disks, food waste, foundry sand, furniture fluff, glass vials, ink, paint, plastic, rubber blankets, steam, steel, sulfuric acid, unheated water, wire and wood		Telephone calls, in-plant interviews and site visits. Discussions with multiple potential suppliers and users and brainstorming sessions with local manufacturing experts. Geographic information system maps with an associated project database	2001	[60]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
USA	Texas		Recycling, remanufacturing and waste treatment firms	Commercial, industrial and municipal waste		Questionnaire survey of a sample of recycling, remanufacturing and waste treatment firms. Modified total design method	2005	[117]
USA	Pittsburgh		Roadway construction and/or repair, steel and iron industry	Coal ash, foundry sand, and slag		Geographic Information System data; highway density map, road density, and total highway density; optimization analysis; life cycle analysis (Pavement Life Cycle Assessment Tool for Environmental and Economic Effects program); transportation cost analysis	2008	[118]
Canada	Ontario		Solar photovoltaic manufacturing plant, glass manufacturing plant, glass recycling facility, greenhouses, and grow rooms	Crushed cullet, waste heat, and CO_2		Inputs and outputs analysis	2009	[119]
				South America				
Brazil			Agricultural activities, livestock sector, and alcohol-chemical industry	Industrial by-products, animal waste, straw, ashes, and bagasse		Economic evaluation; indexes of economic efficiency: financing, liquid present value, internal return tax, contribution margin, economical revenue, return time, equilibrium point, and accumulated cash register flow; environmental and social analysis; emergy method; emergy indices: transformity, emergy yield ratio, emergy investment ratio, environmental loading ratio, renewability, and emergy sustainability index	2007	[120]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Brazil	Norte Fluminense region	14	Sugarcane farm, sugar and ethanol production facilities, combined heat and power generation unit, biorefinery consisting of the Pre-treatment & Separation, Saccharification & Co-fermentation, and Concentration & Recovery units, soft drink production, distilled spirits production, animal feed production, industrial surfactants production, effluent treatment facility and biogas production unit, adhesives manufacturer, wax production, and lube oil re-refinery	Bagasse, straw, filter cake, vinasse, CO_2, fusel oil, used yeast, ash, lignin, pentose, mother liquor, flue gas and particulate matter, molasses, bio-SA off-specification, diluted salt effluent, off-gases (non-recycled portion), used lube oil, and other effluents		Interviews with stakeholders and coordinators and visit to the mill facilities; scenario analysis, mass balance, synergy matrix, and material flow analysis; environmental, social, and economic indicators: waste emission reduction, greenhouse gases savings, potential job creation, and feedstock remuneration premium from bio-SA production	2018	[121]
Colombia	Bogotá, Tocancipá, Sopó, Soacha, El Rosal, Cajicá, Madrid, Mosquera, Cota, Chía, Bojacá, San Francisco, Funza, Nemocón, Saboyá	34	Food processing (coffee), engineering, construction, waste management, beverage (soft drinks), chemical (specialty, agriculture polyethylene films), packaging, container, gas supply, food (dairy, bakery and snacks), glass, agriculture (flower, poultry, mushroom), construction supplies, Styrofoam, construction and home supplies, furniture, flower, consulting, cosmetic, wood, and restaurant	Wood from stowage, plastic waste, polystyrene foam, cardboard boxes, coffee residues, paper, cardboard, glass, sludge/fertilizer, fruit syrup, food residues, wood waste, mycelium, sawdust, plastic waste/geomembrane, Styrofoam, and drainage water	Service sharing: sludge management and shared collection of hazardous waste	Workshops with companies, observations, surveys to the representatives with questions that require evaluations and open answers and semi-structured interviews	2018	[34]
Africa								
Liberia	Konia		Piggery, rabbit farm, fishponds, rice mill, anaerobic digester, garden, and guest house	Rice bran, manure, and biogas digestate	Fishponds	Interviews with a Liberia nongovernmental organization staff; optimization model: maximum number of people supported per year	2014	[45]

Table A1. *Cont.*

Country	Location/Region	NE [1]	Activity	Waste/By-Products	Infrastructure Sharing/Joint Provision of Services	Method	Publication Year	Refs.
Mauritius			Slaughterhouse, edible oil refinery, scrap metal recycling plant, cement manufacturer, wastewater treatment plant, construction products manufacturer, plants operating a boiler, biogas production plants, composting plant, animal feed manufacturer, and agro-industry	Scale, spent bleaching earth, sludge, slag, dust, and paunch manure		Desk analysis, interviews to recyclers, officers at the Ministry of Environment, Sustainable Development, Disaster, and Beach Management and environmental officers, and framework for adopting industrial symbiosis	2017	[122]
Egypt	Borg El-Arab		Food industry, textile factories, wood factory, metal factories, factories for paper products, construction materials factory, chemicals and pharmaceuticals factories, plastic factories, electrical and engineering products factories, brick production factory, animal feed production and fish farms, and organic fertilizers and soil amendments factories	Suspended solid particles, alkaline industrial drainage, chemicals packs and barrels, food residues (organic wastes), gypsum, metal scrub, paper sacks and chips, PVC residues, sawdust, plastic flashes, and wooden pallets		Data from internal unpublished sources at the Ministry of the Environment of Egypt	2018	[61]
				Oceania				
Australia	New South Wales		Serpentinite mining industry, carbonation plant, power generation plants, iron and steel making, and cement and concrete production	CO_2, waste ash, slag, tailings, and fly ash		Aspen modelling	2012	[123]
Australia	Kwinana	12	Titanium dioxide plant, fused materials company, refractory manufacturing industry, coal-fired plant, aluminum industry, chemical manufacturing, construction industry, water supply and treatment company, cement manufacturer, steel market mills, refinery, and fertilizers company	Petroleum coke, phosphate rock digestion off-gases, nitrogen oxides waste gases, and calcium chloride		Triple bottom-line perspective and preliminary sustainability assessment (social, economic, and environmental)	2013	[124]

[1] NE: Number of enterprises

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Chapter 5

Industrial Symbiosis Initiatives in United States of America and Canada: Current Status and Challenges

This chapter consists of the following article:

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Industrial Symbiosis Initiatives in United States of America and Canada: Current Status and Challenges

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Abstract—**Industrial symbiosis ties companies from all business sectors with the aim of improving the efficiency of resources at an intersectional level through the commercial exchange of materials, energy and water and sharing assets, logistics and experience. It involves industries and other organizations that have always been separated in a collective approach to achieve competitive advantages that imply the physical exchange of materials, energy, water and by-products together with the shared use of goods, logistics and experience. This model raises the need to address a new perspective in the production of waste, its recovery and reuse, reducing the environmental impact and generating new business models that positively impact the economy of a region. This paper aims to analyze the industrial symbiosis initiatives in USA and Canada published by the research community in order to assess the current status, its challenges, successes and failures.**

Keywords-industrial symbiosis; eco-industrial park; industrial ecology; industrial ecosystem; circular economy

I. Introduction

The idea of industrial parks with zero residues is the starting point of the concept of industrial symbiosis. In this type of initiative, generated mainly by the pressure exerted by the costs of disposal of waste, more restrictive environmental regulations and concerns about environmental degradation has led several companies to review their strategies [1].

One of the key points of the concept of industrial symbiosis is the mutually beneficial relationship between companies and organizations that are part of an industrial ecosystem, where a company uses the waste of another as new inputs for productive processes [2].

The industrial symbiosis allows a company to benefit from the "leftover" resources of its activity (by-products, waste, heat, rainwater, warehouses, logistics, etc.), selling them to a nearby company or exchanging them for others that are necessary. This approach allows reducing the cost of waste management and the subproduct for the producer and the cost of raw materials and energy. In the end, it could have a significant reduction in environmental impact. Thus, industrial symbiosis consists in identifying and materializing synergies between industrial activities that minimize underutilized or residual elements, achieving economic and environmental benefits [3].

There are other benefits to be had, such as environmental improvement, innovation that involves rethinking how things are done, and the fact of making efficient management of resources, extending their useful life.

Several examples of the industrial symbiosis concept already exist [4]–[6]. Industrial ecosystems already exist on six continents and have already been incorporated as a strategic tool for economic development, green growth, innovation and resource efficiency. In Europe, for example, the Roadmap to a Resource Efficient Europe recommends Industrial Symbiosis for all members of the European Union in order to generate gains and benefits in the management of resources [7].

The OECD also recognizes industrial symbiosis as a systemic innovation for green growth. China, has had a program of eco-industrial parks since 2001, with 60 industrial sites deployed with the vision of Industrial Symbiosis as a background and, furthermore, as a fundamental strategy for promote resource efficiency and reduce pollution [8].

The symbiosis from the biological realm is a metaphor adopted for the industrial symbiosis term with the aim to encourage industries that have always been separated to cooperate together for mutual benefit. If this type of symbiosis is applied to the industry, there are endless opportunities to group companies for mutual benefit [9].

The industrial symbiosis is a relatively new term. An example is the city of Kalundborg in Denmark, where a series of industries, such as a power plant, an oil refinery, a gypsum factory, a chemical and pharmaceutical companies, began little by little to exchange by-products, which allowed them to save resources to and reduce the environmental impact of their waste [10].

The ideal environment where there are concentrations of companies and where it is easier to carry out this analysis are the industrial parks. However, there are mainly two barriers that must be overcome in order to advance in the industrial symbiosis. The first is the lack of cooperation or the sharing of knowledge and experiences among neighboring companies. The second is the certain legal obstacles that obstruct the implementation of innovative methods to be implemented.

To overcome these obstacles, locations could be created inside the industrial parks in which companies can explain success cases, raise problems, doubts, and propose initiatives. However, in order for it to succeed, a dedicated individual who collects the information of each of the companies and analyze it from a global point of view must exist.

In [11] it is argued that majority of the industrial symbiosis efforts were unsuccessful due to the reason that industrial ecosystems bear a resemblance to complex adaptive systems, which are exposed to constant alterations, thus making hard to keep the industrial symbiosis relationships between the involved organizations. The current obstacle is to take into account this complexity.

One of the possible solutions to this challenge could be the implementation of the industrial symbiosis as a line of industrial ecology, which includes concepts such as life cycle analysis, ecological accounting and ecological production. It can be considered as a metaphor of nature according to which if we organize ourselves in the industrial world more like nature, thus becoming more sustainable [12].

In the field of industrial waste and through this concept there is a great opportunity for business innovation since it comprises a change of paradigm that has economic benefits for the public sector as well as private and certainly for the environment.

This paper aims to analyze the industrial symbiosis initiatives in United States of America and Canada published by the research community in order to assess the current status of industrial symbiosis in this region of the world and to study its challenges, successes and failures.

This paper is organized as follows. In section II the methodology used to find the United States of America and Canada case studies is described. In section III each case study is identified and described. In section IV the successes and challenges of industrial symbiosis are analyzed. Finally, in section V the concluding remarks are given.

II. Methodology

Several steps were made in order to make a wide-ranging review of the available literature. The first step is to "identify, evaluate, and synthesize the existing body of concluded and published studies shaped by researchers, scholars, and practitioners" [13]. Therefore, in this paper the second step is to identify the distribution of case studies of industrial symbiosis around the world. The third step is to select the case studies that analyze the industrial symbiosis initiatives in United States of America and Canada and to classify them according to their characteristics and the methods used.

