Heliyon 7 (2021) e07778

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Review article

Trends in global research on industrial parks: A bibliometric analysis from 1996–2019

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ARTICLE INFO

Keywords:
Industrial park
Social network analysis
Industrial ecology
Circular economy
Sustainability
Development sustainable

ABSTRACT

Industrial parks have been used to promote the economic development of countries. However, its rapid growth has generated environmental problems related to the depletion of natural resources and pollution. Consequently, the network analysis and the bibliometric analysis applied in this research generated qualitative and quantitative information from a systemic perspective on the thematic and community evolution of research on industrial parks (IP) performed to improve its negative environmental impact and reach sustainability. This study used the Web of Science (WoS) database from 1996 – 2019. The main trends and critical research points were identified in four periods of 6-year each. Social network analysis (SNA) was used to identify the intellectual structure main and the academic collaboration networks established among countries/territories, institutions, and authors. The most productive country in articles is currently China (882), however, when we consider the frequency of articles per million inhabitants, it ranks seventh. The WoS database grouped 63.6 % of the articles published in the subjects of "Environmental Sciences & Ecology", "Engineering", and "Science & Technology - Other Topics". Industrial Ecology (IE), Industrial Symbiosis (IS), and Circular Economy (CE) were the author keywords with the highest frequency, indicating that IP research has focused from these perspectives to promote the exchange of byproducts and to evaluate the performance and environmental impact of industrial areas through the use of methodologies such as carbon footprints, emergy analysis, and life cycle analysis (LCA). Finally, some themes were identified and proposed for future research based on analyzing research trends and hot spots from the literature review on industrial parks.

1. Introduction

An industrial park (IP) is a designated piece of land, subdivided and designed for the use of different industrial activities simultaneously, with transport facilities and other supporting infrastructure to promote its integration [1, 2, 3]. The IPs objective is to allow companies with different economic activities to perform their tasks independently and to use the competitive advantages offered by colocation and centralization of infrastructure and services in a common area [4]. There are different types and synonyms of IPs, such as industrial processing zones, industrial districts, industrial clusters, and industrial states [5]. Similarly, technology parks appear to be a typology of IPs in which science, technology, and innovation are promoted through the establishment of relationships between companies and universities, research centers, and other higher education institutions to develop knowledge and environmentally sustainable cities [6]. The concept of the IP was developed in 1890 [3] and it has been used since 1980 as a strategy to promote and accelerate the economic and social growth of countries [7, 8, 9]. However, the rapid development and growth of IPs, reflected in the more than 20,000 IPs built worldwide [10, 11] has generated problems related to intensive resource consumption and pollution caused by industrial activities developed inside them by planning problems and the inappropriate oversight of environmental regulation [12, 13, 14]. These problems have aroused the interest in and pressure of society on the industrial sector to seek alternative sources of resources and energy, as well as new methods to apply in industrial processes [15, 16], intending to promote the development of industrial processes and products that diminish their environmental impact while maintaining social and economic benefits

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https://doi.org/10.1016/j.heliyon.2021.e07778
Received 6 March 2021; Received in revised form 11 May 2021; Accepted 10 August 2021

[17]. The principles of sustainable development (SD) have been integrated into the industrial sector through the sustainable business model concept. This model use eco-innovation to generate competitive advantages for the organization and give superior value to the customer [18]. These business models have focused on creating value from the waste generated for its use in other activities, based on the idea of a circular system of shared value to reduce pollution and maximizing efficiency in the use of materials and energy to create a virtuous circle of sustainable production and consumption [19, 20].

Thus, Industrial Ecology (IE) appears as a knowledge area that study the flows of materials and energy in industrial and consumer activities to analyze their effect on the environment and provide solutions through optimization in the use of materials and energy from industrial sector products and processes through systematic imitation of natural systems in industry [21, 22]. In other words, IE presents a systemic vision that studies the interrelationships of human industrial systems with their environments [23, 24]. From the perspective of IE, the concept of the eco-industrial park (EIP) was developed to achieve an economic benefit for companies while minimizing their environmental impacts through the exchange of materials, energy, and residual flows or byproducts, allowing a sustainable operation of industrial areas (IA) [25, 26, 27, 28].

The literature reviews published on IPs and EIPs have focused on the study of the effects of government policy intervention mechanisms on the development and evolution of industrial symbiosis (IS) [29], the socio-material network analysis for integrating natural and social sciences on IE [30], the optimization methods applied to the design of eco-industrial parks [31], the searching of quantitative tools and methods developed to identify and cultivate industrial symbiotic exchanges in IPs [11], the classification of sustainability indicators according to criteria of understanding, pragmatism, relevance, and partial representation of sustainability for assessing EIPs [32], the analysis theoretical contribution of IE to CE [33], understanding of IS emergence [34], the exploring of energy synergies on EIPs for promoting the renewable energy sources use at the industrial level [20], the IS concept evolution [35], the institutional analysis based on key policy documents for the development of EIPs [36], the research on the technical and non-technical aspects of regional industry symbiosis (RIS) [37], and the integrated tools review for the optimization of resources on IS [38]. Accordingly, it is observed that the different literature reviews analyzed on IPs and EIPs have been focused on the IS analysis from approaches conceptual, political, institutional aspects, and quantitative tools and methods for developing of IS. However, there are important issues related to the characteristics of research articles, cooperation networks, topics, and critical points of current research in IPs that are still susceptible to being analyzed and improved, which are also the main focus of this research.

The present study aims to investigate the characteristics and implications of the literature published in IPs and EIPs from 1996 to 2019 to show thematic evolution in global IP research from a bibliometric perspective. The research addresses the following research questions:

- What are the core literature and journals about IPs/EIPs?
- What are the leading countries and institutions in IP/EIP research, and what are their collaboration networks?
- What are the main topics, perspectives, and trends in IP/EIP research?
- Who are the principal authors in IP/EIP research, and what are their collaboration networks?

To answer these questions, we applied quantitative and qualitative techniques and methods from the bibliometric analysis and SNA. This bibliometric analysis provided a holistic view of the classification and analysis of the reviewed scientific literature [39]. The article is organized in the following manner. Section 2 presents the methodology used in this research for the selection of the database and the keywords, in addition to the methods applied for bibliometric analysis and SNA. Section 3 describes the results obtained in bibliographic statistics from performance analysis and scientific mapping, showing the leading authors, journals, countries, and institutions in IPs related research. Similarly, this section presents the cooperation networks established between countries/territories, institutions, and authors. Keyword analysis was conducted to determine trends, approaches, and future research perspectives in this field to serve as a reference to future studies. Likewise, this section carried out a co-author analysis to identify the most productive authors, know the cooperation networks established between them, and present their research approaches, and the authors most cited in their publications. Finally, section 4 presents the main conclusions of this investigation.

2. Methodology

This article conducts an in-depth review of the scientific literature related to IP research using bibliometric analysis and SNA techniques. This section summarizes the main features of the applied methodology.

2.1. Selection and data description

The largest and most used databases in most bibliometric analysis studies are Google Scholar, Scopus, and Web of Science (WoS) [40, 41].The WoS database has been used for this bibliometric analysis. The search for articles associated with the keywords "Industrial Park" or "Eco-Industrial park" during the period of 1996 - 2019 was by topic. The criteria used to select the starting year corresponds to the appearance of the first research articles related to the analysis of IPs as a strategy for economic development [42, 43], and the application of IE in the IPs [25, 44, 45]. Furthermore, this period corresponds to the year from which the thematic coverage begins in the WoS database. The files were downloaded in plain text format (.txt). The downloaded information included the complete record (author, title, abstract, author keywords, keyword plus, title words, country, institution, citation, and source) and references cited from the principal WoS collection. The term "Article from a single country" was used when all of the researchers belonged to the same country. The term "International Collaboration" was assigned to articles with authors from several countries [46, 47].

2.2. Material and methods

Bibliometry is a statistical method used for the quantitative evaluation of academic growth by counting the literature on a particular subject [47, 48]. Performance analysis was used to evaluate research performance at different scales [49]. In this article, performance analysis was applied to assess the characteristics of the publications downloaded at the level of authors (AU), publications (TP), authors number by TP (AU/TP), citation (NR), citations by TP (NR/TP), institutions, countries, and journals, resulting in the identification of critical points and research trends of IE on IPs.

Scientific mapping is a procedure used in bibliometric analysis that aims to show the structural and dynamic aspects of an area of scientific research [50, 51]. This procedure was employed in the present study to determine and evaluate the relationship between countries and institutions. Scientific mapping tools applied in this study include citation analysis, co-citation analysis, and word analysis. Citation analysis is traditionally used to classify pioneering scientific articles [52]. This method is based on counting the number of times that an article is cited as a source by other documents; hence, it is argued that the more citations of a document, the greater that the impact is [39, 53]. Citation analysis was adopted in the present study to identify the central literature related to IP

Table 1. Annual characteristics of scientific publications on IPs over the last 25 years.

Y	TP	AU	AU/TP	NR	NR/TP
1996	2	3	1.5	12	6.0
1997	3	4	1.3	32	10.7
1998	5	13	2.6	62	12.4
1999	4	8	2.0	138	34.5
2000	8	20	2.5	67	8.4
2001	9	31	3.4	156	17.3
2002	6	14	2.3	120	20.0
2003	9	29	3.2	148	16.4
2004	28	87	3.1	675	24.1
2005	25	82	3.3	675	27.0
2006	22	68	3.1	582	26.5
2007	34	103	3.0	1025	30.1
2008	30	123	4.1	867	28.9
2009	36	130	3.6	1271	35.3
2010	37	143	3.9	1120	30.3
2011	32	143	4.5	1228	38.4
2012	49	203	4.1	1642	33.5
2013	43	154	3.6	1627	37.8
2014	47	194	4.1	2028	43.1
2015	82	328	4.0	3187	38.9
2016	91	391	4.3	3934	43.2
2017	96	396	4.1	4022	41.9
2018	136	636	4.7	5894	43.3
2019	132	634	4.8	6170	46.7
Average	-	-	3.4	-	29.0

Y: year; TP: total publications; AU: author number; AU/TP: author number per paper; NR: cited reference count; NR/TP: cited reference count per paper.

or EIP research. The co-citation analysis presents the number of times that an article has been cited simultaneously in the literature [54]. Therefore, this analysis can show how articles relate to a body of literature and how strong these relationships are [55]. This research uses co-citation analysis to discover collaborative networks for research between authors and countries. Co-word analysis is a technique used to describe the interactions that exist between the different phases of the research process through the measurement of the intensity in the co-occurrence of words [56]. This work used these techniques to determine the main research topics in the study area and understand their evolution.

