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Deepening in the field of industrial symbiosis: A scientometric analysis approach

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Abstract

This dissertation was written as part of the MSc in ‘Energy Systems’ at the International Hellenic University. The aim of this thesis is to quantify the scientific articles published in the database "Science Direct" about "Industrial Symbiosis" from 2004 to 2022. A scientometric analysis was performed and data tables and visualization maps were created, showing that there is an increasing trend since the year 2017 with China's participation being particularly determined. The keywords 'industrial symbiosis' and 'circular economy' are regularly found in the articles showing the increased interest of the scientific community in the financial field.

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Keywords: Industrial Symbiosis, Bibliometric Analysis, Scientometric Analysis, Industrial ecology, Circular Economy

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Preface

Energy from human activity creates increased energy demands. As a result, a large amount of fossil fuels is needed. Finally, greenhouse gas emissions increase, and the global average temperature of the planet rises. It is imperative to find applicable and efficient solutions. This dissertation

Industrial symbiosis is a branch of industrial ecology that concerns cross-collaboration and is well recognized in the area of study on the sustainability of industrial systems. It is often used to refer to the exchange of underutilized or wasted resources, including materials or power, among industrial units in geographically concentrated regions. Some examples of these resources include materials and energy. When one manufacturing process is combined with another, the first process's outputs become the second procedure's inputs, and vice versa. This approach results in economic advantages (such as decreased disposal costs), environmental benefits (such as lower CO_2 emissions), and social benefits (such as increased business prospects) for those involved in industrial symbiosis as well as society.

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1 Introduction

The number of resources and commodities used globally has increased at an astounding rate because of increased industrialization and urbanization. Because of this, we have poor efficiency, which has resulted in tremendous waste of resources and contamination of the environment. It is essential to improve the effectiveness with which resources are used if one wants to speed the process of transitioning to sustainable development. Both the circular economy and the valuing of trash are excellent examples of alternate routes that might be taken to reach this goal. Developed economic entities like the European Union and Japan have already built complex legal frameworks and technology standards.

It is essential to determine what sorts of lessons might be gained from them, as well as the implications such lessons have for emerging nations. Also, it's important to investigate the best ways to move to a circular economy. The shift to models of a circular economy is being emphasized as a fundamental driver by the Horizon Europe program, which has made the transition to a circular economy a primary focus of the talks that are taking place on sustainability.

The state of the art around circular economies has advanced thanks to the findings of several studies that shed light on the fundamental principles and defining characteristics of this form of economic structure. It is anticipated that this study will give more precise information on the degree of implementation in the field of circular economy in EU Member States, identifying the countries that are leading the way and those that are following in their footsteps regarding this problem.

Not only does the expansion of enterprises has an influence on the economic system of an area, but it also has an effect on the environment that is directly around it. There is now a conversation taking place all over the globe with the objective of bringing together economic interests and global sustainability in order to make both society and businesses sustainable. This discussion is going on all over the world. The development of what is being termed the "circular economy" comes to defend the potential of simultaneously enhancing economic well-being and environmental well-being.

At the international level, the concept of an "industrial ecosystem" needs to be implemented to realize a uniform state of sustainability for industrial applications. There is a connection between the build-up of waste and pollution and the strategic function that energy and materials play. This connection is significant. The practice of industrial ecology is dedicated to the development and implementation of improved methods of decision-making that are tied to both public and private entities. The essential principle of industrial ecology is the idea that all cultural and technological activities take place entirely inside the biosphere and nowhere else on earth. Since natural systems recycle materials and have a closed-loop mechanism for cycling nutrients, this expression is often employed as a metaphor.

Industrial ecology is a technique for handling problems that is predicated on the assumption that industrial systems may be altered in such a manner as to have a lesser impact on the natural environment by making use of the same kinds of principles that are used in natural systems. It entails keeping track of the flow of resources and energy across local and regional economies, and it is predicated on the concept of systems thinking as well as territorial intelligence. There are still a few hurdles that need to be overcome before input-output matching can be put into practice, even though it is a useful tool in the process of eco-industrial development. These challenges include stumbling blocks in the areas of technology, business and finance, information and markets, politics and the law, and regional policies.

Ideas such as "cradle to cradle," "industrial engineering," and "closed-loop supply chains" are used by a great number of corporations, public and private organizations, public administrations, and practitioners. These tools make the circular economy model viable and can open new doors of opportunity.

It is vital to have a recycling system in place to facilitate the production of a diverse range of items, and the concept of recycling should be further developed within the design. The construction of new supply chain activities, both inside and outside of the enterprises, is required to put the recycling system into practical effect. These operations may be carried out either within or outside of the businesses. Not only is the collection of garbage and its recycling system connected to enterprises, but it is also connected to residents and, more broadly speaking, to the concept of both local and national social responsibility.

There is a need for a method to be developed to collect insights that will assist in enhancing environmental relationships. This process can be used to describe the formation of connections within the Kalundborg and to explain the factors that promote long-term collaboration. Given that support policies for industrial symbiosis projects are likely to be context-specific, the policy insights will be most relevant to policymakers in Kalundborg. The Kalundborg Symbiosis will be just as important to future theorists of sustainable urban development as it has been in supporting the development of the industrial ecology theory.

The concept of industrial symbiosis is a significant tool that may be used in a variety of different industrial situations. It has been discovered to offer a wide variety of beneficial impacts, such as reduced emissions and decreased use of raw resources. The people who started the project are worried about reducing their impact on the environment and enhancing the overall quality of the environment, while the members of the community are more concerned with the preservation of ecosystems and the removal of annoyances. In the eyes of the stakeholders, a social benefit is achieved when there is an effort made to keep or create local employment, when social responsibility is shown, and when there is an effort made to achieve sustainability within the context of local development.

2 Literature review

The factors that make industrial ecology vital in the design of industrial processes are discussed in this chapter. The primary explanation has to do with the surrounding environment. Because of this, industrial symbiosis, which is an important subfield of industrial ecology, is a topic that covers a broad range of study topics. Because of this, the impact of industrial symbiosis in a variety of industries is analyzed, and the prospective advantages of this phenomenon are outlined. These benefits are not only beneficial to the environment but also to the society, with a core contribution to the circular economy. It has also been pointed out that the presence of an industrial symbiosis results in the creation of new employment. In addition, the people who live in the nearby region will have an improved quality of life, which will result in an increase in benefits as well as an improved social position. This chapter also details the standards that must be met by corporations as well as any applicable limitations, the "Kalundborg Symbiosis" is broken down as an illustration. Finally in this chapter, the corresponding literature is referenced.

2.1 Circular economy

The use of a wide range of resources and materials, such as electricity, minerals, and even water, has been expanding at an astounding pace, which presents a tremendous deal of pressure on the supply of those items. This is due to the rapid expansion of global industrialization and urbanization. Aside from that, the widespread utilization of materials has also resulted in low efficiency, which has led to significant waste of resources in addition to serious environmental pollution and degradation. This has severely hampered the sustainable development of both the economy and society, particularly in those rapidly developing countries. In order to hasten the transition to sustainable development, it is necessary to increase the efficiency with which resources are used; the circular economy and the valorization of waste are great alternative pathways for accomplishing this objective (Figure 1).

Parts of the globe have been operating under a "circular economy" model for millennia. Nevertheless, the most important components of the conceptual framework behind the circular economy must be identified. When it comes to implementing a circular economy and waste valorization, developed economic entities such as the European Union and Japan have already established sophisticated legislative frameworks and technological standards. The question that must be answered is how these are developed economic entities performing in terms of the circular economy. It also should be identified what kinds of things may be learned from them, and what kinds of implications do they have for developing countries. Furthermore, the most efficient routes leading to the shift to a circular economy and the valorization of waste should be investigated.

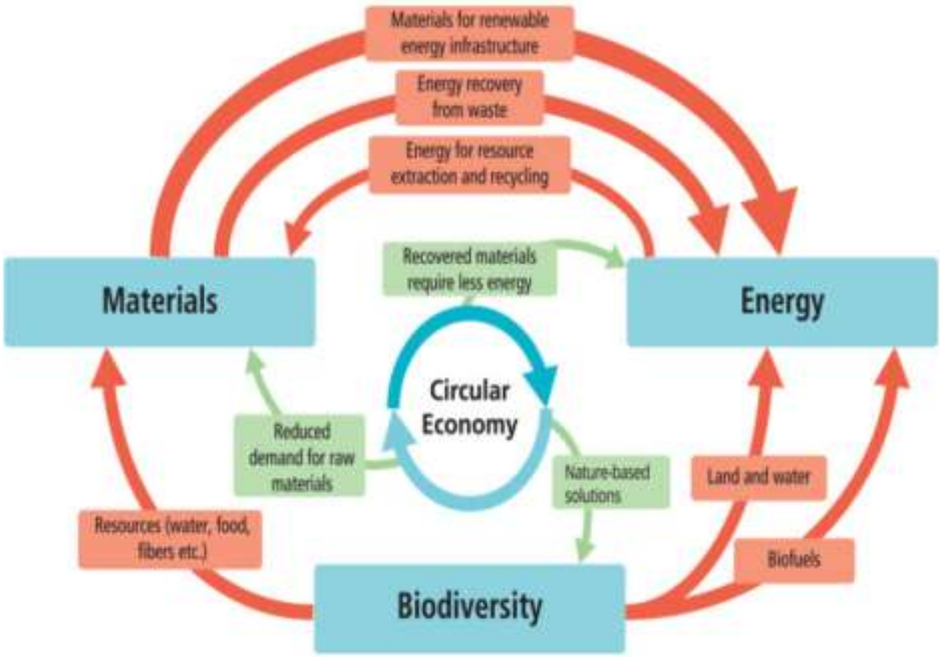

Figure 1: Circular economy flows (Friant, et al., 2020)

The transition to a circular economy is a primary focus of the discussions taking place about sustainability. In particular, the Horizon Europe initiative (which will run from 2021 to 2027) emphasizes the transition to circular economy models as a key driver. Circular economy models focus on the "restorative use" of resources and the "sustainable use" of materials in manufacturing, with the goal of reducing the amount of trash that ends up in landfills.

The circular economy models' regenerative property draws attention to an economic system that has significant implications not only in terms of economy and society, but also on environmental elements. Many studies present a broad scientific review of the circular economy to identify the many analytical methodologies. They do so by following a continuous research stream that has evolved over the past decade on these themes. In fact, the studies advance the state of the art in the field of circular economies by highlighting the core principles and distinguishing features of this type of economic structure as recognized by most researchers and practitioners. This is accomplished through a consistent analysis of the published research. Furthermore, the research develops a macro-level (Ghisellini, et al., 2016) performance assessment at the international level to compare the EU Member States as they transition to a circular economy. This kind of quantitative analysis is based on a variety of measuring components that consider environmental factors in addition to economic and social considerations. Other studies make use of the measurement elements described above and develop a performance assessment relying on a breakdown of the European countries to comprehend the contribution of such elements to the overall implementation level of the circular economy in each country that is analysed.

This line of inquiry begins with theory and progresses to an operational level so that it can be determined whether or not the policies that have been adopted by the countries have been sufficient for improved implementation and a more rapid transition from the linear economy to the circular economy global system (Marino & Pariso, 2020). The current research is expected to provide more detailed knowledge on the degree of implementation around circular economy in EU Member States, identifying the leader and follower nations on this issue, as it is hoped that the study will allow. It is anticipated that the present analysis could be of interest on the one hand for policymakers and government planners, who can acquire information for the development of circular economy policies in long-term plans (Guo, et al., 2020), and on the other hand for European entrepreneurs, who can obtain knowledge of strategic elements to support the sustainability of the European economy. This is because policymakers and government planners can acquire information for the development of circular economy policies in long-term plans.

The growth of businesses has an effect not only on the economic system of a region but also on the environment that is immediately around that region. There is now a discussion taking place throughout the world that aims to bring together economic interests and global sustainability to make both society and enterprises sustainable. The argument that there is a conflict between economic (growth and profitability), social (occupation and well-being), and environmental (preservation of the environment for future generations) goals has, over the course of the past forty years, been gradually lost in favor of the necessary integration of all terms (Amate Fortes & Guarnido Rueda, 2011). The advent of the so-called "circular economy" comes exactly to defend the possibility of increasing economic and environmental well-being at the same time.

There are a few distinct schools of thought on the best way to address this new commitment to the economic and productive system. There is a proposition for a new method of construction and production that gets rid of items that have a negative effect and cuts down on the detrimental consequences of manufacturing by increasing the efficiency with which products and systems are designed. In addition, a concept known as “natural capitalism” has been proposed (Hawken, et al., 2013). This concept tries to turn a system into one that decreases the use of natural resources and invests resources from the economic system in the environment. On the other hand, some have advocated for industrial ecology. There have been several studies published about the circular economy's application and definition, and its fundamental notion has developed into new ways of thinking (Rizos, et al., 2017).

Recently, there has been an explosion in the number of publications that discuss the circular economy. A recent study shed light on its significance as well as the scientific relevance of the issue (Srisruthi, 2020). There have also been studies that highlight the opportunities presented by the circular economy in companies that have a high tendency towards innovation and entrepreneurship (Veleva & Bodkin, 2018), as well as studies that highlight the application of the circular economy to the enhancement of company administration and management (Ormazabal, et al., 2018). Nevertheless, it is also crucial to recognize the extension of the circular economy in particular industries, like businesses that have a clearly technological component. In this regard, it is helpful to think of businesses that provide solutions and that have an obviously technological component.

2.2 *Industrial ecology*

To accomplish unified sustainability for industry applications, an "industrial ecosystem" should be adopted at the global level (Frosch, 1992). In particular, the strategic role of energy and materials is very important and has a relation to the accumulation of waste and pollution. Some of the subjects that have been developed over the last decade include technological innovation and industrialization, environmental and social challenges (Mikielewicz, et al., 2020), at the global and local level, along with methods connected to these topics. The administration of waste is a subject that is important across many academic disciplines. It is plain to see that industrial ecology ought to be compatible with the activities of governments and the choices made by businesses (Lacko, et al., 2021). The concept of industrial ecology is committed to implementing better decision-making processes connected to public and private institutions (Doukas & Nikas, 2020).

The concept that cultural and technical processes are contained inside the biosphere and do not occur outside of it is the fundamental tenet of industrial ecology. Because it has been seen that natural systems recycle materials and have a mostly closed-loop system for cycling nutrients, ecology is often utilized as a metaphor owing to this fact. Industrial ecology is a way of approaching issues based on the concept that industrial systems may be modified to lessen their influence on the natural environment by employing similar ideas as natural systems. This approach is derived from the term "industrial ecology". Industrial ecology adopts this comprehensive point of view because it acknowledges that, to solve issues, it is necessary to have an awareness of the links that occur between the different systems; individual components cannot be considered in isolation.

The study of environmental problems through the lens of systems thinking is the focus of industrial ecology, which is based on this concept. When seen from these perspectives, there is a clear connection to be made between this forward-thinking methodology and territorial intelligence. Keeping track of the movement of materials and energy across local and regional economies is an essential part of industrial ecology initiatives. This kind of accounting is often referred to as "territorial metabolism." Input-output matching seems to be a beneficial instrument in the process of eco-industrial development. The collection and processing of these data need methodological and technological assistance.

Even if there are many financial, environmental, and social benefits associated with the notion of industrial ecology, there are still certain obstacles that need to be cleared before it can be implemented. The obstacles that stand in the way of industrial ecology may be broken down into six distinct categories: technological, market and informational, finance and business, political, legal, and area policies.

To address the technical challenges involved, a significant amount of creativity is required to either turn waste into profit or minimize waste from occurring in the first place. The markets for waste products will eventually grow or fall depending on their economic vitality, and their strength may be improved using techniques that are associated with information technology. "Waste exchanges," which are specialized marketplaces where traders exchange industrial wastes like some other commodities, are one of the available options for waste markets. Creating actionable business strategies and offering monetary assistance are two ways to assist in the dissemination of the idea of industrial ecology. The private company is the fundamental organizational unit of the economy and, taken as a whole, is the mechanism that brings ideas and innovations into practical use. The government should regulate industrial ecology and environmentally responsible development strategies. Factors such as availability of raw resources, accessible transportation, technological competence, and markets tend to play a role in the formation of spatial clusters of industries in certain geographic locations. In order to do this, regional policies must be developed and implemented by local governments and the federal government.

2.3 Principles crucial to the circular economy

Numerous businesses, public and private organizations, public administrations, and practitioners utilize ideas including “cradle to cradle”, “industrial engineering”, and “closed-loop supply chains” almost interchangeably with one another. The associated ideas are instruments that make the circular economy model possible and have the potential to create new avenues of opportunity within this business model. These essential ideas are not meant to be equally relevant; moreover, they are not arranged according to their level of significance; rather, they are categorized as having both theoretical and practical consequences.

McDonough W. and Braungart M. (2002) came up with the theory that they named "cradle to cradle". In the 1970s, Stahel W. (1994) was the first expert to use the idea in a practical manner. The main emphasis of this idea is sustainability, with particular attention paid to the many diverse processes of the linear model that have the potential to do damage to the environment. Along this path, a number of interesting tools related to social responsibility and the environmental friendliness of production, processes, products, delivery, operations, and disposal have been set up (Thies, et al., 2019) (Visser, 2010).