Firstly, the identification and analysis of every publication is made. This search research was completed by employing the most known and significant publishers, such as Wiley Online Library, Elsevier, Springer, Taylor & Francis Online, ACS Publications, Inderscience Online, IEEE Xplore, MDPI, SAGE Journals, Nature Research, and Emerald Insight. With the purpose of identifying the highest quantity of publications, the keyword utilized in this search was "industrial symbiosis". For this study, the search comprises the following types of papers: reviews, research articles, conference papers, editorials, book chapters, short communications, encyclopedia articles, product reviews, and opinion articles. Papers that were not published in English were excluded from this study.

The final number of identified publications is 539 articles. After the identification of all the publications, they were classified according to the content type.

For this study, only the case study papers are relevant. Case studies were the second type of paper that is most common when classified according to the content type. A total of 166 case study papers were identified, corresponding to 31% of the entire set of publications. The diversity of the case study papers is high concerning the type of industrial activity, location, utilized methods and formation of symbioses.

In Figure 1 it is possible to observe the classification of the number of case study papers per country. From this figure, it is possible to assess that the country with the most case studies is China, and it is followed remotely by United States of America in the second place.

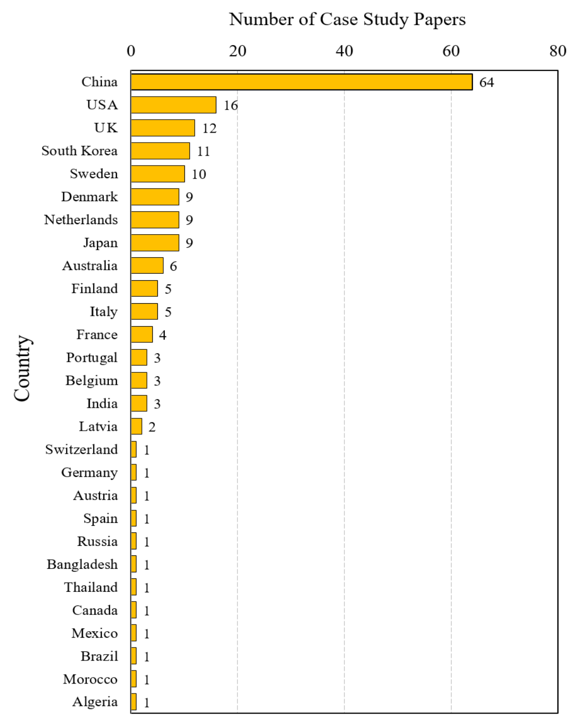

Figure 1. The number of case study papers per Country.

III. Industrial Symbiosis Initiatives in United States of America and Canada

From the review made above only the case studies that analyze the industrial symbiosis initiatives in United States of America and Canada were selected. The classification of the aforementioned case studies according to the type of industrial units and the utilized methods can be seen in Table I, as well as the year of publication and region of the case study.

TABLE I. THE LIST OF THE IDENTIFIED CASE STUDIES

Country	Region	Nº	Type of Industrial Units	Type of Study	Year	Ref.
USA	Guayama, Puerto Rico	-	Coal-fired power plant, public wastewater treatment plant, petrochemical refinery, and waste stabilization	Interviews	2005	[14]
USA	Barceloneta, Puerto Rico	15	Pharmaceutical manufacturing facilities, hay farm, animal feed producer, paint manufacture, energy recovery, wastewater treatment facility, and waste management firms	Interviews, social network analysis	2008	[15]
USA	Barceloneta, Puerto Rico	-	Pharmaceutical firms, hay farm, animal feed producer, paint manufacture, energy recovery, wastewater treatment facility, and waste management firms	In-person and telephone interviews, congruence method, and integrated framework based on economic geography, industrial ecology, and complex systems theory	2009	[16]
USA	Barceloneta, Puerto Rico	-	Pharmaceutical manufacturing facilities, hay farm, animal feed producer, paint manufacture, energy recovery, wastewater treatment facility, and waste management firms	Open-ended interviews and in-person semi-structured interviews	2011	[17]
USA	Pennsylvania	-	-	Evaluation of the difference in environmental impacts (primary energy and emissions) between reuse and production of the substituted material using the life cycle inventory databases of GREET and Ecoinvent	2009	[18]
USA	Honolulu	11	Coal-fired power plant, oil refinery, city water recycling plant, concrete production company, quarry, construction and demolition waste landfill, city water agency and recycling company	Interviews. Quantification of environmental benefits (changes in consumption of natural resources, and emissions to air and water), and economic benefits (revenue streams from by-products, disposal costs avoided, reductions in raw material and transportation costs).	2010	[19]
USA	Honolulu	11	Biosolids beneficiation company, local golf course, wastewater treatment plant, oil refineries, power plant, oil and tire recovery company, municipal water authority, cogeneration plant, cement company, and private construction and demolition waste landfill	Life cycle assessment	2013	[20]
USA	Kansas City	9	Synthetic resins and plastics materials producer, long steel producer, greeting cards and gift products company, motorcycle manufacturer, solid waste treatment, electric utility company, construction materials company, organic recycling facility, and provider of by-product co-processing services	Material flow network and mixed integer programming model	2011	[21]
USA	North Dakota	-	1st generation bioethanol and combined heat and power plants	Interviews, surveys, and direct observations. Stochastic mixed integer linear programming model, Sampling average approximation. Bioethanol production, economic, GHG emission, irrigation land usage, water usage, and energy efficiency analysis	2015	[22]
USA	Upper Valley	2	Solid waste resource management company and manufacturer	Interviews	2017	[23]
USA	Chicago	-	Real estate developer, education, research and development, agriculture/farming, consulting, compost collection, beverage producers and food producers	Measurements of material and energy flows on-site and off-site, interviews, routine observations, questionnaires, and material flow analysis	2018	[24]
USA	New York/New Jersey	-	Port-based industrial complexes	On-site visits, and individual or collective interviews performed on site	2014	[25]
USA	Long Beach	-	Ports and marinas			
USA	Barceloneta, Puerto Rico	-	Pharmaceutical firms, hay farm, paint manufacture, energy recovery, wastewater treatment facility, and waste management firms.	Field research at industrial sites, in-person interviews, detailed questionnaires, empirical observation, and material flow analyses	2008	[26]
	Guayama, Puerto Rico	-	Refinery, cogeneration plant, pharmaceutical firms, industrial landfills, road construction, and wastewater treatment facility.			
USA	Choctaw	-	Car disassembly factory, home appliance recycling factory, PCB treatment facilities, composite core facility; and plastic bottle recycling, waste office equipment, construction waste treatment, fluorescent lamps, empty cans, reused computer, recreational machine, waste wood and plastics, cooking oil, styrofoam, ink cartridges, scrap car, and organic solvent and waste plastics plants	Social network analysis and network connectedness analysis. Degree of connectedness and sub-network relationships. Density and core-periphery structure analytical methods	2013	[27]
Canada	Sarnia-Lambton	-	Fertilizer company, greenhouse operator, gas specialist company, power plant, medium-sized fine-particle manufacturer, oil refinery, chemical company, integrated energy company, and cattle farmers.	Interviews	2009	[28]

By analyzing Table I, it is possible to ascertain that the studies regarding industrial symbiosis in United States of America and Canada are quite scarce. Also, that the majority of these studies are from the 2000-2010 decade with only 2 being from the last 5 years. Furthermore, many publications (as much as 33%) focus on Puerto Rico, which is an unincorporated U.S. territory. As for Canada, only one study was found. It is also possible to deduce from Table I that the type of study more prevalent is interviews and on-site visits.

This finding highlights the fact that the interest in industrial symbiosis in the United States of America and Canada is low, and has been diminishing in the last years.

IV. Trends and Initiatives

By observing Table I it is possible to assess that several attempts have been performed to implement industrial symbiosis in United States and Canada on a wide range of industries, however, they are scarce. These numbers are pale in comparison with Europe or China. Several reasons could explain this scenario.

According to the authors in [21] despite the potential benefits of industrial symbiosis, it is implemented and experimented only occasionally in the United States and it is not followed consistently at a regional level. Efforts have been made, albeit with limited success, to establish industrial symbiosis or material exchanges, as it can be observed in table I. However, according to the same authors, such types of initiatives usually rely on economic incentives and rarely take advantage of industrial symbiosis innovations.

By utilizing a survey of remanufacturing, recycling, and waste treatment industrial units in Texas, the authors in [29] inquired if these organizations could operate in a symbiotic process, that is, through the commercial exchange of materials and energy. However, these authors found out that while the majority of the materials and used products were collected locally, only a few were re-consumed locally. The authors concluded that the nature that characterizes the types of interactions of industrial symbiosis of more successful industrial units was developed poorly in the sector of the studied region. The authors determined that at the time, in 2005, it was debatable that remanufacturing, recycling, and waste treatment industrial units could become important players in the production, consumption and waste cycle loop until the stakeholders were able to develop production design, marketing and consumption philosophies that that were to embrace remanufacturing and recycling at a central level.

In addition to these technical aspects, social reasons have been pointed out as conditioning for the creation of new industrial symbiosis and the development of existing ones. The main reasons are that companies are often not available to share information about their production process and wastes generated, and although there are studies that demonstrate the advantages of this information sharing in order to obtain more fruitful synergies and in ways of not jeopardizing business confidentiality [30], many are still very reluctant to share this information, which hampers the development of new synergies and the study of the best options for waste sharing. Another reason is the confidence that companies that have or are thinking of creating industrial symbiosis have to develop among themselves, so that the receiver companies of the waste are assured of the supply of these in sufficient quantity and quality for their operation, since the amount of waste from the supplier companies depends on their own production and a failure to provide a certain amount of waste can jeopardize many companies belonging to the industrial symbiosis network [28]. And the impact of this failure on the other companies is greater the further away they are from the location core of the major companies, as studied for the industrial symbiosis network located in Choctaw, in the United States [27].

Although the distance between companies is not a limiting factor in the development of industrial symbiosis, the fact that companies are close makes it easier to create synergies. And if, in addition to the physical space, companies are inserted in a park where there is collaboration between them and concerns about sustainability, eco-industrial parks [31], this will facilitate the creation and development of industrial symbiosis, such as examples of Kalundborg in Denmark and Tianjin Economic-Technological Development Area in China. In the United States, existing eco-industrial parks have been developed through a national initiative promoted by the President's Council on Sustainable Development and the US Environmental Protection Agency, and despite these incentives, the industrial symbiosis essential for achieving sustainability in eco-industrial parks are still underdeveloped. Some reasons are related to the apparent lack of motivation of the companies to create industrial symbiosis, much because of the strong involvement of the government, since projects in the United States are initiated by local and regional governments and with access to government funds, they see these projects as way of boosting the local or regional economy [32]. Another reason is related to the existing regulations in the United States that sometimes hinder the creation of industrial symbiosis, namely the US Resource Conservation and Recovery Act in which many wastes are defined as hazardous waste, making it impossible to create synergies [33]. However, some of these parks have a lot of potential for developing synergies, such as Red Hills Ecoplex, Choctaw County in Mississippi and Londonderry Eco-Industrial Park, Londonderry in New Hampshire, which have power plants and which by their nature are considered as anchor tenant and therefore capable of boosting industrial symbiosis with surrounding companies.