SNA is a method that presents and measures the relationships or links between entities that interact [57]. This social perspective studies a network of nodes and links through which information circulates. The present research applied this method to a network of nodes created with the authors, author keywords, titles, institutions, and countries of the articles downloaded to evaluate the influence and importance of a node through the measurement of its centrality, proximity, and intermediation in the network. Centrality, closeness, and intermediation are measures fundamentally related to the concept of social influence in terms of the structural effects of a network of nodes and edges [58]. The degree of centrality is the number of direct links that a node has in the network, and it indicates the visibility of the node. The proximity focuses on measuring how close a node is to the other nodes of the network and shows its ability to communicate with other actors in the network. Moreover, intermediation refers to the ability of a node to control the interaction of a pair of non-adjacent network nodes [57].

The software used for the bibliometric analysis worked in the *R* environment; specifically, the *R-package bibliometrix* was used, which provides a set of tools for quantitative research in bibliometrics and scientometrics [59]. This tool is useful for analyzing and visualizing structural, dynamic, and temporal patterns and the trends in the scientific literature [60].

3. Results and discussion

3.1. Document types and records

As a result of the analysis performed with the *R program* and its *bibliometrix* extension, 966 documents were obtained from 1996 to 2019. These 966 records analyzed were classified into 4 categories. Among them, articles (914) represented 95.7 % of the total number of publications, followed far behind by proceedings papers (4.7 %), news items (1.5 %), and data papers (0.1 %). The articles came from 410 sources; 2199 keywords plus, and 2868 author keywords were found. The articles were written by 2703 authors.

3.2. Characteristics of publication outputs

The characteristics of the publications between 1996 and 2019 are presented in Table 1 to obtain an overview of the IP research. The papers on IPs or EIPs increased from 2 in 1996 to 132 in 2019; the publication count was performed in January 2020. The year that had the highest number of publications was 2018 with 136. The number of publications has risen considerably since approximately 2014, revealing a greater interest in the IP research. The annual growth rate of scientific production found was 19.98 %. Additionally, 6.0 references were cited per article in 1996, compared to 46.7 references per document in 2019. The number of authors who have researched IPs increased from 3 in 1996 to 634 in 2019. The progressive increase in publications, authors, and references numbers indicates a growing trend in IPs and EIPs research for achieving innovation processes that encourage the transition towards a circular system [61]. The largest number of authors of a single article was 13, published in *Environment International* in 2017, who investigated the distribution and transport of perfluoroalkyl acids (PFAAs) in agricultural land, irrigation water and precipitation, followed by bioaccumulation in

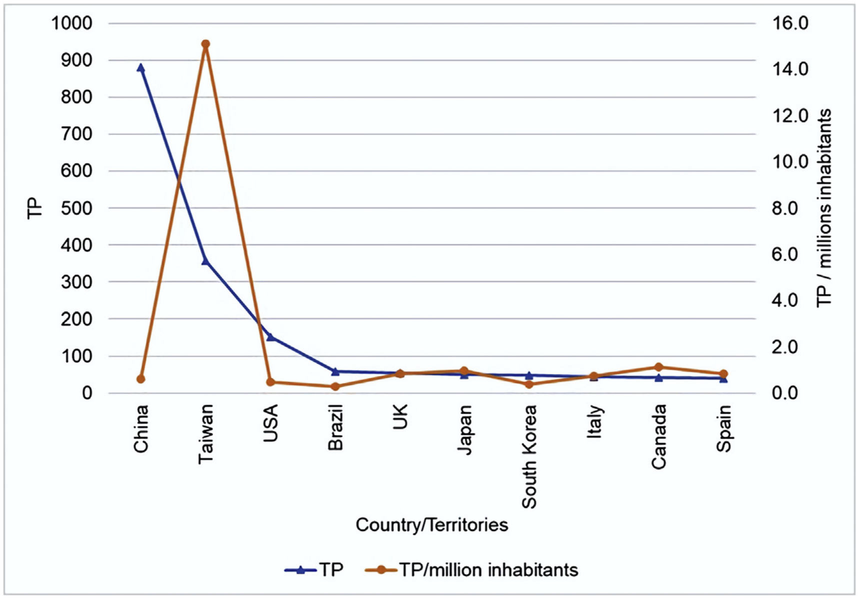

Figure 1. TP and TP/million inhabitants by Countries/territories.

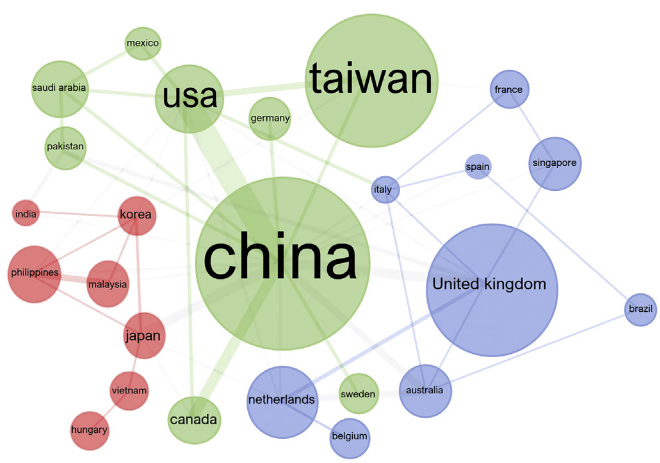

Figure 2. Cooperation network of the top 20 most productive countries/territories in the research on IPs from 1996 to 2019.

crops and finally human exposure in a radius of 10 km around a mega-fluorochemical industrial park [62].

3.3. Contributions of the countries/territories and institutions

The contribution of the countries/territories and institutions of the authors was determined with the address information and affiliations of the downloaded records. There were 18 articles without the authors address information; therefore, 948 records were used to analyze the distribution of countries/territories and institutions. Of all of the publications with the authors addresses, 705 (74.4 %) were articles from one country, and 243 (25.6 %) had international collaboration. The productivity of the countries/territories analyzed the total number of articles with records, the number, and the percentage of articles that involve international collaboration. There is a broad geographic diversity that spanned 67 different countries or territories that contributed to the IP research from 1996 to 2019. This geographic diversity indicates a relationship between the increase in IPs construction worldwide and the study of their environmental, social, and economic impact. According to Figure 1, the most productive country in articles is currently China (882), followed by Taiwan (357), and the USA (153). These countries lead research in IPs due to the large number of IPs built in their territories. However, when we consider the frequency of articles per million inhabitants, China ranks seventh. Taiwan leads production per million inhabitants by country/territory (15.12), followed by Canada (1.11), Japan (0.96), and Spain (0.83) (Figure 1). The cooperation relationships among the 20 most productive countries/territories were analyzed using SNA through a network of nodes (circles) and links (lines) (Figure 2). The nodes are the countries, and their size is related to the frequency of the publication of articles; this indicates that the larger nodes represent the countries with the more frequent publication of research on the subject analyzed. The lines represent cooperative relations between countries/territories and their thickness shows the closeness and strength of the cooperative relation. As shown in Figure 2, there are 3 cooperation groups in the network (nodes of the same color), China is the country with the largest node; therefore, it is the country with the highest relevance in the research on IPs today. This relevance is due to the need to face environmental and management problems generated by rapid industrial development, represented in the more than 2,534 IPs built in China [63, 64], which is equivalent to 20 % of the total IPs built in the world (more than 20000), approximately. Additionally, China and the USA are connected by the thickest line on the network, indicating that they have the closest and strongest cooperation relationship, playing a key role in IP and EIP research. Taiwan, Japan, and the Netherlands have acted as important countries in the global communication of the cooperation network. Finally, it is observed that the network is highly interconnected, evincing the increase in research for the transformation of IPs into EIPs.

The contribution of the different institutions was estimated with the institution of affiliation of at least one author of the downloaded articles. The 20 most productive institutions during the period of 1996 - 2019 are displayed in Figure 3. Among them, *University Chinese Academy Sciences (UCAS)* is ranked first with 48 publications, followed by *Tsinghua University (THU)* (46 papers), *Dalian University Technology* (DLTU) (36 papers), *De La Salle University* (DLSU)*, National Chiao Tung University (NCTU), and National Taiwan University (NTU)* with 28 articles, each. Of the top 20 most productive institutions, 50 % are in China, followed by Taiwan (20 %). The cooperation of the top 20 of the most productive institutions was analyzed with SNA and appears in Figure 4. As shown, there are four established cooperation clusters (circles or nodes of the same color). The largest nodes are UCAS, Shanghai Jiao Tao University

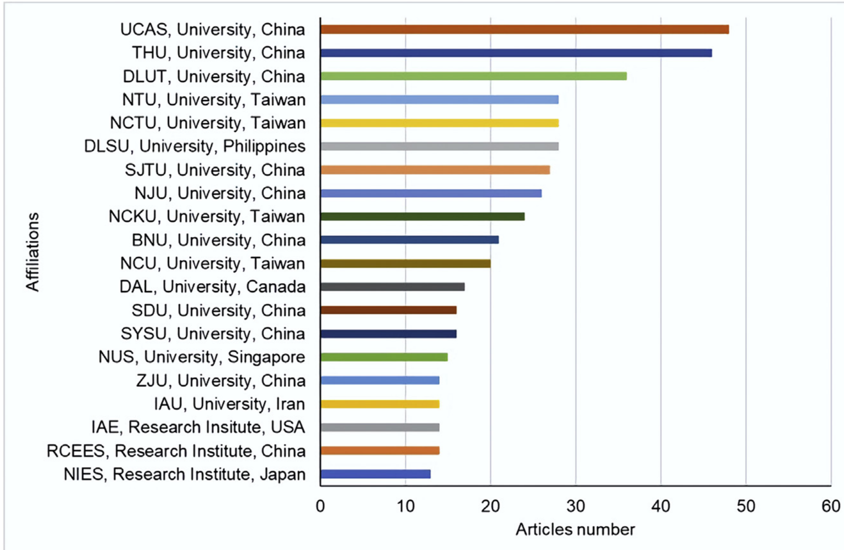

Figure 3. Institutions with the highest scientific production on IPs from 1996 to 2019.

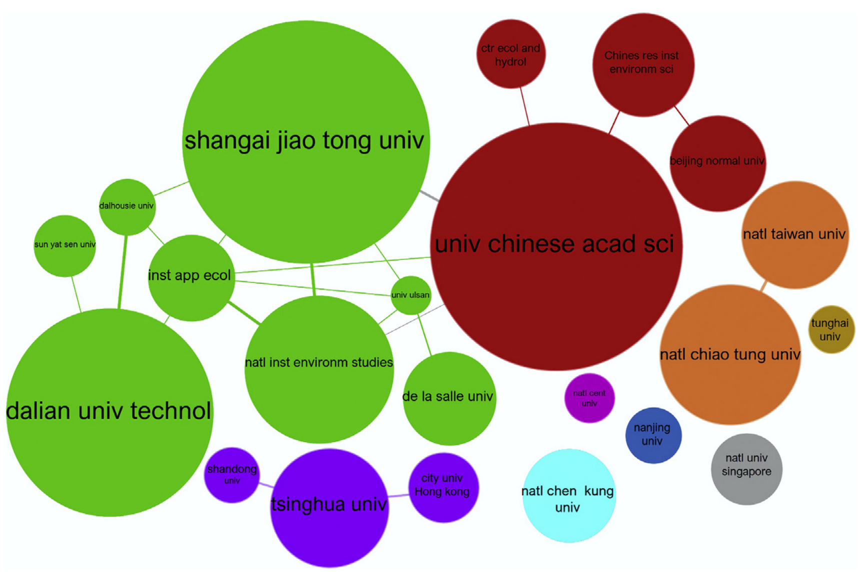

Figure 4. Cooperation network of the top 20 most productive institutions over the last 25 years.