Beginning with the concept of cradle to cradle, the researchers have also focused their attention on the closed-loop supply chain that was created by De Pauw I. et al. (2013). The authors emphasize how important it is to have a recycling system so that a variety of goods may be made, and the idea of recycling is expanded upon in the design, as established by Suárez-Eiroa B. et al. (2019). Furthermore, the recycling system is a functional concept in circular economy industrial systems (Rajput & Singh, 2019), particularly in relation to material fluxes. In addition, items might be engineered to have a longer life cycle while also having a less negative effect on the environment (in the form of trash) (Pires & Martinho, 2019). The operational implementation of the recycling system necessitates the establishment of new supply chain operations, both inside and outside of the enterprises. This operational level has a strong connection to the idea of reverse logistics. The collection of waste and its recycling system are linked not only to businesses, but also to citizens and, more generally, to the notion of both local and national social responsibility (Esposito, et al., 2017).

The term "blue economy" alludes to the blue hue of the sky and the ocean. Pauli G. A. (2010) was the one who came up with the idea. In addition to the colour, it is easy to see that the ocean and the sky make up the two greatest parts of the world. At this level, the attention is focused on the local environment and the actions that it takes, such as the development of the sea. Along this path, developing the industry implies taking into consideration the fundamental ideas of the blue economy. It is possible to define the blue economy by applying the five ideas that are given below:

- On a local level, as opposed to focusing only on the global market, businesses make use of the resources they already possess in their own communities.
- Businesses should "replace something with nothing" in their operations.
- Because natural resources are limited, it is preferable to use them in a methodical manner whenever possible.
- "Multiple cash flows" is a strategy that may help overcome the limitations of expansion.
- "All fundamental requirements" may be supplied.
- The blue economy is an initiative that aims to protect the environment around the world and create new job opportunities at the same time.

“Regenerative design” is connected to the use of energy and materials. The practical applications of regenerative design may be found in both the manufacturing sector and the services sector, with a special focus on goods and services that have been refreshed and reinvigorated.

The fundamental strategy of regenerative design is referred to as the closed-loop input–output model. It is often accomplished by means of the bioeconomy (Lieder & Rashid, 2016). From this point of view, trash is also considered to be a substance that needs to be reintroduced into the industrial system in order to generate fresh economic value and a lengthy life cycle for goods and raw materials. The goal of the regenerative design is to create a system that generates no waste and treats waste as a substance that can be used and regenerated, as stated by Stegmann P. et al. (2020). Gosnell H. et al. (2019) focused on a renewable agricultural project, and one of their fascinating aims was to realize important objectives based on this notion. This theoretical and operational approach also finds applicability in the primary sector.

2.4 Industrial symbiosis

The ideas behind industrial ecology and industrial ecosystems serve as the foundation for the notion of industrial symbiosis. Frosch R. A. & Gallopoulos N. E. (1989) were the ones who first conceived the idea of an industrial ecosystem in its present form. Their fundamental concept was that the "take it, produce it, and sell it" triad of industrial production should be replaced with a more all-encompassing perspective on the manufacturing process. Their suggestion was to create industrial ecosystems, which entails the formation of a network of separate industrial units connected in such a way that the products of one unit serve as the raw materials for another. A basic flow can be seen in Figure 2: Conceptual sketch of a two-way trade of industrial by-products

According to Lowe E. A. & Evans L. K. (1995) definition of industrial ecology, the field is governed by the following four principles:

1. All commercial operations, including buildings, services, and infrastructure, are natural systems that have to function within the constraints imposed by the biosphere and the ecosystems in their immediate vicinity.
2. Ecosystems can be used as a model for how to design and run industrial systems by looking at how they work and what rules they follow.
3. Achieving high efficiency in production, usage, recycling, and service delivery regarding energy and materials will contribute to competitive advantages as well as economic gains.
4. The idea of financial success is devoid of any significance in the absence of the long-term viability of both global and local ecosystems, which is the goal of all economic activity.

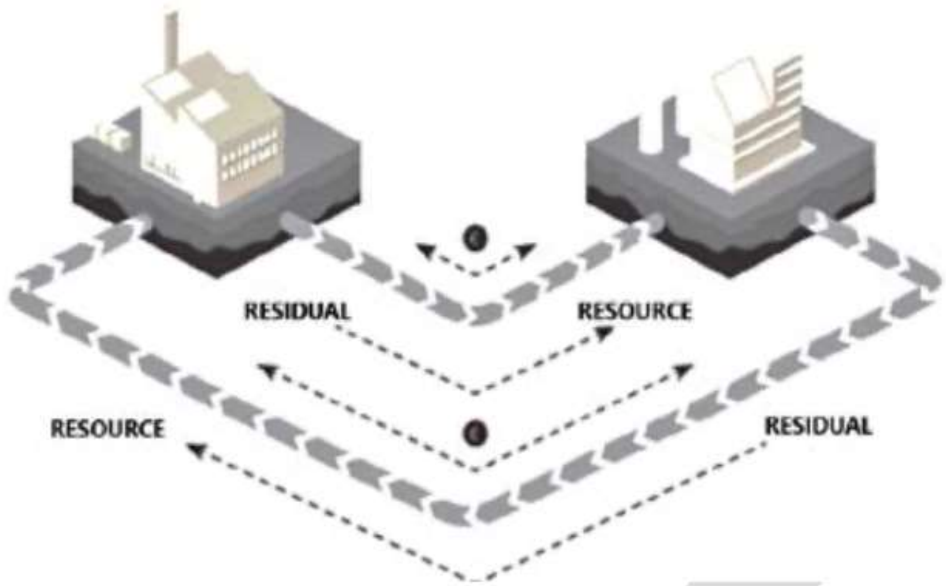

Figure 2: Conceptual sketch of a two-way trade of industrial by-products (Danielson, et al., 2018)

There have been many different conceptions of what industrial ecology and industrial ecosystems are ever since then and up until the recent past. Their citation would be useful for the study of the evolution of the scientific discussion. Industrial ecology is a systematic approach that resembles natural ecosystems in variety, connectedness, interdependence, symbiosis, and adaptability. This method has the potential to contribute to the development of sustainability. In conclusion, even though the term "industrial" is employed, the notion is applicable to all spheres of human activity, including agriculture, transportation, and service industries.

The imitation of natural systems is the overarching principle of industrial ecology, and this principle is adhered to by industrial symbiosis. The idea of "industrial symbiosis" was first put forward in the small Danish town of Kalundborg, where the term was first used. In natural science, the term "symbiosis" refers to a kind of connection in which two or more organisms that are not genetically linked form a mutually beneficial partnership. The free and beneficial trade of resources (including knowledge, energy, and physical goods) is the organization's primary goal (Chertow, 2004). The interaction between at least two distinct entities, often industrial units, with the aim of achieving a shared benefit that is higher, or qualitatively better, than the sum of the individual advantages is referred to as "industrial symbiosis".

Even though this is by far the most typical scenario, there is no need for the symbiosis to take place inside the borders of a commercial or manufacturing district. The realization of industrial symbiosis is the consequence of the interchange and use of currents, which in other circumstances would be waste or by-products, but also of knowledge. This exchange and use of currents is what allows for the implementation of industrial symbiosis. "Rule 3-2" must be completed for a link to be termed an industrial symbiosis. According to this criterion, for there to be a symbiotic network, there must be a minimum of three entities (for example, industrial units) that are trading at least two distinct resources with one another. None of these organizations should prioritize recycling as their primary business activity.

The successful completion of several predetermined objectives is necessary for the growth of industrial symbiosis. The primary activities that contribute to the development of industrial symbiosis are as follows: the passing of material flows from one unit to another; and the recycling of energy.

It is evident, both from the planned and spontaneous ways of industrial symbiosis, that the various entities (such as the government, government institutions, business, etc.) have certain crucial responsibilities to play to attain objectives (i.e., reducing cost and getting higher benefits considering the environmental improvement). It is possible for the government and its institutions to take the lead role by implementing certain initiatives, such as lowering taxes or offering economic incentives for businesses that incorporate symbiosis into their production processes. Research groups may be of assistance to organizations that embrace the industrial symbiosis idea by providing the design as well as information on resources to help companies make more informed decisions. After establishing information systems in the industry or organization, they need to create their own internal capabilities.

The parties that embrace industrial symbiosis may set up a particular department that will be in charge of maintaining an up-to-date inventory of things like the amount of water used, the amount of energy used, the amount of garbage generated, and so on (Figure 3: Cross-sectional exchange between the energy, water, and material layers). It is possible that this could result in an increase in early production costs, but in the long term, this will result in an improvement in performance since the parties involved will no longer need to seek assistance from other external entities.

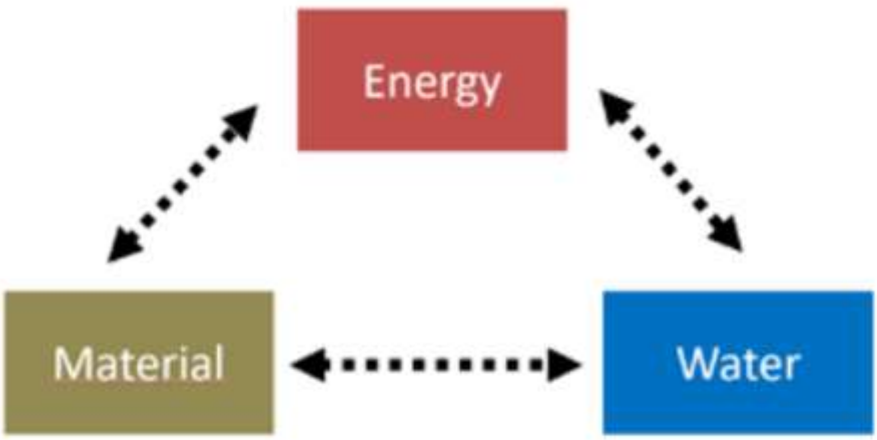

Figure 3: Cross-sectional exchange between the energy, water, and material layers (Danielson, et al., 2018)

Regional resource synergies increase the flow and interchange of natural resources to produce more efficient use of material, energy, or water. This is like how industrial symbiosis refers to the benefits that result from companies being collocated with one another. Bossilkov A. et al. (2005) distinguished three different types of regional synergies: resource exchange, which refers to the resource that is being traded between companies; processing involved, which refers to the degree to which the "wasted" resource is being handled before it can be applied by another business (ies) engaged in the synergy project; and synergies, which refers to the business relationship that is governing the synergy project.

Utilizing one's available resources in the most effective manner possible is the primary focus of the symbiotic system of businesses. Water and electricity are the two essential and most significant resources, and almost every sector of the economy is reliant on them. Reusing water is preferable to other options since it not only helps cut down on the cost of energy use but also conserves water for later applications. Used water has a wide variety of applications in industry, one of which is to provide cooling.

The performance of both businesses involved would improve because of the bilateral sharing of resources, creating a scenario in which both industries would emerge victorious while the environment would be protected as a side benefit. It is important to sort out everything that can be reused from the trash before getting rid of it. Again, the components that are not useful for one manufacturing system could be necessary for another. Because of this procedure, the massive amount of garbage that now exists will be reduced to a more manageable level, and the economy will also profit from this.

2.4.1 Distinct forms of industrial symbiosis

As previously mentioned, industrial symbiosis can develop both inside the confines of an industrial sector and beyond its borders. Even though it is not significant, this distinction produces various objectives, barriers, and benefits. There are two primary categories of industrial symbiosis, which are as follows:

A symbiosis of the closed kind

The closed type of symbiosis is also the simplest to identify since it forms in a particular geographic region, which is often an industrial sector, and is contained within the limits of a municipality. Its primary benefits are as follows:

1. Because the units are close to each other geographically, it is easier to send currents between them.

2. The presence of an organized industrial region implies the existence of certain infrastructure components, such as the administrative point, which might play a catalytic role in the development of symbiotic activities. Specifically, the existence of an administrative point.

Finding adequate "matches" between units is difficult in closed-type symbioses, which presents a problem. This task becomes much more difficult when the industrial area in which the establishment of industrial symbiosis is sought is not an eco-industrial park built in advance to suit the logic of symbiosis, but rather a "naturally developed" one. This is something that occurs very often (Martin, et al., 2012).

Open type symbiosis

Open symbiosis, on the other hand, is not restricted to any one place geographically, in contrast to closed symbiosis, which is confined to a single location. Exchanges of currents between various organisms, some of which may even be situated on separate continents, are what constitute open symbiosis. Open symbiosis has several benefits, one of which is an increase in the potential synergies that may be achieved because symbiotic acts are not confined to a certain geographic region. The difficulty in discovering the symbiotic "match" and producing synergies is one of the drawbacks of this approach, particularly in situations where there is no coordinating organization. A farther distance means a greater environmental effect as well as higher transportation expenses. This is system’s disadvantages.

2.4.2 The Kalundborg Symbiosis

It is said that a coordinated project in 1961 that involved the formation of a 13-kilometer-long funnel to transport water from Lake Tiss to a new oil refinery that was at the time called Dansk Veedol A/S sowed the seeds for what has occurred in Kalundborg since that time. This project was said to have sown the seeds for what has happened in Kalundborg (eventually to become Statoil). The municipality, in a bold move, consented to accept a loan from Dansk Veedol in order to construct the pipeline (Christensen, 2014).

In 1972, Saint-Gobain Gyproc and Dansk Veedol worked together on the first initiative that featured companies working together. This meant that a pipeline had to be built to send gas that was being burned off as a waste product of refining oil to Gyproc, where it would be used to dry gypsum boards.

Over the course of time, several additional ideas started to take form, and new companies joined the game. The water pipeline that ran from Statoil to the Asnaes Power Station, which is owned and operated by DONG Energy, was lengthened so that the coal-fired power plant could recycle the cooling water that was used at the refinery. The power station and the municipality have come to an arrangement wherein the power station would deliver heat to Novo Nordisk and the oil refinery, while also providing district heating to the town. As a direct result of this, more piping was installed throughout the town in order to make the transmission of steam easier. By the end of the 1980s, the companies based in Kalundborg symbiosis had participated in at least 12 different material trades with one another.

This emergent network of collaborations was not formally noticed until a meeting of the "Environment Club" in 1988. This was held in Kalundborg as a follow-up sustainability strategy to the Brundtland Commission's work. The Brundtland Commission was established because of the work of the Brundtland Commission. The emergent network did not have a real distinction until October 1989, when Kalundborg's sixth-form college arranged a project week that concentrated on challenges related to sustainability. Prior to then, the network did not have a name. Valdemar Christensen, a manager at the Asnaes coal-fired power station, was at home preparing for his role in the discussions when his wife, Inge, pointed out another parallel between what was happening with the cooperative group of businesses in Kalundborg and the symbiotic relationships that exist in the natural world between different organisms. Inge's observation was made while Valdemar Christensen was preparing for his role in the discussions. Valdemar, appended the word "industrial" to this particular type of symbiotic network, and in doing so, the couple coined the term "industrial symbiosis." Today, this term is widely used to describe collaborations between firms in which the activities involve waste from one organization being applied by other businesses as a resource.

In the year 1990, a cardboard model that portrayed the shared flows that were taking place inside the Kalundborg municipality attracted the attention of a local newspaper, which ultimately led to the publication of an article on the events that were taking place. The Financial Times took up this piece and later reported on the phenomenon based on what they learned from it. By the time that global leaders were gathering in Rio de Janeiro for the Earth Summit in 1992, the Kalundborg Industrial Symbiosis had already established itself as a hot topic in environmental circles.

By the year 1996, there was a level of interest in what was going on in Kalundborg that was extensive enough to encourage the local trade council in Kalundborg to coordinate the planning of a "Kalundborg Symbiosis Centre". This project was led by a committee comprised of members from the businesses that were taking part in the Kalundborg symbiosis, and it was coordinated by the Kalundborg local trade council. All these years after the initial transaction, the Kalundborg Symbiosis has a central office that is sponsored by members of the Kalundborg Symbiosis, and resource exchanges are happening among approximately 20 autonomous businesses. The expansion of these collaborative transactions has been remarkable, given that they are all taking place between businesses that are not connected to one another in any way that is strategic and that have taken place in an organic manner without any form of centralized control. The Kalundborg started with a few industrial enterprises coming to an agreement to work together in order to pool a valuable resource (water) and make use of resources that would otherwise be wasted (heat, steam and gas). Following that, some of the companies' cooperation has grown deeper, and these companies are now seizing new possibilities to begin closed-loop collaborative processes. Furthermore, as time has passed, more businesses have joined the Kalundborg, and the amount of resources and garbage traded has increased.

Up until very recently, all of this was accomplished without the assistance of a centralized body that was responsible for coordination. The Kalundborg Symbiosis is among the few instances in the world of a naturally occurring system of strategically unconnected economic units that persist in work collaboratively to enhance resource utilization and share knowledge. This makes it one of the few examples of its kind in the world. This one-of-a-kind network, which has been operational for over 40 years, has the potential to provide useful insights into the mechanisms that drive environmental networks to move from engaging in one-time cooperative endeavours to establishing long-term collaborative partnerships.

