sustainability

Article

Industrial Symbiosis: A Mechanism to Guarantee the Implementation of Circular Economy Practices

Lledó Castellet-Viciano *, Vicent Hernández-Chover, Águeda Bellver-Domingo and Francesc Hernández-Sancho

Water Economics Group, Inter-University Institute for Local Development (IILD-WATER), University of Valencia, C/ Serpis 29, 46022 Valencia, Spain
* Correspondence: lledo.castellet@uv.es

Abstract: There is a growing concern regarding the scarcity of natural resources. The levels of resource exploitation generated by the current system of production and consumption has led the European Commission to develop a set of guidelines that aim to reduce the pressure on natural resources. The set of guidelines proposed by the European Union is based on the transformation of the current linear economic system into a circular system in which resources and materials remain in the production system for longer. However, for this change to take effect, practical measures are required. This paper presents an industrial symbiosis approach as a practical application of a circular economy model. The aim of this paper is to develop a guide to successfully implement an industrial symbiosis network, demonstrating that industrial symbiosis can achieve the goals of a circular economy. To demonstrate this, an example of its implementation is provided in a region of Spain, which is responsible for producing approximately 95% of the total ceramics products in the nation. This study emphasises the set of barriers that need to be addressed in order to make new models a reality for business and consumers, society, and the environment.

Keywords: industrial symbiosis; circular economy; barriers; sustainability

Citation: Castellet-Viciano, L.; Hernández-Chover, V.; Bellver-Domingo, Á.; Hernández-Sancho, F. Industrial Symbiosis: A Mechanism to Guarantee the Implementation of Circular Economy Practices. *Sustainability* **2022**, *14*, 15872. https://doi.org/10.3390/su142315872

Academic Editor: Antonis A. Zorpas

Received: 25 October 2022
Accepted: 23 November 2022
Published: 29 November 2022

1. Introduction

The first step towards industrialisation took place in the mid 18th and early 19th centuries in Great Britain, with the mechanisation of production processes that lead to a mass production of products. This phenomenon, accompanied by the Industrial Revolution and capitalism, gave rise to an economic model based on industrial activity and the current consumer society. This new economic and social model, which once represented a breakthrough for society [1], has also caused irreversible environmental damage. Numerous authors [2–4] agree that the increasing exploitation of natural resources to satisfy production and consumption demands has now reached unsustainable levels.

The economic model that governs our society is a linear and unidirectional model, in which natural resources are extracted from the environment and then used as raw materials for different products, which are consumed and then discarded. The premise of this "extract, produce, use, dispose" model (Figure 1) is that natural resources are abundant, easily accessible, and affordable to manage as waste [5]. However, the dynamics of this model are neither sustainable nor feasible in the long term [6] because of the short life cycle of the products; the high demand for resources, which in many cases are limited; and the pollution generated by the immense amount of generated waste.

To address this situation and reduce the environmental impact of the current economic system, the European Commission has been working for several years on the development of plans, packages, and proposals that aim to transform the current linear economic model into a circular economic model [7,8]. The first step towards the transition to a circular economy model by the European Union began in 2014 with the communication "Towards a circular economy: a zero-waste agenda for Europe", which aims to reduce the amount of waste. This publication was followed by the 2015 "Action Plan for a circular economy in Europe", in which the European Commission proposed a series of measures that go beyond simply reducing the amount of waste and affect all stages of product life cycles. In 2018, the "Circular Economy Legislative Package" was presented, in which the "European Strategy for Plastics in a Circular Economy" and the "Sustainability Strategy for Chemicals" are highlights. In order to popularise the implementation of a circular economy, the "New Circular Economy Action Plan for a cleaner and more competitive Europe", as a key element of the European Green Deal and Europe's new programme for sustainable growth, was published in 2020.

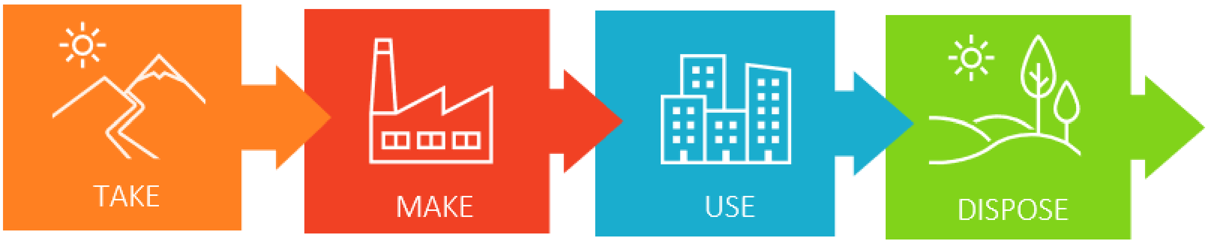

Figure 1. Linear economy model.

Although there is no single definition for the term "circular economy" [9], it is closely linked to other concepts, such as "efficiency", the principal of which is to do more with less, and "sustainability", which reminds us that actions in the present must not compromise the environmental, social, and economic well-being of future generations. Thus, to ensure the efficiency and sustainability of the economic system, the circular economic model is based on maintaining materials and circulating products in a closed cycle [10,11]. To implement this model, actions such as sharing, renting, reusing, repairing, renewing and recycling existing materials and products as often as possible are necessary. In this way, materials and products are given added value and their useful life is extended, reducing the demand for resources and generating less waste.

The transformation towards a circular economic model (Figure 2) requires the efforts of society in particular and the industrial sector, which has a fundamental role to play in the transformation of consumption and production patterns. For this reason, the European Commission focuses many of its measures and recommendations on the transformation of the industrial sector, as these measures have a high potential to reduce environmental impacts and increase the durability and recyclability of materials.

In the industrial sector, the first circular economy strategies aimed to implement actions such as recycling and reusing products in production systems. However, strategies based on circular economy models initiated in the early 2000s seek to go a step further, by implementing actions not only vertically along the supply chain but also transversally. Thus, in order to ensure the sustainability of the industrial sector, it is essential to implement the circular economy in a cross-cutting manner through intersectoral networks involving multiple production and supply chains [12,13].

There are numerous examples of industries working towards achieving a circular economy, mainly focusing on waste streams and seeking alternatives to reduce and reuse the waste generated by such processes [14–19]. However, despite the individual efforts of some companies or industries, companies and sectors must interact to scale up the effects of their actions and guarantee the flow of recovered and reused materials. To ensure the sustainability of industrial processes in this context, approaches such as industrial symbiosis, which some European countries are already applying, must be universally implemented [20–22]. According to [23], industrial symbiosis is an effective approach to accomplishing the principles of the circular economy.