However, analyzing the existing case studies, it is possible to conclude that many of them have characteristics considered determinant for the success of the industrial symbiosis, not only during their formation, but also that will favor their growth over time. The existence of anchor tenants companies that will foster the creation and development of synergies is one of them, as the example of the coal-fired power plant existing in Guayama in Puerto Rico [14], [26] and in Honolulu County [19] and the set of pharmaceutical industries existing in Barceloneta, Puerto Rico where there are industrial symbiosis since 1970 [16]. The involvement of companies that have industrial symbiosis in search for more sustainable solutions and common problem solving are decisive for the evolution of existing synergies. One of the case studies where this happens is in Barceloneta, Puerto Rico, where the managers of the participating companies meet frequently to discuss common problems and to find solutions [26]. Another determining factor is the benefits obtained from the industrial symbiosis, whether economic ones such as those verified in Guayama in Puerto Rico [14], environmental ones such as those reached in Honolulu County [20] and

Pennsylvania [18], or in energy savings such as those in Pennsylvania [18]. Another factor considered important is the actions of both regional and national governments to promote and encourage the use of alternative solutions that promote the saving of resources, as happened in Guayama in Puerto Rico [14] with the action of the regional government for the promotion of wastewater reuse.

V. Conclusions

In this paper an analysis of the industrial symbiosis initiatives in United States of America and Canada published by the research community was made. All the publications concerning case studies were identified and classified. Then, the current status of industrial symbiosis in this region was analyzed. It was ascertained that several attempts have been made to implement industrial symbiosis in United States and Canada on a wide range of industries, however, they are scarce and many challenges persist. Several challenges were identified and several possible solutions were proposed.

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Chapter 6

Current Status, Emerging Challenges and Future Prospects of Industrial Symbiosis in Portugal

This chapter consists of the following article:

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Current Status, Emerging Challenges, and Future Prospects of Industrial Symbiosis in Portugal

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Abstract: Industrial symbiosis has proven to be an important tool for improving business sustainability with numerous environmental, economic, and social benefits. The literature on this subject has been provided with countless case studies of the application of this practice in different geographical locations. However, studies concerning Portugal in this area are still scarce. Thus, this article aims to map and analyze the existing cases of industrial symbiosis in Portugal, as well as the current state and the legislative context regarding this practice. It also aims to analyze the main barriers to the growth of synergy relations and outline new paths for the development of industrial symbiosis in Portugal. From the analysis to the case studies, it was possible to conclude that most industrial symbiosis networks have few actors, and networks with two and three are common. However, owing to strategic plans, the type of existing economic activities, and the waste generated, there is much potential for industrial symbiosis networks to be established and to contribute to emission reductions, more efficient use of resources, and reduced external dependence. However, in order to increase industrial symbiosis, concerted action must be taken at various levels to encourage companies to develop synergy relations. Changing the legislative framework, making funds available, the role of local governments, the existence of a facilitator, and the use of some industries as anchor tenants are some of the aspects that can contribute to the increase of industrial symbiosis in Portugal.

Keywords: industrial symbiosis; Portugal; sustainability; eco-industrial parks; circular economy

1. Introduction

Population growth, consumption, and production patterns have led to growth in resource and energy consumption, as well as consequent environmental impacts, which are expected to increase in the coming years [1,2]. Moreover, the growing industrialization and urbanization have also led to increased resource consumption and carbon dioxide emissions, which are largely responsible for the increase in greenhouse gases [3–5]. Thus, it is essential to find solutions that allow the reduction of resource consumption and environmental impacts, without compromising economic growth. Changing from a linear to circular paradigm is critical to achieving this goal by allowing a reduction not only in resource consumption, but also in the amount of waste sent to landfills and incinerators [6,7].

Industrial symbiosis, often defined as the incorporation of one company's waste as a raw material into another company's production process [8,9], similar to the concept of the "industrial ecosystem" introduced by Frosch and Gallopoulos [10], enables the optimization of resource consumption, the effective reduction of carbon dioxide emissions, job creation, and economic gains [11–14]. Industrial symbiosis allows companies that traditionally operate separately to come together to achieve greater environmental and economic benefits than they would be able to achieve individually, through physical exchanges of materials, by-products, energy, and water [15]. In addition to this exchange of resources, industrial symbiosis can also encompass utility and infrastructure sharing and the joint provision of services [16].

There are numerous cases of industrial symbiosis networks around the world; however, the case of symbiosis in Kalundborg, Denmark is the most often cited as a success case, which has spontaneously emerged among companies in the region driven by water scarcity [8,17], and which has developed over the years, not only in the amount of waste exchanged, but also in the increase in synergy network players [18]. Also, in the United Kingdom, largely owing to the National Industrial Symbiosis Programme that has driven the establishment of symbiosis networks, several cases have arisen, such as in Humber [19,20], West Midlands [20,21], Grangemouth, and Forth Valley [22]. Also, several of the existing cases of industrial symbiosis in Europe are located in Sweden [23–25], Netherlands [26,27], France [14,28], Finland [29,30], and Italy [31,32]. However, it is in Asia where there are more reported cases in the literature [33], with China being the country with the most industrial symbiosis networks [12,34,35], largely owing to the plans that have been implemented to reduce carbon dioxide emissions and promote the circular economy. Also, as a result of the programs that were instituted in South Korea and Japan to promote industrial symbiosis, namely the National Eco-Industrial Park Development Program and Japan's Eco-Town Program, respectively, there have been several cases of industrial symbiosis both in South Korea [13,36,37] and in Japan [38–40]. In North America [41–43], South America [44], Oceania [45,46], and North Africa [47], there are also several cases of industrial symbiosis.

Several studies have shown the numerous environmental, economic, and social benefits that can come from industrial symbiosis relationships. For example, in Kalundborg, Denmark with the replacement of groundwater with surface water, all symbiosis network industries reduced more than 30 million m^3 of groundwater [48]. In an Italian tannery cluster located in Tuscany, it was concluded that the existing industrial symbiosis allowed, in the climate change impact category, an absolute reduction of approximately 4.3 kg of CO_2 equivalent per m^2 of finished leather against a scenario with less developed symbiosis relations [31]. Given that this cluster produces approximately 45 million m^2 of finished leather [31], the environmental benefit obtained owing to synergy relations is very significant. In Liuzhou, China, the three symbiosis activities provided an economic revenue of over 36.55 million USD, a reduction of solid waste of 2.4 Mt/y, and a reduction of virgin material of over 2 million ton/y [49].

Knowledge of these environmental, economic, and social benefits can enhance the development of industrial symbiosis relationships. However, the factors that may influence the establishment of symbioses are not limited to the knowledge of the potential benefits and, as has been reported in several publications, there are many and diverse factors that influence the development of industrial symbiosis [20,50,51]. These include economic, technical, political, organizational, social, and informational factors. The economic factor that encompasses cost savings, payback time, revenue generation, and size of capital investment, among others, is one of the most frequently pointed to as driving companies to start industrial symbiosis relations [52–54]. Furthermore, while this factor crosses various geographic locations, there are other factors that depend on a country's social, political, and business context. Political or institutional factors, encompassing environmental policies and standards, laws and regulations, taxes, fees, fines, and subsidies differ greatly by region and are a decisive factor in driving or curbing the development of industrial symbiosis. Examples are national programs for the promotion of the circular economy and industrial symbiosis carried out in the United Kingdom [6,21], China [55,56], Japan [39,57], and South Korea [13,58] that have driven the development of industrial symbiosis. Also, the application of taxes, fees, and the provision of subsidies has been shown to be a driving factor [59–63]. However, existing regulations do not always facilitate the development of symbioses. The study for the large-scale reuse of inorganic by-products in Kwinana, Australia is one such example in which the authors found that existing regulation was an obstacle to this realization [64]. Also, in the study in Fucino upland, Italy, regulatory restrictions were pointed to as a barrier to the development of industrial symbiosis [65]. Technical factors, such as the availability of technologies that enable the development of industrial symbiosis; the availability of utilities, infrastructure, and logistics; and the existence of a sufficient quality and quantity of input and output streams have also been identified as influencing the development of symbiosis [20,50]. Apart from these, organizational and social factors also play an important role in the creation and development of symbiosis relationships. These encompass the organizational culture of companies; knowledge not only of the concept, but also of the potential benefits of symbiosis relationships; risk perception; openness to new practices and new relationships; trust; and the level of social integration and interaction [20,50,51,66,67].

Although the reported success cases and the European Commission in some communications have highlighted the important role of industrial symbiosis in achieving sustainability in all three aspects, there are still few cases in Portugal. Moreover, the number of publications referring to these cases of symbiosis is very scarce [68–71] and a publication compiling the various cases of industrial symbiosis in Portugal reported in articles and grey literature was still missing. Furthermore, given the small number of cases, it is essential to outline ways to increase the industrial symbiosis networks in Portugal that will allow for economic growth to be augmented without inferring an increase in carbon dioxide emissions or resource consumption. Also, while there are some studies that have addressed the challenges and drivers for the creation and development of industrial symbiosis [50,51,66,72], these are not adapted for the Portuguese context.

Therefore, the aim of this paper is to map and characterize the existing cases of industrial symbiosis in Portugal reported in peer reviewed publications and grey literature and to analyze the current state and legislative framework of Portugal in the context of industrial symbiosis. It also aims to analyze the main barriers to the growth of synergy relations and outline new paths for the development of industrial symbiosis in Portugal. In some of these paths, a parallel has been made with some of the industrial symbiosis success cases around the world in order to transpose some of the best practices and success factors of these cases into national reality. This transposition of best practices from success cases facilitates the establishment of new symbiotic relationships. Grant et al. [73] concluded that one of the most common processes for identifying new synergies involves mimicking success cases from similar organizations. Also, Patricio et al. [24] referred to the importance of this mimicking of existing industrial symbioses as a way of increasing the network of symbiosis at regional level, reinforcing the ease of dissemination of these solutions.

The remaining article is organized as follows. Section 2 describes the methodology that was adopted to achieve the proposed objectives. Section 3 presents the results and analysis of Portugal's situation with regard to existing industrial symbiosis cases; the current state of Portuguese industry, waste and emissions, and the Portuguese legislative framework; and also discusses the main barriers and the main pathways for increasing industrial symbiosis in Portugal, based on existing success cases. Finally, the main conclusions are made in Section 4, as are the paths for future research.

2. Materials and Methods

To fulfill the purpose of this article, a systematic and extensive literature review was conducted. Initially, the search criteria for publications including the definition of the keyword, the choice of academic and non-academic databases, and the initial exclusion and inclusion criteria were established. This was followed by the screening of articles in order to select those most relevant for the study. Finally, a content analysis was proceeded, in which the articles were analyzed in more depth in order to examine the cases of industrial symbiosis existing in Portugal and to draw conclusions from the factors that prompted them.

For the article search, "industrial symbiosis" AND Portugal was used as a combination of keywords in the academic databases Scopus and Web of Science, into which no temporal imposition was placed. The research resulted in three articles from Scopus and two from the Web of Science. Given the small number of publications, a further search was extended to publishers with more publications in this area, such as Elsevier, Wiley Online Library, Springer, MDPI, Inderscience Online, IEEE Xplore, Taylor & Francis Online, ACS Publications, SAGE Journals, Nature Research, Emerald Insight, Annual Reviews, and the Google Scholar academic database. The publishers yielded 244 publications and 1020 from Google Scholar. After elimination of the repeated publications, the articles were screened. All publications analyzing cases of industrial symbiosis in Portugal were included in the study. Thus, titles, keywords, and abstracts were read in order to gauge the relevance of the article for the purposes of the study. If doubts remained as to the inclusion of the publications, an analysis of the article was carried out in order to verify if the cases of industrial symbiosis relating to Portugal were only mentioned as an example or if there was in fact a deeper study of the synergies. Thus, this screening process resulted in six articles, which included five research articles and one book chapter.

In order to more broadly cover the existing cases of industrial symbiosis in Portugal, the search was extended to non-academic databases and grey literature in English and Portuguese. Thus, Google searches led to web pages, reports, and other publications from government, the European Commission, public and private institutes, technical and business associations, theses, and dissertations.