There is a need for having a process for gathering insights that will help enhance environmental partnerships. To that end, this process could describe the evolution of relationships within the Kalundborg and attempt to explain the forces that foster long-term cooperation. Because there is a significant gap in knowledge regarding how progressive innovation is encouraged between organizations that work together (Patala, et al., 2014), there is, by logical extension, a dearth of information regarding how policymakers can successfully encourage gradual collaborations to improve environmental governance in a particular community (Jiao & Boons, 2014). Given that support policies for industrial symbiosis proposals strive to be context-specific, the key focus of these policy insights will be most relevant to policymakers in Kalundborg. This is because van Beers D. et al. (2009) have argued that support policies for industrial symbiosis initiatives tend to be context-specific. However, it is anticipated that the policy lessons that can be learned from the Kalundborg Symbiosis will be as important to theorists of sustainable urban development as the tale of the Kalundborg Symbiosis has been in supporting the origin of industrial ecology theory.

2.4.3 Industrial symbiosis benefits

As was stated in a previous part of this investigation, industrial symbiosis is an important instrument that may be used in many industrial settings. Multiple investigations have uncovered its many positive effects, which may be summarized as follows: The fundamentals of ecological sustainability and industrial symbiosis predict that converting the waste output of one facility into the materials for another facility will lead to environmental benefits because of lowered consumption of virgin material and/or reduced emissions. A combination of lower emissions and less use of virgin materials will result in these advantages.

It is abundantly evident that the individuals who initiated the initiative are extremely worried about lowering their influence on the environment and improving the quality of the environment, while the community members are placing an emphasis on the protection of ecosystems and the elimination of nuisances. Outside of the realms of local growth and regional planning, most stakeholders are focusing their attention, from an economic point of view, on achieving greater cost efficiency. Stakeholders believe it to be a social benefit if local jobs are maintained or created, if social responsibility is shown toward the protection of the environment, and if there is an attempt to achieve sustainability in the context of local development.

Economic benefit

Economic benefit for businesses from investments in input costs and waste management, as well as revenue generation opportunities generated by higher values of by-products and waste streams (Aparisi, 2010). Economic benefit for businesses arising from investments in the cost of inputs and the management of waste.

Environmental benefit

Typically, environmental benefit is understood to entail a decrease in resources because of a reduction in the total resource demands of the industrial system, the recycling and reuse of waste streams, and the management of pollutants. There are three types of benefits that come from different industrial symbiosis projects: environmental, social, and economic.

Social benefit

Advantages for society as a source for new employment, securing existing jobs, enhancing local ecosystems, or the construction of a cleaner and safer environment.

Economic benefit

Advantages for society as a source of additional employment, safeguarding the current workforce.

The concept of industrial symbiosis is adaptable to a variety of subfields within the manufacturing industry. Industrial symbiosis speeds up the creation of eco-industrial networks, which makes it easier to find more ways to work together (Geng, et al., 2010).

The following are some of the several industries that might potentially be included in the larger schemes of industrial symbiosis: waste minimization; waste recycling and energy production; materials and product exchange; power saving, etc.

2.4.4 Obstacles to the development of industrial symbiosis

Even though the practices of industrial symbiosis have the potential to provide advantages in a variety of areas, including economics, the environment, and others, the effective application of this concept requires overcoming several challenges. These aspects are the obstacles that stand in the way of industrial symbiosis.
Barriers posed by technology Information systems initiatives need certain technical advancements, which might result in impending difficulties for the sectors that are involved. There will inevitably be phases of transition and adjustments to be made in some business sectors. It is also necessary for the stability of industrial systems to go through certain adjustments.

Economic obstacles

Although industrial symbiosis projects offer numerous benefits, both environmentally and economically, many sectors continue to find them “virtual” despite their many benefits. This is because the industrial setting for all company industries is not the same. These disparities act as a barrier to economic growth. For example, the production cycle might vary significantly from one industry to the next; as a result, it is highly debatable whether one industry's by-products can be used as a source of input in another industry within the allotted amount of time. Another crucial factor is the physical closeness of the two locations, which might be problematic for the interchange of products because of the lack of an accessible and affordable transportation infrastructure.

Knowledge obstacles

During the uncovering stage, it's hard for businesses to develop self-organized industrial symbiosis because they usually don't know the state of by-products and waste flows from other businesses. This is due to knowledge barriers.

Trust obstacles

For industrial symbiosis programs to be successful, it is necessary for a number of different industries to collaborate and operate in accordance with a number of different symbiotic exchanges. Some of the reasons why industries in and of themselves might be seen as obstacles include reluctance to change, competition between sectors that are environmentally analogous, and a general lack of environmental concern among businesses. The existence of communication-related obstacles contributes to the formation of enterprise-level barriers. When there are hurdles to cooperation and interconnection on other levels, it is also possible for there to be barriers at the intercompany level.

Laws and regulations

Laws and regulations, on the other hand, may be both beneficial and detrimental to the process of identifying instances of industrial symbiosis. Regulatory tools have the potential to obstruct the trading of by-products and the formation of new partnerships. The regulatory tools used by the government might constitute a roadblock in the way of synergies (e.g., through the legislative process). It is important for the government to have a role in both the formulation and implementation of regulation to initiate a symbiotic relationship. This is also mentioned as a political obstacle.

Risk and uncertainty obstacle

The result, performance, or cost-benefit ratio of an industrial symbiosis exchange may be accompanied by an element of risk and uncertainty. Another factor that might raise susceptibility and, as a result, increase the risk associated with investment is the growing interdependency across sectors. As a result, susceptibility to changes in the environment.

2.5 Waste and recourses

To decarbonize the globe, it is essential to consider the use of renewable resources for both economic and social activities, particularly the input of energy (Paredes-Sánchez, et al., 2019). In circumstances like these, it is essential to make every effort to reduce the negative effects these choices have on the surrounding environment. Plastics made from biodegradable sources might be an alternative that should be thought about in these situations when using renewable resources. Nevertheless, the rising inflow of these items necessitates more investigation into these alternatives, particularly regarding the end of life (Briassoulis, et al., 2019). One other reason for a modified approach to the circular economy is the European Union's dependence on raw commodities purchased from markets located outside of the EU. Only a tiny fraction of the waste materials that are generated across the globe, and especially in the context of Austria, are recycled. This is sometimes the result of the use of trash and leftovers in the creation of bioenergy (Pieratti, et al., 2019). Because of this, there is a need to change the metrics, and reporting waste might be one way to do this. In some circumstances, the nations with the highest rates of recycling are also the most efficient countries.

Recycling is always an intriguing approach to manage trash from the standpoint of sustainability, as is reuse. This is dependent, however, on the alternatives that are available. However, within these streams, there are still certain issues that need more evaluation, so that waste management and the protection of human health may be made compatible with one another (Gomes, et al., 2019). This holds true across a wide variety of circular economy-related characteristics. In these circumstances, metropolitan regions are the ones that are primarily responsible for the creation of solid trash, which results in solid municipal garbage being a genuine concern. However, they aren't the only sources, and the structure might look quite different in other parts of the world, depending on the traits that are unique to those areas. As an example, Croatia recycles around 15% of its municipal solid garbage.

Instead of burning garbage or dumping it in landfills, waste management practices like recycling and reuse contribute to the growth of the circular economy. The benefits of recycling and reuse toward economic circularity due to the extension of a product's life cycle have been highlighted, as have the drawbacks of existing approaches such as landfills and incineration. This was done to contrast the advantages of recycling and reuse with the drawbacks of traditional technologies.

These methods for the management of solid waste, together with the methods for the management of liquid waste, such as chemical treatment and sewage treatment, each have their own unique detrimental effects on the surrounding environment. To steer clear of activities that are incompatible with the natural world, it is possible to investigate alternate options, such as the ones that are listed below: Detoxification; usage in industry; carbon sequestration; recovery of minerals. It's possible that waste management may turn out to be an especially difficult challenge for the future members of the European Union. The truth on the ground in each of the member states of the European Union is, in fact, quite different (Taušová, et al., 2019).

2.6 The complexity of industrial symbiosis

In addition to large amounts of heterogeneous data from multiple sources and domain expertise to perceive the information, identifying, evaluating, and comparing potential exchanges requires a shared understanding of the system and a common terminology among various fields of science (Zhang, et al., 2017). Researchers from a variety of institutions feel that help from IT has the potential to encourage the exchange of data and information and to improve communication (van Capelleveen, et al., 2018). However, even though it has been sought and spoken about, the difficulty of having a unified nomenclature and shared understanding of that area is still something that academic research is struggling with (Boons, et al., 2017)).

Because industrial symbiosis draws on expertise from a wide range of fields, including economics, ecology, engineering, and social science, it inevitably generates a variety of terminologies, ideas, objects of observation, and points of view pertaining to these topics. Additionally, industrial symbiosis represents complex systems that are the consequence of interaction between parts of the system and their environment, which makes them more challenging to comprehend. Therefore, capturing and comprehending the intricacy of industrial symbiosis is a task that is difficult to do. The absence of a uniform language and, therefore, a shared understanding among the community makes it difficult for researchers and practitioners to communicate with one another. This also makes it difficult to analyse and compare the results of different studies. In the field of information technology, this results in current IT artifacts that do not have adequate interoperability, reusability, or integration (Halstenberg, et al., 2017).

Despite the vast amounts of published material that are available on the topic of industrial symbiosis, there remains an absence of consistent terminology and, subsequently, a common understanding among the community. This is especially the case due to the interdisciplinarity and complexity of the field. Because of this, it is difficult to compare the results of different studies and to integrate them. As a result, the objective of the study by Kosmol L. and Esswein W. (2018) is to give a language that is distinctive to the domain and can accurately express the structure of the domain in addition to establishing a common knowledge of industrial symbiosis. To accomplish this objective, a definitional domain taxonomy was conceived of and constructed.

As a result, they began by doing a literature search and conducting an analysis of previously developed ontologies to establish the appropriate ideas and vocabulary. In the second step, they collected all the terminology and organized all the ideas, including the external ideas. In addition to this, they expanded the ontology by including a distinct technical and functional perspective of resources, technology, and infrastructure, as well as the connections between these three categories. This was very necessary to characterize or examine the suitability of technologies and resources, in addition to the ecological and technical viability of prospective exchanges. In addition, they suggested that different levels of abstraction can be included (for example, new tech, industrial sites, eco-industrial parks) because a change at a lower level will result in changes at higher levels. This is because higher levels are built upon lower levels. This enables the required and potential modifications to be made to implement resource exchanges, and it promotes the identification of levers at industrial plants or parks.

They were able to get a more all-encompassing representation of the domain. Despite this, they did not guarantee that the concept is exhaustive, and any further improvements, expansions, or recommendations are very much appreciated.

This effort was merely a first step that gives a concrete description of the structure of the domain, taking into consideration the domain's borders as well as its various abstraction levels. Both the dynamic context (such as the temporal offset between production and consumption, the changing of resource demands over time, the exiting of park members, and the changing behaviour of participants) and the social context (such as embeddedness and trust) are important factors that add to the complexity of the domain. The dynamic context includes things like these. These are the kinds of things that must be taken into consideration in order to accurately portray the behavioural dependencies and influencing elements of synergy and, finally, to analyse the potential risks and uncertainties for participants.

The goal of the extended literature on this topic is to make the proposed ontology practical so that it may be utilized in conjunction with information technology. This is even though its original purpose was to facilitate the development of shared comprehension and standardized terminology. The ontology will be further codified so that it may serve as a foundation for modelling information systems or other IT tools and so that it can finally allow interoperability between various IT products. Because the data that is used to investigate industrial symbiosis comes from a variety of information systems, each of which has its own unique data structure and interface, these aspects must also be taken into consideration. Therefore, the next step is to determine whose formal ontologies or meta data underpin these data systems and which interfaces for data interchange between them are already established. This is the next phase in the process. Ontology-based data interchange and integration may become feasible if ontologies and meta data are standardized and brought into alignment. As a result of this, the amount of human labour required for data gathering and processing might be reduced, while the utility of industrial symbiosis instruments could be increased.

2.7 Industrial symbiosis ontologies

As it relates to industrial symbiosis, three distinct ontologies have been uncovered. Two of them, “eSymbiosis” and “Enipedia”, were developed with industrial symbiosis in mind. Enipedia was created to gather and distribute data from industrial symbiosis case studies or academic references online and to give additional statistics (Nooij, 2014), while eSymbiosis serves as a resource matching tool for industrial users (an online B2B platform) (Trokanas, et al., 2014).

Zhou L. et al. (2017) originally planned to use eSymbiosis for their ontology-based simulation, but ultimately decided to use ontoCAPE instead. The latter refers to an ontology developed specifically for use in the field of process engineering. It's highly comprehensive, covering a wide range of topics that may or may not have immediate application to industrial symbiosis. The level of information, however, exceeds the real comprehension of industrial symbiosis's core principles and linkages. This ontology was thus disregarded, and efforts were redirected toward other, more niche ontologies for industrial symbiosis.

Connections between ideas are laid forth in these ontologies from several perspectives, including physical, informational, and social. When it comes to input-output matching and querying, eSymbiosis shines. It does this by offering several resource categorization systems (properties, type, etc.) and processing technologies (by type, by input, etc.). This allows for the proper assignment of resources despite their differing names or appearances in other situations. Although they both cover ground in the domain, the two ontologies don't talk about the same things or use the same language when defining classes and connections between them.

While Enipedia's SynergyLink symbolically connects two facilities, eSymbiosis does not have a corresponding idea for resource sharing across facilities. The system matches available or needed resources with potential providers or consumers by establishing connections between them and the processing methods that can make use of those resources. The notion of exchanging resources is presented in eSymbiosis as a distinct idea, whereas in Enipedia it is treated as a characteristic of the SynergyLink. Enipedia is devoted to a higher level of abstraction of the industrial plant, whereas eSymbiosis concentrates on the more concrete level of the technology being exchanged.

Both ontologies include organizational notions (such as role and facility) and attributes with respect to monetary values, reflecting their shared economic perspective on the topic (e.g., disposal costs, savings through exchanges). Moreover, in both cases, environmental features and trade impacts are considered (e.g., CO_2 emission savings). Enipedia adds a social perspective that is missing from eSymbiosis. The engineering perspective reflected in eSymbiosis (including the idea of technology and its qualities like capacity and conversion rate) is underrepresented in Enipedia. To sum up, the ontologies have their own jargon, consider their own notions of the domain, and focus on various aspects of the same topic.

2.8 Bibliometric analysis

It is possible to assess the impact of individual researchers or whole research areas via the use of bibliometric analysis, which is a collection of techniques for performing quantitative assessments of scientific literature (Železnik, et al., 2017). Mathematical and statistical techniques are used in this kind of analysis to look at the overall trends in document usage and publishing to learn more about the interconnected nature of scientific endeavours and their discoveries (Bjurström & Polk, 2011). Library and information science, technology management, scientific assessment, prediction, and quantitative management are just a few of the many areas that have found useful applications for bibliometrics (Garg & Sharma, 2017). Previous research has made substantial use of citation analysis, co-citation analysis, and co-authorship analysis (Muhuri, et al., 2018).

The co-word analysis approach, which stems from citation coupling in bibliometrics and the co-citation notion, was employed in some studies to set them apart from others. Its meaning may be summed up as follows: Due to the existence of certain important linkages, two or more keywords might be stated as a study subject or research direction in the same body of literature meaning may be summed up as follows: Due to the existence of certain important linkages, two or more keywords might be stated as a study subject or research direction in the same body of literature. The greater the frequency with which two terms appear together, the stronger the connection between them. The co-word analysis assisted in examining the evolution and progression of the literature.

2.9 Analysis of social network

The fields of economics, business, and sociology all greatly benefit from social network analysis. The fundamentals and principles of social networks were presented by Mitchell (1969). It's evolved into a potent method for exploring networks and extracting the specialized subject matter that makes up various academic fields. Relationships between individuals and organizations, as well as the dynamics, sentiment analysis, and activities in which other circles of networks are participating, are just a few examples of how this tool may aid academics in their study of social phenomena and social structure (Akuma, et al., 2016).

The primary focus of social network analysis is on identifying the most pivotal node and quantifying centrality (Yustiawan, et al., 2015). In most cases, it examines the composition of a network via its ties. Therefore, the entities and their connections are what the social network analysis is concerned with. Social network analysis, as opposed to the traditional individual method, may improve the performance of the whole system rather than just its individual elements (Stanton, 2014). A growing body of management research supports the theoretical and quantitative components of social network analysis as a useful tool for mapping connections and quantifying interaction among interdependent actors. Density, centrality, subgroup cohesiveness, and core-periphery analysis are all useful tools for studying the network.

2.10 Bibliometric analysis of industrial symbiosis in literature

Over the past two decades, a great deal of academic work has gone into clarifying the concept of industrial symbiosis, defining its boundaries, outlining its evolution, progression, practices, and the various strategies adopted for implementing it. The focus of industrial symbiosis research shifted several times during this time. The conceptual frameworks of inquiry in industrial symbiosis are evolving because of technical and social developments, as Chertow M. and Park J. (2016) have shown.