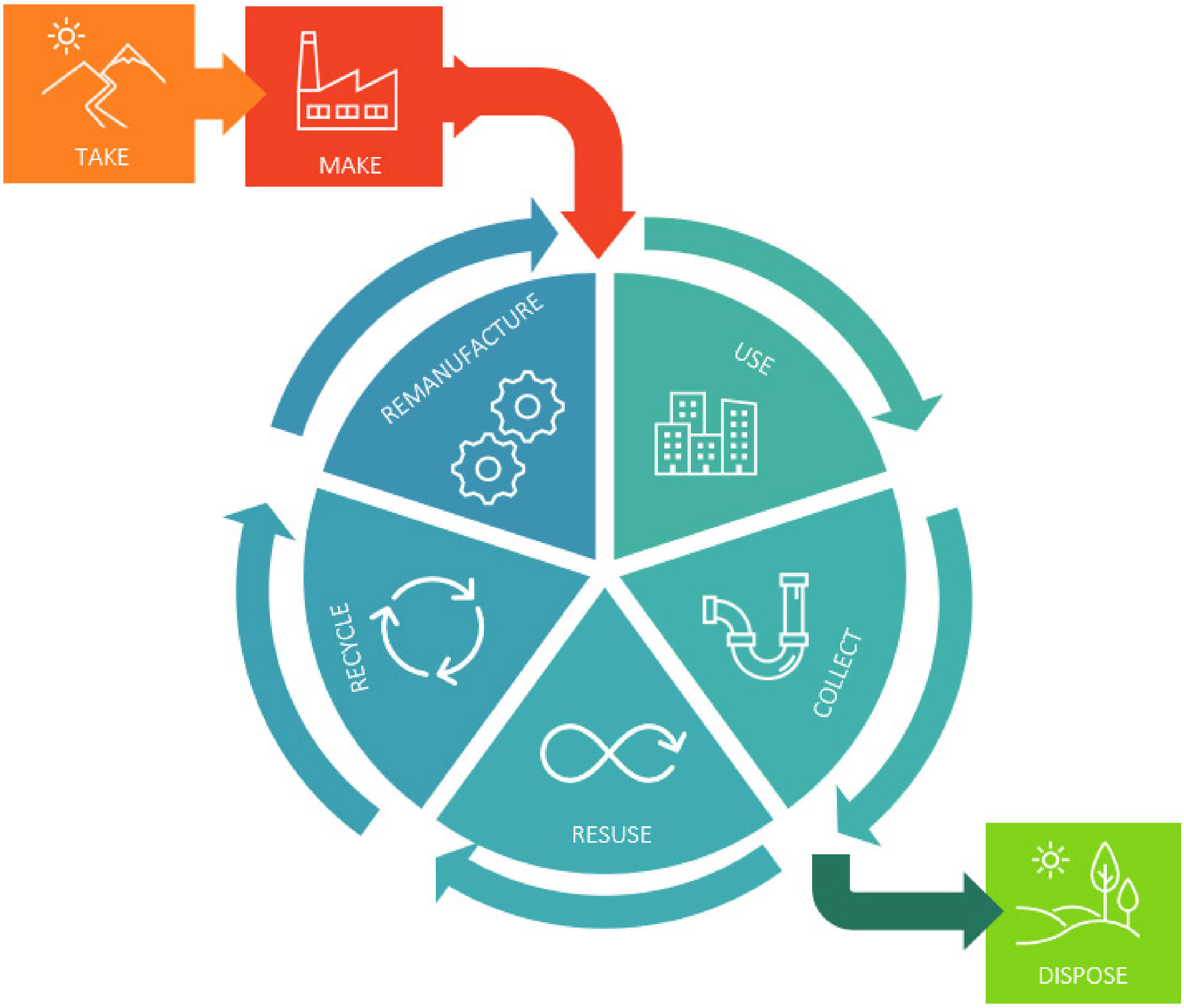

Figure 2. Circular economy model (own elaboration).

Currently, there are numerous success stories of industrial symbiosis, especially in sectors related to the forestry and paper industry, chemicals, metals, mining, and construction [24]. Perhaps one of the best-known national examples is the strategy developed in the United Kingdom, known as NISP. In Europe, particularly the Nordic countries, there are numerous examples of industrial symbiosis networks, including the Cleantech Östergötland project developed at a regional level in Sweden, and others of a local nature, such as the project implemented in Kalundborg, Denmark. Some examples of industrial symbiosis are as follows:

- A national symbiosis network
  The National Industrial Symbiosis Programme (NISP) has been identified by the European Commission as the most efficient resource management policy [20]. It is a national industrial symbiosis programme developed by the UK government, involving companies in the industrial sector, and governments, and research bodies. The benefits of this complex network of partnerships are that it improves resource efficiency, boosts economic growth, creates new jobs, and enables the transition to a low-carbon economy. Factors that have made this model of industrial symbiosis successful include government funding to support the programme, a wide and diverse network of organisations, dedicated professionals committed to maximising and extracting maximum benefit from their business interactions, and the existence of a system for managing and exchanging information and data.

- A regional symbiosis network
  The Östergötland region in Sweden is a successful example of industrial symbiosis relationships at a regional level [21]. Although there is no direct mention of industrial symbiosis or the circular economy in the development of this region, there has always been an interest in the environmental sustainability of the area. Therefore, on many occasions, symbiotic relationships have arisen under the slogan of turning environmental problems into business opportunities. The key factor in achieving this is the collaboration of companies with their predisposition and economic investment in new technologies, as well as the support of municipalities that promote more-sustainable strategies or business models. There are numerous types of symbiotic relationships in this area, although perhaps the most notable is that between different heat generation companies and the public transport system, which comprises buses and taxis that use biogas as fuel. The decision taken by the local governments of the municipalities involved was to reduce environmental pollution in the cities. Another equally interesting example is the Handelö industrial area, which combines a renewable energy industrial symbiosis cluster with a Natura 2000 logistics centre [25]. In the renewable energy cluster, the combined heat and power plant of E.ON is associated with a biogas plant and ethanol plant:
    - The E.ON plant has a fuel mix of 95% renewable resources, including household waste, rubber, wood chips, and wood waste.
    - A biogas plant produces biogas from sludge derived from the Norrköping wastewater treatment plant. After fermentation, biogas is converted into vehicle fuel and distributed to local filling stations.
    - The ethanol plant uses wheat, triticale, and barley as raw materials, and 29% biogas is produced by the biogas plant for the annual production of 210 million litres of bioethanol and 195,000 tonnes of protein pellets for livestock feed. The remaining part of the sediment is converted into feedstock for another biogas plant.
- A local symbiosis network
  Industrial symbiotic relationships in Kalundborg have evolved over time with the exchange of by-products between local companies that were originally independent of each other. The beginning of this relationship dates back to 1961, when the company Statoil (formerly Esso) needed water for its refinery, so a network of pipes was built between the company and the area around Lake Tissø. A decade later, an agreement was reached between Statoil and Gyproc, so that Gyproc could make use of the surplus gas generated at the refinery for the cooling process of the gypsum slabs. The following year, a third company, Dong Energy (formerly the Asnæs plant), became part of this industrial symbiosis, sharing the water supply system that was initially built for Statoil. Other companies, such as Novo Group, a pharmaceutical and biotechnology company, and Soilrem SA, a soil remediation company, have since joined this network of relationships. Today, this industrial symbiosis network is composed of eight public and private partners and involves approximately 50 symbiotic exchanges [26].

This network of symbiotic relationships leads to a more efficient use of resources, as demonstrated by a study carried out in 2008, which quantified the following savings:

- Groundwater: ~2,000,000 m^3/year;
- Surface water: ~1,000,000 m^3/year;
- Natural gypsum: ~100,000 tonnes/year;
- Petroleum: ~20,000 tonnes/year.

In addition to reducing the use of raw materials, this type of relationship also reduces CO_2 emissions, which were estimated to be as high as 275,000 tonnes per year.

Much of the success of Kalundborg industrial symbiosis is due to the existence of the intermediary figure, a development department of the municipality that operates from the Danish Symbiosis Centre. This department acts as a secretariat for the industrial symbiosis network partnership, through which direct contact is established with the managers and local administrators of related companies.

The remainder of this paper is organised as follows. Section 2 details the methodology, where an introduction to the concept of industrial symbiosis precedes the implementation guide of an industrial symbiosis network elaborated by the authors. In Section 3, the results and discussion of the implementation guide, as shown in the previous section, are applied in a local area of the Valencian Community (Spain) to one of the most relevant sectors at a national level: the ceramics industry. Finally, Section 4 presents conclusions and further recommendations.