After this collection and screening of all publications, a content analysis was performed in order to characterize and analyze the cases of industrial symbiosis in Portugal.

Along with this literature review to identify and analyze the cases of industrial symbiosis in Portugal, a bibliographical survey of the cases of industrial symbiosis around the world was carried out, with the aim of analyzing and drawing lessons on the main factors that contributed toward their success and to study the feasibility of transposing these factors into the Portuguese context.

3. Results and Discussion

In this section, the cases of industrial symbiosis in Portugal are mapped and characterized, and the framework and national legislation on this subject are analyzed. The discussion focuses on the factors that may be decisive in the proliferation of industrial symbiosis cases in Portugal and how some good practices in other countries leading to successful symbiosis cases can be carried over to the national context.

3.1. Industrial Symbiosis in Portugal

3.1.1. Current Status

International agreements and European Commission communications and recommendations have led countries to adopt increasingly sustainable policies that lead to an increasingly effective response to the fight against climate change. In this context, Portugal has, in recent years, undertaken a set of measures aimed at promoting sustainability, such as the approval of plans and legislation, launching a portal to disseminate the knowledge produced about the circular economy, and the operationalization of European program funds through Portugal 2020. However, much remains to be done to be resource efficient and in order to have a sustainable economy. In terms of carbon dioxide emissions, in 2017, Portugal was still far from the targets set by the Europe 2020 strategy [74]. In addition to this, the manufacturing industry spends 53% of its turnover on raw material procurement [75] and, in 2017, resource productivity, measured as gross domestic product at "market prices expressed in current prices converted into purchasing power standards" over domestic material consumption, was 1.45 euro/kg, while for the EU-28 aggregate economy, the figure was 2.24 euro/kg [76].

In 2017, according to the National Institute of Statistics, 1,260,436 companies were active in Portugal [77], whose distribution by sector of economic activity is shown in Figure 1. The largest number of enterprises, around 17.4% of the total, belongs to the wholesale and retail trade, followed by administrative and support service activities, accounting for 14.0% of the total, and agriculture, forestry and fishing activities, with 10.5% of the total enterprises. Manufacturing activities account for about 5.4% of total enterprises, and the overall value of product sales and service provision increased by 9.3% over the previous year [77]. Within this section, 43.2% of the total sales value of products and services is provided by five activities. Further, 13.0% of the total corresponds to manufacture of food products; 9.2% to manufacture of coke and refined petroleum products; 9.0% to manufacture of motor vehicles, trailers, and semi-trailers; 6.8% to manufacture of fabricated metal products; and 5.2% to manufacture of chemicals and chemical products [77].

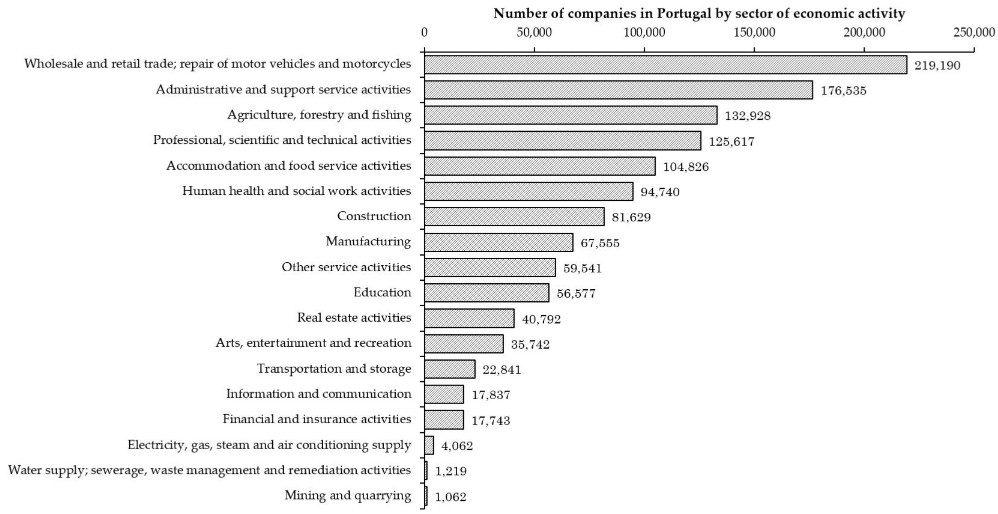

Figure 1. Number of companies in Portugal by sector of economic activity. *Source*: Own elaboration using data from INE (Instituto Nacional de Estatística), Statistics Portugal.

The number of companies in each area and their distribution among the different economic activities is very different, as shown in Figure 2. The largest number of companies is verified in the North, followed by the Lisbon Metropolitan Area and Center.

The total waste generated in Portugal by all economic activities and household has been growing since 2012, reaching a value of 14.7 million tons in 2016, corresponding to 1427 kg per inhabitant, well below the European average of 4968 kg per inhabitant [78]. However, this increase is not seen in all economic activities, as illustrated in Figure 3. In this it is possible to verify that the activity related to mining and quarrying had a significant increase in 2014 compared with 2012, however, the section of manufacture and agriculture, forestry, and fishing, although insignificant, presented a reduction in the total waste, compared with 2012. Of the total waste generated in 2016, 5.7% was classified as hazardous waste [78]. In Portugal, in the same year, about 9.7 million tons of wastes were treated. Of these, 34.7% were disposed in landfills and others, 0.2% were incinerated, 43.5% were recycled, 12.1% were incinerated with energy recovery, and 9.5% were used for backfilling [78]. The amount of waste subject to disposal decreased from 2004, from 46.4% to 34.7% of the total treated in 2004 and 2016, respectively. The amount recycled went from 40.6% in 2010 to 43.5% in 2016 and the amount used for backfilling went from 0.7% in 2010 to 9.5% in 2016 of the total treated.

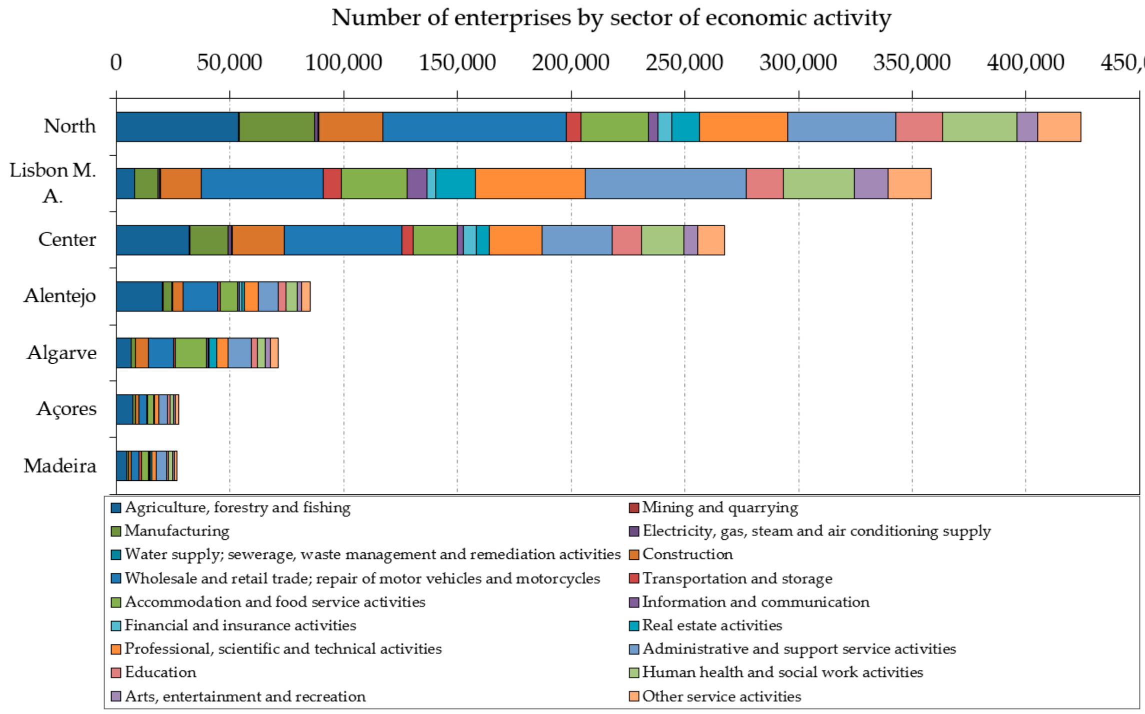

Figure 2. Number of enterprises by sector of economic activity and by geographical location. *Source*: Own elaboration using data from INE. Statistics Portugal.

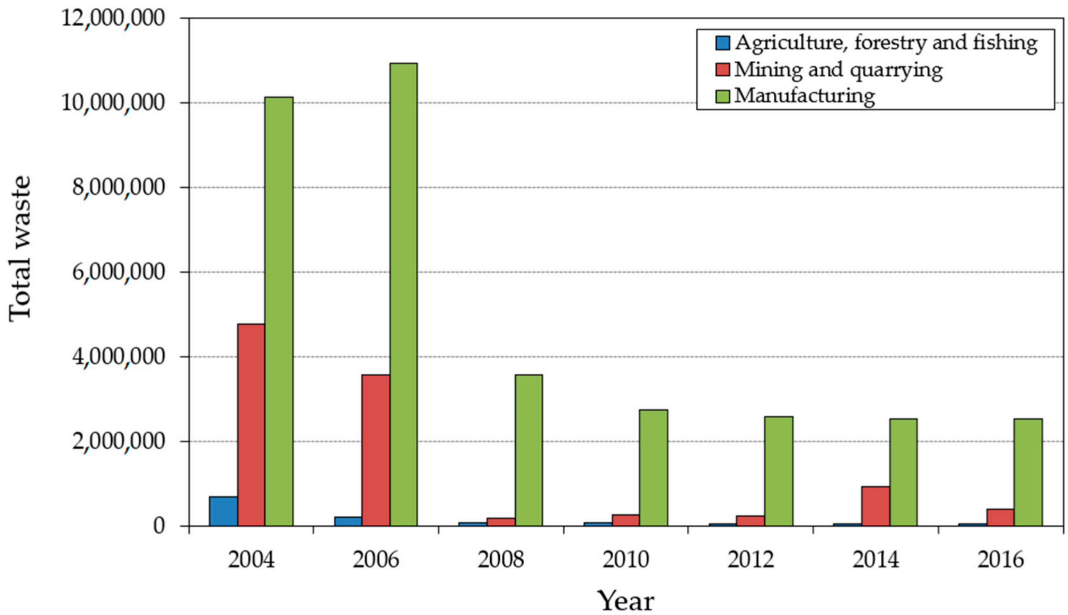

Figure 3. Evolution of total waste generated by the sections of agriculture, forestry, and fishing; mining and quarrying; and manufacturing. *Source*: Own elaboration using data from Eurostat.

Of the total waste generated, households are the largest contributors, accounting for 33.2% of the total, followed by waste collection, treatment, disposal activities, and materials recovery with a weight of 18.6%; manufacturing with 17.3%; construction with 11.6%; services with 6.3%; wholesale of waste and scrap with 6.1%; water collection and treatment, water supply, sewerage, and remediation activities with 3.1%; mining and quarrying with 2.8%; electricity, gas, steam, and air conditioning supply with 0.6%; and, finally, agriculture, forestry, and fishing with 0.4% [78].

Of the 14.7 million tons of wastes generated, 13.9 are considered non-hazardous. Of these, 38.1% are mixed ordinary wastes (household and similar wastes, mixed and undifferentiated materials, and sorting residues), 29.7% are recyclable wastes (metal, glass, paper and cardboard, rubber, plastic, wood, and textile wastes), 22.5% are mineral and solidified wastes, 5.0% are common sludge, 2.7% are chemical and medical wastes, 1.6% are animal and vegetable wastes, and 0.4% are equipment [78].