Case studies, investigation mechanisms, investigation suggestions, and analysis modeling methodologies were all thought to exhibit these tendencies. At this point, Paquin R. L. and Howard-Grenville J. (2013) highlighted a second evolutionary trend, calling it the transition from blind dating to planned marriages (Paquin & Howard-Grenville, 2013). They went on to argue that many recent advances in the field of industrial symbiosis research are currently being assisted either by governmental or non-governmental causes, expanding on the point made above. These claims are often backed up by data showing a rise in interest in studying industrial symbiosis at universities throughout China.

The China National Demonstration Eco-Industrial Park Program has made it possible for the nation to build extensive networks of eco-industrial parks (EIP), which has led to a rise in the number of scholarly works devoted to industrial symbiosis in the country. There exist two other important programs with similar goals: the UK's National Industrial Symbiosis Program and Europe's Resource Efficiency Flagship Initiative (Laybourn & Lombardi, 2012).

Despite industrial symbiosis' growing significance and popularity, studies that look back at the field's established achievements have been surprisingly few. Yu C. et al. (2014)

aimed to completely examine the directions of research in this area. During that time, the study attempted to objectively map and discuss the noteworthy strides made in this sector from 1997 to 2012. This study has done more than just locate the foundational works in this field; it has also isolated significant debates, practitioners, and periodicals. Researchers concluded that industrial ecology was the ancestor of industrial symbiosis. Wastewater management and treatment, solid waste disposal, power efficiency, self-organization of industrial symbiosis systems, policy making and assessment of industrial symbiosis projects, and so on are the five different issue areas that have been highlighted in studies. In contrast, Chertow M. and Park J. (2016) broke down their claims into seven subheadings depending on the kind of research conducted: background, effectiveness, function, simulation, framework, case analysis, and recommendation.

On the other hand, all these studies used bibliometric analysis in their evaluations. In informatics, a visual method known as bibliometric or scientometric mapping is used (Cobo, et al., 2011). The quantitative results of this evaluation method show the trends in the structure and dynamics of scientific research throughout the selected time (Liu & Gui, 2016). In the field of ecology, the method may be used to create quantitative estimates and visual maps that can be replicated. These characteristics help to grasp the substantial development in interest for the purposes of systematic reviews and evaluations. Researchers are given the tools they need to understand how different fields have influenced each other's methods. Speculating on future trends and directions in research is another useful use of bibliometrics. Methodologies with comparable structures have been used to examine historical shifts and recent changes in a variety of disciplines (Eito-Brun & Rodríguez, 2016).

Akhtar N. et al. (2018) in their study, had as a goal to evaluate papers to gauge current trends in industrial symbiosis research. The main purpose of this study was to extract the most important aspects of the current industrial symbiosis literature. The survey aims to do more than just pinpoint research preferences; it also gives a view of major research hubs and the most popular topics in recent publications. As a result, their research offers a chance to coordinate actions for environmental sustainability throughout the current era of fast population expansion, urbanization, and impending industrialization in developing countries.

To make sense of the current trends in the field of industrial symbiosis research, a bibliometric or scientometric mapping strategy was used. The researchers in this study used a co-occurrence analysis method to map out the interconnected webs of institutions, nations, citations, and authors.

Using nodes and linkages, the approach makes it possible for connected objects to be represented on network maps. As centrality is represented by the size of the node, the significance of the effects is shown. When doing the study, the bigger nodes acted as hubs to show how important certain articles, keywords, and authors were.

This approach, which has been shown to be accurate, was used to analyze the spatial and temporal tendencies in industrial symbiosis research and to pinpoint the communities of scholars who are actively working in this area. Later, the "keyword co-occurrence analysis test" used it to decipher recent breakthroughs in the field of industrial symbiosis research. In Figure 4: Geographical network of IS research productivity retrieved from corresponding author addresses (2012-17), Figure 5: Co-authorship network with seven clusters working on IS, and Figure 6: Co-citation network map of cited authors in documents retrieved from Scopus database, the corresponding visualizations from the outputs are depicted.

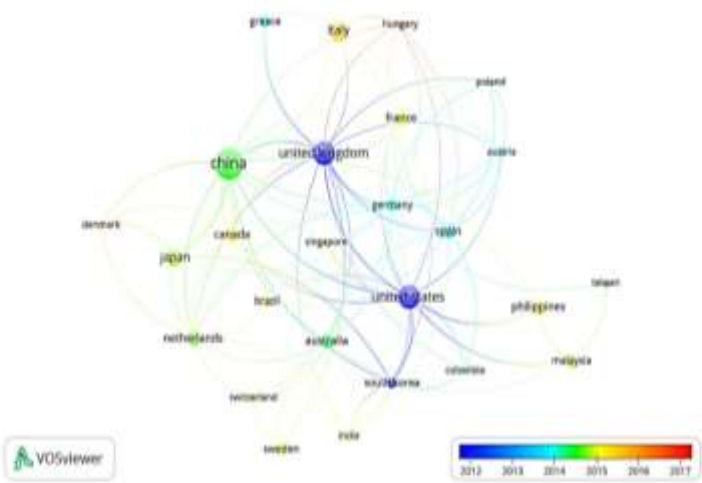

Figure 4: Geographical network of IS research productivity retrieved from corresponding author addresses (2012-17) (Akhtar, et al., 2018)

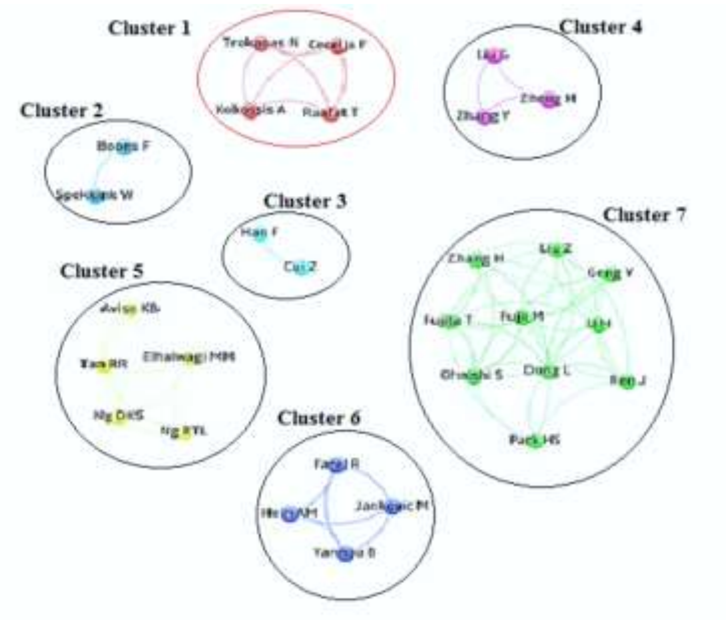

Figure 5: Co-authorship network with seven clusters working on IS (Akhtar, et al., 2018)

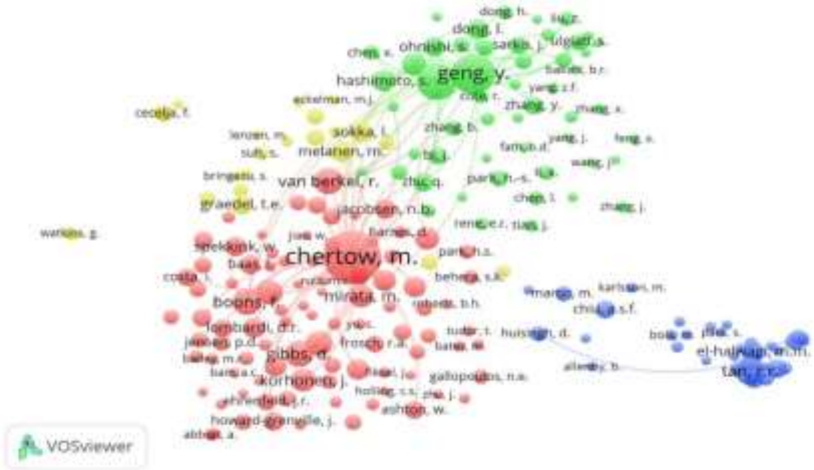

Figure 6: Co-citation network map of cited authors in documents retrieved from Scopus database (Akhtar, et al., 2018)

Both the Journal of Cleaner Production and the Journal of Industrial Ecology (JIE) were found to have contributed significantly to the total number of publications (34%), a result that is consistent with the previous mentioned studies.

The results also suggested a rise in research partnerships between and across countries, on scales from regional to transcontinental. These findings are consistent with those of previous studies. China in Asia, the United Kingdom in Europe, and the United States of

America in North America were singled out as centers of activity and drivers of research momentum, respectively. However, this research also showed that the bulk of cooperation is being done by advanced industrial nations. When compared to the northern hemisphere, the southern hemisphere demonstrated an early interest in industrial symbiosis research. In contrast, an increasing preference for such international partnerships was also seen, for example, in India, which is moving from an agrarian to an industrial economic foundation.

Working together on research is essential for coming up with workable solutions to problems in different contexts. Studying who has written what about industrial symbiosis may reveal which organizations do the most influential research. These interactions led to the development of seven separate lines of inquiry.

Researchers from China, Japan, the Philippines, and the United Kingdom were found to collaborate the most often. Nine papers came out of the most prolific group, which consisted of members aged seven. Researchers from NIES in Japan, the Chinese Academy of Sciences in China, the University of Southern Denmark, and the University of Ulsan in South Korea all worked together on this. In terms of the number of researchers working together, this cluster is likewise the largest.

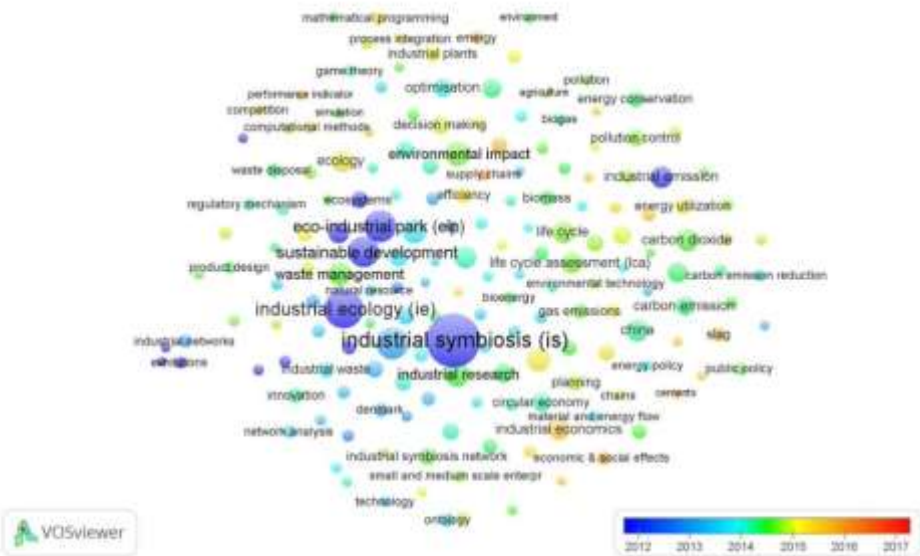

Figure 7: Keywords occurrences in Industrial Symbiosis related literature (Akhtar, et al., 2018)

The structure of a field may be seen using a tool called a "keyword co-occurrence map". The choice of keywords conveys the central emphasis and overarching direction of the scientific investigation. To accomplish this goal, the keywords from the papers were extracted and put through an analytical procedure. Figure 7 is an illustration of the results obtained. Only recurrent concepts, such as those that appeared at least five times, were discussed. To get around the problem of excessive noise, this technique was used. The magnitude of the node is reflective of the frequency, and the color of the node is indicative of the publication time frame. The terms "industrial symbiosis" (277), "industrial ecology" (123), "sustainable development" (77), "industry" (76), and "eco-industrial park" are represented by the major nodes of the network (67). However, the study discovered that the terms "waste management" (43), "environmental effects" (42) "recycling" (41) and "economics" (39) were also significant.

A more recent bibliometric analysis conducted by Mallawaarachchi H. et al. (2020) concluded with the results depicted in Figure 8: Leading journals published articles on IS 9Figure 10: Leading authors in industrial symbiosis .

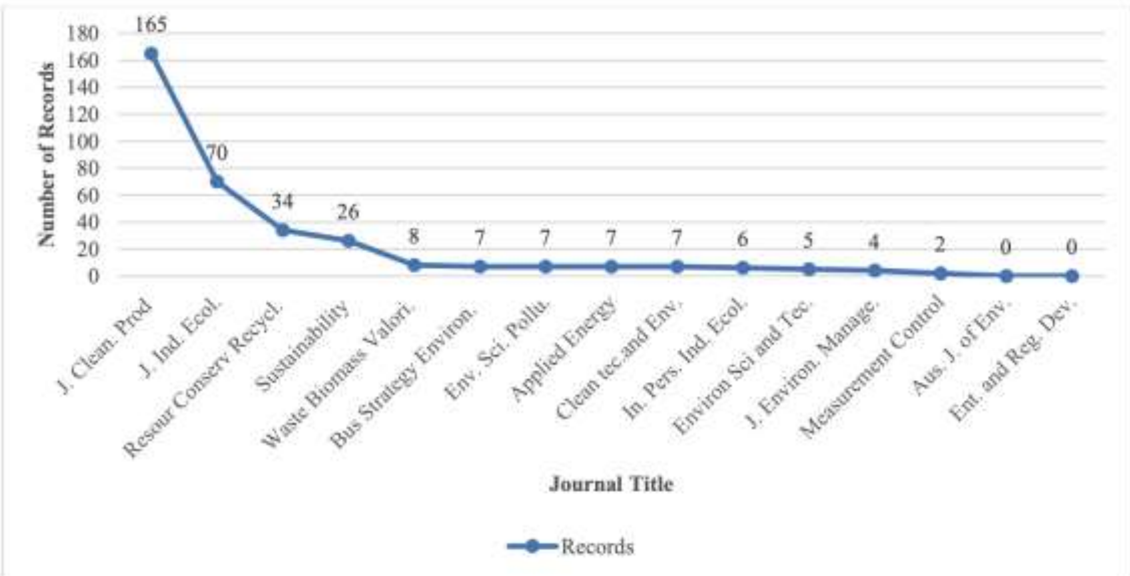

Figure 8: Leading journals published articles on IS (Mallawaarachchi, et al., 2020)

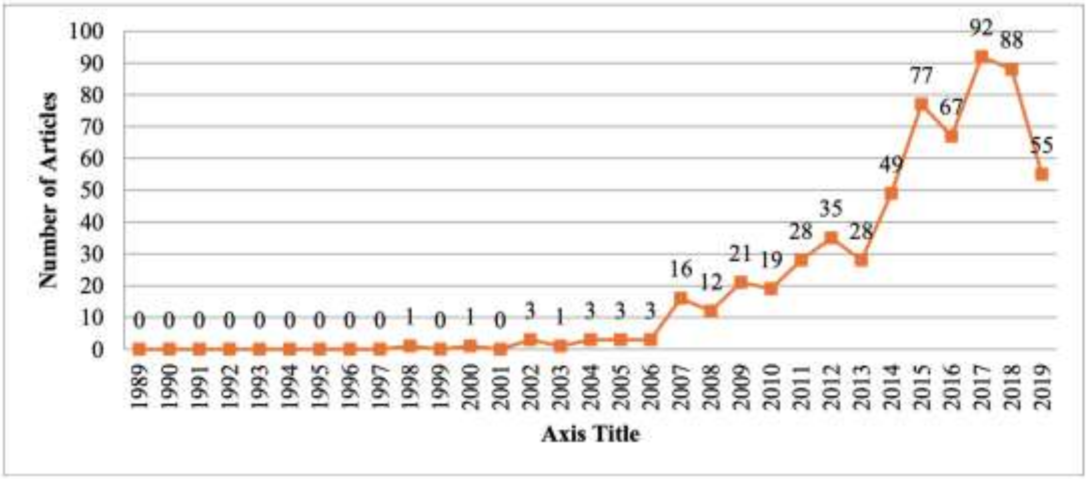

Figure 9: Evolution of the number of articles (Mallawaarachchi, et al., 2020)

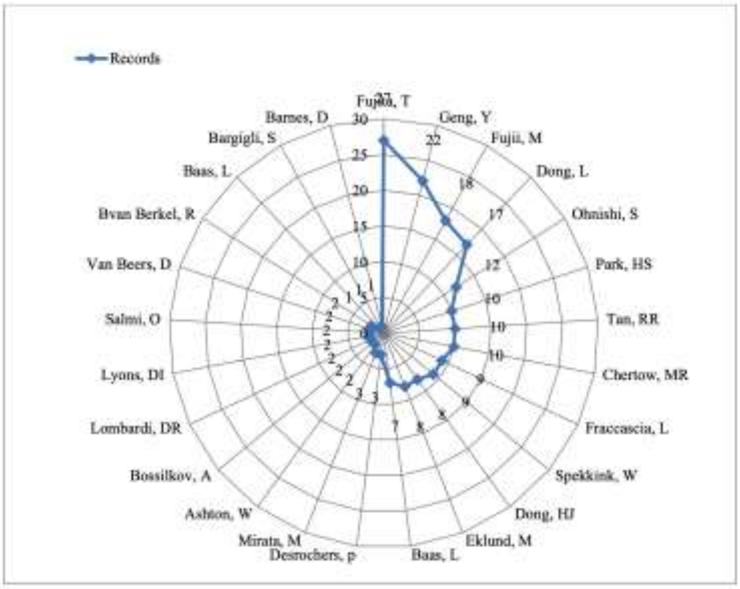

Figure 10: Leading authors in industrial symbiosis (Mallawaarachchi, et al., 2020)

This overview examines the body of literature that discusses the many alterations and reinterpretations that have been made to the idea of industrial symbiosis since its inception. The fact that many information systems projects from all over the globe have been included in the different information systems theories and literature is proof that the notion has developed.