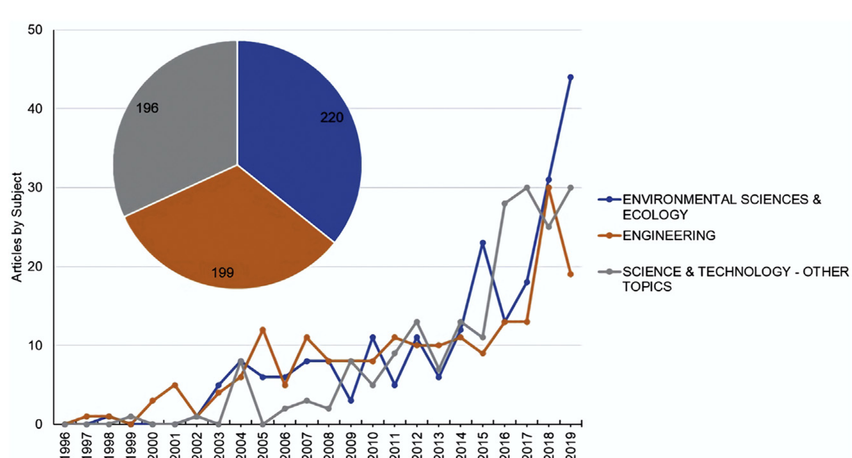

Figure 5. The subjects from WoS used most frequently for publishing IP research over the last 25 years.

Table 2. Most relevant journals in IP research from 1996 to 2019.

Journal	TP	(%)	h-index
Journal of Cleaner Production	123	12.7	32
Science of the Total Environment	29	3.0	10
Resources, Conservation and Recycling	23	2.4	11
Journal of Industrial Ecology	21	2.2	12
Chemosphere	18	1.9	10
Sustainability	17	1.8	4
Environmental Science and Pollution Research	16	1.7	5
Computers & Chemical Engineering	12	1.2	6
Environmental Science & Technology	12	1.2	10
Atmospheric Environment	11	1.1	9

TP: total publications; **(%):** percentage of total publications; **h-index:** relation of the number of articles published to the citation of those articles.

(SJTU), and DLTU, indicating that these three institutions were those that established collaboration networks with other institutions more frequently. It is also observed that SJTU appeared as a critical institution in the communication of three clusters because it connects with institutions from different groups. It is notable that THU, which is second in the ranking of most productive institutions, only has established cooperation connection with Shandong University (SDU), appearing as a collaborative group isolated and disconnected from the other clusters, as seen in Figure 4. Nanjing University (NJU), National Cheng Kun University (NCKU), National Central University (NCU), and National University of Singapore (NUS), institutions that appear in the top 20 most productive institutions during the period of 1999 - 2016, do not have collaboration networks with others. In contrast, the thickness of the line connecting the nodes reveals that the institutions that worked together the most frequently were "DLTU - Dalhousie University (DAL)", "SJTU - National Institute for Environmental Studies (NIES)" and "UCAS - Center for Ecology & Hydrology (UKCEH)".

3.4. Distribution of output by WoS subject and journals

In total, 966 research papers on IPs were published across a broad range of 56 WoS subjects. Among these research topics, 53 (36.4 %) published fewer than 10 articles per year. Figure 5 presents the top 3 subjects, representing 63.6 % of the total number of posts. The thematic areas with the largest numbers of publications are *"Environmental Sciences & Ecology"* (220, 22.8 %), *"Engineering"* (199, 20.6 %), and *"Science & Technology - Other Topics"* (196, 20.3 %). Figure 5 also presents the annual evolution of publications in the three most frequent categories of publication for research in IPs. The number of publications in the *"Environmental Sciences & Ecology"* category had an unstable behavior in the number of articles published between 2009 and 2015, but from 2016 to 2019, the number of documents increased considerably. The subject *"Engineering"* presented variable growth in the documents published since 2002. Finally, the research area related to *"Science & Technology - Other Topics"* presented steady growth in the number of publications

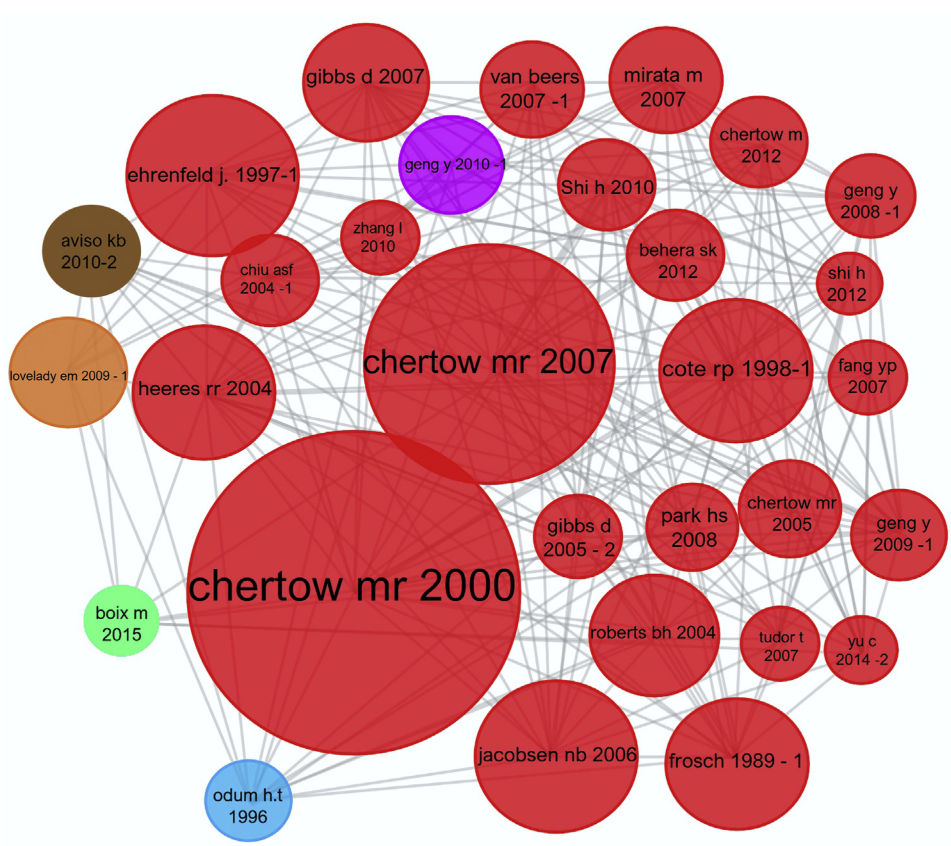

Figure 6. Network of the main articles published on IP research from 1996 -2019.

Table 3. Top 30 frequency of author keywords used in four different periods of IP research.

1996–2001 (periodo 1)		2002–2007 (periodo 2)		2008–2013 (periodo 3)		2014–2019 (periodo 4)	
Keywords	Freq	Keywords	Freq	Keywords	Freq	Keywords	Freq
Taiwan	3	Industrial ecology	14	Industrial park	32	Industrial park	85
Industrial park	2	Eco-industrial park	12	Eco-industrial park	23	Eco-industrial park	57
Information technology	2	Industrial park	10	Industrial ecology	20	Industrial symbiosis	37
Agricultural irrigation	1	Sustainable development	6	Industrial symbiosis	16	Industrial ecology	36
Bioindicators	1	Coagulation	5	China	9	China	35
Brazilian industrial sector co2 emissions	1	Taiwan	5	Industrial	8	Sustainability	27
Business information	1	Wastewater	5	Sustainable development	7	Circular economy	25
Chemical coagulation	1	Eco-industrial development	4	Environmental management	6	Eco-industrial parks	20
Chemistry	1	Ambient air	3	Artificial neural network	4	Chemical industrial park	14
Delivery of health care	1	Gis	3	Cost-effectiveness	4	Emergy analysis	14
Developing countries	1	Industrial	3	Life cycle assessment	4	Optimization	14
Dewatering	1	Industrial ecosystem	3	Management	4	Heavy metals	13
Discrete event systems	1	Industry	3	Sediment	4	Sustainable development	13
Earthquake	1	Management	3	Wastewater treatment	4	Emergy	9
Eco-industrial park	1	Reverse osmosis	3	Circular economy	3	Heavy metal	8
Emission factor	1	Suburban	3	Conventional activated sludge process	3	Model	8
Emission rate	1	Sustainability	3	Development	3	Network	8
Erod activity	1	Water	3	Eco-efficiency	3	Assessment	7
Fenton	1	Water reuse	3	Ecology	3	Development	7
Ferrous ions	1	Cluster	2	Efficiency	3	Eco-efficiency	7
Filtration	1	Combined heat and power	2	Emergy	3	Health risk	7
Glutathione-s-transferases	1	Eco-industrial networking	2	Energy	3	Uncertainty	7
Glutathione content and redox status	1	Economics	2	Exergy	3	Distribution	6
Ground improvement	1	Emergy	2	Heavy metals	3	Ecological network analysis	6
Health-care unit	1	Environmental management system	2	High-tech industrial park	3	Governance	6
High-tech development	1	Evolution	2	Industrial ecosystem	3	Indicator	6
Hydrogen peroxide	1	Heavy metal	2	Industrial park wastewater	3	Industrial wastewater	6
In situ tests	1	High-tech industry	2	Model	3	Process integration	6
Indicators for energy consumption	1	Industrial pollution	2	Monitoring	3	Air pollution	5
Industrial ecology	1	Industrial symbiosis	2	Optimization	3	Cluster	5

between 2015 and 2016. The three categories of the most productive research initiatives seem unlikely to be overcome in the future; they have mainly focused on investigating IPs from the perspectives of IE, IS, Sustainability, Sustainable Development (SD) and Circular Economy (CE).

Table 2 presents the results of the key journals in IP research from 1996 to 2019. A total of 966 articles were published in 409 journals. *Journal of Cleaner Production* (123, 12.7 %), *Science of the Total Environment* (29, 3.0 %), *Resources, Conservation and Recycling* (23, 2.4 %), *Journal of Industrial Ecology* (21, 2.2 %) and *Chemosphere* (18, 1.9 %) were the top 5 of the journals with the most research publications in IPs and represented only 22.2 % of the total publications. The percentage of the top 5 journals was not high, indicating the breadth of the distribution of the publication in journals and a growing interest in IP research from different research perspectives. Table 2 shows the *h-index* calculated by *bibliometrix R-package* to determine the impact of each journal. *The h-index* consists of a metric from the author or journal that considers the number of articles published and the citations of these articles [65, 66]. *Journal of Cleaner Production* (32), followed by the *Journal of Industrial Ecology* (12), and *Resources, Conservation and Recycling* (11) were the three journals with the highest *h-indices* during 1996–2019.

