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

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Received: 22 August 2019; Accepted: 1 October 2019; Published: 4 October 2019

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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].

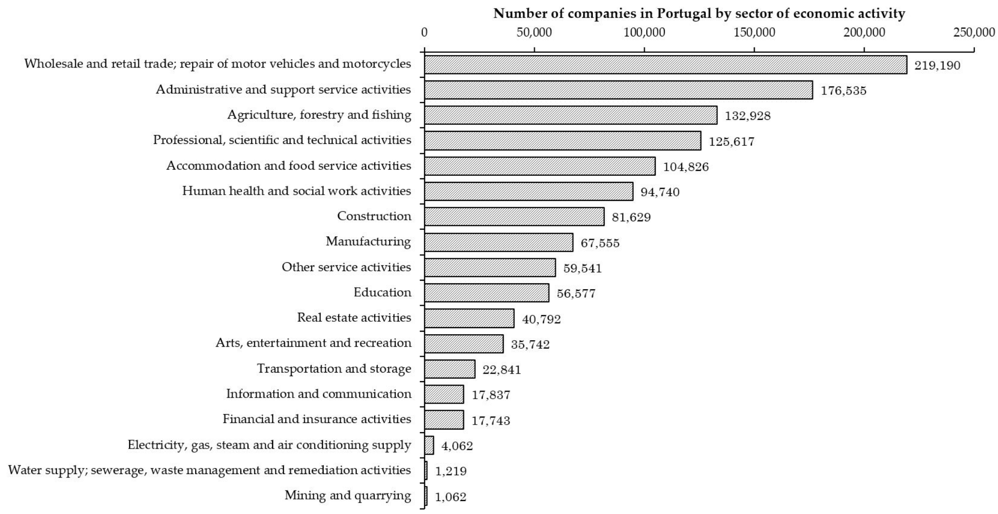

Figure 1. Number of companies in Portugal by sector of economic activity. *Source*: Own elaboration using data from INE (Instituto Nacional de Estatística), Statistics Portugal.

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.

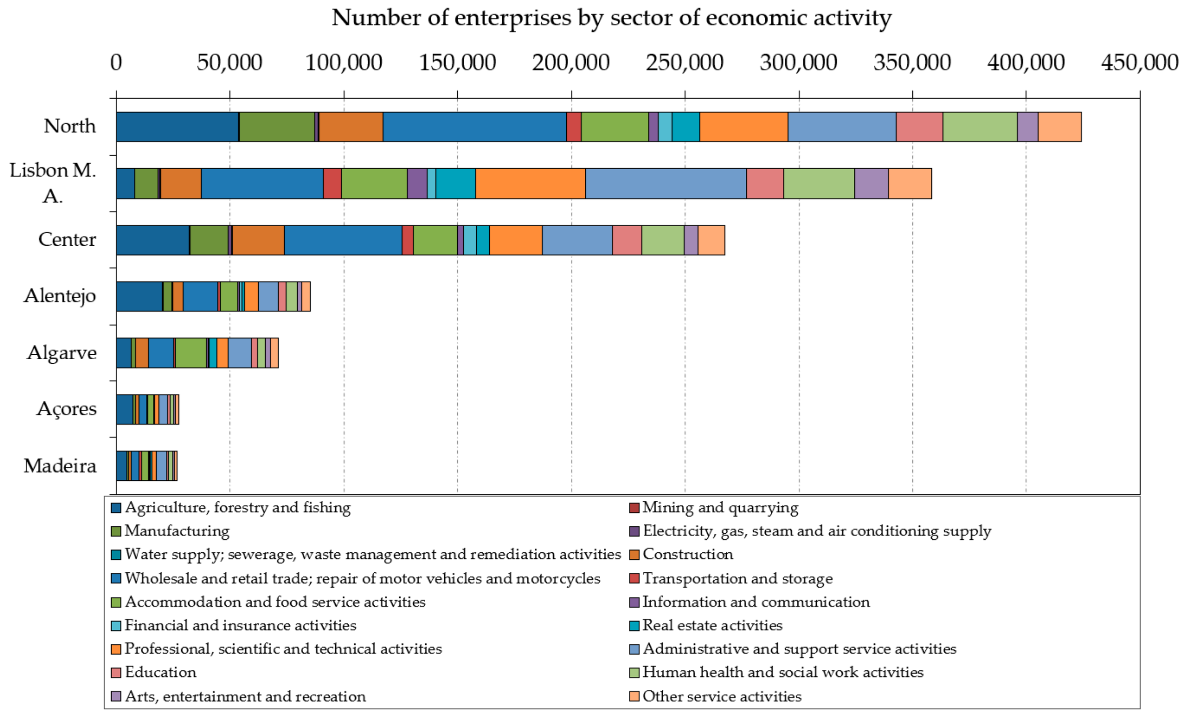

Figure 2. Number of enterprises by sector of economic activity and by geographical location. *Source*: Own elaboration using data from INE. Statistics Portugal.