The purpose of this last research was to determine, using analysis, the progression of the publications on industrial symbiosis from the years 1989 to 2019, and this was accomplished. An ever-increasing amount of focus has been placed on study in this area, which has resulted in a meteoric rise in the number of publications devoted to industrial symbiosis. The Journal of Cleaner Production, the Journal of Industrial Ecology, and Resources Conservation and Recycling are examples of some of the most influential publications that have made significant contributions to the development of the idea of IS.

Since its inception, the idea has developed further through its engagement with a wide variety of other ideas and uses, all of which are touched upon in this research. The definitions that were offered by academic researchers working on the field of industrial symbiosis were put through a filter during the second step of the analysis. It was identified and reported that there were sixteen essential factors that were examined by many researchers in their interpretation of the industrial symbiosis from the years 1989 to 2019.

These critical aspects were provided under the three suggested levels of network, context, and externalities. As a result, the study achieves its goal of providing researchers with a well-supported overview and a more evident foundation concerning the scientific development of the industrial symbiosis concept for the purpose of furthering the concept's development.

The next step in this study will be to illustrate the obstacles that companies face while implementing the conceptual advancements of industrial symbiosis to suggest relevant enhancements. This will be done to propose the appropriate improvements.

2.11 Research approaches used in the field of industrial symbiosis

Many academics, to accomplish their study objectives, presented certain models and then utilized relevant instances to test their model. Scholars have deemed certain cases of industrial symbiosis to be canonical. These cases come from countries such as the United States, Finland, Sweden, Denmark, Australia, South Korea, and the United Kingdom, as well as an increasing number of cases from China (Fraccascia, et al., 2017).

Boons F. et al. (2011) utilized a dataset consisting of 233 projects to test the hypothesis that, for businesses to form symbiotic links, certain social conditions must first be satisfied. Jiao et al. (2014) used a definition of policy that was static; they analyzed a case with policy translations for the circular economy idea and an eco-industrial park in

China, to prove that policy was, at its heart, a dynamic activity. To simulate the agent-based model, other studies made use of real-world case studies.

Gonela V. and Zhang J. (2014) compared the efficiency and efficacy of the suggested model via the use of a case study that they had previously completed. Zhu Q. et al. (2007) studied industrial symbiosis in China by looking at the Guitang Group as a case study.

In other studies, an analysis of the financial and environmental benefits was conducted, as well as the drawbacks that symbiosis partners in Guayama experienced. To determine the elements that can have a role in the formation of industrial symbiosis, Simboli A. et al. (2014) conducted research on one major company in addition to 18 small and midsize firms known as SMEs operating in the motorcycle sector.

In other studies, specific economic and environmental data is used to look into the primary industrial symbiotic exchanges. This is done to learn about the important economic and environmental performance. Yang S. and Feng N.'s (2008) research on the Nanning Sugar Co., Ltd. in China led to the discovery of four things that were important for this symbiosis to work.

Lehtoranta S. et al. (2011) investigated the history of a pulp and paper factory in Finland as well as its impact on the surrounding ecosystem. So, no matter what factors affect industrial symbiosis or what level of efficiency can be reached, there are many cases that can be studied, such as the Xinfa Eco-Industrial Park, the Songmudao Chemical Industrial Park in China, an Italian tannery cluster in Tuscany, three eco-industrial coal parks in China, the Ningdong Coal Chemical Eco-Industrial Park, and so on.

Several different techniques have been devised in order to quantify the positive effects that industrial symbiosis projects have had on the surrounding ecosystem. The life cycle assessment, or LCA, is one of the most important ways that the positive effects of industrial symbiosis on the environment have been measured (Scheepens, et al., 2016).

In the beginning, it was used for the process of analyzing each material replacement to establish how successful it was, notably in the chemical industries. Sokka L. et al. (2011) utilized it to evaluate the effects that a pulp and paper mill had on the surrounding ecosystem, while Adiansyah J. S. et al. (2017) examined different management techniques for coal mine tailings by using life cycle assessment and land-use area metrics as their primary research tools. In addition, Song M. et al. (2017) developed an Malmquist–Luenberger - life cycle assessment technique (known as ML-LCA) to enhance the theory of environmental technology measurement. This method is based on life cycle assessment, which is often used to quantify environmental impacts but not to evaluate the progression of technology.

In addition, various techniques for the synthesis and optimization of symbiotic resource networks inside Eco-Industrial Parks have been established. Material flow analysis was a method of evaluation that was used to quantitatively measure the flow of materials and forecast the environmental load to the system that was caused by the flows. The findings demonstrate how economic growth affected the environmental load by analyzing material inputs and outputs. Material flow analysis, which was created in the 1970s, was used to figure out if a region could be turned into an efficient and environmentally friendly zone.

The data envelopment analysis, often known as DEA, is a method for determining the suitability of various decision-making units as well as the relative efficacy or utility of those units. It has been shown in several studies that data envelopment analysis has an impact on the optimum design of ecological industry chains. Additionally, it may be used to assess the effectiveness of ecological industry chains. In the meantime, an updated model called ISBM-DEA was introduced to monitor and evaluate the efficiency of certain unwanted outputs, such as environmental contamination. Concurrently, a model was developed to evaluate environmental efficacy, and hierarchical cluster analysis was used to identify the output that was not ideal.

After using the grey-Delphi method to quantify the important role that eco-industrial parks play in the economy, the study assessed the detailed benefits of eco-industrial parks by using a hybrid multi-criteria decision-making approach. This was done in order to evaluate the parks' overall value. It has been shown that an emerging energy analysis based on thermodynamic theory is an efficient and effective method for assessing the overall eco-efficiency of a system.

The social network analysis has been used to determine the prevalence of industrial symbiotic linkages. This line of inquiry investigates the structure of industrial ecosystems. This line of inquiry investigates the structure of industrial ecosystems.

According to research conducted by Ashton W. (2008), the manufacturing industry network in Barceloneta was predicated on industrial symbiosis practices, even though these activities were less common than other forms of corporate partnerships. SNA was used by Doménech T. and Davies M. (2011) to get an understanding of the social dynamics at play, as well as the function that trust plays in the process of constructing and actualizing industrial symbiotic exchange.

2.12 Planning of production

Production planning in eco-industrial parks has the potential to improve efficiency as well as the long-term viability of eco-industrial parks production. This is since eco-industrial parks were initially developed to ensure the appropriate utilization of resources as well as the availability of raw materials. The use of specific techniques in production planning is a useful instrument for the production strategy of businesses that are confronted with seasonal stock-outs in demand and supply. This is because the use of such techniques in production planning acts as an effective tool. Singhvi A. et al. (2004) examined this potential outcome in their research.

Ludwig J. et al. (2009) presented production planning that sought to address the potential for future competition caused by the exploitation of biomass by attempting to reduce the issue of seasonal output. This was done to cut down on the issue. Utilizing various sources of renewable energy is a key component, which can result in a significant reduction in the financial burden borne by the government in the form of subsidies.

In a similar vein, Pennsylvania views energy as a flow and energy cost as a quality, and it is reducing its reliance on diesel-based power generation. In addition, Tan R. et al. (2018) came up with a graphical PA approach that could be used for optimal CO_2 planning and management based on biochar. This strategy presented a few possibilities and functioned as an additional method for stakeholders and decision-makers, providing them with a simpler way to graphically visualize the data. This approach secured the availability of biochar via a variety of sources to meet a wide range of requirements. As a result, achieving the greatest possible level of carbon capture.

2.13 Interplant power integration

The planning of the "total site utility system" is an extremely important part that contributes to the efficient operation of the industrial processes that are implemented in eco-industrial parks. Most of the time, to ensure the efficient operation of eco-industrial parks, a centralized utility system, also known as a CUS, is developed. This system integrates the many energies needs of the processes. As a result of this, Ghannadzadeh A. et al. (2012) devised a utility co-generation targeting model for "total site utility system".

The iterative bottom-to-top model, also known as IBTM, is a model that was developed to determine the steam header temperature, flow rate, and shaft power produced by the steam turbines. Additionally, iterative bottom-to-top model was developed to estimate the potential for cogeneration within the total site utility system prior to the detailed design phase.

The above was extended in the work of Ren X. Y. et al. (2018), whose work also targeted the co-generation potentials of TS utility systems. This most recent work was an extension of previous studies and other efforts that were similar. The use of a commercial simulator rather than the iterative process and programming is the most significant departure from previous efforts. It was observed that the commercial program produced more accurate results and required fewer parameters compared to the earlier methods.

In addition, Theo W. L. et al. (2016) created an additional mathematical model for the optimum designing and planning of a hybrid system, with a focus on the usage of renewable energy resources for energy infrastructure projects. So that the unpredictability of energy from renewable sources could be considered in the design of on-grid hybrid power system, another quantitative optimization method was made.

Considering the sporadic nature of the supply of renewable energy sources, this method was developed for on-grid hybrid power system that operates independently from the grid. For determining the optimal capabilities of power and energy storage, a programming approach that is chance constrained has been applied in numerous cases. In figure 11, the total number of articles during the years for "interplant power integration" is depicted. In addition, in 12, the total number of articles on "industrial symbiosis" is depicted.

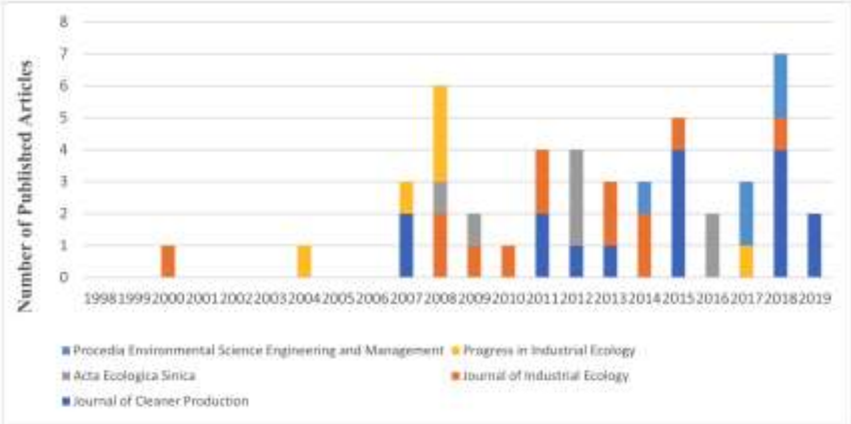

Figure 11: Articles on Interplant Power Integration in the relevant journals, 1998 to 2019 (Lawal, M.; Alwi, S.; Manan, Z.; Ho, W., 2021)

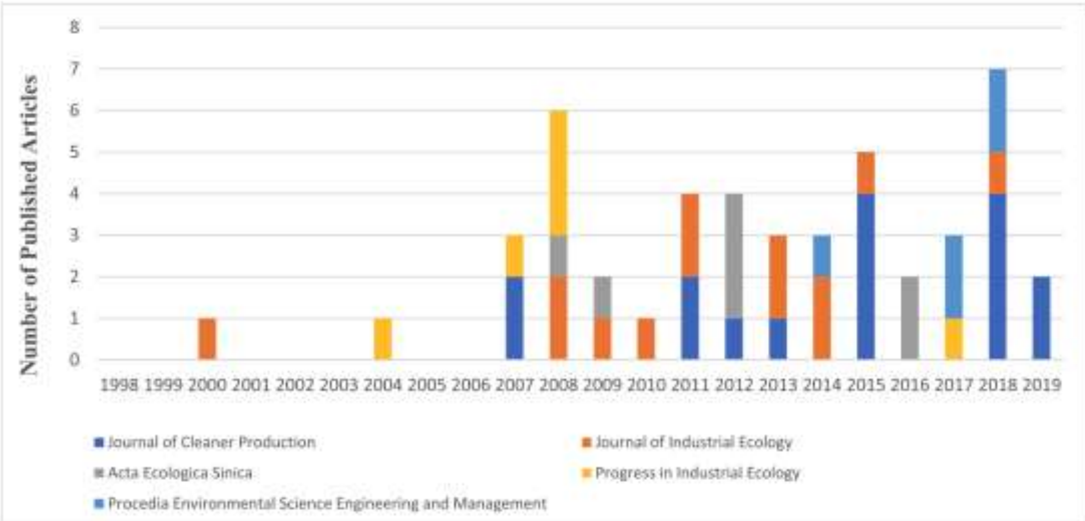

Figure 12: Articles on Industrial Symbiosis Tools in the relevant journals, 1998 to 2019 (Lawal, M.; Alwi, S.; Manan, Z.; Ho, W., 2021)

3 Methodology

Existing literature was the source of data. Information was drawn from it that formed the structural elements of this research.

3.1 Bibliometric / scientometric analysis

Using the bibliometric/scientometric analysis can be achieved the quantification of scientific research and its qualitative evaluation. Data related to scientific publications can be recorded and processed to extracted special bibliometric indicators. In this way, the participation of researchers in their scientific field is quantified. In addition, via bibliometric scientists' interaction with other fields of research is determined and this helps to determine their scientific activity, macroscopically. In addition, it enables a holistic approach to each scientific topic. The most common scientific fields use the bibliometric analysis is information technology and libraries.

The objective of the study was the bibliometric analysis based on literature related to industrial symbiosis, the presentation in bibliometric maps and finally the conclusion. In the present study, the research articles used are published in «Science Direct». This database of scientific publications was selected because it has several features and easy-to-use tools that facilitate the bibliometric analysis process. «Science Direct», is a property of Elsevier (Netherlands). It is a reliable electronic database, the use of which is universal. This is due to its wide coverage of peer-reviewed scientific literature and large number of references.

Some of the common bibliometric indicators are:

- The year of publication: «Science Direct» enlists scientific publications for each year, so the number of publications per year for specific words is known.
- The document type: "Science Direct" categorizes publications according to the type of published texts, such as review articles, research articles, encyclopedia, book chapters, conference abstracts, discussion, editorials, errata, mini reviews, product reviews, and short communications.

-The language: The most common language of the articles in the Bibliographic database "Science Direct" is English.

-The subject area: The scientific database "Science Direct" classifies scientific publications according to the scientific field they serve. Because a scientific publication can be classified in more than one scientific discipline, the sum of publications per scientific discipline is much larger than the actual number of publications. The subject areas where Industrial Symbiosis covers, are the: environmental science, energy, engineering, chemical engineering, social sciences, agricultural and biological sciences, computer sciences, materials science, decision sciences, economics, econometrics, and finance.

-The number of citations: Citations may be considered a measure of the impact of the articles cited, as well as their timeliness and utility.

-The number of co-authors: The number of paper's co-authors is an indicator of co-operation at national or international level.

- The co-occurrence' of words: This indicator examines the frequency with which two given words (co - words) in a specific scientific field are used in cooperation in papers. For each word, its co-occurrence with another word is analysed, along with its frequency.

- The Hirsch index (h-index) and the impact factor is used as a bibliometric indicator to evaluate the impacts and the quality of the research. This indicator has values proportional to research productivity and the number of references.

Three steps were followed in this research. First the relevant articles were extracted, then the information was extracted and interpreted, and finally tables and visualization maps were produced. The study of the elements of the inquiry framework is based on the information received from the combination of the existing literature. Only papers published between 2004 and up to April 2016. All the articles are written in English, and all article abstracts, keywords, and titles were read. To ensure the reliability of the research and to avoid biases and deviations the files were downloaded within April 2022, specifically on the 20, 23, 25 and 26 April. The selected publications contained the words or «industrial symbiosis» in its title, keywords, or abstract, was identified. A database with 280 identified papers was created. Using Microsoft Excel, the names of the authors, the title of the articles, the name of the journals, the year of publications, the countries and keywords were recorded. The Appendix contains a list of the papers selected. The target was to find journal articles from the base that deal with industrial symbiosis. Finally bibliometric maps created using VOSviewer (version 1.6.5, developed by Van Eck and Waltman). According to Van Eck and Waltman (2010), the software gives the ability to design easy-to-use bibliometric maps.

3.2 VOSviewer

The creators of the software are Nees Jan Van Eck and Ludo Waltman. It is a free software, and anyone can download it from the official website www.vosviewer.com. Using the Java programming language, it creates bibliometric multidimensional scaling maps. Items are represented by their label and by default also by a circle.

When an object has a high weight, the circle has a large dimension. The colour of an item is determined by the cluster to which the item belongs. Lines between items represent links. The lines connect items represent links. The distance between two items in the visualization approximately indicates the relatedness of the items.