3.1.2. Portuguese Legislative Context Related to Industrial Symbiosis

Industrial symbiosis has proven to be an important tool for reducing greenhouse gas emissions and for more efficient use of resources [12], thus contributing to compliance with international requirements. The European Commission in its communications and the recent adoption of Directive 2018/851 of the European Parliament and of the Council of 30 May 2018, which amended Directive 2008/98/EC on waste [79], has recognized the role of industrial symbiosis and has provided information and support for the dissemination of this practice by Member States [79,80].

In order to transpose European Directive 2008/98/EC on waste into the legal system, Portugal published Decree-Law No. 73/2011, which amended Decree-Law No. 178/2006, which comprises the general regime of waste management [81]. In this document, to comply with the recommendations of the European Directive, not only the concept of by-product was defined, but the conditions that would have to be met for a substance or object to be considered as a by-product and not waste. Considered to be the result of a production process in which the main purpose was not its production, in order to be considered as a by-product rather than a waste, the Directive has established that subsequent use of the substance or object must be effective; that it can be used directly in industrial practice without further processing, which is an integral part of the production process; and that its subsequent use complies with the relevant requirements and does not entail environmental and health protection impacts [81,82]. In Portugal, the request for by-product classification must be made to the Portuguese Environment Agency individually or through sectoral associations by submitting a duly instructed form and a payment of 5000 euros [81]. Although this by-product classification entails administrative costs and it is not always easy to comply with the four conditions, it facilitates and simplifies the ways in which products and substances are used, as it is no longer covered by the general waste management scheme by ceasing to be considered as waste, and thus relieves companies of a number of obligations that would have to be incurred if it were to be considered as waste [81,83]. The Portuguese Environment Agency, on its website, provides a list of by-product classification decisions [83]. Since the Decree-Law was published, only 16 by-product classification decisions have been posted on the Portuguese Environment Agency's website [83]. This may illustrate the difficulties encountered in the by-product classification and verification of all the required conditions and underlines the low importance attached to industrial symbiosis relationships by companies. However, the recent publication of Directive 2018/851 on waste can help to foster this practice and overcome these barriers, as there is a clear recommendation to facilitate classification as a by-product.

There are other legislative measures that, although not referring to industrial symbiosis, can indirectly contribute to the application of this practice if there is a strategic direction in this regard. Extended producer responsibility under European Directive 2008/98/EC and at national level in Decree-Law No. 73/2011, by holding producers accountable for the life cycle of products and materials and not just the end-of-life phase [81,82], enhances the most efficient use of resources and encourages changes in the production process. In this way, industrial symbiosis can be an ally as it reduces the impact associated with the use of raw materials. Also, as the result of Community guidelines, Council of Ministers Resolution No. 38/2016 [84] approved the National Strategy for Green Public Procurement 2020, the main objective of which is to promote the reduction of pollution and the reduction of the consumption of natural resources. The practices of industrial symbiosis are aligned with this purpose, and thus the government can privilege purchases to producers who, in their production process, have incorporated waste from other industries.

Beyond the legislative framework, a set of plans has been established to define actions leading to the fulfillment of the recommendations and requirements of a more sustainable economy. Although the industrial symbiosis does not appear mentioned in the Decree-Laws, in the strategic plans, it has been stated quite often. An example of this was the Council of Ministers Resolution No. 11-C/2015, which approved the National Waste Management Plan for the 2014–2020 horizon, in which the important role of industrial symbiosis is highlighted and where some measures for its promotion have been indicated [85]. The Organized Waste Market, established by Decree-Law No. 210/2009 and amended by Decree-Law No. 73/2011, was pointed out in this plan as important for the promotion of industrial symbioses [85]. This instrument considers the gathering of various platforms where waste transactions are processed and aims to facilitate and promote trade in various types of waste and enhance their reintroduction into the economic circuit [81].

More recently, in the Council of Ministers Resolution No. 190-A/2017 that approved the Action Plan for the Circular Economy in Portugal, industrial symbiosis was included in a set of actions to be taken at regional level, in which several entities were indicated to be involved in the process and defined as guidelines information and awareness actions for this practice with companies, survey of potential industrial symbiosis relationships, identification of barriers to its implementation and its elimination, and the training of qualified technicians for the development of synergy processes [75].

In July 2019 and following the demands of the Paris Agreement to contain the global average temperature increase, the Roadmap for Carbon Neutrality 2050 was approved by the Council of Ministers Resolution No. 107/2019, in which the promotion of industrial symbiosis appears as one of the main decarbonization vectors and guidelines for a carbon neutral society [86].

These action plans can represent an important step towards increasing industrial symbiosis relations, especially the Action Plan for the Circular Economy in Portugal, in which a more concerted and structured set of actions has been defined to drive industrial symbiosis initiatives. However, most of the objectives set out in this plan for symbiosis relationships are quite qualitative, that is, without quantitative targets or the respective deadlines for achieving them. In addition, although indicators have been defined, the values to be achieved have not been specified. Moreover, it would also be important to involve educational institutions and companies in the definition of these objectives; in the case of Portugal, this cooperation has been shown to be an important factor to improve waste management performance [87].

3.1.3. Industrial Symbiosis Networks in Portugal

The number of cases of industrial symbiosis in Portugal reported in peer-reviewed publications is still very few. Most of the cases have been described in reports from private and public associations and institutions that have looked into the circular economy and industrial symbiosis, mostly created from community funds and national support. The "Alentejo Circular" Program, created mostly from European funds to promote the competitiveness of the Alentejo region, is one such example. Resulting from the partnership between a private entity, ISQ (Instituto de Soldadura e Qualidade), and the University of Évora, its primary objective is the adoption of circular practices by the olive oil, wine, and pig farming sectors [88]. The non-profit association, the Business Council for Sustainable Development (BCSD) Portugal, has also contributed to the dissemination of cases of industrial symbiosis and its increase by supporting member companies in their search for sustainable solutions [89].

Table 1 compiles the published cases of industrial symbiosis in Portugal, stating the activities; types of waste and by-products involved; and sharing utilities, infrastructure, services, and resources. Two cases that evaluated potential industrial symbiosis networks are also included. The cases were grouped according to the various intermunicipal entities defined by Law No. 75/2013, which include the metropolitan area and the intermunicipal communities. From the analysis of the existing cases, it can be concluded that most networks involve a small number of actors, and there are often industrial symbiosis cases with only two companies. Given that there is no national concerted plan in Portugal to support the establishment of industrial symbiosis networks, unlike those in other countries, such as the

United Kingdom with the National Industrial Symbiosis Programme [6,20], and owing to the evidence showing only a small number of participants within the networks, there is a strong likelihood that they were the result of self-organized activity, that is, through the direct initiative of the companies involved. In addition, cases of industrial symbiosis with two to three companies are mostly in the same or neighboring areas, having an average distance of 39 km between them, which is common in self-organized networks [90]. The largest and most organized network of industrial symbiosis in Portugal is Relvão Eco Industrial Park in Chamusca. This was the result of the interaction between national, local government, industries, and other entities who, from a set of concerted actions, such as the provision of a large area at lower prices for industries implementation, holding meetings to inform and promote relationships between agents, and through waste management facilities, provide a cluster for waste treatment and recovery, attract more companies to the site and make them participate in the industrial symbiosis network, and thus contribute to the development of the municipality [68].

Table 1. List of existing and potential industrial symbiosis networks in Portugal.

Location/Region	NE	Activity	Waste/By-Product	Sharing Facilities/Utilities/Services	Publication Year	Refs.
Industrial Symbiosis Networks						
Coimbra, I.C.						
Souselas		Cement manufacturer	Agricultural, urban, industrial, and construction and demolition wastes		2018	[91]
Leiria, I.C.; West, I.C. and Lisbon, M.A.						
Leiria, Alcobaça and Setúbal		Shipyards and cement manufacturers	Steel shot		2018	[91]
Lisbon, M.A.						
Lisbon Metropolitan Area	44	Manufacturer of paper pulp; repair and maintenance of ships and boats; construction of railways and underground railways; wholesale of waste and scrap; manufacturer of doors and windows of metal; manufacturer of other fabricated metal products; shaping and processing of flat glass; production of electricity; logging; manufacturer of cement; manufacturer of concrete products; manufacturer of household and sanitary goods and of toilet requisites; aluminum production; manufacturer of plastic plates, sheets, tubes, and profiles; manufacturer of basic iron and steel and of ferro-alloys; and manufacture of flat glass	Waste bark and wood, bottom ash, slag, boiler dust, sludge, plastics, rubber, waste blasting material, paper, cardboard, aluminum, ferrous metals, waste glass, waste concrete, concrete sludge, mixtures of concrete and bricks and ceramics, linings, refractories, welding waste, and lime mud waste		2015	[69]
Lisbon		Restaurants, coffee shops, and mushroom producer	Coffee grounds		2019	[92]

Table 1. *Cont.*

Location/Region	NE	Activity	Waste/By-Product	Sharing Facilities/Utilities/Services	Publication Year	Refs.
			Alentejo Litoral, I.C.			
Sines		Oil refinery; manufacturers of fertilizers, paper, and sulphuric acid; microalgae production; and manufacturer of plastics in primary forms	Sulphur, industrial gases (CO_2), hydrogen, liquefied petroleum gas, fuel, and others fuels (naphtha)		2011	[93]
Sines		Power plant and cement manufacturer	Ashes		2011	[93]
Sines		Recovery of sorted materials (tyres), power plant, chemical industry; and cement/concrete/construction materials manufacturer	Waste tyres and gypsum		2011	[93]
			Lezíria do Tejo, I.C.			
Chamusca	>16	Integrated recovery, treatment and elimination center for hazardous wastes, municipal waste management, wastewater treatment facilities, container refurbishment, battery recycler, paper pulp producer, plastic recycler, end of life vehicles disassemblers, aluminum slag processor, biomass processers, fertilizer producers, and local farms	Containers, acids, biomass, plastics, ferrous metals, batteries and oil filters, ash, food waste, and sludge		2010	[68]
Rio Maior	2	Furniture manufacturer and mixed farming	Wood shavings		2011	[93]
Salvaterra de Magos and Rio Maior	2	Carpentry and pig farm	Wood shavings		2011	[93]
Benavente and Rio Maior	2	Fruit processer and wholesale of grain	Unsuitable fruit materials		2011	[93]
Santarém	2	Pig farm and agricultural production	Manure		2011	[93]
Santarém	2	Stone quarry and mechanical repair	Oils		2011	[93]
Santarém	2	Sewerage and agricultural products	Wastewater sludge		2011	[93]
Santarém	2	Furniture manufacturer and ceramics manufacturer	Wood shavings		2011	[93]
Santarém	2	Olive oil production	Washing sludge		2011	[93]
Santarém	3	Stone quarries and stone cutting and shaping	Excavation wastes, stone cutting wastes, and freshwater drilling muds		2011	[93]
Santarém and Benavente	3	Meat processer, paper products manufacturer, and printing	Paper/cardboard		2011	[93]