2. Materials and Methods

2.1. Industrial Symbiosis Definition

Industrial symbiosis is framed within the field of industrial ecology [23,27,28], which attempts to connect the principles and elements of ecology with industrial processes. Therefore, as with ecosystems, each process and/or chain of industrial processes presents a cyclical pattern in such a way that each one becomes a dependent component of and interrelated with the holistic ecosystem in which it is produced. Industrial ecosystems can therefore be understood as a set of industrial processes interconnected so that the waste and by-products or energy surpluses of one component can be used as raw materials for others [29].

In addition, different types of relationships between different organisms can occur in ecosystems, such as symbiotic relationships, where two or more species exchange materials, energy, or information for mutual benefits. Similarly, "industrial symbiosis" refers to the mutual benefit that can be obtained from the relationship between different companies or industries. Thus, the concept of industrial symbiosis refers to the relationships established between different companies or industrial sectors, which have certain competitive advantages in the exchange of materials, energy, water, or other by-products of their processes through innovative collaborations, finding ways to use the waste of one component as raw material for another [30]. However, these relationships need not necessarily involve a direct flow of materials and can lead to a more efficient use of resources, such as sharing infrastructure or equipment [31]. The study of [32] further analyses industrial symbiosis as a business model, whereby the relationship established between different entities has a strategic or business purpose.

Hence, industrial symbiosis can be understood as a model of industrial ecology, where the fundamental aspect is the collaboration and productive synergy that may exist between different economic activities as a result of the exchange and sharing of resources.

Linked to the concept of industrial symbiosis are so-called eco-industrial parks [33], which represent the practical application of industrial symbiosis. Although this has various definitions, the fundamental idea in all of them is the same, referring to the development of a business community with material exchange networks in which the by-products or waste of a company or industrial process are converted into products that can be reused by other processes, reducing the number of required raw materials and the waste generated (Figure 3). This, together with the shared use of infrastructures, services, information, or other logistical aspects, leads to a more sustainable consumption and production system [34,35].

There are several characteristics that allow us to distinguish between different types of industrial symbiosis. The first classification presented here takes into consideration the kind of element that links or generates the synergy between different industrial entities [36]. Prioritising this criterion yields three distinguished groups:

- Mutuality synergies: there is no flow of materials or products, but these synergies involve sharing services, facilities, or infrastructures. (e.g., energy supply or waste treatment, emergency planning, training, logistics, and transport).
- Substitution synergies: these are transfers of products where the waste of one company or industrial process is part of the resource flow of another (e.g., exchange of by-products, waste, waste heat, etc.).

- Genesis synergies: these involve the creation of an original activity to satisfy the reuse requirement of any flow or company.

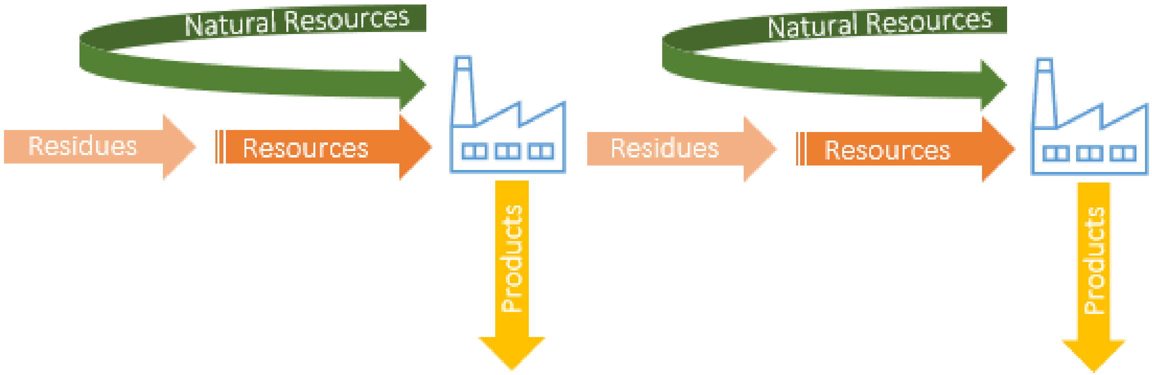

Figure 3. Diagram of the industrial symbiosis process (own elaboration).

In addition to this classification, industrial symbiosis relationships can also be grouped according to their origin or type of management, differentiating between three types of networks [24]:

- Self-managed ("self-organised activities" or "bottom up"): this refers to those relationships that spontaneously arise from the direct interaction between different industrial actors, because both parties can benefit from this collaboration. They are often local in nature and linked to a cluster of manufacturing activities, usually involving primary sectors. Although they are usually driven by private actors, in many cases they are supported by and involved with local governments. This type of symbiotic relationship is characteristic of countries with a high degree of environmental awareness and strict environmental regulations.
- Facilitated networks ("facilitated networks" or "intermediary"): these are symbiotic relationships with a third actor, acting as an intermediary in the activity. This type of relationship can easily be applied at all levels: local, regional, and national.
- Planned networks ("planned networks" or "top down"): these are symbiotic relationships that have been planned for a given industrial area and often share infrastructures and services that ensure the flow of resources between them.

Regardless of the type of the symbiotic relationship, once established, they may evolve in diverse ways. According to [37], the type of evolution can be as follows: (a) serendipitous, where the interaction occurs by chance between parties who base their relationship on their individual benefits, or (b) goal directed, when the actors involved act according to a plan or to achieve certain objectives. Moreover, according to the analysis carried out by the abovementioned authors, both forms of evolution can occur in the same industrial symbiosis network, but at different time points.

To achieve the objectives of the circular economy and make strategies such as industrial symbiosis feasible, several barriers must be overcome [4], and the information and management of waste streams generated by different industrial sectors should be improved, with an awareness of their commercial and industrial potential.

2.2. Method to Successfully Implement an Industrial Symbiosis Method

As observed in the success stories of industrial symbiosis, these can arise spontaneously in response to a need of the companies (industrial symbiosis in Kalundborg) or be planned in advance (NISP, UK). However, spontaneously emerging relationships do not take place, not because there is no demand for them but rather because of the following situations:

- Companies are unaware of the impacts and potential of their waste streams;

- Despite being aware of resource potential, companies are unaware of other companies with which to establish synergies;
- Despite being aware of their potential and with which companies to establish synergies, companies do not have the resources (financial, time, technological, etc.) to implement this.

Therefore, in order to face the situations mentioned above and to guarantee the development of industrial symbiosis networks, one solution may be to design industrial symbiosis projects in a premeditated and planned way. In the implementation of industrial symbiosis projects, the following phases can be distinguished (Figure 4).