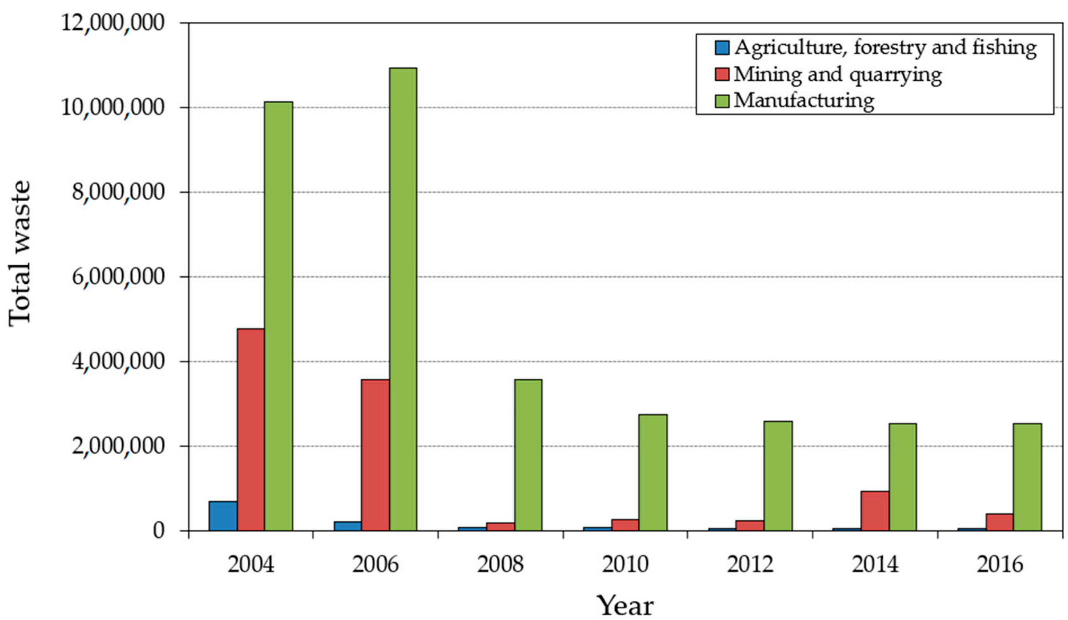

Figure 3. Evolution of total waste generated by the sections of agriculture, forestry, and fishing; mining and quarrying; and manufacturing. *Source*: Own elaboration using data from Eurostat.

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].

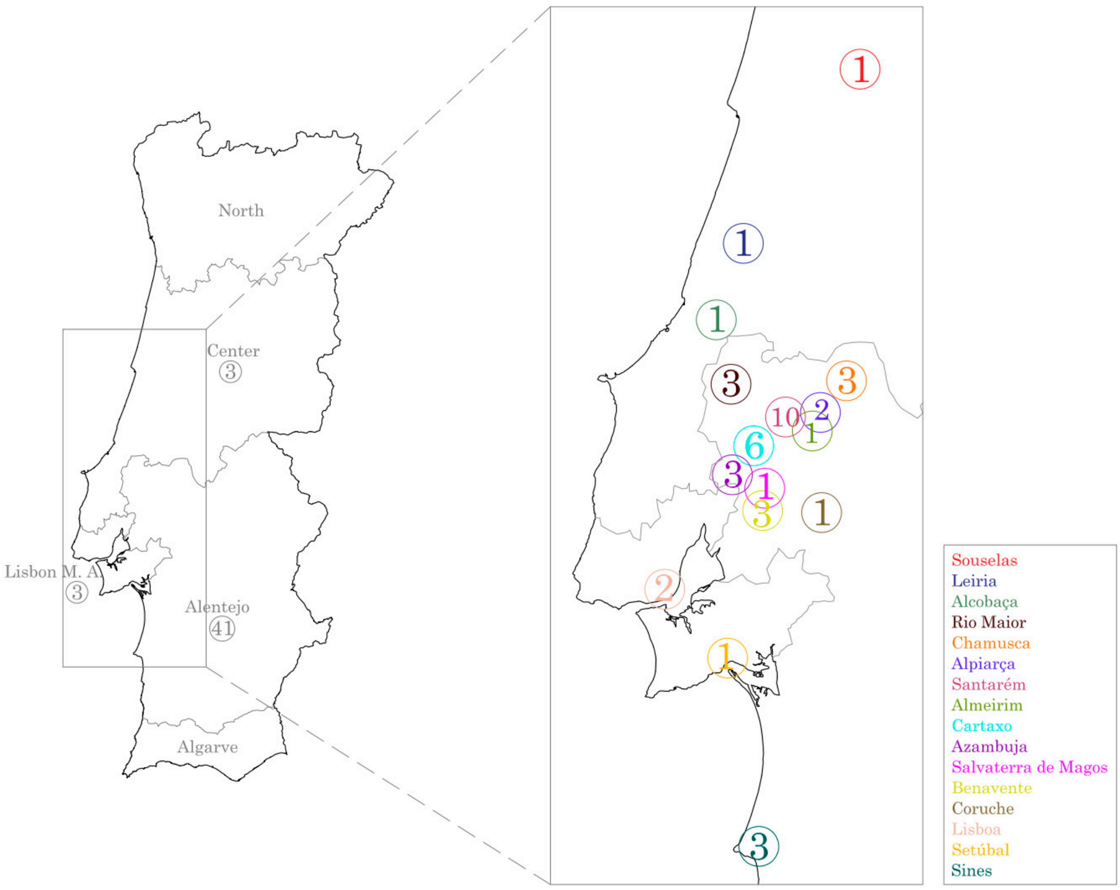

Figure 4. Geographic distribution of the different cases of industrial symbiosis in Portugal. Each color is associated with a different location. The indicated values identify the number of cases of industrial symbiosis present in each location.