Table 1. *Cont.*

Location/Region	NE	Activity	Waste/By-Product	Sharing Facilities/Utilities/Services	Publication Year	Refs.
Santarém and Alpiarça	3	Brewery, raising of farm animals, and agricultural production	Biomass and sludges		2011	[93]
Santarém, Almeirim and Alpiarça	3	Vineyards and distiller	Unsuitable beverage materials and washing/mechanical process wastes		2011	[93]
Santarém and Cartaxo	3	Manufacturer of wires, chains, and springs; hardware retailer; and cold forming or folding	Ferrous metal dust and particles and ferrous metal fillings		2011	[93]
Chamusca	2	Winery and mixed farming	Washing/mechanical process wastes		2011	[93]
Chamusca and Azambuja	2	Aviary and recovery of sorted materials	Discarded electronic equipment		2011	[93]
Azambuja	2	Veneer sheets and wood panels manufacturer and agricultural products retailer	Wood shavings		2011	[93]
Azambuja and Coruche	5	Manufacturer of parts for motor vehicles, recovery of sorted materials, car manufacturer, and construction	Steel mill scales and lead batteries		2011	[93]
Benavente and Cartaxo	2	Manufacturer of medical products and manufacturer of steel drums	Metal containers		2011	[93]
Cartaxo	2	Juice manufacturer and post-harvest crop activities	Washing/mechanical process wastes		2011	[93]
Cartaxo	2	Stone cutting and shaping and construction	Stone cutting wastes		2011	[93]
Cartaxo	2	Manufacturer of parts for motor vehicles and manufacturer of wires, chains, and springs	Ferrous metal fillings		2011	[93]
Cartaxo	2	Printing and school	Paper/cardboard packaging		2011	[93]
			Alentejo			
Alentejo		Olive oil and wine industries, paper mill, and poultry farmer	Olive lump, by-products of pruning of vines and olive trees, stalks, sludge from wastewater treatment plants of paper mill, and poultry manure	Infrastructures, human resources, waste management (with a common waste park and wastewater treatment plant), and equipment	2018	[88]
Alentejo	2	Wine, olive oil, and pig farmers	Swine effluent	Facilities and human resources	2018	[88]
Alentejo		Cooperatives and producers	Organic matter		2018	[88]
Alentejo		Olive oil farmers and poultry farmer	Olive lump		2018	[88]
Alentejo		Pig farmers and farmers	Liquid and solid effluents		2018	[88]
			Undefined region			
		Paper and pulp industry and mortar producer	Aggregate (sand) re-used from fluidized bed boilers		2016	[94]

Table 1. *Cont.*

Location/Region	NE	Activity	Waste/By-Product	Sharing Facilities/Utilities/Services	Publication Year	Refs.
		Paper pulp producer and sustainable forest management company	Organic waste		2018	[91]
		Electricity producer, distributor and trader, and international companies	Coal slag		2018	[91]
		Pulp and paper industries, ceramic, cement, and other industries	Waste and by-products from pulp and paper industries		2019	[70]
Potential industrial symbiosis network						
Alentejo Litoral, I.C.						
Sines		Refinery and cement industry	Used catalyst and hydrocarbon sludge		2018	[91,94]
Undefined region						
		Pulp and paper plants, sand producers, and mortars producers	Fluidized bed sands		2019	[71]

NE: number of enterprises; I.C.: intermunicipal community; M.A.: metropolitan area.

Regarding the geographical location of cases of industrial symbiosis, as illustrated in Figure 4, it can be seen that there is a predominance in the Alentejo region, especially in the intermunicipal community of the Lezíria do Tejo, where there is a higher density of cases. In the right figure, the distribution of the various cases of industrial symbiosis by the different locations is illustrated. Each number identifies the symbiosis cases in which each location is involved. For example, in the case of Leiria and Alcobaça, although it is the same case of symbiosis, it is accounted for in different locations. It should be noted that in the right figure, only the cases of industrial symbiosis where the location is known are represented. In the case of Alentejo, in five of the existing cases of industrial symbiosis, the specific location is not known, and is thus accounted for in the left, but not the right figure. However, through informal conversations with companies from other regions and judging by the reported number of industrial symbioses involving two companies, it can be concluded that the number of cases of industrial symbiosis in Portugal is much higher and much more dispersed than reported in the publications.

With reference to the type of economic activities involved in the industrial symbiosis cases, there is a predominance of manufacturing activities, as illustrated in Figure 5, accounting for approximately 56% of the total entities, with the paper and pulp and cement industries predominating in this section. As can be seen from Figure 6, manufacturing activities are not only present in all regions, but are the dominant section in all but the Alentejo. Activities related to the primary sector, such as agriculture and livestock, are the second most frequent in cases of synergy, with Alentejo and the intermunicipal community of the Lezíria do Tejo being the regions having the most participants in this section. This cannot be dissociated from the predominance of this type of activity in these regions (Figure 2). Industrial symbioses are also often found between the manufacturing and agricultural sectors, either in the use of manufacturing waste in agriculture such as the use of biomass for animal feed and sludge as fertilizer [93], or agriculture in manufacturing such as the use of food waste from local farms for fertilizer production [68]. Companies in the waste and water management and recycling sectors are also present in synergies and can play a key role, as in the case of Relvão Eco Industrial Park, which indirectly helped trigger actions for the subsequent creation of the industrial symbiosis network [68].

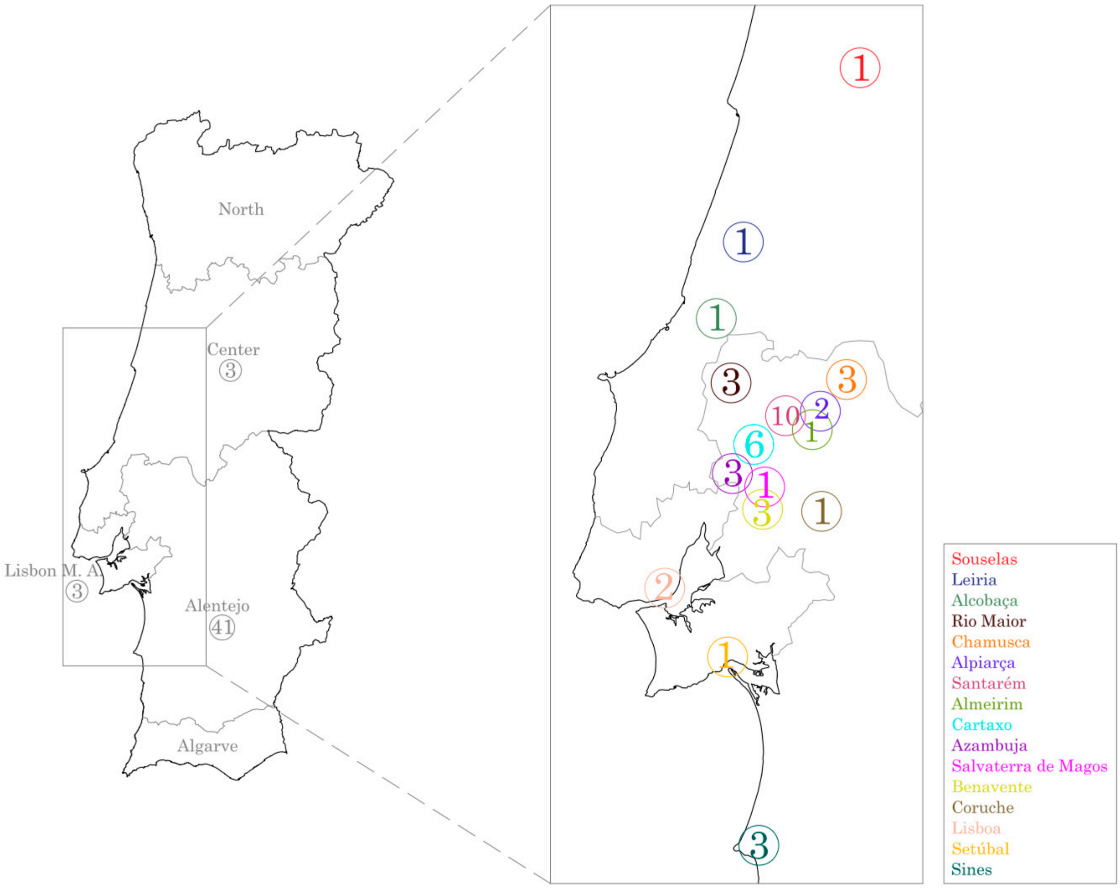

Figure 4. Geographic distribution of the different cases of industrial symbiosis in Portugal. Each color is associated with a different location. The indicated values identify the number of cases of industrial symbiosis present in each location.

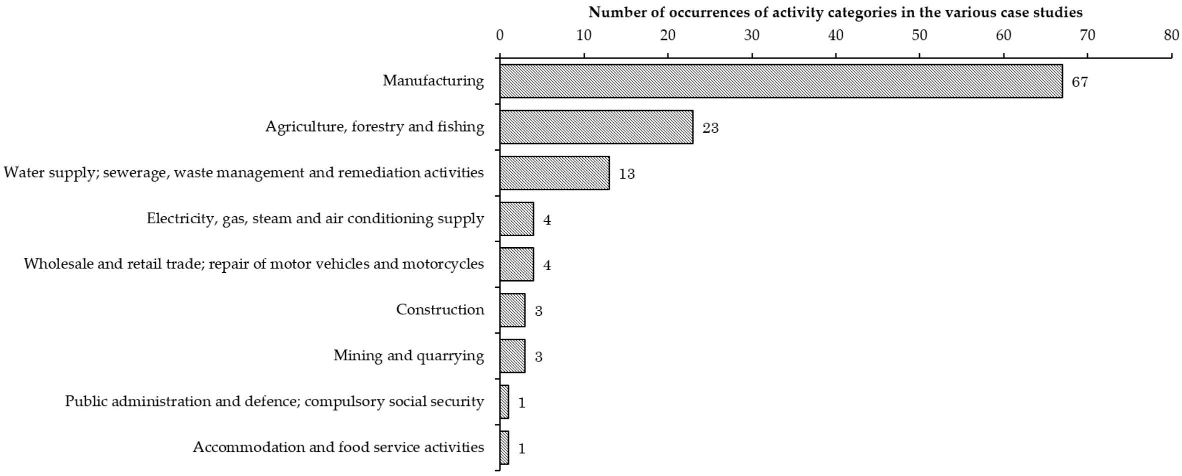

Figure 5. Number of occurrences by sector of economic activity in the various case studies.

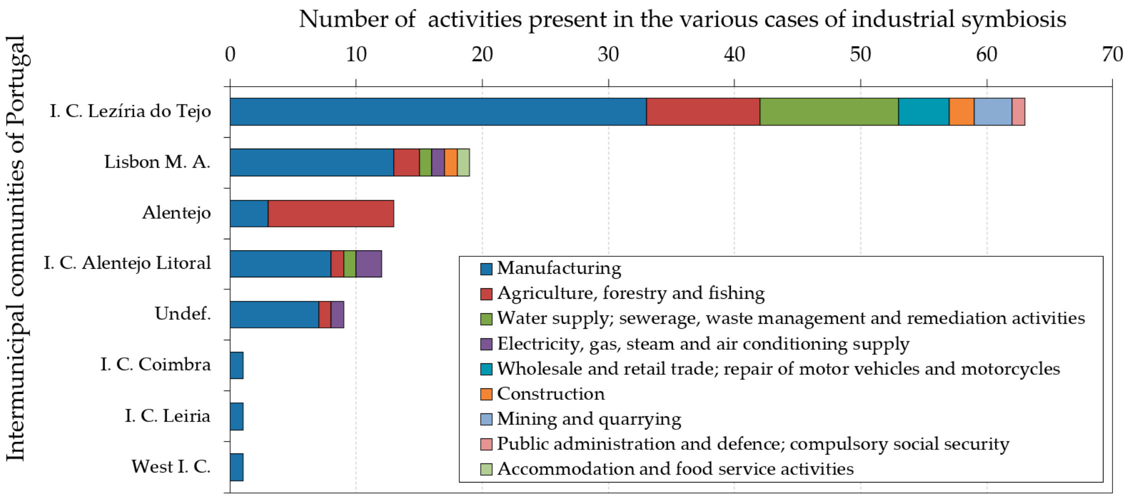

Figure 6. Number of occurrences by geographical location and by sector of economic activity in the various case studies. I.C.: intermunicipal community; M.A.: metropolitan area.