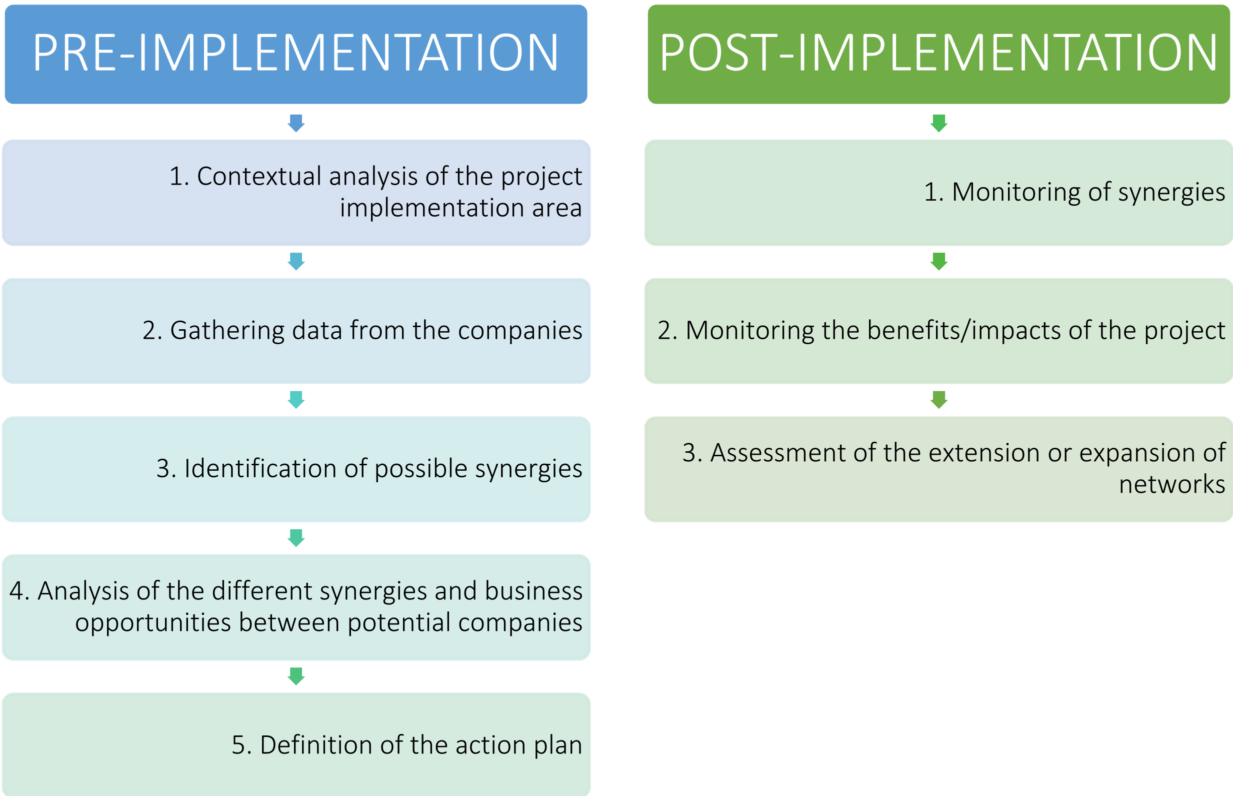

Figure 4. Implementation phases of an industrial symbiosis project. Source: adapted from [6].

To implement an industrial symbiosis project, it is necessary to carry out a study of the environment in which a project is set to be implemented and the possible relationships that may exist. This is developed in a series of phases that are part of a preimplementation stage, consisting of the following phases:

A.1. Contextual analysis of the project implementation area: an analysis is carried out to identify the possible companies that form part of the symbiosis system and the available means to carry out the synergies.

A.2. Gathering data from the companies: once the companies have been identified, information is collected on their process flow, identifying resources and generated waste.

A.3. Identification of possible synergies: after identifying the needs of the companies and the generated waste, the possible relationships that may exist between the companies are considered, and drawing up a resource map that shows the systematic vision of the project is essential.

A.4. Analysis of the different synergies and business opportunities between potential companies: in this stage, different alternatives should be analysed, and the collective and individual objectives of implementing the symbiosis network should be set out.

A.5. Definition of the action plan: in this final section, the steps to be taken to set up the project and achieve its common and individual objectives must be established.

After the start-up of the project, the postimplementation stage begins. To guarantee its long-term feasibility, it is necessary to monitor this stage and analyse new opportunities or potentialities, adapting the project to possible changes in the market. For this, the following phases are necessary:

B.1. Monitoring of synergies: once the project has been implemented, it is necessary that the enterprises receive support to carry out the action plan and fulfil the objectives.

B.2. Monitoring the benefits/impacts of the project: in order to measure or evaluate the benefits associated with industrial symbiosis and its contribution to achieving the circular economy, it is useful to develop a system of indicators capable of measuring both environmental and economic benefits.

B.3. Assessment of the extension or expansion of networks: furthermore, to ensure the feasibility of industrial symbiosis processes, it is important that a single company or industrial process not depend on only one other, as any setback in one process can affect another. The study of [38] analyses the importance of the redundancy of firms in industrial symbiosis models and concludes that the network of relationships should be formed by an optimal number of firms. This is because an excess of firms offers greater resilience to any disturbance but reduces the economic benefit. On the contrary, if the network is formed by a reduced number of firms, the gains are greater, but they are more vulnerable to any disturbance.

3. Results and Discussion

In this section, the developed guidelines are applied to the ceramic industry in the province of Castellón in the Valencian Community (Spain) to demonstrate the usefulness of developing an industrial symbiosis network.

3.1. Preimplementation Stage: Contextual Analysis of the Project Implementation Area

To ensure compliance with the purposes of the circular economy and transform the current economic model into a more sustainable, decarbonised, and resource-efficient model in Spain, the Spanish Circular Economy Strategy (EEEC) was developed, which set out the objectives to be met by 2030:

- Reduce the national consumption of materials in relation to GDP by 30%, where 2010 is the reference year.
- Reduce waste generation by 15% compared to 2010.
- Reduce food waste generation throughout the food chain: 50% reduction per capita at household and retail levels and 20% reduction in production and supply chains from 2020 and afterwards.
- Increase the reuse and preparation for reuse to 10% of the generated municipal waste.
- Improve water efficiency by 10%.
- Reduce greenhouse gas emissions to below 10 million tonnes of CO_2 equivalent.

To facilitate the achievement of these objectives, eight action plans are presented, five of which are based on closing the product cycle: production, consumption, waste management, secondary raw materials, and water reuse. The other three plans are of a cross-cutting nature: awareness and participation; research, innovation, and competitiveness; and employment and training. In addition, the EEEC identifies six priority sectors of activity for which action should be taken, namely the construction, agrifood, fisheries and forestry, industrial, consumer goods, tourism, and textiles and clothing sectors.

This strategy is one of the bases for the implementation of industrial symbiosis models, which have a high potential to achieve many of the proposed objectives, especially in the Valencian Community, where many of the sectors identified as priority sectors are the basis of its economy.

One of the key sectors in the territorial scope of the province of Castellón is the ceramics industry, being the main economic motor of the region (Figure 5). It is estimated that approximately 95% of national production comes from this region [39], being the most competitive in Europe within the sector and a coleader in innovation, together with the

Sassuolo cluster (Italy). It is also a productive activity that is a great consumer of resources, mainly silicates and silicate rocks, as well as a wide variety of minerals. It is estimated that Spain is the third largest consumer of this type of material in the world [40]. In addition to rocks and minerals, this sector requires the consumption of water and energy to carry out the processes.