3.5. Top cited publications in the field of IP or EIP research

The analysis of the most cited publications in the IP or EIP research used the global and local approaches. The global approach used SNA for analyzing the main structure intellectual on IP research. This focus performed a betweenness analysis of documents with the highest number of global citations (GC) to identify the papers used more frequently in writing research articles in this field. The Betweenness is a measure designed to represent an actors importance based on its ability to control the interaction between two nonadjacent actors, therefore having a large value of Betweenness implies a relevant role in the network [57]. Figure 6 presents the main intellectual structure network with the top 30 documents with the highest betweenness. The largest nodes documents are "Chertow mr, 2000″, "Chertow mr, 2007″ y "Jacobsen nb 2006". The "Chertow mr, 2000″ paper belongs to "*Industrial Symbiosis: Literature and Taxonomy"* published by *Annual Review of Environment and Resources*. This article highlights the importance of Industrial Symbiosis (IS), defined as the physical exchange of materials, water, energy, and byproducts between companies through a literature review of IS experiences in small industries [26]. *"Uncovering" Industrial Symbiosis"* and *"Industrial Symbiosis in Kalundborg, Denmark A Quantitative Assessment of Economic and Environmental Aspects"* published by *Journal of Industrial Ecology* were the second and third papers, respectively. The second article compared experiences of planned (15) and self-organized (12) EIPs to understand the factors to create symbiotic relationships for the exchange of resources between companies to deliberately replicate them in other places [27]. The third paper analyzed the experience of the industrial district of Kalundborg, Denmark, for understanding the economic and environmental performances connected to this case [67]. The three leading articles in the number of global citations indicate the relevance and interest that research on the development of IS networks for the materials exchange in IPs and its possible environmental and economic impact has aroused in the academic community Appendix A shows the network's 30 most relevant documents in the intellectual structure main on IPs research (See table A1 - supplementary material).

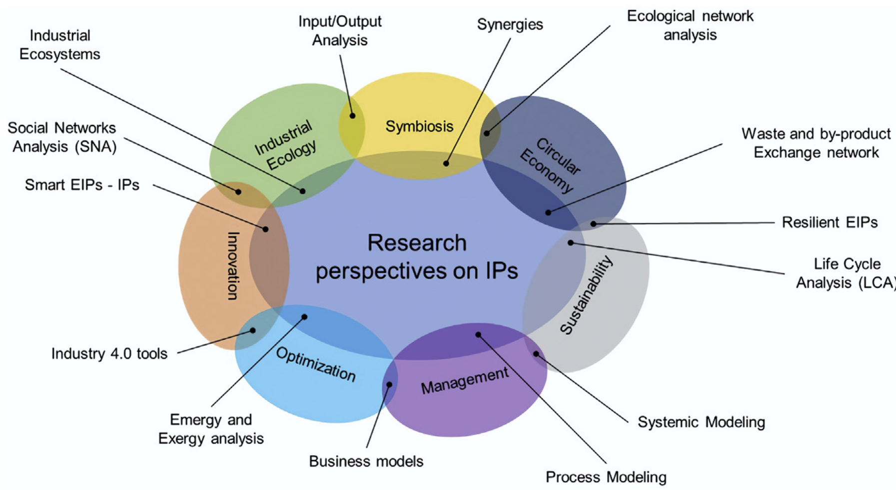

Figure 7. Research perspectives and strategies research incorporated for the development of IPs from 1996 - 2019.

The local analysis used the number of local citations (LC) from database documents, which means that the publication used the papers most cited by other articles from the downloaded database to guarantee that the documents focused on the same research topic. Appendix A presents the list of the 30 most cited publications in this collection with additional information about the author, title, year, journal, country/institution, and LC from 1996 to 2019 (See table A2 - supplementary material). The most cited paper in the database was *"Eco-industrial park initiatives in the USA and the Netherlands: first lessons"*, published by *Journal of Cleaner Production*, with 51 citations. This publication compared the differences in approaches and results at the national-level of six projects for the development of EIPs in the Netherlands and the USA [68]. *"The application of industrial ecology principles and planning guidelines for the development of eco-industrial parks: an Australian case study"* and *"Developing country experience with eco-industrial parks: a case study of the Tianjin economic-technological development area in China"*, published in *Journal of Cleaner Production*, were the articles the second and third most citations, 49 for each. The second described the planning tools and guidelines for achieving more sustainable industrial development in the state of Queensland, Australia, from the construction of EIPs based on the concept of IE [69]. The third assessed the environmental benefits of the key symbiotic exchanges, and it summarized the unique features for the transformation of the largest IP in China, Tianjin Economic Development Area (TEDA) into an EIP [70]. The 4th article, entitled *"Reflections on implementing industrial ecology through eco-industrial park development"* from the *University of Hull*, had 45 citations. This research applied a survey of 16 EIPs from the USA and Europe to determine whether these areas offer possibilities for implementing sustainable development (SD) policies [71]. "*Strategies for sustainable development of industrial park in Ulsan, South Korea - from spontaneous evolution to systematic expansion of industrial symbiosis*", published by Journal of Environmental Management, was ranked fifth with 42 citations. This document outlined South Korean national policies to convert existing IPs in Ulsan city into EIPs, based on the interindustrial exchange of waste, energy, and materials in these industrial complexes [72]. The results of an analysis of the 5 most cited articles and the ranking in general indicated that the investigation in IPs from 2002 focused on the study and implementation of the EIP concept, based on the exchange of waste, byproducts, materials, energy, and information between companies as a strategy for achieving sustainability in industrial areas and promoting the development of countries, from the perspectives of general systems theory, self-organization, complexity, complex adaptive systems and the concept of SD.

3.6. Popular issues and research trends

The bibliometric method used in this research to identify research trends and critical points is word analysis, considering that it has been developed in many previous studies [46, 51, 73, 74]. The author keywords are the item selected to determine the critical points and discover the emerging trends in a field of research because they present representative and concise descriptions of the content of the articles [46, 53, 60]. Of the 966 publications, 863 articles (89.3 %) had information about the author keywords. In total 2868 author keywords were found in this study, they were classified according to frequency and period. This analysis was performed in different periods to reveal the critical points and know the development track of the field [75]. In order to show the changes in trends and critical points in the IPs research from 1996 to 2019, we subdivided the analysis of words into four different periods, namely, 1996–2001 (period 1), 2002–2007 (period 2), 2008–2013 (period 3) and 2014–2019 (period 4).

Table 3 presents the top 30 most used author keywords in the different periods in the IPs research, combining their plural forms, abbreviations, and other transformations. The most frequent author keywords in period 1 (1996–2001) were "Taiwan", "IP", and "Information technology", which indicates that the research in this period focused on the construction of high-tech IPs as a strategy to promote the socio-economic development, especially in Asia through science parks [42]. In the second period (2002–2007), the keywords "IE", "EIP" and "IP" present the higher frequency, which implies the ecological perspective used by IE in the study of the processes of production and services in their different stages, through the imitation of the reuse and conservation of resources that emerge in natural ecosystems (Gibbs and Deutz, 2005; Chertow, 2007; Valenzuela-Venegas et al., 2016) [27, 32, 76]. Apart from the author keywords used in the search in this research, the most frequently used keywords from the third period were "IE", "IS", "China", "Circular economy", "Sustainability", "SD", "heavy metals", "Emergy analysis", and "optimization," indicating that IP research has mainly focused from IE on the development of methodologies for the sustainability of industrial areas by optimizing their production processes based on the tools and metrics proposed in IS and CE [77]. Accordingly, one of the critical points of research in IPs seeks to establish networks to exchange energy, water, byproducts and waste in companies that have traditionally been separate [78, 79, 80]. The word "China" indicates the importance of this country in IP research due to the number of establishments built as a strategy to promote economic growth [81]. This rapid industrialization has promoted the development and

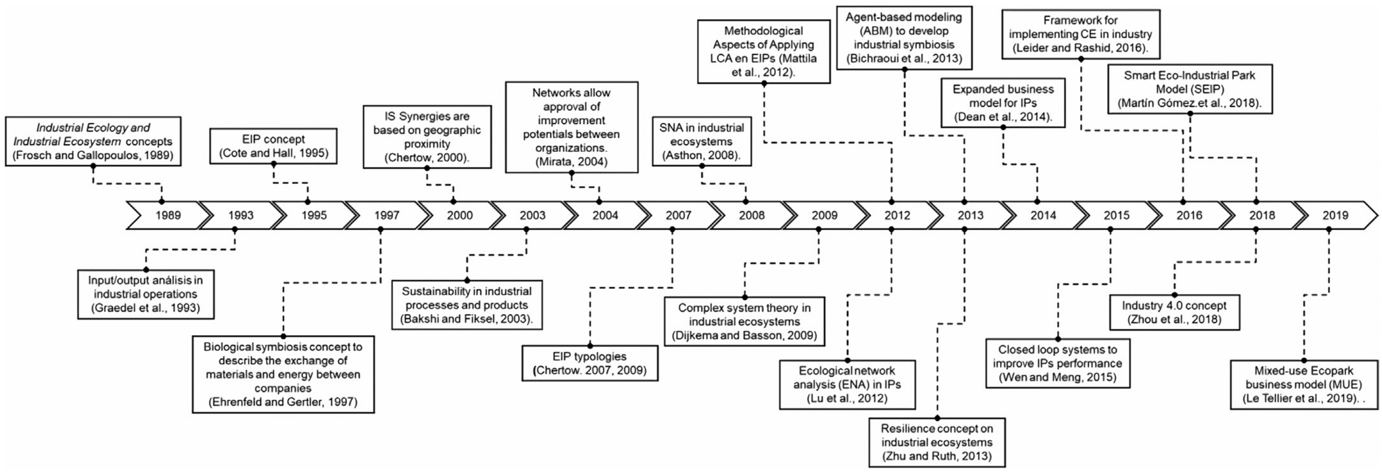

Figure 8. Thematic evolution of the research on IPs and EIPs.

implementation of innovative strategies to transform their traditional industrial areas into EIPs [39, 82, 83].

Additionally, "circular economy" appears as a critical concept of sustainable development that promotes in the industrial, especially "between firm-level", a change in the linear production model to a circular flow model of “resources - products - renewable resources” to address environmental deterioration and resource depletion [84, 85, 86]. Regarding the author keywords “Emergy Analysis” and “sustainability” played an essential role in the evaluation of IP production processes and their transformation into EIPs [11, 87, 88]. Finally, "Life cycle assessment" (LCA) appears as a methodological development undertaken to expand the scale of analysis and complexity to achieve sustainability in the industrial sector from the vision proposed by the SD [89]. It is also used as an indicator by IE to measure the performance of the IS in EIPs [90, 91].