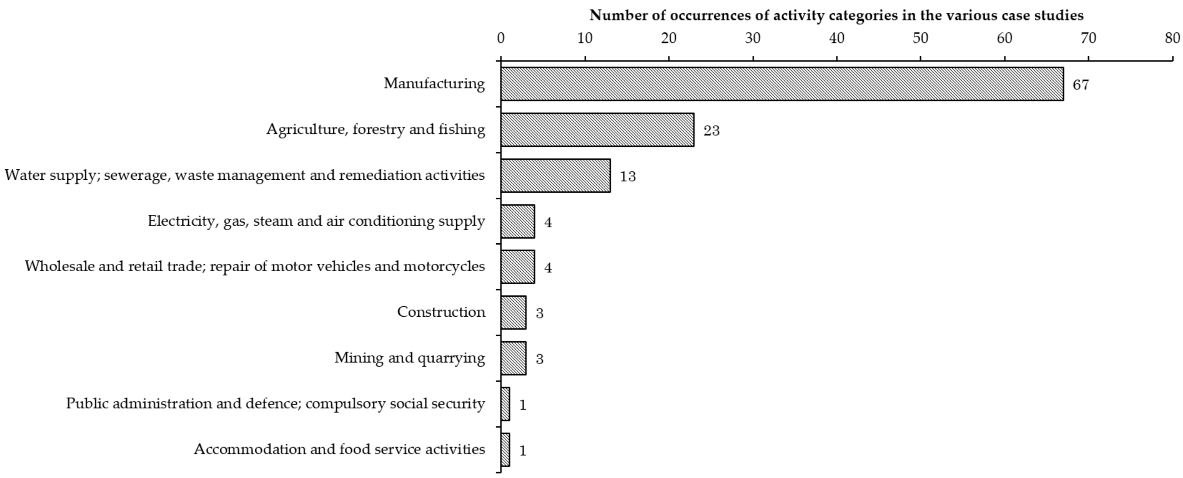

Figure 5. Number of occurrences by sector of economic activity in the various case studies.

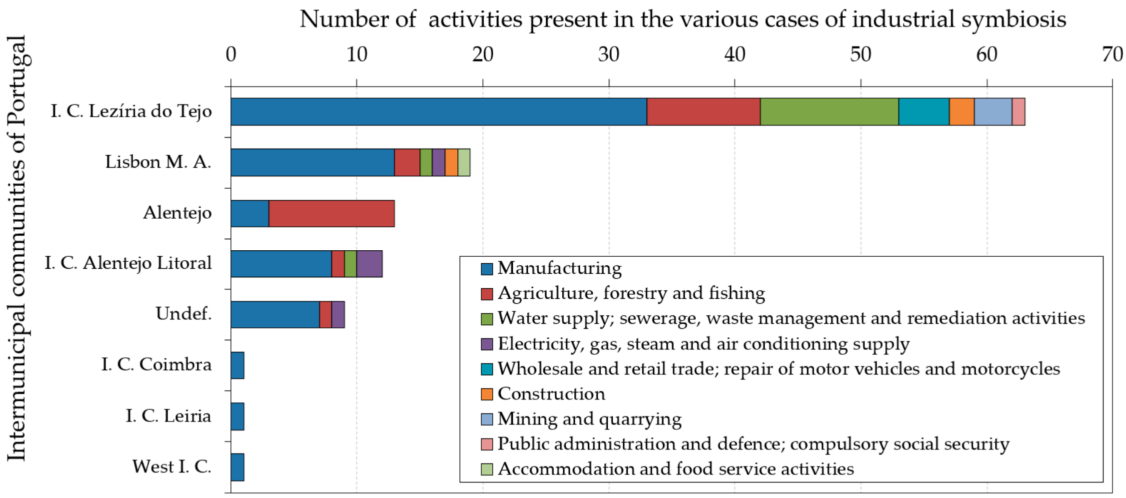

Figure 6. Number of occurrences by geographical location and by sector of economic activity in the various case studies. I.C.: intermunicipal community; M.A.: metropolitan area.

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.

Author Contributions: A.N. conducted the study and performed the writing and original draft preparation. R.G. handled the conceptualization, as well as the writing and editing of the manuscript. S.G.A. and J.C.O.M. supervised, revised, and corrected the manuscript.

Funding: Radu Godina would like to acknowledge financial support from Fundação para a Ciência e Tecnologia (UID/EMS/00667/2019).

Conflicts of Interest: The authors declare no conflict of interest.

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