4 Scientometric Analysis

4.1 Distribution of articles per year

The first year that the term 'Industrial Symbiosis' appeared in the Science Direct community was 1997. In that year only one article was published. Until 2001 there was only one publication in the 'Science Direct' database, only in 2002 two articles were published. The year after, there was no interest, as no article was published on the subject. 2004 is the year that three published articles appear. This year is the starting point for this research (Figure 13).

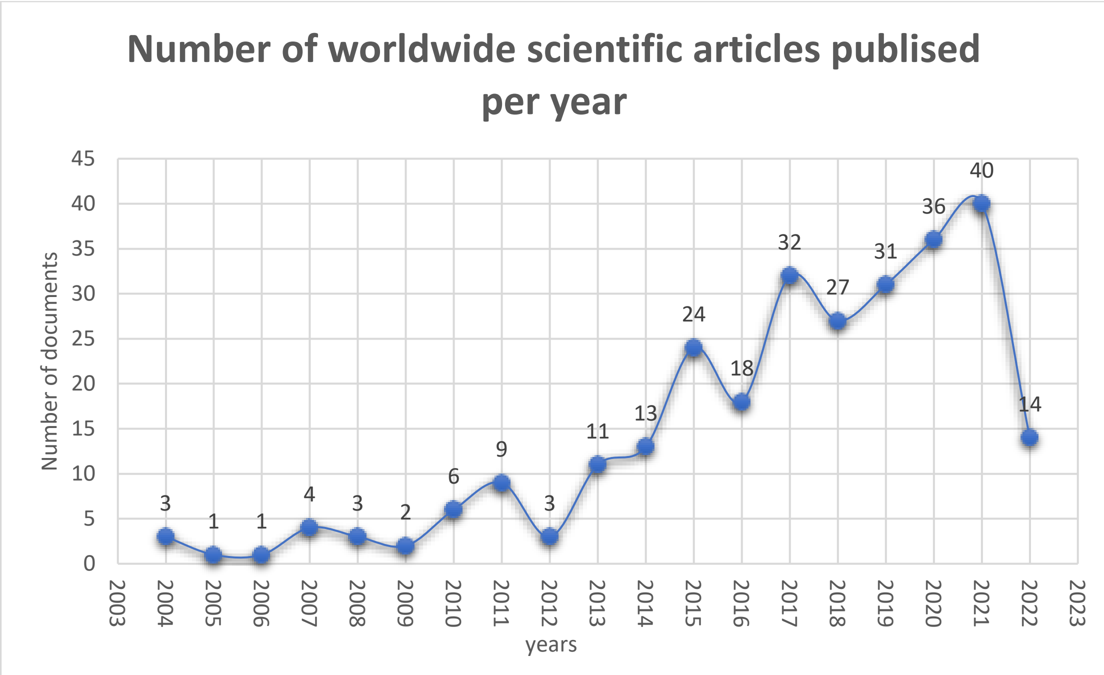

Figure 13 Distribution of worldwide scientific articles published per year – source: Science Direct database.

4.2 The most popular journals in the dataset with publications in industrial symbiosis

Scientific literatures have evolved over time in terms of specialization and target audience. Several Science Journals are multidisciplinary. Basically, however, most journals are highly specialized and publish articles related to specific scientific fields (Figure 14).

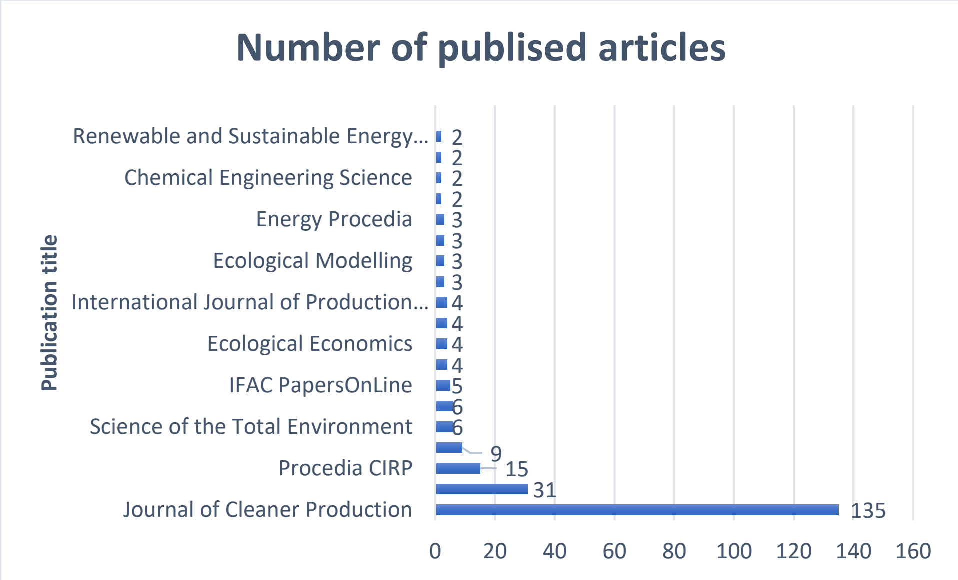

Figure 14: The most popular journals in the dataset with publications

4.3 *The most frequent keywords of the 280 articles*

To study the keywords in the database a bibliometric map was created. The analysis chosen was that of common occurrence and all the keywords of the publications were selected as objects of the map. The map is based on bibliographic data and shows the keywords of the 280 articles. The map was created with the VOS viewer software. This software was chosen because it can build and visualize bibliometric networks.

The relevance of map objects, by choosing their common appearance, is determined by how frequently the objects appear together in publications. The minimum number of occurrences of a keyword was a defined two. From observing the map, the similarity between words can be calculated, and in this way, clusters can be identified. The spacing of words on the bibliometric map is indicative of the similarities between them. The related words are displayed closely spaced. Distant words are not relevant to the subject of the research. The first bibliometric map shows the clusters that the keywords of the 280 publications belong to.

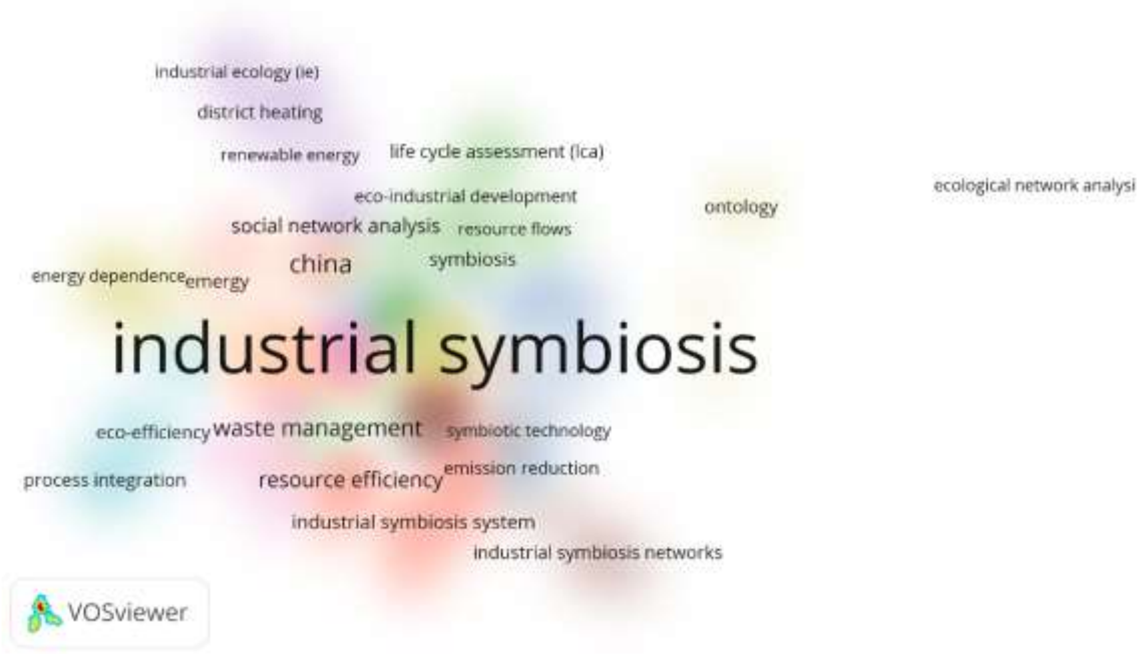

Figure 15: The most frequent keywords _ clusters

The keywords of the articles were grouped into 16 clusters (Figure 15). To evaluate the results obtained from the keyword clustering, Table 1 was created. The first column of the table shows the selected colour representing each cluster, the second column shows the name of the cluster and the number of items, finally the third column lists the keywords of each cluster.

Table 1: All the keywords for the clusters

Colour	No cluster	keywords
	Cluster 1 (18 items)	absolute sustainability, barriers, bioenergy-based industry, by-product synergy, carbon metabolism, cooperative game theory, evolution, industrial symbiosis (is), industrial symbiosis network, industrial symbiosis system, industry 4.0, networks, redundancy, resilience, resource efficiency, stability, sustainability, sustainable manufacturing.
	Cluster 2 (15 items)	By - product exchange, complex network, eco-industrial development, eco-industrial park, energy efficiency, Finland, forest industry, industrial ecosystem, life cycle assessment (Ica)

		life cycle assessment, policy instrument, resource flows, symbiosis, synergies vulnerability.
	Cluster 3 (14 items)	anaerobic digestion, biogas, circular business model, emission reduction, energy, energy conservation, facilitation, institutional capacity building, iron steel industry, symbiotic technology, synergy, system dynamics, value chain, waste-to-energy.
	Cluster 4 (11 items)	by-product, decision making, energy dependence, energy management system, environment, environmental performance, industrial production systems, integration, models, product development, renewable energy systems.
	Cluster 5 (11 items)	district heating, energy symbiosis, governance, industrial ecology (ie), inter-organizational collaborate, low carbon, multi-objective optimization, product service systems, renewable energy, social network analysis, waste heat.
	Cluster 6 (10 items)	eco-efficiency, eco-industrial park (eip), energy recovery, municipal solid waste management, pinch analysis, process integration, scenario analysis, urban sustainability, urban symbiosis, urban industrial symbiosis.
	Cluster 7 (9 items)	eco-industrial parks, energy analysis, industrial networks, industrial park, institutional capacity, resource productivity, sustainable development, urban metabolism.
	Cluster 8 (9 items)	agent-based modelling, agent-based simulation, circular economy, cleaner production, environmental sustainability, industrial symbiosis networks, performance indicators, waste reduction.
	Cluster 9 (7 items)	end-of-waste, geographic proximity, industrial ecology, industrial waste, nisp, recycling, symbiosis product.
	Cluster 10 (7 items)	carbon footprint, china, emergy, low-carbon city, material flow analysis, regional eco-industrial development, urban industrial symbiosis.

	Cluster 11 (6 items)	collaboration, mathematical modelling, optimization, policy, supply chain, waste management.
	Cluster 12 (5 items)	biorefinery, energy, life cycle assessment, waste, water footprint.
	Cluster 13 (5 items)	Eco-innovation, industrial symbiosis, ontology, semantics, sustainable industrial development.
	Cluster 14 (2 items)	Ecological network analysis, iron and steel industrial symbiosis.
	Cluster 15 (2 items)	conceptual framework, investment.
	Cluster 16 (1 items)	reuse.

After grouping the objects, the map was created and presented in all the formats available in the software. figure 15 shows the network representation and figure 16 the overlay representation. In the network visualisation (figure 16), the colours represent the clusters where the objects belong. How large each object is depending on how often it occurs in the literature of the 280 publications.

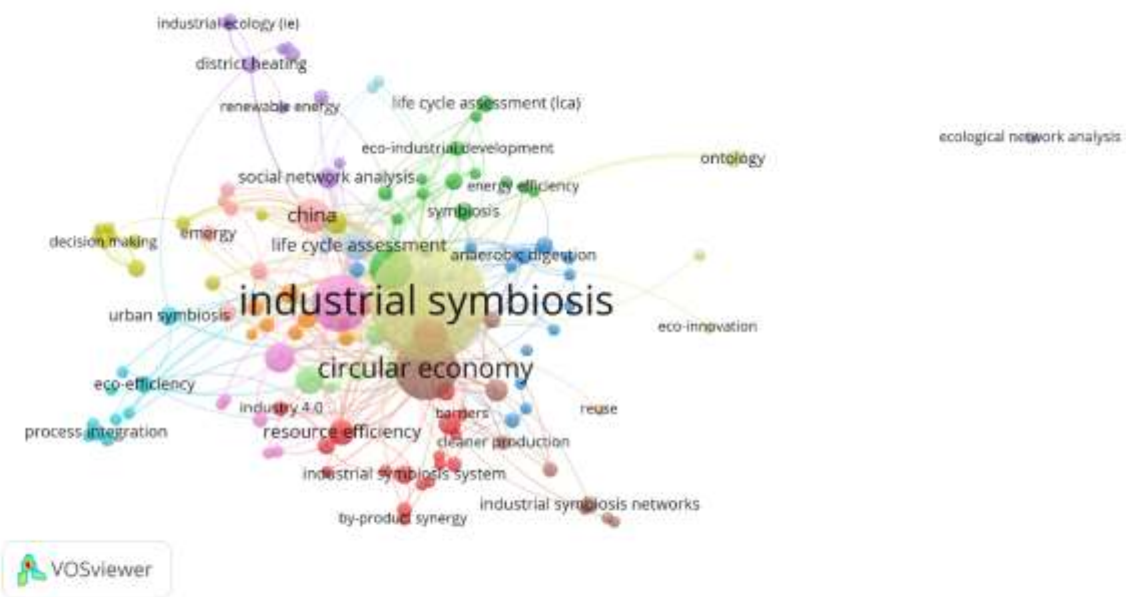

Figure 16: The most frequent keywords _ networks visualization

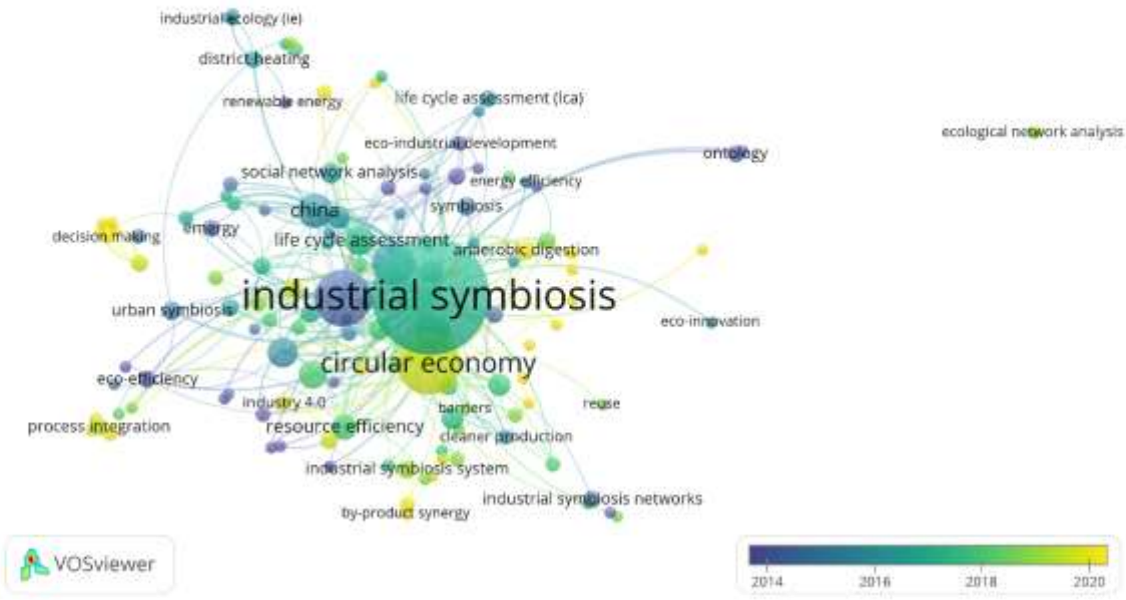

Figure 17: The most frequent keywords _ overlay visualization

Figure 16 shows the overlay visualization of the bibliometric keyword map. The structure of the two maps (Figures 16 & 17) is the same, although the colours change. The overlay feature is only available if the map objects are characterized by a score that measures a common property. In this case this property is the year of publication of each item, each keyword. The colours of the bar at the bottom right of the image, initially are navy that gradually turns blue, green, and finally turn yellow.

The keyword density visualization of the bibliometric map is shown in Figure 18. Specifically, in the object density display, the background is dark blue. The area covered by the keywords is illuminated in yellow and is determined by the number of keywords and their weight. The colour of a region tends towards yellow if the keywords in the region have higher weights and if there are many keywords in that region.