Figure 7 presents the different perspectives and strategies incorporated in the development of IPs during the last 25 years, to search for an alternative operating model that integrates the principles of sustainable development [92]. The industrial ecosystem concept proposed by EI encouraged the symbiotic relationships between companies with one IP or between IPs, based on the analysis of the inputs and outputs of materials [25, 26]. The CE appears as a philosophy that seeks to increase the circularity of the resources and waste used in the industry through the analysis of ecological networks based on the recycling of materials to design more resilient and sustainable EIPs and IPs [86, 93, 94, 95, 96]. Since sustainability and management, the influence and dependence of industrial ecosystems and IPs on market forces have been studied, making them susceptible to unexpected, non-linear and discontinuous changes, characteristics of complex adaptive systems (CAS) [97, 98, 99]. That implies the use and development of tools based on the modeling of non-linear systems to describe their behavior, looking for networks of industrial symbiosis lasting over time and overcome the challenges between economic compensation and environmental performance [100, 101, 102]. On the other hand, the development of materials exchange networks for adding value, reducing costs and improving the environment involved the use of methodologies such as emergy and exergy analysis that present the interrelation among economic development and environmental protection derived from the optimization of production processes [103, 104, 105]. Finally, the multiple intersectoral networks established to loop-closing that have evolved from CE, EI, and IS have used innovative approaches and concepts based on the SNA, Smart EIPs - IPs and the emerging technologies of industry 4.0 (cyber-physical systems, the Internet of Things (IoT), Cloud Computing and Cognitive Computing), for analyzing large amounts of operational data from multiple companies for optimizing the solutions aimed at reducing the intensity of resource consumption and emissions of industrial systems [106, 107, 108].

The thematic evolution of the research on IPs and EIPs is presented in Figure 8. The change of focus for the study of IPs began with the concepts of IE and the industrial ecosystem, which stated that industrial systems should imitate ecological systems behavior to optimize the consumption of materials and energy [109]. Graedel et al. (1993) applied inputs/outputs analysis to have a perspective of the use and availability of materials and resources of industrial processes [25]. The concept of symbiosis continued the analogy among natural and industrial ecosystems, and it described the exchange of materials and energy among companies [110]. Chertow (2000) argued that geographic proximity is a key factor for establishing synergies between companies that traditionally work separately. Bakshi and Fiksel (2003) expressed the need to rethink the design, construction, operation, and evaluation of industrial processes and products to implement the principles of sustainability raised by the SD. In 2004, Mirata [111] evaluated the importance of industrial symbiosis networks to improve organizational interfaces through collaborative interactions between companies in an EIP. Chertow (2007) established different typologies for EIPs to identify early precursors of this type of industrial area. The SNA was used to examine the organization of different relationships in the industrial ecosystem [112]. Dijkema and Basson (2009) [113] incorporate the perspective of complex systems theory and its tools to understand the relationship between the biophysical system and the socio-technical system (industry). In 2012, the methodological aspects of applying the LCA in the exchange of products were raised [114]. The analysis of ecological networks in IP was applied to study the connectivity of the system and quantify its direct and indirect flows [115]. Agent-based modeling (ABM) was applied to carry out contextual analysis and identify the structural factors and the main motor forces for the development of industrial symbiosis [116]. Zhu and Ruth (2013) [117] studied the concept of resilience in industrial ecosystems. In 2014, an expanded operations model (EBOM) was developed to help corporate communities measure their environmental stewardship goal [118]. Wen and Meng (2015) [84] analyzed how to promote the closure of cycles for the circularity of materials in IPs. Later, a framework was proposed to implement CE in the industry [119]. In 2018, the concept of Industry 4.0 was proposed to utilize technological tools to analyze the large amount of data generated by the industrial

Table 4. Top 10 most productive authors on field IPs or EIPs research from 1996 to 2019.

Rank	Name	Institution	Country	TP	TC	TC/TP	Number of Papers with greater than or equal citations to				
							≥80	≥60	≥40	≥20	<20
1	ZHANG Y	Beijing Normal University	China	32	441	14	1	0	1	6	24
2	GENG Y	Shanghai Jiao Tong University	China	31	964	31	3	2	3	7	16
3	TIAN JP	Tsinghua University	China	16	300	19	0	0	2	5	9
4	CHEN LJ	Yangtze Delta Region Institute of Tsinghua University	China	15	287	19	0	0	2	5	8
5	LU YL	University of Chinese Academy of Sciences	China	14	162	12	0	0	0	4	10
6	TAN RR	De La Salle University	Philippines	14	400	29	1	1	0	7	5
7	TAI YT	Kainan University	Taiwan	13	103	8	0	0	0	1	12
8	WANG P	University of Chinese Academy of Sciences	China	13	195	15	0	0	0	5	8
9	PEARN WL	National Chiao Tung University	Taiwan	12	101	8	0	0	0	1	11
10	CHEN B	Beijing Normal University	China	10	144	14	0	0	1	0	9

TP: total publications; **TC**: total citations.

symbiosis [106]. The concept of an intelligent eco-industrial park (SEIP) was also raised, in which the knowledge models proposed by the ENA are integrated to define parameters in the evaluation of the design of products and processes [107]. Finally, in 2019 a mixed-use ecopark business model (MUE) was proposed [120].

3.7. Agenda proposals for future research

According to the literature review, some of the possible lines for future research in IPs and EIPs were identified. In the first place, the need to develop tools or methodologies that incorporate a systemic approach and use the advantages of computing technology to promote industrial symbiosis networks was identified. These tools should include models to analyze the effects generated by a fluctuation of materials price and the waste management costs in the establishment and evolution of networks for the exchange of materials, besides evaluating their impact on the profits of the companies that are part of these industrial areas. Likewise, the incorporation of IS concepts to create value from by-products and waste through the exchange of materials between companies implies the development of indicators to evaluate the impact of these networks on social and environmental aspects and the performance in sustainability. On the other hand, the presence of social factors in the IPs and EIPs provides a behavior with characteristics of non-linearity, dynamism, and uncertainty [121]; consequently, it is necessary to involve the bottom-up approach in the study and analysis of these industrial areas to incorporate the own complexity of socio-technical systems [122]. Similarly, future research should also explore the study of the ecological dimension through the perspective of food web analysis in the study of EIPs to ensure a harmonious integration of these areas with their surrounding environment [25, 123]. This perspective promotes the closes loops, circularity and increases the resources use efficiency on the EIPs, based on the identification and analysis of the companies that perform the function of collectors and decomposers in the EIPs. The above, considering that these companies are responsible for collecting and

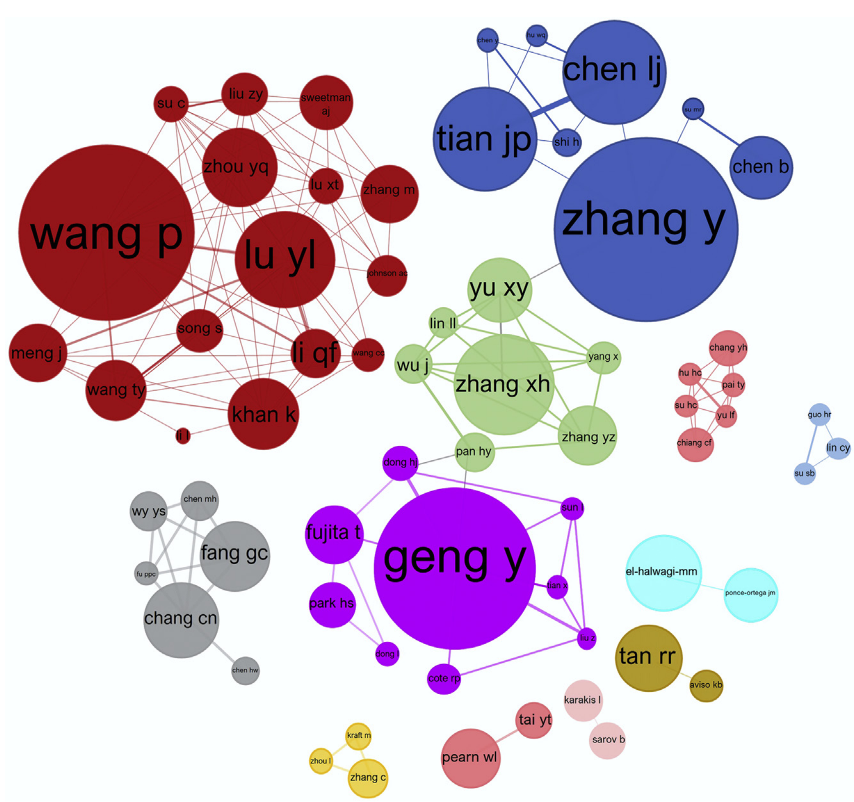

Figure 9. Cooperation network of the top10 most productive authors from 1996 to 2019.

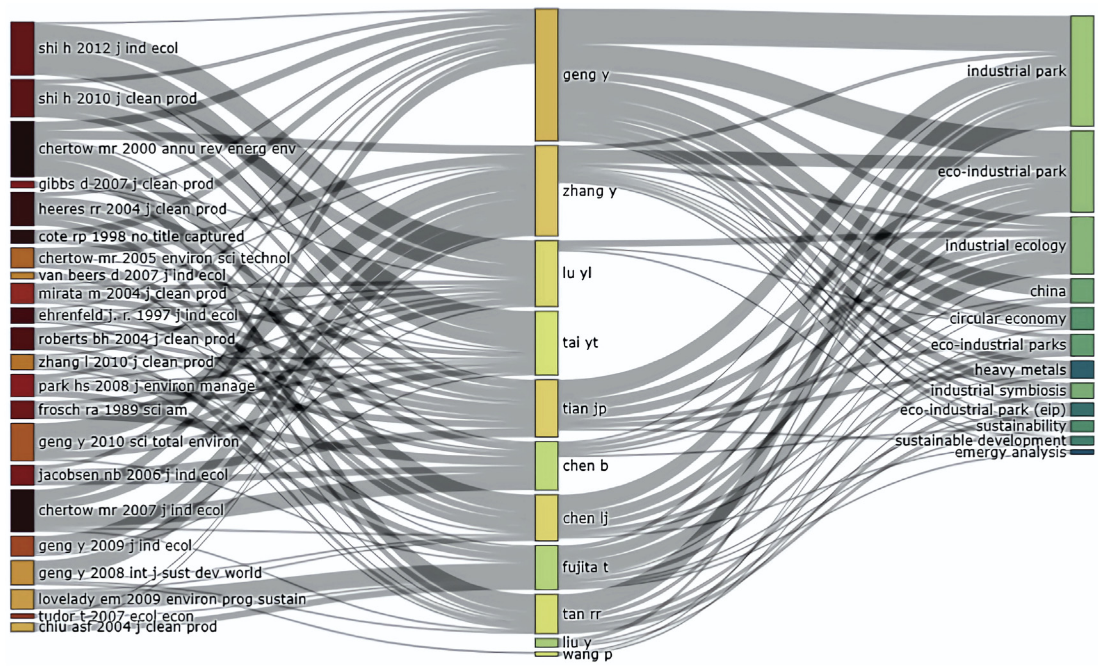

Figure 10. Relationship among the top 10 most productive authors, top keywords and most referenced authors.

redistributing discarded materials within IP or EPs to be used in the production processes of other companies [124]. Finally, the need to integrate the concept of CE in the study of IPs and EIPs is observed to promote the transition towards a circular system that incorporates the multiscale approach [125] to transform cities into eco-cities [126], based on the creation of industrial symbiosis networks between companies from different productive sectors. The future research perspectives proposed in this paragraph aim to promote a socially and environmentally responsible industrialization, considering that IPs and EIPs have been identified as key actors to achieve this objective [127].