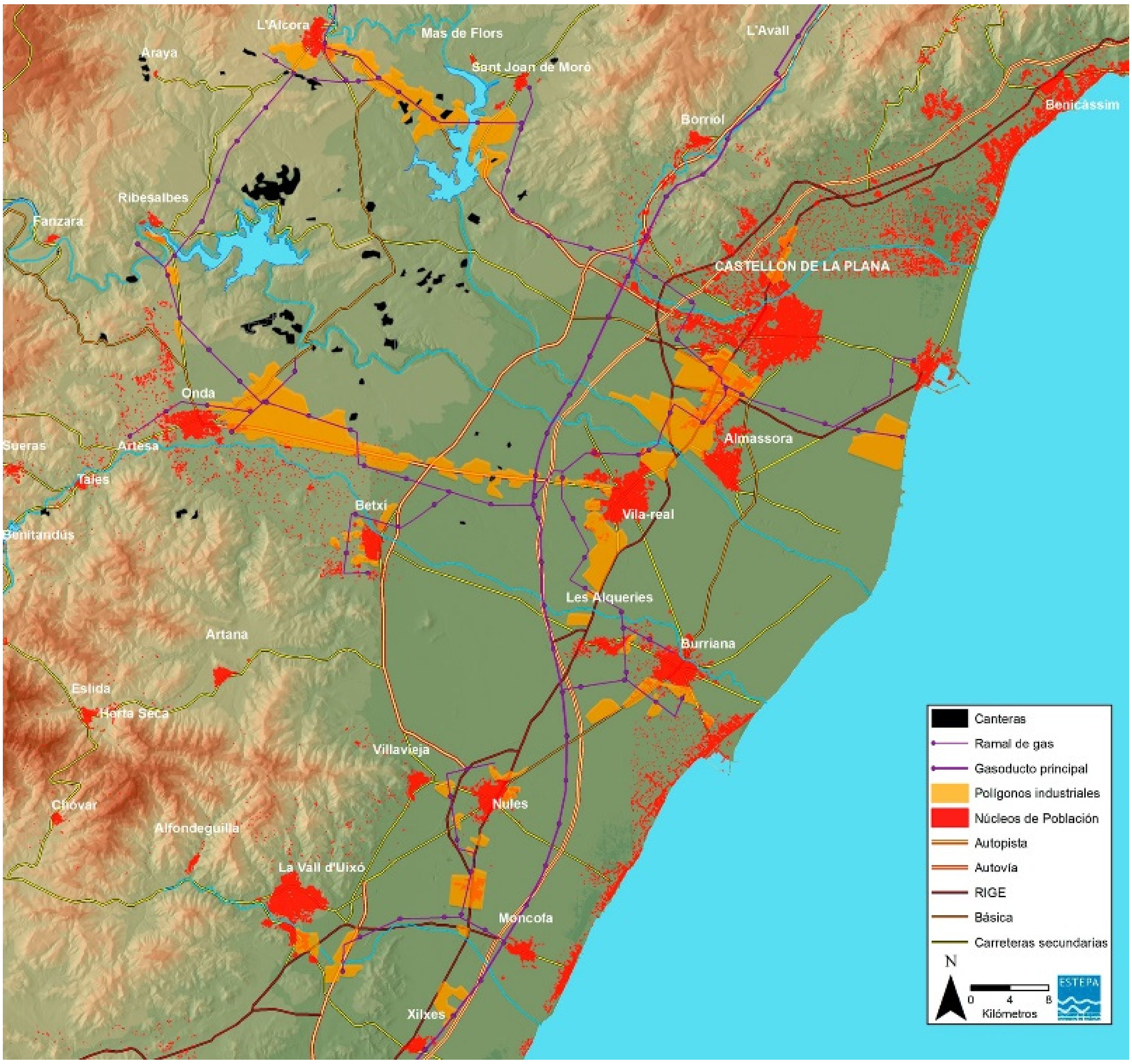

Figure 5. Distribution of industrial parks and quarries in the province of Castellón. Source: Valencian tourist landscapes, valuable and valued (http://paisajesturisticosvalencianos.com/paisajes/la-industria-ceramica-de-la-plana/ accessed on 8 June 2022).

To become one of the economic sectors of reference, the ceramic industry in Castellón has developed cutting-edge technologies to adapt not only to market demand, but also to environmental requirements. Thus, the ceramics sector has great potential to implement a wide network of industrial symbiosis relationships, both for its technological capacity and environmental awareness and for the great possibility of reducing the consumption of resources and the generation of waste.

3.2. Preimplementation Stage: Gathering Data from the Companies

Some industrial symbiosis relationships already exist in the sector, such as the use of glass waste or the reuse of sludge from the glazing process at atomised powder manufacturing companies. However, this network of relationships could be even more widespread than demonstrated by the REWACER, LIFE EGGSHELLENCE: a potential raw material for ceramic wall tiles (REF.: LIFE19 ENV/ES/000121) or LIFE In-BRIEF (REF.: LIFE14 ENV/ES/000427) projects.

The objective of the REWACER project is to encourage the reuse of wastewater and promote its use in the ceramics sector to reduce the pressure on the main source of supply in the province, which is of subterranean origin. The implementation of this project involves the development of a new business/service model, specifically reclaimed water and a new link between the ceramic industries and wastewater treatment plants.

In addition to water, ceramics industries are energy consumers, generally obtained from fossil fuels. Therefore, in order to decarbonise ceramic processes, the LIFE In-BRIEF project proposes the use of biogas generated from agrifood waste and sewage sludge in an agrifood waste treatment plant in the region, specifically located in Vall d'Uixò. This biogas plant currently has the capacity to treat 40,000 tonnes of waste per year, producing 200 Nm^3/h and 500 kW of electrical energy in a cogeneration engine. In the anaerobic digestion process, as well as while obtaining biogas, the by-product digestate is produced, which can be used as a liquid fertiliser.

However, perhaps the most innovative industrial symbiosis project involving the ceramics sector is LIFE EGGSHELLENCE, which once again brings together the ceramics and food sectors, in this case promoting the reuse of thousands of tonnes of eggshells in order to incorporate the calcium carbonate they contain as a raw submaterial in ceramic tile compositions.

3.3. Preimplementation Stage: Identification of Possible Synergies

With the aim of optimising resources in the ceramics sector, as well as establishing symbiotic relationships involving the flow of materials, the use of shared infrastructures or logistical systems between companies in the sectors that use the same resources can be promoted, which increases efficiency and minimises costs. Figure 6 shows the relationships that could be established among the companies.

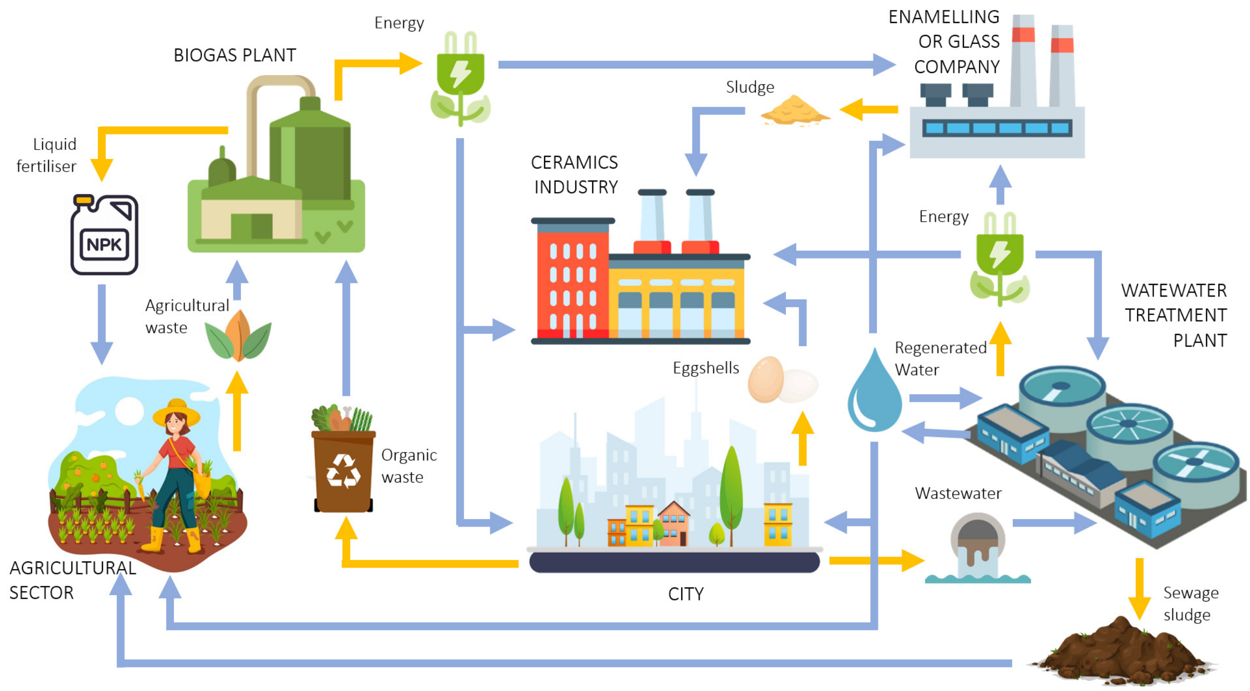

Figure 6. Example of industrial symbiosis in the ceramics industry (own elaboration).