Waste flow was the type of industrial symbiosis most often found in case studies. Biomass and agriculture by-products, metallic wastes, non-metallic wastes (e.g., construction and demolition wastes, and waste glass), and sludge were the most commonly exchanged waste in symbiosis networks. Apart from these, wood wastes, ash, chemical, plastics, and rubber and paper wastes were also frequent streams. In Alentejo, in addition to the exchange of waste and by-products stream, there were also other types of industrial symbiosis, namely the sharing of infrastructure and services. An example is the sharing of waste management in an industrial complex, with a common waste park and wastewater treatment plant [88]. Also, among the olive oil and wine sectors and owing to the common practice of economic agents acting simultaneously in these two sectors, cases of sharing of social areas, waste management, offices, warehouses, laboratory, and equipment were reported [88]. In addition, a sharing of facilities and human resources has also been reported between these two sectors and pig farming [88].

3.2. Current Development, Challenges, and Future Prospects

Portugal has made an effort to undertake measures and plans that can lead the country to economic growth decoupled from increased carbon dioxide emissions and increased resource consumption. Further, while there has been an improvement in recent years with regard to economic and environmental indicators, as described in Section 3.1.1, there is still a large margin for improvement. The challenges and future prospects that are posed to Portugal with regard to the development of industrial symbiosis are of various kinds, as illustrated in Table 2.

The evolution of environmental policies and measures carried out by Portugal cannot be dissociated from the setback that has taken place as a result of the global economic crisis and the consequent financial rescue of the country. The package of measures implemented had economic repercussions, which caused the economy to contract and caused a decrease in purchasing power due to redundancies and wage cuts, with severe implications for companies. It is not surprising that there has been a decrease in the number of companies since 2008, a trend that only reversed in 2013 [77]. In this scenario of recovery from the economic crisis, the governments' priority is not sustainability, but improving the public budget, rescuing banks, and reducing unemployment [95]. Also, for most of the companies, with the exception of some larger ones, it is more concerned with survival issues, which relegate environmental issues to a lower level. However, recessions can also represent an opportunity to improve inefficiencies [95,96] and, in this sense, national and European institutions can play a key role in shaping policies and strategies that effectively promote sustainable growth and support companies to adopt more efficient ways to use resources and reduce waste—not just goal setting, as in some action plans.

Table 2. Challenges and future prospects for the development of industrial symbiosis in Portugal.

Categories	Main Challenges and Future Prospects
Political	Establishment of policies and strategies by national and European institutions that effectively promote sustainable growth and support companies Definition of a concerted action plan tailored to the reality of small- and medium-sized enterprises Increased waste disposal taxes Creation of dissemination and encouragement mechanisms for companies Tax reduction for companies that adopt more sustainable waste treatment practices Creation of funds specially designed to increase industrial symbiosis Promotion of legislative changes, such as streamlining and reducing bureaucracy in the application for by-product classification
Organizational	Existence of a facilitator who promotes industrial symbiosis relations between companies
Technical	Industrial symbiosis between manufacturing and agriculture, forestry, and fishing companies Promoting symbiosis relationships with more representative and waste-generating industries such as the paper industry and the manufacturing industry of basic metals and fabricated metal products Boost symbiosis by using larger companies that are already present in industrial symbiosis networks, acting as anchor tenants Promotion of infrastructure sharing and joint provision of services

Industrial symbiosis has been applied in different countries with different social, economic, and political contexts, but in all of them, it has contributed to improving sustainability in economic, environmental, and social aspects. In Portugal, the cases reported in the literature are still small and, with the exception of Relvão Eco Industrial Park, which has a larger organization and more participants, most of the existing industrial symbiosis networks are small, mostly with two to three participants. Although industrial symbiosis is referred to in some strategic plans as important for the achievement of the objectives set internationally and by the European Community, the measures that have been implemented are still insufficient for symbiosis relationships to be established more consistently. In addition, although legislation contemplates the possibility of a waste becoming classified as a by-product, which facilitates the use of substances or products as they no longer have to comply with the administrative requirements associated with waste management [81], the process involves administrative costs and not always meeting all the required conditions is easily achievable. Moreover, companies have referred to the difficulty they have in obtaining the decision to consider a substance as a by-product from the public authorities responsible [91].

The lack of trust and the difficulty that companies have in sharing information are also pointed out as barriers to the creation of industrial symbiosis relations in Portugal [91]. In addition, although waste recovery figures improved in 2017 from previous years, the amount of waste disposed of in landfills and others in 2006 was 55.1% of total waste [78], indicating that Portugal has only recently increased its recycling practices, which somehow indicates that circular economy practices are not yet solidly established, which eventually constrains companies to start industrial symbiosis relations. Moreover, the weight of small and medium enterprises is 99.9% and that of micro enterprises is 96.2% [77], which makes it difficult to spread industrial symbiosis relationships, as such companies face some obstacles to environmental performance, such as resource scarcity, lack of specific knowledge on environmental issues, and lack of information [24]. It is not surprising that in Portugal, only 16.2% of companies with less than 49 employees have adopted environmental protection measures [77], which clearly restricts the implementation of synergy relations. However, small- and medium-sized enterprises by size (99.9%), production volume (57.1%), and gross value added (58.8%) relative to all enterprises are vital for the spread of industrial symbiosis practices. It is, therefore, necessary to define a concerted action plan tailored to the reality of this type of companies to foster symbiosis relations. Avoiding and reducing disposal costs, pointed out by beer and mushroom producers in the industrial symbiosis in Västra Götaland Region of Sweden [24], and the intervention of government and public institutions [97] are some of the main reasons given for the development of industrial symbiosis relations between small and medium enterprises. Thus, government and other organizations can play an important role in this regard, with implications not only for these types of companies, but also for larger ones to increase industrial symbiosis.

The increase in waste disposal taxes has been an important incentive for changing the behavior of various companies to seek sustainable solutions in waste treatment and recovery and, consequently, for the implementation of industrial symbiosis [6,61]. In the United Kingdom, the creation of the landfill tax in 1996 had a very positive impact on increasing industrial symbiosis, not only because companies were driven to find more sustainable solutions, but the value of the tax was a source of funding for the National Industrial Symbiosis Programme [20]. Denmark is another example of the positive impact that rising landfill rates have had on increasing symbiosis relations [98]. In Portugal, increasing landfill taxes could act as an incentive for companies to look for more sustainable ways to treat waste generated and to promote industrial symbiosis relationships, as the value of existing landfill taxes is still low [69].

However, the government's role in encouraging industrial symbiosis does not end with increasing taxes. There are many examples of how concerted business support action for creating synergies coupled with making funds available can have a very positive impact. The National Industrial Symbiosis Programme in the United Kingdom [20], the National Pilot Circular Economy Zone Program [99] and the National Eco-Industrial Park Demonstration Program [100] in China, and the National Eco-Industrial Park Development Program in South Korea [13], although with different forms of action—for example, the United Kingdom follows the 'bottom-up' approach, while China follows the 'top-down' approach—are some of the examples of strategic plans that have allowed to increase the number of symbioses. In addition to these examples, Portugal can also use the experience gained in implementing Relvão Eco Industrial Park and create a more concerted plan at the national level. Furthermore, while, as mentioned in Section 3.1.2, there is a set of actions defined for the enhancement of symbiosis relationships, it is necessary to speed up the process and to create mechanisms for the dissemination and encouragement of companies, such as the tax reduction for companies that engage in more sustainable waste treatment practices and the creation of funds specially designed to increase industrial symbiosis. It would also be necessary to promote legislative changes that would drive companies towards the practice of industrial symbiosis and facilitate waste streams such as streamlining and reducing bureaucracy in the application process for by-product classification.

The role of a facilitator, which promotes the concept of industrial symbiosis to companies and demonstrates the many advantages that can come to companies if they participate in this kind of practice, is also very important for the creation and development of symbiosis, as found in the United Kingdom, Italy, Poland, Belgium, and France [90]. As Portugal has an integrated electronic waste registration system, provided for in Decree-Law No. 73/2011 [81], which allows "the recording and storage of data on waste generation and management and products placed on the market within the specific waste streams", this database may be essential for the promotion of new relationships. Thus, provided with this data, it was important to have a facilitating entity that analyzed the possible symbioses in advance with the quantification of some of the potential benefits to be achieved and promoted with the companies trusting relationships that served as the foundation of the industrial symbiosis networks. This facilitating role can be performed by different entities, whether public or private, such as local authorities and private or public organizations [24,90]. Regional governments can also play an important role in creating industrial symbiosis relationships because they are closer to businesses and have an interest in developing the municipality from an economic and environmental point of view. Further, the example of Relvão Eco Industrial Park illustrates how important local government is and how it can act as a driving force for symbiosis relations. However, there is a need for the central government to provide information and sensitization to local authorities so that they are motivated to take action to trigger the establishment of industrial symbiosis networks.

By analyzing the type of entities and waste generated from various existing cases of industrial symbiosis, it can be concluded that the types of economic activity and types of waste in Portugal reveal much potential for the development of synergies. The presence of a wide range of manufacturing industries and the weight of agriculture, forestry, and fishing can be decisive for the creation and development of industrial symbiosis. The cases of Kalundborg in Denmark [18], Humber in the United Kingdom [20], Sotenäs in Sweden [101], Guigang in China [34], and Tamil Nadu in India [102] are some of the examples of cases of symbiosis between various industries and agriculture, forestry, and fishing. The most representative manufacturing activities in Portugal are present in several cases of industrial symbiosis. Of note are the manufacturing industry of coke and refined petroleum products, the manufacture of chemicals and chemical products, and the manufacture of paper and paper products, which are the most frequent in existing industrial symbiosis networks, not only for the type of waste they generate, but also for the ability of some to receive waste. Of these three, the one that generated the most waste in Portugal was the paper industry, which accounted for 15.4% of the total waste generated by the manufacturing sector [78]. With a significant sales volume, this sector has been present in some cases of industrial symbiosis in Portugal with recognized benefits for the economy and the environment [68–71]. The manufacturing industry of basic metals and fabricated metal products can also be an important sector for creating potential industrial symbiosis, as it is the fourth most representative industry in the manufacturing sector and generates the most waste, around 19.3% of the total manufacturing sector [77,78].

Large companies can also play an important role in enhancing symbiosis relationships. In Portugal, in 2017, 96.4% of companies with 1000 or more persons employed adopted environmental protection measures [77]. In various economic activities, the five largest companies concentrate much of the total product sales in the industry. Some examples are the manufacture of coke and refined petroleum products; manufacture of electrical equipment; manufacture of chemical and chemical products; manufacture of motor vehicles, trailers, and semi-trailers; electricity, gas, steam, and air conditioning supply; and manufacture of paper and paper products. In addition, some of these industries are already involved in industrial symbiosis networks (Table 1), which may be a driver for network growth and to aggregate more businesses, acting as anchor tenants, similar to some existing symbiosis cases, such as the power plant in Honolulu in the United States [103], the pulp and paper mill in the region of Kymenlaakso in Finland [104], and a cement company in Kawasaki in Japan [105].