3.8. Coauthorship analysis

Table 4 shows specific information of top 10 most productive authors, including institution, country, TP and so on. The top three authors with the most significant number of articles published during the period are Zhang Yan (32), Geng Yong (31), and Tian Jinping (16). Geng Yong has the largest number of total citations (968) by the other authors. The most cited article by Geng Yong was "Emergy analysis of an industrial park: the case of Dalian, China" with 93 citations, published by *Science of the Total Environment* in 2010. The article applied an emergy analysis to learn about the performance and sustainability of an IP [88]. Appendix B presents the published articles and the number of citations received by each one, for the top 10 most productive authors (See table B1 - supplementary material).

The cooperation relationships between the authors were analyzed in Figure 9. The cooperation network has 12 groups; it is widespread and dispersed, implying that IP research was carried out by many authors. Notably, six of the most productive authors interacted with six or more researchers. The largest nodes correspond to the researchers Geng Yong, Zhang Yan, Lu Yonglong, and Wang Pei. A cooperation cluster was established between Lu Yonglong and Wang Pei. This group has focused on urban and rural ecology research in China. The cooperation among Geng Yong, Dong Huijuan and Fujita Tsuyosi connects the investigation of China and Japan in the evaluation of the performance and environmental impact of IPs through the emergy analysis and the carbon footprint, among other topics. The researchers Geng Yong and Zhang Yan have the highest numbers of network publications (Table 4), but they are not directly connected; however, Pan Hy and Yu Xy are nodes that can become connectors between these researchers. Research on air and water pollutants at the IP level has focused on the scientists Chiang Chow-Feng, Yu Lufeng, Pai Tzuyi, Chuang S.H, Hu H.C., and Su Hanchang. Investigators Tan Raymond and Aviso Kathleen worked on the development of models for the establishment of exchange networks from the perspectives of game theory, linear programming, and fuzzy logic.

Figure 10 is a three-plot chart showing the relationships among the top 10 authors with the most publications (center column), author keywords (right column), and authors most cited by researchers with the highest production of articles. Zhan Yan is the author with the most publications. However, he has the smallest number of keywords associated with his work. The research conducted by this author focused on IE and IS. The most referenced researchers by this author are Chertow M, Jacobsen NB, Ehrenfeld J, and Mirata M. The second author with the most significant number of articles is Geng Yong, and he is also the researcher with the largest number of associated keywords; his works were mainly conducted in China and were related to IPs, IE, IS, EIP, emergy analysis, CE, SD, and sustainability. The authors most referenced by this author are Marianne Chertow and Cote RP. Tan Raymond is the author who has most directed his work toward EIPs, and the most cited authors in his articles are Chertow M, Lovelady E, and Frosch R.

4. Conclusions

This study presented an overview of the research on IPs and EIPs for attempting to clarify the complexity of academic development in this field, analyzing information related to countries, institutions, journals, cited publications, keywords, and authors for identifying cooperation networks, current critical points, and future research trends. Research on IPs increased considerably over the last decade; the number of published articles changed from 37 in 2010 to 132 in 2019. China (39.6 %), Taiwan (16.3 %), and the USA (15.8 %) have high productivity concerning total publications. The USA and Taiwan are the only countries/territories that have published articles on IPs and EIP during all the years analyzed by this study. The first countries to publish articles related to the subject analyzed were the USA (4), Taiwan (1), the UK (1), and Belgium (1). China, the country with the largest number of publications (882), only started publishing in 2001 and showed a notable increase in the number of publications between 2013 and 2019. However, Taiwan (15.12), Canada (1.11), Japan (0.96) and Spain (0.83) lead the production of articles per million inhabitants. Based on the Social Network Analysis (SNA), China and the USA were the countries/territories that established the closest and strongest connections and links during the period analyzed (1996–2019) in the cooperation network of the top 10 most productive territories. Additionally, it is essential to mention that Taiwan, Japan, and the Netherlands appear as key countries in the global communication of the network; therefore, they can serve as a link to establish cooperation networks between countries/territories that did not have it. UCAS was the institution that led the ranking of publications with 48 research articles followed by THU (46) and DLTU (36). UCAS, SJTU, and DLTU were the institutions that established collaboration networks with other institutions more frequently. The thematic categories "Environmental Sciences & Ecology", "Engineering", and "Science & Technology - Other Topics" grouped 63.6 % of the articles of IP or EIP published in WoS. The three leading journals in the number of research publications on IPs and EIPs were the *Journal of Cleaner Production*, *Science of the Total Environment*, and *Resources, Conservation, and Recycling*. The analysis synthesized by author keywords provided clues about the key points and emerging research trends. The development of methodologies to achieve the sustainability of IPs through the optimization of production processes from the perspective of the IS and the CE was one of the main trends observed. Likewise, there is an increase in the use of emerging technologies of industrial 4.0 for the management and analysis data on IPs. The authors with the largest numbers of publications from database were Zhang Yan (32), Geng Yong (31), and Tian Jinping (16) among the total publications. Finally, this research used techniques from the bibliometry and SNA to provide useful information for researchers seeking a broader understanding of IPs research-related issues.

Declarations

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

Supplementary content related to this article has been published online at https://doi.org/10.1016/j.heliyon.2021.e07778.

Acknowledgements

The authors are grateful to the Universidad Tecnológica de Pereira for supporting the article's publication.

References

[1] M. Peddle, Planned industrial and commercial developments in the United States: a review of the history, literature, and empirical evidence regarding industrial parks and research parks, Econ. Dev. Q. 503 (1993) 122–136.
[2] H. Schmitz, Collective efficiency: growth path for small-scale industry, J. Dev. Stud. 31 (1995) 529–566.
[3] S.M. Walcott, Industrial parks, in: A. Kobayashi (Ed.), Int. Encycl. Hum. Geogr., second ed., Elsevier, 2020, pp. 243–247.
[4] S.M. Walcott, Industrial parks, in: R. Kitchin, N. Thrift (Eds.), Int. Encycl. Hum. Geogr., First Edit, Elsevier, 2009, pp. 408–412.
[5] G. Festel, M. Würmseher, Benchmarking of energy and utility infrastructures in industrial parks, J. Clean. Prod. 70 (2014) 15–26.
[6] D.S. Salvador, S. Toboso-Chavero, A. Nadal, X. Gabarrell, J. Rieradevall, R.S. da Silva, Potential of technology parks to implement Roof Mosaic in Brazil, J. Clean. Prod. 235 (2019) 166–177.
[7] Z. Liu, Y. Geng, S. Ulgiati, H.S. Park, F. Tsuyoshi, H. Wang, Uncovering key factors influencing one industrial park's sustainability: a combined evaluation method of emergy analysis and index decomposition analysis, J. Clean. Prod. 114 (2016) 141–149.
[8] UNIDO, Industrial States, Principles and Practice, UNIDO, Vienna, Austria, 1997. https://digitallibrary.un.org/record/414834.
[9] UNIDO, Europe and central Asia regional conference on industrial parks as a tool to foster local industrial development, Reg. Conf. Ind. Park. (2012) 79, 17 – 18 April 2012, https://www.unido.org/fileadmin/user_media/UNIDO_Worldwide/Europe_and_NIS_Programme/Documents/Europe and Central Asia Regional Conference on Industrial Parks as a tool to foster local industrial development.pdf.
[10] D. Sakr, L. Baas, S. El-Haggar, D. Huisingh, Critical success and limiting factors for eco-industrial parks: global trends and Egyptian context, J. Clean. Prod. 19 (2011) 1158–1169.
[11] C.A. Kastner, R. Lau, M. Kraft, Quantitative tools for cultivating symbiosis in industrial parks; a literature review, Appl. Energy 155 (2015) 599–612.
[12] N.C. Kunz, C.J. Moran, T. Kastelle, Conceptualising "coupling" for sustainability implementation in the industrial sector: a review of the field and projection of future research opportunities, J. Clean. Prod. 53 (2013) 69–80.
[13] Z. Liu, M. Adams, R.P. Cote, Y. Geng, J. Ren, Q. Chen, W. Liu, X. Zhu, Co-benefits accounting for the implementation of eco-industrial development strategies in the scale of industrial park based on emergy analysis, Renew. Sustain. Energy Rev. (2017) 1–8.
[14] X. Li, X. Lai, F. Zhang, Research on green innovation effect of industrial agglomeration from perspective of environmental regulation: evidence in China, J. Clean. Prod. 288 (2021).
[15] H. Zhang, J. Calvo-Amodio, K.R. Haapala, A conceptual model for assisting sustainable manufacturing through system dynamics, J. Manuf. Syst. 32 (2013) 543–549.
[16] O. Genc, G. van Capelleveen, E. Erdis, O. Yildiz, D.M. Yazan, A socio-ecological approach to improve industrial zones towards eco-industrial parks, J. Environ. Manag. 250 (2019) 109507.
[17] C.B. Joung, J. Carrell, P. Sarkar, S.C. Feng, Categorization of indicators for sustainable manufacturing, Ecol. Indicat. 24 (2013) 148–157.
[18] F. Lüdeke-Freund, Towards a conceptual framework of "business models for sustainability, in: Knowl. Collab. Learn. Sustain. Innov. ERSCP-EMSU Conf., 2010, pp. 1–28. https://www.semanticscholar.org/paper/Towards-a-Conceptual-Framework-of-%27Business-Models-Lüdeke-Freund/63fc71be62c8162a90e3d08220642cbbe5f6eccc.
[19] S.W. Short, N.M.P. Bocken, C.Y. Barlow, M.R. Chertow, From refining sugar to growing tomatoes: industrial ecology and business model evolution, J. Ind. Ecol. 18 (2014) 603–618.
[20] M.A. Butturi, F. Lolli, M.A. Sellitto, E. Balugani, R. Gamberini, B. Rimini, Renewable energy in eco-industrial parks and urban-industrial symbiosis: a literature review and a conceptual synthesis, Appl. Energy 255 (2019).
[21] Y. Qu, Y. Liu, R.R. Nayak, M. Li, Sustainable development of eco-industrial parks in China: effects of managers' environmental awareness on the relationships between practice and performance, J. Clean. Prod. 87 (2015) 328–338.
[22] L.W. Ayres, Robert U. Ayres, A Handbook of Industrial Ecology, Edward Elgar Publishing Limited, Cheltenham, UK - Northampton MA, USA, 2002.
[23] T.P. Seager, T.L. Theis, A uniform de nition and quantitative basis for industrial ecology, J. Clean. Prod. 10 (2002) 225–235.
[24] B.R. Allenby, Implementing industrial ecology: the AT&T matrix system, Interfaces 30 (2000) 42–54.
[25] R. Côté, J. Hall, Industrial parks as ecosystems, J. Clean. Prod. 3 (1995) 41–46.
[26] M.R. Chertow, Industrial Symbiosis : literature and Taxonomy, Annu. Rev. Energy Environ. 25 (2000) 313–337.
[27] M.R. Chertow, " uncovering " industrial symbiosis, J. Ind. Ecol. 11 (2007) 11–30.
[28] M. Chertow, Dynamics of geographically based industrial ecosystems, in: M. Ruth, B. Davidsdottir (Eds.), Dyn. Reg. Networks Ind. Ecosyst., Cheltenham, UK - Northampton MA, USA, 2009, pp. 6–27.
[29] W. Jiao, F. Boons, Toward a research agenda for policy intervention and facilitation to enhance industrial symbiosis based on a comprehensive literature review, J. Clean. Prod. 67 (2014) 14–25.
[30] F. Schiller, A.S. Penn, L. Basson, Analyzing networks in industrial ecology - a review of Social-Material Network Analyses, J. Clean. Prod. 76 (2014) 1–11.
[31] M. Boix, L. Montastruc, C. Azzaro-Pantel, S. Domenech, Optimization methods applied to the design of eco-industrial parks: a literature review, J. Clean. Prod. 87 (2015) 303–317.
[32] G. Valenzuela-Venegas, J.C. Salgado, F.A. Díaz-Alvarado, Sustainability indicators for the assessment of eco-industrial parks: classification and criteria for selection, J. Clean. Prod. 133 (2016) 99–116.
[33] Y.M.B. Saavedra, D.R. Iritani, A.L.R. Pavan, A.R. Ometto, Theoretical contribution of industrial ecology to circular economy, J. Clean. Prod. 170 (2018) 1514–1522.