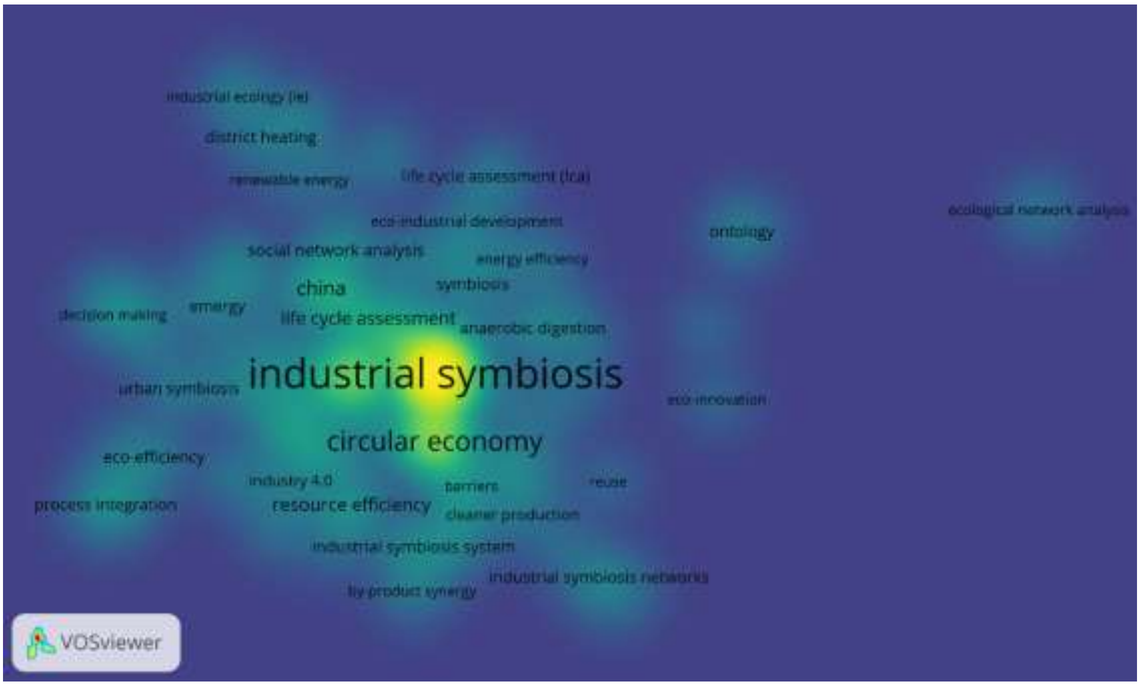

Figure 18: The most frequent keywords _ density visualization

4.4 The country/region collaboration network from 2004 to 2022

Figure 19 shows the number of first author articles published for each country included in this study. In order to study collaboration trends by country, we devised a dataset that included specific fields (Table 2).

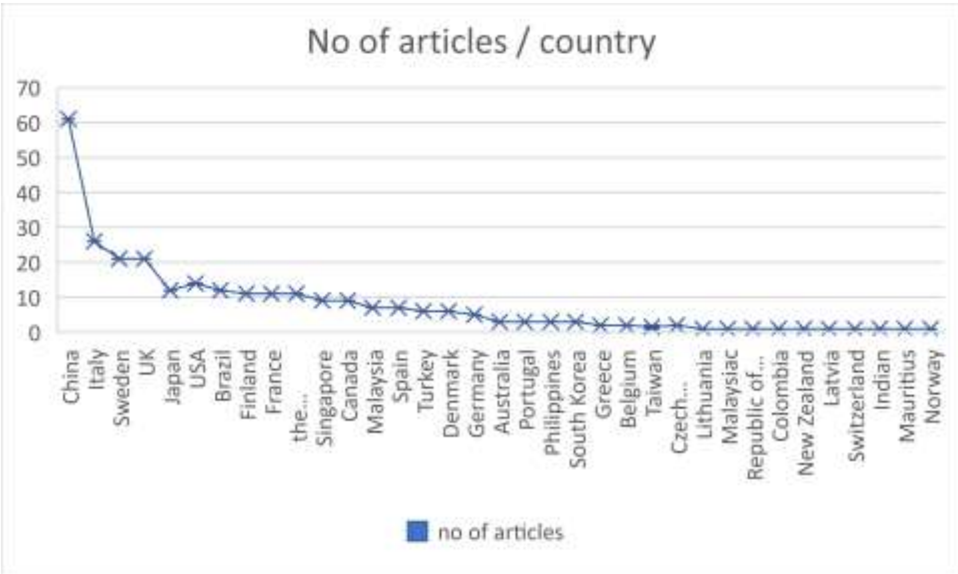

Figure 19: Productivity of articles by country

Table 2: Collaboration between countries

Cooperating countries	No of articles	Cooperating countries	No of articles
Belgium, France, Slovenia	2	Japan, China, Denmark	1
Belgium, Greece	1	Japan, China, the Netherlands,	1
Brazil, Cuba	3	Japan, China, the Netherlands,Denmark, Canada	1
Brazil, Italy	1	Japan, the Netherlands, South Korea, Philippines	1
Brazil, Spain	1	Lithuania, France	2
Canada, China, Japan	4	Malaysia, Australia	1
Canada, Germany, USA	1	Malaysia, Czech Republic	1
Canada, Singapore	1	Malaysia, Philippines	1
Canada, Switzerland	1	Malaysia, Philippines, USA	1
China, Japan	5	Philippines, Malaysia, USA	1
China, Australia	1	Portugal, Switzerland, UK	1
China, Canada	1	Republic of Korea, Pakistan, China	3
China, Denmark, the Netherlands, Japan	1	Singapore, Germany	
China, Japan, Denmark	1	Singapore, USA, Germany	1
China, the Netherlands, Japan	3	South Korea, India	3
China, UK	2	South Korea, Philippines	1
China, UK, Philippines	1	South Korea, USA	1
China, USA	1	Spain, Colombia	1
China, USA, Austria	1	Spain, Italy	1
Czech Republic, Russian Federation	1	Spain, Italy, Germany, Brazil, Colombia, Portugal	1
Czech Republic, India	1	Spain, Portugal	1
Denmark, Germany, Australia	1	Spain, UK	1
Denmark, Germany, Italy	1	Sweden, UK	1
Denmark, Germany, the Netherlands	1	Taiwan, Hungary, Australia, Philippines, Malaysia	1
France, Belgium	1	the Netherlands, Greece	1
France, Mexico	1	the Netherlands, Italy	1
France, Morocco	1	the Netherlands, Sweden	1
France, the Netherlands	1	the Netherlands, USA	1
Germany, China, the Netherlands	1	Turkey, the Netherlands	2
Germany, Singapore	1	UK, the Netherlands, Russia	1
Grance, USA, Singapore	1	UK, Belgium	1
Italy, Belgium	1	UK, China	1
Italy, Brazil	1	UK, China	1
Italy, Denmark	1	UK, Greece	2
Italy, Switzerland	1	UK, Portugal	1
Italy, the Netherlands	7	UK, Singapore	1
Japan	2	UK, South Africa	1
Japan, Austria, China	1	UK, the Netherlands, France, USA, Canada	1
Japan, China	5	USA, India	1
		Finland, Sweden	1

4.5 Top 5 most co-cited articles in industrial symbiosis

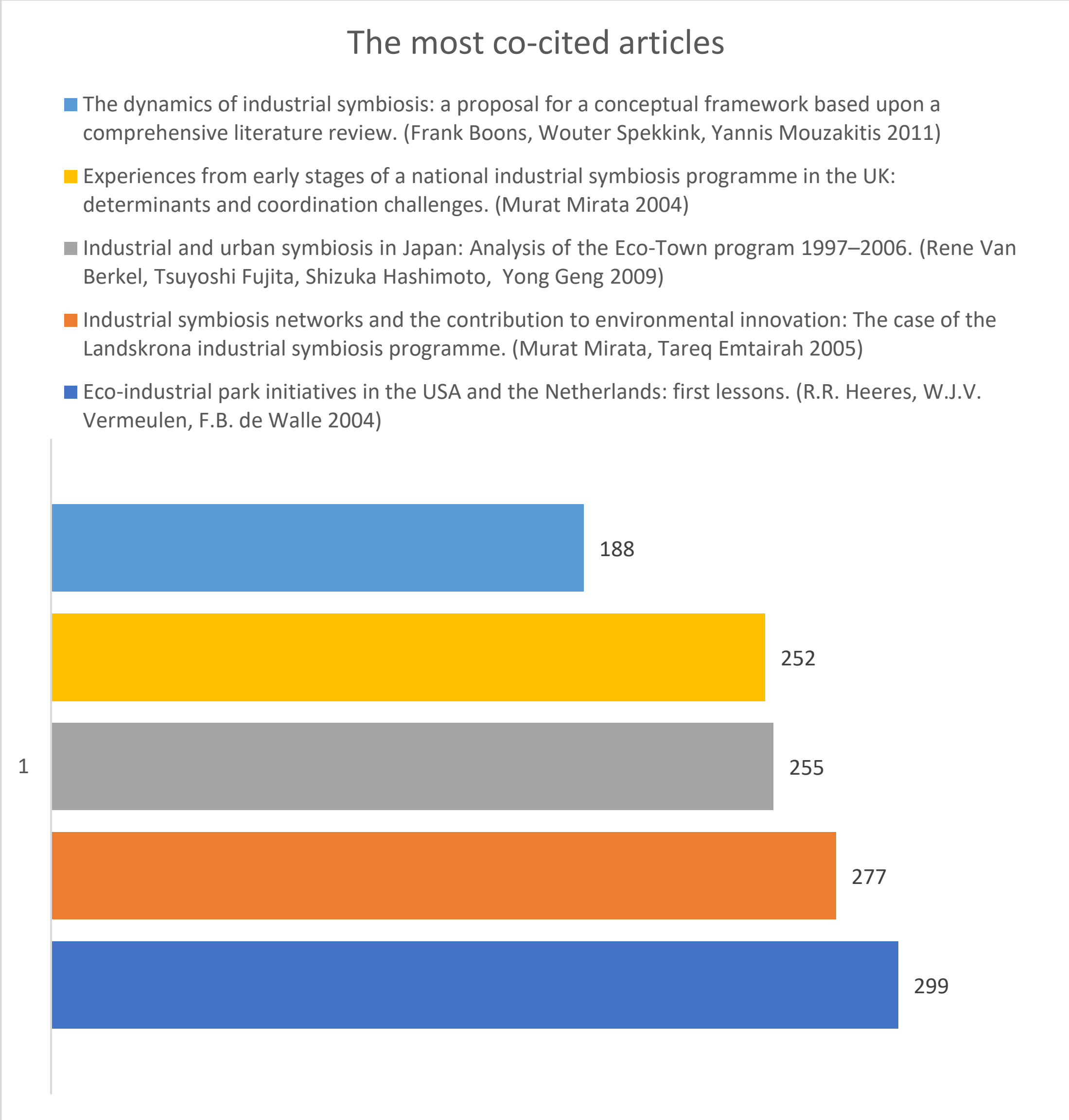

Figure 20: The most frequent keywords _ overlay visualization

4.6 Author co - working on industrial symbiosis

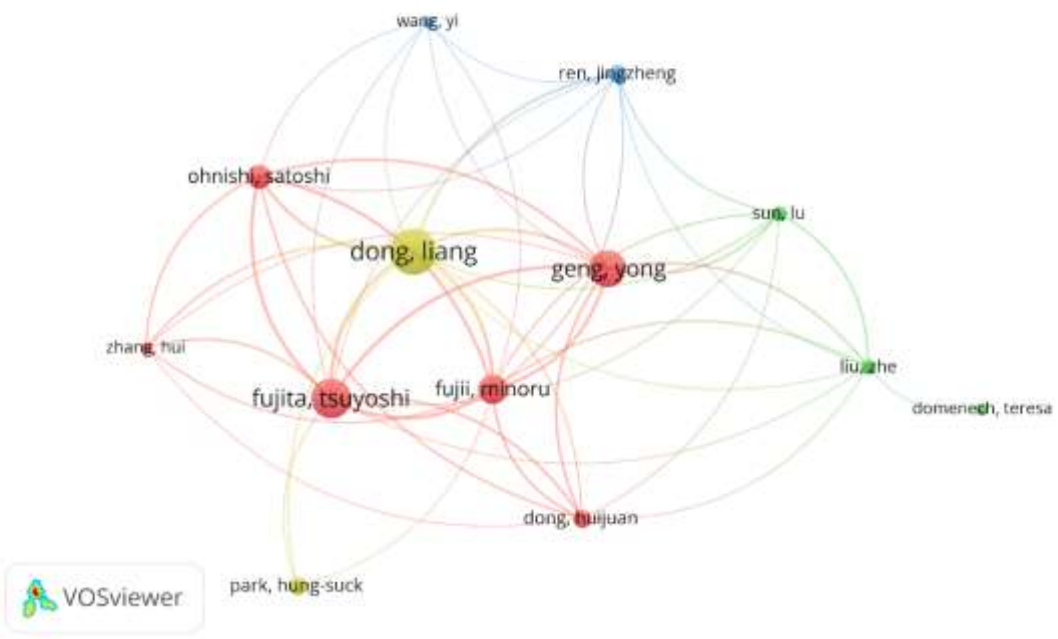

Figure 21: Co-authorship network with three clusters working on IS _ networks visualization

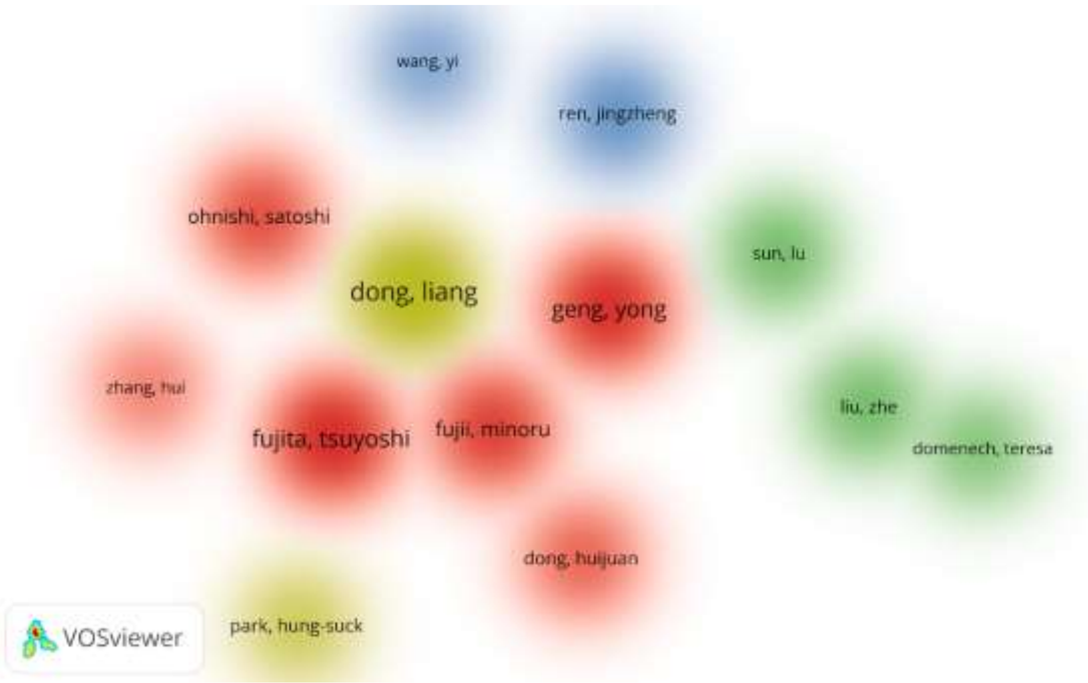

Figure 22: Co-authorship network with three clusters working on IS _ networks visualization