In addition to the flow of waste and by-products, there is also a great potential in Portugal for infrastructure sharing and the joint provision of services. The geographical proximity between companies located in industrial areas, or the common practice of some sectors, such as the case reported in Alentejo, may favor the development of this type of industrial symbiosis. Thus, joint waste management, sharing of infrastructure, transport, knowledge, equipment, and human resources are some of the examples with potential to be implemented.

4. Conclusions

Portugal, in recent years, has implemented some policies and strategic plans towards sustainable development. However, some indicators show that is still far from having an efficient economy in the use of resources. By disseminating the application of industrial symbiosis at the national level, Portugal can obtain numerous advantages provided by this practice, at the environmental, economic, and social levels.

The analysis of the existing cases of industrial symbiosis reported in the literature allowed for concluding that they are still very few cases, and the areas of the Lisbon Metropolitan Area and Alentejo are where there is a higher concentration of cases. The analysis also led to the conclusion that most were developed from self-organized initiatives and that the number of actors presents in the networks is, in most cases, reduced. In addition, the economic activities of manufacturing and agriculture, forestry, and fishing are the most present in industrial symbiosis networks. However, for the enhancement of industrial symbiosis relations, political, cultural, and economic barriers have to be overcome. The definition of a concerted action at the national level that acts in different fields may be essential for the spread of industrial symbiosis in Portugal. Improving the legislative framework to facilitate industrial symbiosis and reduce bureaucracy in the by-product classification process, create tax relief, provide access to support funds, inform and support businesses, and encourage industries that can function as anchor tenants are some of the challenges facing Portugal in order to establish industrial symbiosis in a solid way.

The study, carried out on industrial symbiosis in Portugal, allowed to outline some paths for future research with the aim of increasing the number of symbiosis networks. Thus, future research could focus on the quantification of the environmental, economic, and social impacts of the cases of industrial symbiosis in Portugal in order to evaluate the contribution of this practice to the sustainable growth of the country and to promote the dissemination of results among the various stakeholders with the aim of boosting new industrial symbiosis relationships. It would also be important to evaluate in future research the dynamics of the creation and development of existing industrial symbiosis cases in Portugal in order to promote the dissemination of this practice.

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Chapter 7

Conclusions and recommendation for future work

1. Conclusions

Finding solutions that limit resource consumption and greenhouse gas emissions is essential to ensure sustainable economic growth. Industrial symbiosis has proved to be a strong ally for the achievement of these objectives, evidenced by the growing number of publications on this subject, especially since 2007. This practice provides environmental, economic and social benefits, bringing innumerable advantages to companies and communities, such as reduction of the consumption of raw materials, energy and natural resources, reduction of greenhouse gas emissions, reduction of waste sent to landfills and incinerators, reduction of costs with the purchase of raw materials, reduction of landfill costs and treatment of waste, revenue from the sale of waste and creation of jobs. These results can be interpreted as drivers for decision-makers in companies and governments to start or continue their efforts to create and develop industrial symbiosis. From the analysis to the various cases of industrial symbiosis reported in the literature, it was possible to conclude that the drivers for the development and creation of synergies can be several. The diversity between industries, geographical proximity, the existence of facilitating entities and legislation, plans and policies are also often pointed as drivers for the establishment of synergies. However, in order to realize this potential, there are still some obstacles, such as companies' lack of knowledge of industrial symbiosis, lack of confidence, reluctance to provide waste data, uncertainty in revenues and costs, stringent regulations on the use of waste, and the initial costs that some types of industrial symbiosis entail.

The economic motives are the most frequent ones in the initiatives taken by the companies for the creation of industrial symbiosis relations. Whether on its own initiative or through associations organized by companies that support the search for partners for synergy networks, the reasons why companies are driven to achieve symbiosis relationships are economic profits, increased competitiveness and the intention to avoid costs with taxes or waste treatment and disposal. Environmental and social reasons are most often found as driving the action of governments to promote industrial symbiosis. Reducing waste, reducing greenhouse gas emissions and increasing job creation are some of the reasons why governments have created plans and measures to encourage the creation and development of synergies and to apply additional taxes to penalize companies that do not implement sustainability measures and to dissuade them from sending waste to landfills and incinerators.

The analysis of publications on industrial symbiosis also showed the huge diversity of case studies and potential cases, in terms of location, industries involved in the synergies, and in the methods employed. From the analysis done to the case studies, it was possible to conclude that there are cases spread all over the world, with China having the highest incidence of studies on industrial symbiosis, justified by the growing concern about the reduction of greenhouse gases, due to the strong presence of industries characterized by high energy consumption and large carbon dioxide emissions and due to the limitations of emissions set by the international community. And while there is a greater tradition of implementing sustainability promotion measures in Europe, China has made an effort to contain greenhouse gas emissions by implementing a number of policies and programs that curb the negative effects of rapid industrialization and urbanization that have occurred in recent years. It was also possible to conclude that there is a huge potential of application of this practice, in countries where symbiosis already has wide application, such as China, Sweden, Australia, and the United States of America, as well as in countries where this practice has little or no expression, such as Egypt, the Philippines and Colombia.

The manufacturing sector was the one that presented the highest prevalence in the industrial symbiosis relations, due to the wastes generated but also in the capacity of integrating wastes and by-products into the production cycle. Within this section, the chemical industry, cement industry, paper industry, steel and iron industry, power plant, and refineries are those that appear most frequently in industrial symbiosis. The fact that the refineries, iron and steel, pulp and paper, and chemicals industries are most involved in industrial symbiosis can be explained by the high overall industrial final energy consumption of these industries, as well as being responsible for a large proportion of carbon dioxide emissions [1], which encourages measures to make them more efficient and to reduce the negative effects of the process. Power plants and waste and wastewater companies were also part of a large number of industrial symbiosis cases.

The methods used to quantify the impacts of industrial symbiosis were the most widely used and were very diverse, being the life cycle assessment the most used in these assessments, and the environmental dimension was the most analysed, followed by the economic one. The predominance of environmental impact assessment can be explained by growing concerns about climate change, the urgency of reducing greenhouse gas emissions, the need to conserve natural resources and the consequent increase in environmental policies that have been applied.

Regarding the industrial symbiosis in Portugal, it was possible to conclude that in recent years some policies and strategic plans towards sustainable development have been implemented. However, some indicators show that is still far from having an efficient economy in the use of resources. By disseminating the application of industrial symbiosis at national level, Portugal can obtain numerous advantages provided by this practice, at the environmental, economic and social levels.

The analysis of the existing cases of industrial symbiosis reported in the literature allowed concluding that they are still very few and the areas of the Lisbon Metropolitan Area and Alentejo are where there is a higher concentration of cases. The analysis also led to the conclusion that most were developed from self-organized initiatives and that the number of actors presents in the networks is, in most cases, reduced. In addition, the economic activities of manufacturing and agriculture, forestry and fishing are the most present in synergy networks. However, for the enhancement of industrial symbiosis relations, political, cultural and economic barriers have to be overcome. The definition of a concerted action at national level that acts in different fields may be essential for the spread of industrial symbiosis in Portugal. Improving the legislative framework to facilitate industrial symbiosis and reduce bureaucracy in the by-product classification process, create tax relief, provide access to support funds, inform and support businesses and encourage industries that can function as anchor tenant are some of the challenges facing Portugal in order to establish industrial symbiosis in a solid way.

2. Future research

The research work developed in this thesis started a way to increase the industrial symbiosis by analyzing the existing cases and providing a series of drivers and best practices for the diffusion of this practice. However, much remains to be done to make synergy networks spread across the country in a more concerted and solid way.

Thus, one of the recommendations for future work would be to provide greater knowledge of existing cases. For this purpose, it would be important to use other types of sources in order to collect more information about cases of industrial symbiosis. In this sense, research with local authorities, industrial associations, and associations that coordinate industrial symbiosis could provide a better understanding of existing cases.

Although the industrial symbiosis is spread all over the world, in some regions the number of cases reported in the publications is very small, for example in Canada, Mexico, Brazil, among others. Thus, future research could deepen the knowledge about the industrial symbiosis in these places. On the one hand investigate whether there are more cases of symbiosis, and on the other hand evaluate the potential of new synergies, i.e. to assess local reality in terms of existing industries, legislation, and other constraints, and to study the best ways of disseminating these practices in those locations. Future research is also needed to make a greater comparison of case studies in different countries with industrial symbiosis with different levels of development, in order to draw conclusions about the reasons for this development and the surrounding reality of each one and how this translates into drivers and barriers to development.

Of the cases analysed about potential industrial symbiosis, it would be important in future research to assess whether these were implemented in order to increase understanding of the mechanisms that drive or condition the creation of synergies and thereby promote the growth of industrial symbiosis initiatives.

Future research could also focus on the quantification of the environmental, economic and social impacts of the cases of industrial symbiosis in Portugal in order to evaluate the contribution of this practice to the sustainable growth of the country and to promote the dissemination of results among the various stakeholders with the aim of boosting new synergies. It would also be important to evaluate in future research the dynamics of the creation and development of existing synergies in Portugal in order to promote the dissemination of this practice.

The expansion of industrial symbiosis to the surrounding communities has also revealed a strong ally for the reduction of carbon dioxide emissions and the amount of waste sent to landfills and incinerators. However, the published studies are still small in view of the great potential of these synergies. Thus, future research on industrial and urban symbiosis is essential, not only to quantify the impacts and improve existing synergies, but also to foster the creation of new symbioses. Thus, the economic viability of the construction of structures for the industry to supply the urban part of residual heat or studies to evaluate the integration of urban waste in the productive process of several industries, are some of these examples.

Contrary to environmental and economic indicators, social indicators are translated by some subjectivity and complexity, and data for their quantification are more difficult to obtain [2–4]. Thus, it is not surprising that in the case studies analysed, the social component is the least studied. However, this component may be very important for the development of industrial symbiosis, since if the surrounding community and regional governments are aware of the advantages of these synergies, they can become active agents in the development of industrial symbiosis. Thus, future research is needed to study the impacts on society derived from this practice. For example, quality of life, translated by better social and economic conditions, spending on health, employment and income, improvement of roads and accesses can be developed to assess the impacts of industrial symbiosis in the surrounding communities. In addition, research should also focus on ways to measure them and how to decouple the effects of industrial symbiosis from other measures that are taken to increase sustainability and it would also be important to assess which factors are most valued by the surrounding populations.

Another future active area of research would be the development of indicators or methods, aimed at industrial symbiosis, which would allow quantifying the impacts of the three dimensions of sustainability, environmental, economic and social. Although there are several studies that have encompassed these three dimensions, they are not aimed at industrial symbiosis. In addition, encompassing the environmental, economic and social components has entailed some difficulties, such as the integration of qualitative and quantitative indicators in the same evaluation framework [5], the possibility of considering several objective functions simultaneously in the optimization studies [6], and the difficulty of integrating the social component with the other dimensions, since it is more related to the practices of an organization and not to the unit processes [7]. Thus, future research would be necessary to overcome these barriers and to define a specific indicator for industrial symbiosis that would allow to quantify the total impact of this practice on companies, the environment and society and that allows the comparison of industrial symbiosis in different realities, that is, different characteristics of the network and taking into account the particularities of the region where it develops. Future research is also need to develop the integration of these indicators or methods with decision-making methods in order to serve as a tool in the final decision-making process.

In short, there is still a long way to go to spread the industrial symbiosis around the world and in particular in Portugal. However, the demands for sustainable development and more efficient use of resources will drive companies and governments to take action to find increasingly effective solutions and industrial symbiosis can play a very important role in meeting all of these requirements.

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