3.4. Preimplementation Stage: Analysis of the Different Synergies and Business Opportunities between Potential Companies

Industrial symbiosis is a sustainable business model with multiple business, social, and environmental benefits [41]. Because of this new business model, which is based on the principles of the circular economy, our dependency on raw materials, the availability of which has significantly decreased in recent years, has been reduced [42]. In addition, it allows for the use of alternative resources and waste in such a way that it is reintroduced into the production cycle. This resulted in a more efficient use of resources and a reduction in the generation of waste [33]. Some of the most relevant contributions of industrial symbiosis are listed below:

1. Social benefits:
    - Creation of new business opportunities;
    - Protection and creation of new jobs;
    - Improved health;
    - Community membership.
2. Environmental benefits:
    - Reduction of CO_2 emissions;
    - Efficient use of resources, e.g., reduction in the volume of water used;
    - Reduction in waste that is hazardous, destined for landfills;
    - Protection of ecosystems.
3. Economic or business benefits:
    - Strengthening of market image;
    - Cost reduction;
    - Generation of additional income;
    - Creation of new business.

3.5. Preimplementation Stage: Definition of the Action Plan

Despite the benefits of industrial symbiosis models, their practical implementation is not straightforward. Achieving the objectives and principles of the circular economy, and making strategies, such as industrial symbiosis, feasible requires going a step further and overcoming several barriers [4], as well as improving the information and management of the waste streams generated by the different industrial sectors and being aware of their commercial and industrial potentials. The main constraints encountered that hinder the implementation of industrial symbiosis models and collaboration between companies are the following:

1. Civil society commitment to the circular economy:
   Transforming the current linear economic model requires changing production and consumption patterns, thus requiring the collaboration and commitment of society as a whole [43]. To this end, it is important to replace "buying a new product" with "sharing", "renting", "reusing", "repairing", "renewing", and "recycling" [22,44].
2. Increase information on the potential of waste as a resource:
   Today, there are still many prejudices about the use of waste materials as a source of resources; therefore, to ensure the establishment of industrial symbiotic relationships, it is essential to overcome this barrier and promote the potentiality of waste as a resource [44].
3. Availability of waste treatment technologies:
   In order to make use of waste as a resource, it is possible that waste may require pre-treatment or conditioning, for which it is necessary to have certain technical knowledge or skills or have sufficient financial resources [45].
4. Business models and coordination between actors in the value chain:
   A crucial aspect of boosting industrial symbiosis models is to highlight their role as business models [38]. To this end, the specificities and limitations of each company

must be considered in order to maximise the opportunities that the establishment of a network of relationships with other companies can offer, highlighting economic benefits, among which the following should be addressed:

- Transport cost savings through collaboration with local companies;
- Increased bargaining power for companies as a result of sharing services;
- Savings in waste management and additional income from waste recovery;
- Reduced dependence on traditional resource-supply channels.

Furthermore, the study of intermediaries in this type of relationship is, in many cases, essential to ensuring a dialogue between different actors and to enhancing values of trust, confidentiality, openness, equality, and cooperation [26].

5. Raising awareness of the environmental and social impacts of the current production system: It is important to raise awareness not only of the economic potential of industrial symbiosis but also of the environmental and social issues [23]. The reduction in environmental impacts that can be avoided because of the recovery of waste generated in industrial processes can favour social acceptability, which is essential for promoting industrial symbiosis projects.
6. Harmonisation of technologies, processes, and policies:
Having a common regulatory framework containing standards of technologies that should be applied and in what form (certifications of application of circular economy principles, guarantees of correct application, etc.) can be useful for promoting the implementation of industrial symbiosis projects [24]. In addition, government support through funding, training, tax policies, etc., is also significant for ensuring environmental investments.

Once the main barriers have been identified, they should be overcome in order to guarantee the success of the implementation plan. In this sense, digitalisation or 4.0 technologies could be vital to guaranteeing the implementation of a symbiotic relationship in the area under study and, ultimately, to achieving circular economy principles [46]. Digital technology can change the traditional production and consumption system, helping companies and the production sectors to meet one of their main challenges—becoming sustainable producers. In fact, [47] developed a software tool that could help to achieve the principles of circular economy, bringing great benefits through implementing the following practices [48]:

- Identifying unknown sustainable benefits, such as improved efficiency increases profitability, but it can also cause a reduction in resource consumption and waste generation, resulting in greater industrial sustainability.
- The application of mathematical and computational optimisation models is a useful decision-making tool for optimising industrial symbiosis practices.
- The monitoring, storing, and processing of data are essential for producing reliable information between supply chains and industrial networks and for optimising the use and flow of resources in business networks.
- Universally applicable indicators capable of measuring resilience and reliability can be developed through a better understanding of the optimisation of resource use and operational data sharing.
- The sharing of data and information fosters mutual trust between sectors that are part of the industrial symbiosis system, promoting sustainable consumption and corporate culture, which ultimately has a positive impact on improving industrial sustainability.

The main advantages offered by 4.0 technologies are their capacity for process monitoring, data collection, data mining, data treatment, and data processing, which generate information that can be easily shared between sectors, companies, and/or individuals. This allows for a rapid and simultaneous flow of information between companies, producers, and consumers, enabling interaction between all agents that take part in industrial symbiosis and promoting a more efficient use of resources and reduction in waste. However, digitalisation not only is important for strengthening the collaborations between all the agents involved in the symbiotic network but also improves the efficiency of the processes.

In remanufacturing, valorisation, recycling, and resource recovery, the implementation of optimisation models offered by digitalisation are useful for choosing what kind of materials or products should potentially be recovered, reused, or recycled, on the basis of costs and time [49].

3.6. Postimplementation Stage

Although the postimplementation stage consists of three stages, the three stages are discussed together because they depend on how the industrial symbiosis project is implemented. To make a follow-up of the synergies carried out in the process, it is necessary to monitor the processes of industries that participate in the symbiotic network. There should be an inventory of all the resources used and waste produced in the sectors involved in the industrial symbiosis of the project (agriculture, ceramics industry, enamelling or glass companies, wastewater treatment plants, etc.). To achieve this, the use of digital technologies that monitor, gather, and process all this information is crucial.

All gathered information will be useful for developing and assessing the benefits of the industrial symbiosis network. To this end, different KPIs can be created. The KPIs could act as individual indicators for each of the companies that take part in the industrial symbiosis network or for the whole project. Referring to individual companies, we can use the following:

Agriculture sector:

- Quantity of waste produced that will be reused/kg of crop production;
- Quantity of ecofertilisers used/kg of crop production;
- Volume of regenerated water used/kg of crop production;
- Quantity of sewage sludge used/kg of crop production.

Ceramic industry:

- Quantity of clean energy used/m^2 of tiles produced;
- Volume of regenerated water used/m^2 of tiles produced;
- Quantity of eggshells used/m^2 of tiles produced;
- Quantity of glass sludge used/m^2 of tiles produced.