Table 3: Clusters 1 productivity

Theory/observations	Authors	Journal	Year	Country	Keywords
Industrial and urban symbiosis in Japan: Analysis of the Eco-Town program 1997–2006	Rene Van Berkel, Tsuyoshi Fujita, Shizuka Hashimoto, Yong Geng	Journal of Environmental Management	2009	Japan, Austria, China	Industrial ecology Recycling Industry modernisation Environmental industries' development
Towards preventative eco-industrial development: an industrial and urban symbiosis case in one typical industrial city in China	Liang Dong, Tsuyoshi Fujita, Ming Dai, Yong Geng, Jingzheng Ren, Minoru Fujii, Yi Wang, Satoshi Ohnishi	Journal of Cleaner Production	2016	Japan, China, Denmark	Eco-industrial development Industrial and urban symbiosis Industrial city Life cycle assessment China
Promoting low-carbon city through industrial symbiosis: A case in China by applying HPIMO model	Liang Dong, Tsuyoshi Fujita, Hui Zhang, Ming Dai, Minoru Fujii, Satoshi Ohnishi, Yong Geng, Zhu Liu	Energy Policy	2013	Japan, China	Low-carbon city Industrial symbiosis HPIMO model
Uncovering opportunity of low-carbon city promotion with industrial system innovation: Case study on industrial symbiosis projects in China	Liang Dong, Fumei Gu, Tsuyoshi Fujita, Yoshitsugu Hayashi, Yoshitsugu Hayashi	Energy Policy	2014	Japan, China	Industrial system innovation Industrial symbiosis Low-carbon city
Environmental and economic gains of industrial symbiosis for Chinese iron/steel industry: Kawasaki's experience and practice in Liuzhou and Jinan	Liang Dong, Hui Zhang, Tsuyoshi Fujita, Satoshi Ohnishi, Huiquan Li, Minoru Fujii, Huijuan Dong	Journal of Cleaner Production	2013	Japan, China	Iron/steel industry Industrial symbiosis Urban symbiosis Circular economy China
Achieving carbon emission reduction through industrial & urban symbiosis: A case of Kawasaki	Huijuan Dong, Satoshi Ohnishi, Tsuyoshi Fujita, Yong Geng, Minoru Fujii, Liang Dong	Energy	2014	China, Japan	Industrial symbiosis Urban symbiosis Lifecycle carbon footprint Material saving Eco-town
Towards preventative eco-industrial development: an industrial and urban symbiosis case in one typical industrial city in China	Liang Dong, Tsuyoshi Fujita, Ming Dai, Yong Geng, Jingzheng Ren, Minoru Fujii, Yi Wang, Satoshi Ohnishi	Journal of Cleaner Production	2016	Japan, China, Denmark	Eco-industrial development Industrial and urban symbiosis Industrial city Life cycle assessment China
Innovative planning and evaluation system for district heating using waste heat considering spatial configuration: A case in Fukushima, Japan	Yi Dou, Takuya Togawa, Liang Dong, Minoru Fujii, Satoshi Ohnishi, Hiroki Tanikawa, Tsuyoshi Fujita	Resources, Conservation and Recycling	2018	Japan, China, the Netherlan ds,	Industrial-Urban Symbiosis District heating Waste heat Land use planning Fukushima
Realizing CO2 emission reduction through industrial symbiosis: A	Shizuka Hashimoto, Tsuyoshi Fujita,	Resources, Conservation and Recycling	2010	Japan, China	Industrial symbiosis Greenhouse gas Co-processing Alternative fuel and

cement production case study for Kawasaki	Yong Geng, Emiri Nagasawa				raw material Life cycle CO2 analysis
Co-benefit potential of industrial and urban symbiosis using waste heat from industrial park in Ulsan, Korea	Hyeong-Woo Kim, Liang Dong, Angelo Earvin Sy Choi, Minoru Fujii, Tsuyoshi Fujita, Hung-Suck Park	Resources, Conservation & Recycling	2018	Japan, the Netherlands, South Korea, Philippines	District heating Eco-industrial park Industrial symbiosis Low-grade waste heat Urban symbiosis Ulsan
Analysis of optimal locations for power stations and their impact on industrial symbiosis planning under transition toward low-carbon power sector in Japan	Hiroto Shiraki, Shuichi Ashina, Yasuko Kameyama, Seiji Hashimoto, Tsuyoshi Fujita	Journal of Cleaner Production	2016	Japan	Waste heat Energy symbiosis Fossil-fuel power plant Generation planning Low carbon
Analysis of low-carbon industrial symbiosis technology for carbon mitigation in a Chinese iron/steel industrial park: A case study with carbon flow analysis	Hui Zhang, Liang Dong, Huiquan Li, Tsuyoshi Fujita, Satoshi Ohnishi, Qing Tang	Energy Policy	2013	China, Japan	Iron and steel industrial park Industrial symbiosis Carbon flow analysis

5 Discussion of results

The quantitative results by years of the searching for articles on industrial symbiosis are presented in the chart in figure 13. The small number of articles from 2004 to 2012 reflects the lack of interest in that period. The rate of growth increases from 2013 onwards, with a sharp increase in the year 2021 with a total of 40 texts. It is important to note that the small number of articles in 2022 is because the literature search for the purposes of this study was carried out in mid-2022. In 2016 the number of publications was 18 and the following year it was 32, almost doubling. The increased productivity can possibly be due to the signing of the Paris Agreement (2016), which aims to enhance the worldwide response to the threat of climate change in the framework of sustainable development.

The main purpose of this analysis is to outline the main sources of publication on industrial symbiosis. The journals’ highlight in figure 14 is «Journal of Cleaner Production» with a share of 56% (or 135 articles) in the sample of 280 articles. «Resources, Conservation and Recycling» with an allotment 13% (31 articles). «Procedia CIRP» has share 6%. The rest of the magazines have a percentage less than 5%.

According to «Science Direct» the most co-cited paper, in February 2023, is by R.R. Heeres, W.J.V. Vermeulen, F.B. de Walle «Eco-industrial park initiatives in the USA and the Netherlands: first lessons» published in Journal of Cleaner Production (2004) (Figure 20). The key words of the article are «the Netherlands, USA, Industrial ecology, Industrial ecosystem, Eco-industrial park, Eco-industrial development, Life cycle management, Industrial metabolism».

Studying keyword’s clusters in Table 1 and connecting the words, the first keyword cluster has meanings in prime industrial processes of sustainable production. The second cluster of words relates to eco-industrial development, the third to the conversion of waste into energy to achieve emission reductions, the fourth to the environmental implications of renewable energy systems, the fifth to the energy-saving-heating correlation, and the sixth to urban living. All other clusters have less than two items, so they are not considered. The keyword "industrial symbiosis" in figure 16 as a circle is in the centre of the bibliometric map and covers the largest area. This proves the validity of the search. The word 'circular economy' is the second largest cycle after industrial symbiosis. The distances between the circles indicate the relativity of the keywords. The more two keywords appear together, the more relevant they are and the closer they will be placed on the map. The degree of relevance of objects is expressed by links (curved lines).

According to the map in figure 17, the average publication year has values from 2014 to 2022. Quantitatively and as expected the minimum score is found in the year 2014 and as we approach 2022 it increases. The changes in the keywords over the years are particularly interesting. In the early years of industrial symbiosis literature, the key words (blue objects) were prime concepts defining industrial symbiosis such. Some of them are ‘eco-efficiency’, ’urban symbiosis’, ‘eco-industrial development’. Between 2016 to 2019 or so, the keywords used (green objects) indicate more the evolution of industrial symbiosis, for example resource efficiency, eco-industrial development, waste management. In recent years, the scientific community has turned its attention to the financial side of industrial symbiosis. The keywords with high scores (yellow objects) are 'circular economy', 'value chain', 'investment', 'industrial production system', revealing this shift in research. In the same map (Figure 17) the keyword "China" is in green, which means that its score is relatively medium and identified around 2017. It is also important to note that this year is the transition point from the medium to the high score, which means that China's technological development has brought about an increase in research related to industrial symbiosis and even towards the economic side. China may have made significant investments in scientific research to achieve its economic goals.

Figure 18 shows that the areas of the map contour are blue as they have few or no objects. Conversely, areas where the groups are present are illuminated by yellow. This is both because the keywords in the clusters are related to each other and because they are near each other, increasing the density of the region. The central keyword is ‘industrial symbiosis’. There are few objects around, however it is strongly illuminated. This is correct as its weight is the highest on the map and all other keywords are related and positioned based on it. Its high gravity leads to increased area density illuminated.

Eventually the area becomes bright yellow. It is worth noting that the next most highlighted word is 'circular economy', followed by 'china' and 'life cycle assessment'. Looking at the diagram in Figure 19 it is clear how a significant part of the literature has China as its country of origin, with 58 publications, followed by Italy with 25. The same countries according to Table 2 participate in international research partnerships. China has the highest number of partnerships. According to the diagram in figure 19 and Table 2, industrial symbiosis is a subject of study in the scientific community of the countries bordering by the sea (the exceptions are Switzerland, Czech Republic, Hungary).

The diagram in figure 21 and figure 22 shows the authors' collaboration network. There are three clusters. The first cluster is coloured red and consists of, Satoshi Ohnishi, Hui Zhang, Tsuyoshi Fujita, Minoru Fujii, Yong Geng, Huijuan Dong. The cluster includes a group of writers from China and Japan. The intensive writing activity started in 2009. The first article was "Industrial and urban symbiosis in Japan: analysis of the Eco-Town program 1997-2006" by Rene Van Berkel, Tsuyoshi Fujita, Shizuka Hashimoto, Yong Geng. Since then and until 2018, other scientists were added to the team, according to Table 3. It is worth noting that the first article in the group is among the top five most co-cited articles (according to ‘Science Direct’. It is worth noting that the first article of the group is among the top five most co-cited articles. The writing career of this group was notably intense in the period 2009 - 2018. The research topics were usually case studies in China. This is linked to the conclusion on the existence of the keyword 'china' mentioned in paragraph 4.3. In the second cluster belong Dong Liang and Park Hung-Suck, in the third cluster Jingzheng Ren, Wang Yi, in the fourth cluster Iu Sun, Liu Zhe, Teressa Domenech.

6 Conclusions

The prevention of resource depletion and the necessity to reduce carbon dioxide levels in the atmosphere make industrial symbiosis an ideal solution that will facilitate the sustainable development of a region, strengthen the country's circular economy, and reduce the ecological impact of industries.

In this study, the quantity and impact of global research output in the field of 'industrial symbiosis' over the past eighteen years was investigated. A bibliometric analysis was conducted using the 'Science Direct' database between 2004 and 2022 to understand research trends. This study highlighted those industrialized economies such as China, the United Kingdom and Italy have strong activity in industrial symbiosis research. This study extends the Akhtar’s, et al. inquiry, which has data up to 2017. There is a logical and temporal sequence in the two studies. As in figure 7 the colour of the node symbolizes the publishing year, it is clear the increase of keywords in 2017 with financial meanings such as ‘industrial economics’, ‘economics and social effects’, ‘supply chains’. No word in green or blue has this property. This confirms the conclusion of this study that the year 2017 is a milestone in the bibliography of industrial symbiosis articles. In addition, while in this study the key word circular economy is regularly encountered in recent years, in their study we see that it does not appear at all.

Finally, it would be interesting to examine the geographical positions of the countries in the future. The fact that most of the countries were wet by the sea indicates that these countries have intense commercial activity and potential commercial partnerships.

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Appendix

	Theory/observations	Authors	Journal	Year
1	Extending industrial symbiosis to residential buildings: A mathematical model and case study	Hamid Afshari, Mohamad Y. Jaber, Cory Searcy	Journal of Cleaner Production	2018
2	The effect of environmental and social value objectives on optimal design in industrial energy symbiosis: A multi-objective approach	Hamid Afshari, Babak Mohamadpour Tosarkani, Mohamad Y. Jaberb, Cory Searcyb	Resources, Conservation & Recycling	2020
3	Sharing carbon permits in industrial symbiosis: A game theory-based optimisation model	Faris Ahmad Fadzil, Viknesh Andiappan, Denny K.S. Ng, Lik Yin Ng, Anuar Hamid	Journal of Cleaner Production	2022
4	Facilitating industrial symbiosis to achieve circular economy using value-added by design: A case study in transforming the automobile industry sheet metal waste-flow into Voronoi facade systems	Ahmed K. Ali, Yi Wang, Jorge L. Alvarado	Journal of Cleaner Production	2019
5	Looplocal e a heuristic visualization tool to support the strategic facilitation of industrial symbiosis	Graham Aid, Nils Brandt, Mariya Lysenkova , Niklas Smedberg	Journal of Cleaner Production	2015
6	Expanding roles for the Swedish waste management sector in	Graham Aid, Mats Eklund, Stefan	Resources, Conservation & Recycling	2017

	interorganizational resource management	Anderberg, Leenard Baas		
7	Industrial symbiosis for a sustainable city: technical, economical and organizational issues	Vito Albino, Luca Fraccascia, Tommaso Savino	Procedia Engineering	2015
8	Exploring the role of contracts to support the emergence of self-organized industrial symbiosis networks: an agent-based simulation study	Vito Albino, Luca Fraccascia, Ilaria Giannoccaro	Journal of Cleaner Production	2016
9	The continuous evolution of the Bazancourt–Pomacle site rooted in the commitment and vision of pioneering farmers. When reality shapes the biorefinery concept	Florent Allais, Honorine Lescieux-Katir, Jean-Marie Chauvet	EFB Bioeconomy Journal	2021
10	Improving the CO2 performance of cement, part III: the relevance of industrial symbiosis and how to measure its impact	Jonas Ammenberg, Leenard Baas, Mats Eklund, Roozbeh Feiz, Anton Helgstrand, Richard Marshall	Journal of Cleaner Production	2015
11	Design of robust water exchange networks for eco-industrial symbiosis	Kathleen B. Aviso	Process Safety and Environmental Protection	2014
12	Analyzing barriers to implementing industrial symbiosis networks using DEMATEL	Lindley R. Bacudio, Michael Francis D. Benjaminc, Ramon Christian P. Eusebio, Sed Anderson K.	Sustainable Production and Consumption	2016

		Holaysan, Michael Angelo B. Promentilla, Krista Danielle S. Yu, Kathleen B. Aviso		
13	Industrial symbiosis and waste recovery in an Indian industrial area	Ariana Baina, Megha Shenoy, Weslynne Ashtona, Marian Chertow	Resources, Conservation and Recycling	2010
14	Industrial Symbiosis: towards a design process for eco-industrial clusters by integrating Circular Economy and Industrial Ecology perspectives	Brian Baldassarre, Micky Schepers, Nancy Bocken, Eefje Cuppen, Gijsbert Korevaar, Giulia Calabretta	Journal of Cleaner Production	2019
15	Evolution of 'designed' industrial symbiosis networks in the Ulsan Eco-industrial Park: 'research and development into business' as the enabling framework	Shishir Kumar Behera, Jung-Hoon Kim, Sang-Yoon Lee, Sangwon Suh, Hung-Suck Park , Jung-Hoon Kim b , Sang-Yoon Lee b , Sangwon Suh c , Hung-Suck Park	Journal of Cleaner Production	2012
16	The use of performance indicators for analysis of resource efficiency measures	Anna Beloborodko, Marika Rosa	Energy Procedia	2015
17	Industrial and urban symbiosis in Japan: Analysis of the Eco-Town program 1997–2006	Rene Van Berkel, Tsuyoshi Fujita, Shizuka Hashimoto, Yong Geng	Journal of Environmental Management	2009

18	Agent-Based modelling simulation for the development of an industrial symbiosis -Preliminary results	N. Bichraoui, B. Guillaume, A. Halog	Procedia Environmental Sciences	2013
19	A big data analytics approach to develop industrial symbioses in large cities	Song Bina,Yeo Zhiquan, Low Sze Choong Jonathan, Derek Koh Jiewei, Denis Kurle, Felipe Cerdas, Christoph Herrmann	Procedia CIRP	2015
20	Co-processing of raw and washed air pollution control residues from energy-from-waste facilities in the cement kiln	Anna A. Bogush, Julia A. Stegemann, Qizhi Zhou, Zhiyong Wang, Bin Zhang, Tongsheng Zhang, Wensheng Zhang, Jiangxiong Wei	Journal of Cleaner Production	2020
21	The dynamics of industrial symbiosis: a proposal for a conceptual framework based upon a comprehensive literature review	Frank Boons, Wouter Spekkink, Yannis Mouzakitis	Journal of Cleaner Production	2011
22	International industrial symbiosis: Cross-border management of aggregates and construction and demolition waste between Italy and Switzerland	Yari Borbon-Galvez, Sergio Curi, Fabrizio Dallari, Giorgio Ghiringhelli	Journal of Cleaner Production	2021
23	How circular is a value chain? Proposing a Material Efficiency Metric to evaluate business models	Johan Brändström, Ola Eriksson	Journal of Cleaner Production	2022

24	Sustainnability-based optimization criteria for industrial symbiosis: the Symbioptima case	C. Brondi, S. Cornago, A. Ballarino, A. Avai, D. Pietraroia, U. Delepliane, M. Niero	Procedia CIRP	2018
25	A model for renewable energy symbiosis networks in eco-industrial parks	A. M. Butturi, M.A. Sellitto, F. Lolli, E. Balugani, A. Neri	IFAC PapersOnLine	2020
26	Experimental and numerical assessment of PV-TvsPV by using waste aluminum as an industrial symbiosis product	Ömer Faruk Can, Erhan Arslan, Meltem Koşan, Mehmet Demirtaş, Mustafa Aktaş¸ Burak Aktekeli	Solar Energy	2022
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39	A Collaboration Platform for Enabling Industrial Symbiosis: Application of the Database Engine for Waste-to-Resource Matching	Jonathan Sze Choong Lowa, Tobias Bestari Tjandra, Fajrian Yunus, Si Ying Chung, Daren Zong Loong Tan, Benjamin Raabe, Ng Yen Ting, Zhiquan Yeo, Stephane Bressan, Seeram Ramakrishna, Christoph Herrmann	Procedia CIRP	2018
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176	Exploratory study of combining Integrated Product and Services Offerings with Industrial Symbiosis in order to improve Excess Heat utilization	Sofia Pȁivȁrinnea, Mattias Lindahl	Procedia CIRP	2015
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181	Creating Economic and Environmental Value through Industrial Symbiosis	Raymond L. Paquin, Timo Busch, Suzanne G. Tilleman	Long Range Planning	2015
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258	Comprehensive evaluation of environmental and economic benefits of industrial symbiosis in industrial parks	Xinyi Chen, Miaoxin Dong, Long Zhang, Xiaoyu Luan, Xiaowei Cui, Zhaojie Cui	Journal of Cleaner Production	2022
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262	The design of industrial symbiosis: an input-output approach	Devrim Murat Yazan, Vincenzo Alessio Romano, Vito Al bino	Journal of Cleaner Production	2016
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