[34] L. Mortensen, L. Kørnøv, Critical factors for industrial symbiosis emergence process, J. Clean. Prod. (2019) 56–69.
[35] H. Mallawaarachchi, Y. Sandanayake, G. Karunasena, C. Liu, Unveiling the conceptual development of industrial symbiosis: bibliometric analysis, J. Clean. Prod. 258 (2020) 120618.
[36] H. Hong, A. Gasparatos, Eco-industrial parks in China: key institutional aspects, sustainability impacts, and implementation challenges, J. Clean. Prod. 274 (2020) 122853.
[37] R. Vahidzadeh, G. Bertanza, S. Sbaffoni, M. Vaccari, Regional industrial symbiosis: a review based on social network analysis, J. Clean. Prod. 280 (2021) 124054.
[38] M. Lawal, S.R. Wan Alwi, Z.A. Manan, W.S. Ho, Industrial symbiosis tools—a review, J. Clean. Prod. 280 (2021).
[39] C. Yu, C. Davis, G.P.J. Dijkema, Understanding the evolution of industrial symbiosis research: a bibliometric and network analysis (1997-2012), J. Ind. Ecol. 18 (2014) 280–293.
[40] F. Rodríguez-Ruiz, P. Almodóvar, Q.T.K. Nguyen, Intellectual structure of international new venture research: a bibliometric analysis and suggestions for a future research agenda, Multinatl. Bus. Rev. 27 (2019) 285–316.
[41] A.W. Harzing, S. Alakangas, Google scholar, Scopus and the web of science: a longitudinal and cross-disciplinary comparison, Scientometrics 106 (2016) 787–804.
[42] L. Xue, Promoting industrial R&D and high-tech development through science parks: the Taiwan experience and its implications for developing countries, Int. J. Technol. Manag. 13 (1997) 744.
[43] R.R. Tan, S. Lung, Promoting collaborative R&D in Taiwan: an empirical study focused on the information processing component of the decision making processes, Int. J. Technol. Manag. 13 (1997) 762–795.
[44] K. Geiser, Pollution prevention and ... or industrial ecology? J. Clean. Prod. 5 (1997) 103–108.
[45] T.E. Graedel, B.R. Allenby, P.B. Linhart, Implementing industrial ecology, IEEE Technol. Soc. Mag. 12 (1993) 18–26.
[46] H.Z. Fu, M.H. Wang, Y.S. Ho, Mapping of drinking water research: a bibliometric analysis of research output during 1992-2011, Sci. Total Environ. 443 (2013) 757–765.
[47] Q. Wang, Z. Yang, Y. Yang, C. Long, H. Li, A bibliometric analysis of research on the risk of engineering nanomaterials during 1999-2012, Sci. Total Environ. 473–474 (2014) 483–489.
[48] M.J. Cobo, A.G. López-Herrera, E. Herrera-Viedma, F. Herrera, An approach for detecting, quantifying, and visualizing the evolution of a research field: a practical application to the Fuzzy Sets Theory field, J. Informetr. 5 (2011) 146–166.
[49] E.C.M. Noyons, H.F. Moed, M. Luwel, Combining mapping and citation analysis for evaluative bibliometric purposes: a bibliometric study, J. Am. Soc. Inf. Sci. 50 (1999) 115–131.
[50] K. Börner, C. Chen, K.W. Boyack, Visualizing knowledge domains, Annu. Rev. Inf. Sci. Technol. 37 (2003) 179–255.
[51] Q. Hou, G. Mao, L. Zhao, H. Du, J. Zuo, Mapping the scientific research on life cycle assessment: a bibliometric analysis, Int. J. Life Cycle Assess. 20 (2015) 541–555.
[52] P. Savov, A. Jatowt, R. Nielek, Identifying breakthrough scientific papers, Inf. Process. Manag. 57 (2020) 102168.
[53] B. Zhong, H. Wu, H. Li, S. Sepasgozar, H. Luo, L. He, A scientometric analysis and critical review of construction related ontology research, Autom. ConStruct. 101 (2019) 17–31.
[54] M.J. Culnan, The intellectual development of management information systems, 1972–1982: a Co-citation analysis, Manag. Sci. 32 (1986) 156–172.
[55] A. Pilkington, J. Meredith, The evolution of the intellectual structure of operations management-1980-2006: a citation/co-citation analysis, J. Oper. Manag. 27 (2009) 185–202.
[56] M. Callon, J.P. Courtial, F. Laville, Co-word analysis as a tool for describing the network of interactions between basic and technological research: the case of polymer chemsitry, Scientometrics 22 (1991) 155–205.
[57] S. Wasserman, K. Faust, Social Network Analysis: Methods and Applications, Cambridge University Press, 1994, p. 430.
[58] C.C. Aggarwal, Social Network Data Analytics, Springer Science+Business Media, LLC, 2011, 2011.
[59] M. Aria, C. Cuccurullo, bibliometrix: an R-tool for comprehensive science mapping analysis, J. Informetr. 11 (2017) 959–975.
[60] A. Darko, A.P.C. Chan, X. Huo, D.G. Owusu-Manu, A scientometric analysis and visualization of global green building research, Build. Environ. 149 (2019) 501–511.
[61] EEA, Circular by Design - Products in the Circular Economy, European Environmental Agency Report, No. 6/2017, 2017. https://www.aktuellhallbarhet.se/wp-content/uploads/2017/06/thal17005enn.pdf?utm_campaign=AktuellHållbarhet-Direkten_170612_Username&utm_medium=email&utm_source=Eloqua&elqTrackId=27f34711ffaf4178bceb478f70ea1265&elq=6de682b8af6646f39926cf2b72095402&elqaid.
[62] Z. Liu, Y. Lu, Y. Shi, P. Wang, K. Jones, A.J. Sweetman, A.C. Johnson, M. Zhang, Y. Zhou, X. Lu, C. Su, S. Sarvajayakesavaluc, K. Khan, Crop bioaccumulation and human exposure of perfluoroalkyl acids through multi-media transport from a mega fluorochemical industrial park, China, Environ. Int. 106 (2017) 37–47.
[63] Y. Geng, Z. Liu, B. Xue, H. Dong, T. Fujita, A. Chiu, Emergy-based assessment on industrial symbiosis: a case of shenyang economic and technological development zone, Environ. Sci. Pollut. Res. 21 (2014) 13572–13587.
[64] X. Yu, H. Zheng, L. Sun, Y. Shan, An emissions accounting framework for industrial parks in China, J. Clean. Prod. 244 (2019) 118712.
[65] J.E. Hirsch, h α, An index to quantify an individual's scientific leadership, Scientometrics 102 (2005) 16569–16572.
[66] J.E. Hirsch, G. Buela-Casal, The meaning of the h-index, Int. J. Clin. Health Psychol. 14 (2014) 161–164.
[67] N. Jacobsen, Industrial symbiosis in Kalundborg, Denmark A quantitative assessment of economic and environmental aspects, J. Ind. Ecol. 10 (2006) 239–255.
[68] R.R. Heeres, W.J.V. Vermeulen, F.B. De Walle, Eco-industrial park initiatives in the USA and The Netherlands: first lessons, J. Clean. Prod. 12 (2004) 985–995.
[69] B.H. Roberts, The application of industrial ecology principles and planning guidelines for the development of eco-industrial parks: an Australian case study, J. Clean. Prod. 12 (2004) 997–1010.
[70] H. Shi, M. Chertow, Y. Song, Developing country experience with eco-industrial parks: a case study of the Tianjin Economic-Technological Development Area in China, J. Clean. Prod. 18 (2010) 191–199.
[71] D. Gibbs, P. Deutz, Reflections on implementing industrial ecology through eco-industrial park development, J. Clean. Prod. 15 (2007) 1683–1695.
[72] H.S. Park, E.R. Rene, S.M. Choi, A.S.F. Chiu, Strategies for sustainable development of industrial park in Ulsan, South Korea-From spontaneous evolution to systematic expansion of industrial symbiosis, J. Environ. Manag. 87 (2008) 1–13.
[73] W. Gao, Y. Chen, Y. Liu, H. cheng Guo, Scientometric analysis of phosphorus research in eutrophic lakes, Scientometrics 102 (2015) 1951–1964.
[74] S. Martinez, M. del M Delgado, R. Martinez Marin, S. Alvarez, Science mapping on the Environmental Footprint: a scientometric analysis-based review, Ecol. Indicat. 106 (2019) 105543.
[75] S. Lozano, L. Calzada-Infante, B. Adenso-Díaz, S. García, Complex network analysis of keywords co-occurrence in the recent efficiency analysis literature, Scientometrics 120 (2019) 609–629.
[76] D. Gibbs, P. Deutz, Implementing industrial ecology? Planning for eco-industrial parks in the USA, Geoforum 36 (2005) 452–464.
[77] B. Corona, L. Shen, D. Reike, J. Rosales Carreón, E. Worrell, Towards sustainable development through the circular economy—a review and critical assessment on current circularity metrics, Resour. Conserv. Recycl. 151 (2019) 104498.
[78] S. Lehtoranta, A. Nissinen, T. Mattila, M. Melanen, Industrial symbiosis and the policy instruments of sustainable consumption and production, J. Clean. Prod. 19 (2011) 1865–1875.
[79] L. Sokka, S. Pakarinen, M. Melanen, Industrial symbiosis contributing to more sustainable energy use - an example from the forest industry in Kymenlaakso, Finland, J. Clean. Prod. 19 (2011) 285–293.
[80] L. Fraccascia, I. Giannoccaro, V. Albino, Rethinking resilience in industrial symbiosis: conceptualization and measurements, Ecol. Econ. 137 (2017) 148–162.
[81] F. Yu, F. Han, Z. Cui, Evolution of industrial symbiosis in an eco-industrial park in China, J. Clean. Prod. 87 (2015) 339–347.
[82] L. Zhang, Z. Yuan, J. Bi, B. Zhang, B. Liu, Eco-industrial parks: national pilot practices in China, J. Clean. Prod. 18 (2010) 504–509.
[83] L. Dong, T. Fujita, M. Dai, Y. Geng, J. Ren, M. Fujii, Y. Wang, S. Ohnishi, Towards preventative eco-industrial development: an industrial and urban symbiosis case in one typical industrial city in China, J. Clean. Prod. 114 (2016) 387–400.
[84] Z. Wen, X. Meng, Quantitative assessment of industrial symbiosis for the promotion of circular economy: a case study of the printed circuit boards industry in China's Suzhou New District, J. Clean. Prod. 90 (2015) 211–219.
[85] H. Zhao, H. Zhao, S. Guo, Evaluating the comprehensive benefit of eco-industrial parks by employing multi-criteria decision making approach for circular economy, J. Clean. Prod. 142 (2017) 226–227.
[86] H. Zeng, X. Chen, X. Xiao, Z. Zhou, Institutional pressures, sustainable supply chain management, and circular economy capability: empirical evidence from Chinese eco-industrial park firms, J. Clean. Prod. 155 (2017) 54–65.
[87] Z. Liu, M. Adams, R.P. Cote, Y. Geng, Y. Li, Comparative study on the pathways of industrial parks towards sustainable development between China and Canada, Resour. Conserv. Recycl. (2016).
[88] Y. Geng, P. Zhang, S. Ulgiati, J. Sarkis, Emergy analysis of an industrial park: the case of Dalian, China,, Sci. Total Environ. 408 (2010) 5273–5283.
[89] B.R. Bakshi, J. Fiksel, The quest for sustainability: challenges for process systems engineering, AIChE J. 49 (2003) 1350–1358.
[90] Q. Liu, P. Jiang, J. Zhao, B. Zhang, H. Bian, G. Qian, Life cycle assessment of an industrial symbiosis based on energy recovery from dried sludge and used oil, J. Clean. Prod. 19 (2011) 1700–1708.
[91] M. Felicio, D. Amaral, K. Esposto, X. Gabarrell Durany, Industrial symbiosis indicators to manage eco-industrial parks as dynamic systems, J. Clean. Prod. 118 (2016) 54–64.
[92] L.B. Elabras Veiga, A. Magrini, Eco-industrial park development in Rio de Janeiro, Brazil: a tool for sustainable development, J. Clean. Prod. 17 (2009) 653–661.
[93] Y. Zhang, H. Zheng, B.D. Fath, Ecological network analysis of an industrial symbiosis system: a case study of the Shandong Lubei eco-industrial park, Ecol. Model. 306 (2015) 174–184.
[94] G. Valenzuela-Venegas, G. Vera-Hofmann, F.A. Díaz-Alvarado, Design of sustainable and resilient eco-industrial parks: planning the flows integration network through multi-objective optimization, J. Clean. Prod. 243 (2020) 118610.
[95] V. Ranta, L. Aarikka-Stenroos, P. Ritala, S.J. Mäkinen, Exploring institutional drivers and barriers of the circular economy: a cross-regional comparison of China, the US, and Europe, Resour. Conserv. Recycl. 135 (2018) 70–82.
[96] M. Zhai, G. Huang, L. Liu, X. Zhang, Ecological network analysis of an energy metabolism system based on input-output tables: model development and case study for Guangdong, J. Clean. Prod. 227 (2019) 434–446.