Enamelling or glass company:

- Quantity of clean energy used/m^2 of glass production;
- Volume of regenerated water used/m^2 of glass production.

Biogas production:

- Quantity of organic and agricultural waste used/Kwh of energy produced;
- Quantity of organic and agricultural waste used/L of fertiliser produced.

Regarding global indicators, we can categorise some of them as environmental indicators, such as the reduction in greenhouse gas emissions; social indicators, such as additional jobs created; and economic indicators, which consider the economic value of the different products that each industry or sector in relation to the reduction in or production of greenhouse emissions.

Another important aspect of the postimplementation stage is to expand the network within the cooperative sectors or to involve companies from other sectors in order to recover or reuse other products. This last part helps to scale up the effects of industrial symbiosis and circular economy principles.

4. Conclusions

When symbiotic relationships do not spontaneously occur in the industrial sector, they can be promoted through a planned relationship by using the guidelines established in this study, which presents useful guidelines to start a symbiotic relationship in areas where there are potential industries that will take part in the network. However, the main limitations of this study lie in economic and regulatory aspects. To ensure the application of industrial symbiosis, these guidelines should be accompanied by a feasibility study to prove that the project is economically feasible, requiring detailed information about the use of resources and waste produced by different sectors, the current price of products, and the necessary investments in infrastructure for implementing the project. Aside from these, this study cannot further predict the possible regulatory barriers that may be encountered in the future.

There is no doubt that industrial symbiosis can be a key factor in the transformation of the current linear and unsustainable economic model towards a more sustainable and circular economic model, in which raw materials and products remain in the economic system for longer, thus increasing the efficiency of resources and reducing generated waste. Industrial symbiosis presents a social, environmental, and economic win-win. The social and environmental benefits associated with industrial symbiosis are more than evident, but industrial symbiosis also represents a new business model in which materials that were previously considered waste are utilised, thus opening up new markets.

It is evident that a change in the production model is necessary and requires the joint collaboration of producers and consumers. Therefore, this is a task that society must jointly carry out on all levels. At European and national levels, guidelines and directives have already been drawn up that set out future lines of action. As we have seen, part of the industrial sector has also shown interest in this. However, for this to become a widespread reality, there is still a long way to go, and a series of limitations must be addressed, such as the social acceptance of the use and reuse of products and institutional and administrative segmentation in terms of waste management, which in many cases hinders recirculation. In addition to this, it would be advisable to draw up a package or programme to help sectors and companies that do not have sufficient economic or technological resources to implement industrial symbiosis. Last but not least, it is imperative that a joint information system be used to optimise relations. It is difficult to develop a system of industrial symbiosis if the resources and products that neighbouring companies need or generate are unknown.

Author Contributions: L.C.-V.: Conceptualization, Formal analysis, Resources, Writing—review & editing, Supervision. V.H.-C.: Methodology, Formal analysis, Writing—review & editing, Supervision. Á.B.-D.: Data curation, preparation, Writing—review & editing, F.H.-S.: Methodology, Resources, Writing—review & editing, Supervision. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Valencian Government (project CIAICO/2021/347-Generalitat Valenciana).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

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

References

1. Haraguchi, N.; Martorano, B.; Sanfilippo, M. What factors drive successful industrialization? Evidence and implications for developing countries. *Struct. Chang. Econ. Dyn.* **2019**, *49*, 266–276. [CrossRef]
2. Oberle, B.; Bringezu, S.; Hatfield-Dodds, S.; Hellweg, S.; Schandl, H.; Clement, J.; Cabernard, L.; Che, N.; Chen, D.; Droz-Georget, H. *Global Resources Outlook 2019: Natural Resources for the Future We Want*; United Nations Environment Programme: Nairobi, Kenya, 2019.
3. Garcia, A.C.; Ambrose, A.; Hawkins, A.; Parkes, S. High consumption, an unsustainable habit that needs more attention. *Energy Res. Soc. Sci.* **2021**, *80*, 102241. [CrossRef]
4. Tan, J.; Tan, F.J.; Ramakrishna, S. Transitioning to a Circular Economy: A Systematic Review of Its Drivers and Barriers. *Sustainability* **2022**, *14*, 1757. [CrossRef]
5. Lieder, M.; Rashid, A. Towards circular economy implementation: A comprehensive review in context of manufacturing industry. *J. Clean. Prod.* **2016**, *115*, 36–51. [CrossRef]
6. Marconi, M.; Gregori, F.; Germani, M.; Papetti, A.; Favi, C. An approach to favor industrial symbiosis: The case of waste electrical and electronic equipment. *Procedia Manuf.* **2018**, *21*, 502–509. [CrossRef]

7. Costa, I.; Massard, G.; Agarwal, A. Waste management policies for industrial symbiosis development: Case studies in European countries. *J. Clean. Prod.* **2010**, *18*, 815–822. [CrossRef]
8. Völker, T.; Kovacic, Z.; Strand, R. Indicator development as a site of collective imagination? The case of European Commission policies on the circular economy. *Cult. Organ.* **2020**, *26*, 103–120. [CrossRef]
9. Korhonen, J.; Honkasalo, A.; Seppälä, J. Circular Economy: The Concept and its Limitations. *Ecol. Econ.* **2018**, *143*, 37–46. [CrossRef]
10. Geissdoerfer, M.; Savaget, P.; Bocken, N.M.P.; Hultink, E.J. The Circular Economy—A new sustainability paradigm? *J. Clean. Prod.* **2017**, *143*, 757–768. [CrossRef]
11. Atabaki, M.S.; Mohammadi, M.; Naderi, B. New robust optimization models for closed-loop supply chain of durable products: Towards a circular economy. *Comput. Ind. Eng.* **2020**, *146*, 106520. [CrossRef]
12. Frig, M.; Sorsa, V. Nation branding as sustainability governance: A comparative case analysis. *Bus. Soc.* **2020**, *59*, 1151–1180. [CrossRef]
13. Oskam, I.; Bossink, B.; de Man, A. Valuing value in innovation ecosystems: How cross-sector actors overcome tensions in collaborative sustainable business model development. *Bus. Soc.* **2021**, *60*, 1059–1091. [CrossRef]
14. Chatziparaskeva, G.; Papamichael, I.; Voukkali, I.; Loizia, P.; Sourkouni, G.; Argirusis, C.; Zorpas, A.A. End-of-Life of Composite Materials in the Framework of the Circular Economy. *Microplastics* **2022**, *1*, 377–392. [CrossRef]
15. Antoniou, N.A.; Zorpas, A.A. Quality protocol and procedure development to define end-of-waste criteria for tire pyrolysis oil in the framework of circular economy strategy. *Waste Manag.* **2019**, *95*, 161–170. [CrossRef]
16. Papamichael, I.; Chatziparaskeva, G.; Pedreño, J.N.; Voukkali, I.; Almendro Candel, M.B.; Zorpas, A.A. Building a new mind set in tomorrow fashion development through circular strategy models in the framework of waste management. *Curr. Opin. Green Sustain. Chem.* **2022**, *36*, 100638. [CrossRef]
17. Nabavi-Pelesaraei, A.; Mohammadkashi, N.; Naderloo, L.; Abbasi, M.; Chau, K. Principal of environmental life cycle assessment for medical waste during COVID-19 outbreak to support sustainable development goals. *Sci. Total Environ.* **2022**, *827*, 154416. [CrossRef]
18. Nabavi-Pelesaraei, A.; Bayat, R.; Hosseinzadeh-Bandbafha, H.; Afrasyabi, H.; Chau, K. Modeling of energy consumption and environmental life cycle assessment for incineration and landfill systems of municipal solid waste management—A case study in Tehran Metropolis of Iran. *J. Clean. Prod.* **2017**, *148*, 427–440. [CrossRef]
19. Mostashari-Rad, F.; Ghasemi-Mobtaker, H.; Taki, M.; Ghahderijani, M.; Saber, Z.; Chau, K.; Nabavi-Pelesaraei, A. Data supporting midpoint-weighting life cycle assessment and energy forms of cumulative exergy demand for horticultural crops. *Data Brief* **2020**, *33*, 106490. [CrossRef]
20. Mirata, M.; Emtairah, T. Industrial symbiosis networks and the contribution to environmental innovation: The case of the Landskrona industrial symbiosis programme. *J. Clean. Prod.* **2005**, *13*, 993–1002. [CrossRef]
21. Baas, L. Planning and uncovering industrial symbiosis: Comparing the Rotterdam and Östergötland regions. *Bus. Strategy Environ.* **2011**, *20*, 428–440. [CrossRef]
22. Ceglia, D.; de Abreu, M.C.S.; Da Silva Filho, J.C.L. Critical elements for eco-retrofitting a conventional industrial park: Social barriers to be overcome. *J. Environ. Manag.* **2017**, *187*, 375–383. [CrossRef] [PubMed]
23. Martin, M.; Svensson, N.; Eklund, M. Who gets the benefits? An approach for assessing the environmental performance of industrial symbiosis. *J. Clean. Prod.* **2015**, *98*, 263–271. [CrossRef]
24. Domenech, T.; Bleischwitz, R.; Doranova, A.; Panayotopoulos, D.; Roman, L. Mapping Industrial Symbiosis Development in Europe_ typologies of networks, characteristics, performance and contribution to the Circular Economy. *Resour. Conserv. Recycl.* **2019**, *141*, 76–98. [CrossRef]
25. Martin, M.; Eklund, M. Improving the environmental performance of biofuels with industrial symbiosis. *Biomass Bioenergy* **2011**, *35*, 1747–1755. [CrossRef]
26. Johnsen, I.H.; Berlina, A.; Lindberg, G.; Teräs, J.; Smed Olsen, L.; Mikkola, N. *The Potential of Industrial Symbiosis as a Key Driver of Green Growth in Nordic Regions*; Nordregio: Stockholm, Sweden, 2015.
27. Frosch, R.A.; Gallopoulos, N.E. Strategies for manufacturing. *Sci. Am.* **1989**, *261*, 144–153. [CrossRef]
28. Graedel, T.E. *Industrial Ecology*; Prentice Hall: Hoboken, NJ, USA, 1995.
29. Côté, R.; Hall, J. Industrial parks as ecosystems. *J. Clean. Prod.* **1995**, *3*, 41–46. [CrossRef]
30. Chertow, M.R. Industrial symbiosis: Literature and taxonomy. *Annu. Rev. Energy Environ.* **2000**, *25*, 313–337. [CrossRef]
31. Lombardi, D.R.; Laybourn, P. Redefining industrial symbiosis: Crossing academic–practitioner boundaries. *J. Ind. Ecol.* **2012**, *16*, 28–37. [CrossRef]
32. Short, S.W.; Bocken, N.M.; Barlow, C.Y.; Chertow, M.R. From refining sugar to growing tomatoes: Industrial ecology and business model evolution. *J. Ind. Ecol.* **2014**, *18*, 603–618. [CrossRef]
33. Neves, A.; Godina, R.; Azevedo, S.G.; Matias, J.C.O. A comprehensive review of industrial symbiosis. *J. Clean. Prod.* **2020**, *247*, 119113. [CrossRef]
34. Liu, F.; Ouedraogo, A.; Manghee, S.; Danilenko, A. *A Primer on Energy Efficiency for Municipal Water and Wastewater Utilities*; World Bank: Washington, DC, USA, 2012.
35. Huang, M.; Wang, Z.; Chen, T. Analysis on the theory and practice of industrial symbiosis based on bibliometrics and social network analysis. *J. Clean. Prod.* **2019**, *213*, 956–967. [CrossRef]

36. Marchi, B.; Zanoni, S.; Zavanella, L.E. Symbiosis between industrial systems, utilities and public service facilities for boosting energy and resource efficiency. *Energy Procedia* **2017**, *128*, 544–550. [CrossRef]
37. Paquin, R.L.; Howard-Grenville, J. The Evolution of Facilitated Industrial Symbiosis. *J. Ind. Ecol.* **2012**, *16*, 83–93. [CrossRef]
38. Fraccascia, L.; Yazan, D.M.; Albino, V.; Zijm, H. The role of redundancy in industrial symbiotic business development: A theoretical framework explored by agent-based simulation. *Int. J. Prod. Econ.* **2020**, *221*, 107471. [CrossRef]
39. Hervas-Oliver, J.; Estelles-Miguel, S.; Mallol-Gasch, G.; Boix-Palomero, J. A place-based policy for promoting Industry 4.0: The case of the Castellon ceramic tile district. *Eur. Plan. Stud.* **2019**, *27*, 1838–1856. [CrossRef]
40. Galán, E.; Aparicio, P. Materias primas para la industria cerámica. *Semin. Soc. Española Mineral.* **2006**, *2*, 31–49.
41. Wadström, C.; Johansson, M.; Wallén, M. A framework for studying outcomes in industrial symbiosis. *Renew. Sustain. Energy Rev.* **2021**, *151*, 111526. [CrossRef]
42. Sonel, E.; Gür, Ş.; Eren, T. Analysis of factors affecting industrial symbiosis collaboration. *Environ. Sci. Pollut. Res.* **2022**, *29*, 8479–8486. [CrossRef]
43. Boom-Cárcamo, E.; Peñabaena-Niebles, R. Analysis of the Development of Industrial Symbiosis in Emerging and Frontier Market Countries: Barriers and Drivers. *Sustainability* **2022**, *14*, 4223. [CrossRef]
44. Demestichas, K.; Daskalakis, E. Information and communication technology solutions for the circular economy. *Sustainability* **2020**, *12*, 7272. [CrossRef]
45. Bacudio, L.R.; Benjamin, M.F.D.; Eusebio, R.C.P.; Holaysan, S.A.K.; Promentilla, M.A.B.; Yu, K.D.S.; Aviso, K.B. Analyzing barriers to implementing industrial symbiosis networks using DEMATEL. *Sustain. Prod. Consum.* **2016**, *7*, 57–65. [CrossRef]
46. Antikainen, M.; Uusitalo, T.; Kivikytö-Reponen, P. Digitalisation as an Enabler of Circular Economy. *Procedia CIRP* **2018**, *73*, 45–49. [CrossRef]
47. Lawrenz, S.; Leiding, B.; Mathiszig, M.E.A.; Rausch, A.; Schindler, M.; Sharma, P. Implementing the Circular Economy by Tracing the Sustainable Impact. *Int. J. Environ. Res. Public Health* **2021**, *18*, 11316. [CrossRef] [PubMed]
48. Tseng, M.; Tan, R.R.; Chiu, A.S.F.; Chien, C.; Kuo, T.C. Circular economy meets industry 4.0: Can big data drive industrial symbiosis? *Resour. Conserv. Recycl.* **2018**, *131*, 146–147. [CrossRef]
49. Chauhan, C.; Parida, V.; Dhir, A. Linking circular economy and digitalisation technologies: A systematic literature review of past achievements and future promises. *Technol. Forecast. Soc. Chang.* **2022**, *177*, 121508. [CrossRef]