[97] M. Chertow, J. Ehrenfeld, Organizing self-organizing systems: toward a theory of industrial symbiosis, J. Ind. Ecol. 16 (2012) 13–27.
[98] J. Spiegelman, Beyond the food web: connections to a deeper industrial ecology, J. Ind. Ecol. 7 (2003) 17–23.
[99] M.R. Chertow, M.J. Eckelman, Using material flow analysis to illuminate long-term waste management solutions in oahu, Hawaii, J. Ind. Ecol. 13 (2009) 758–774.
[100] R.W. Scholz, The emergence of industrial ecology, in: Environ. Lit. Sci. Soc. From Knowl. To Decis., Cambridge University Press, Cambridge, 2011, pp. 307–319.
[101] E. Romero, M.C. Ruiz, Proposal of an agent-based analytical model to convert industrial areas in industrial eco-systems, Sci. Total Environ. 468–469 (2014) 394–405.
[102] L. Fraccascia, D.M. Yazan, V. Albino, H. Zijm, The role of redundancy in industrial symbiotic business development: a theoretical framework explored by agent-based simulation, Int. J. Prod. Econ. 221 (2020).
[103] Y. Fan, Q. Qiao, L. Fang, Network analysis of industrial metabolism in industrial park – a case study of Huai'an economic and technological development area, J. Clean. Prod. 142 (2017) 1552–1561.
[104] Z. Liu, Y. Geng, P. Zhang, H. Dong, Z. Liu, Emergy-based comparative analysis on industrial clusters: economic and technological development zone of Shenyang area, China, Environ. Sci. Pollut. Res. 21 (2014) 10243–10253.
[105] A. El shenawy, R. Zmeureanu, Exergy-based index for assessing the building sustainability, Build. Environ. 60 (2013) 202–210.
[106] M.L. Tseng, R.R. Tan, A.S.F. Chiu, C.F. Chien, T.C. Kuo, Circular economy meets industry 4.0: can big data drive industrial symbiosis? Resour. Conserv. Recycl. 131 (2018) 146–147.
[107] A.M. Martín Gómez, F. Aguayo González, M. Marcos Bárcena, Smart eco-industrial parks: a circular economy implementation based on industrial metabolism, Resour. Conserv. Recycl. 135 (2018) 58–69.
[108] P. Xiang, T. Yuan, A collaboration-driven mode for improving sustainable cooperation in smart industrial parks, Resour. Conserv. Recycl. 141 (2019) 273–283.
[109] R.a. Frosch, N.E. Gallopoulos, Strategies for manufacturing, Sci. Am. 261 (1989) 144–152.
[110] J. Ehrenfeld, N. Gertler, Industrial ecology in practice, J. Ind. Ecol. 1 (1997) 67–79.
[111] M. Mirata, Experiences from early stages of a national industrial symbiosis programme in the UK: determinants and coordination challenges, J. Clean. Prod. 12 (2004) 967–983.
[112] W. Ashton, Understanding the organization of industrial ecosystems: a social network approach, J. Ind. Ecol. 12 (2008) 34–51.
[113] G.P.J. Dijkema, L. Basson, Complexity and industrial ecology foundations for a transformation from analysis to action, J. Ind. Ecol. 13 (2009) 157–164.
[114] T. Mattila, S. Lehtoranta, L. Sokka, M. Melanen, A. Nissinen, Methodological aspects of applying life cycle assessment to industrial symbioses, J. Ind. Ecol. 16 (2012) 51–60.
[115] Y. Lu, M. Su, G. Liu, B. Chen, S. Zhou, M. Jiang, Ecological network analysis for a low-carbon and high-tech industrial park, Sci. World J. 2012 (2012).
[116] N. Bichraoui, B. Guillaume, A. Halog, Agent-based modelling simulation for the development of an industrial symbiosis - preliminary results, Procedia Environ. Sci. 17 (2013) 195–204.
[117] J. Zhu, M. Ruth, Exploring the resilience of industrial ecosystems, J. Environ. Manag. 122 (2013) 65–75.
[118] C.A. Dean, B.D. Fath, B. Chen, Indicators for an expanded business operations model to evaluate eco-smart corporate communities, Ecol. Indicat. 47 (2014) 137–148.
[119] M. Lieder, A. Rashid, Towards circular economy implementation: a comprehensive review in context of manufacturing industry, J. Clean. Prod. 115 (2016) 36–51.
[120] M. Le Tellier, L. Berrah, B. Stutz, J.F. Audy, S. Barnabé, Towards sustainable business parks: a literature review and a systemic model, J. Clean. Prod. 216 (2019) 129–138.
[121] J.R. Ehrenfeld, Understanding of complexity expands the reach of industrial ecology, J. Ind. Ecol. 13 (2009) 165–167.
[122] G.P.J. Dijkema, L. Basson, Complexity and industrial ecology, J. Ind. Ecol. 13 (2009) 157–164.
[123] N.A. Al-Thani, T. Al-Ansari, Comparing the convergence and divergence within industrial ecology, circular economy, and the energy-water-food nexus based on resource management objectives, Sustain. Prod. Consum. 27 (2021) 1743–1761.
[124] Y. Geng, R.P. Côté, Scavengers and decomposers in an eco-industrial park, Int. J. Sustain. Dev. World Ecol. 9 (2002) 333–340.
[125] E. Cohen-rosenthal, What is eco-industrial development?, in: Eco-Industrial Strateg. Unleashing Synerg. Between Econ. Dev. Environ., first ed., Taylor & Francis, London, 2003, pp. 14–29.
[126] C. Yu, G.P.J. Dijkema, M. De Jong, H. Shi, From an eco-industrial park towards an eco-city: a case study in Suzhou, China, J. Clean. Prod. 102 (2015) 264–274.
[127] UNIDO, International, Guidelines for industrial parks, Incl. Sustain. Ind. Dev. 1–66 (2019). https://www.unido.org/sites/default/files/files/2019-11/International_Guidelines_for_Industrial_Parks.pdf.