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Article

A bibliometric study of sustainable technology research

Cogent Business & Management

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Taylor & Francis Group

Suggested Citation: Akbari, Morteza; Khodayari, Maryam; Danesh, Mozhgan; Davari, Ali; Padash, Hamid (2020) : A bibliometric study of sustainable technology research, Cogent Business & Management, ISSN 2331-1975, Taylor & Francis, Abingdon, Vol. 7, Iss. 1, pp. 1-25, <https://doi.org/10.1080/23311975.2020.1751906>

This Version is available at:

<https://hdl.handle.net/10419/244838>

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To cite this article: Morteza Akbari, Maryam Khodayari, Mozhgan Danesh, Ali Davari & Hamid Padash | (2020) A bibliometric study of sustainable technology research, Cogent Business & Management, 7:1, 1751906, DOI: [10.1080/23311975.2020.1751906](https://doi.org/10.1080/23311975.2020.1751906)

To link to this article: <https://doi.org/10.1080/23311975.2020.1751906>



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Received: 09 February 2020
Accepted: 13 March 2020

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Reviewing editor:
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OPERATIONS, INFORMATION & TECHNOLOGY | REVIEW ARTICLE

A bibliometric study of sustainable technology research

Morteza Akbari^{1*}, Maryam Khodayari², Mozhgan Danesh¹, Ali Davari¹ and Hamid Padash¹

Abstract: Sustainable technology is a rather new subject in sustainability which is paying academics' attention recently. This article provides a bibliometric review of sustainable technology studies in the sustainability area. Data from the Web of Science (WoS), database relating to 1122 publications available between 1970 and 2019 is used. Numerous bibliometric methods are used to do this indication. The VOSviewer software is used to graph the bibliographic documents. The findings revealed that publications around this area have been enhanced considerably in the last decade and the USA is the most dominant country. Furthermore, the co-citation network of references revealed five clusters; the competitive advantage of environmental innovation, the development of sustainable technologies, environmental policy tools, undesirable output solutions, and innovative environmental activities.



Morteza Akbari

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PUBLIC INTEREST STATEMENT

Sustainable technologies are technologies that enable you to use more natural resources and dramatically reduce the harmful effects on the environment and reduce waste while increasing productivity. That's why these technologies have gained a lot of attention in recent decades. The increase in publications in this area indicates this. Corporate use of sustainable technologies has not only gained a competitive advantage but governments have also set policies to increase corporate investment in sustainable technologies, innovate and develop sustainable technologies, and thus they have greatly contributed to reducing pollution and undesirable outputs. By innovating in environmental technologies, developing sustainable technologies, companies gain competitive advantage. Companies can achieve sustainable technology development through the creation of innovation systems, technological systems, the creation and enhancement of absorption capacity, and design strategic niche management. Governments also facilitate the use of these technologies by companies with environmental policies such as emission standards, pollution taxes, marketable quotas, and subsidies. Thus, adverse plant emissions will be reduced and their innovative environmental activities will increase.

This is the initial research toward proposing a bibliometric study of sustainable technology investigation in the sustainability area with definite theoretical and applied consequences.

Subjects: Technology; Sustainability; Sustainable Development; Management of Technology & Innovation; Management of Technology

Keywords: sustainable technology; green technology; clean technology; environmental technology; renewable energy technology; bibliometric

1. Introduction

Sustainable development is the greatest challenge of the 21 century (Akbari et al., 2019; Asadi et al., 2008; Mulder et al., 2011; Okura, 2010). It results in numerous global challenges such as pollution; lack and famine; environmental change; reduction of inorganic and organic resources; natural ruin; and global bias (Akbari & Asadi, 2008; Mirakzadeh et al., 2012). Human actions have contributed negatively to sustainable development. In this sense, people must variation course and take steps to move away from this serious fact (Eustachio et al., 2019). It has been commonly acknowledged that a transition to a sustainable development necessitates significant changes in resource and energy consumption (Mulvihill et al., 2011). Recently, an inadequate supply of energy and resources in addition to ameliorating the threat posed by environmental pollution result in the development of sustainable technology (Das et al., 2019).

The key to sustainable technology is attaining an economic advantage for environmental developments (Eckert et al., 2000). Over the past few decades, the number of publications about sustainability has increased dramatically (Khan, 2020; Uusitalo et al., 2019; Wang & Zhan, 2019; Zhang et al., 2019). Sustainable technology is a major aim in environmental sciences and the growth of global economies, usually associated with the design and analysis of sophisticated, integrated management systems and sustainable development. Reducing material and energy inputs and minimizing waste is one of the most important environmental aims (Srebrenkoska et al., 2013). Sustainable technology defined as “technology that provides for our current needs without sacrificing the ability of future populations to sustain themselves” (Hmelo et al., 1995, p. 1).

Terms such as “environmental technology”, “clean technology”, “green technology” (Africa, A. of S. of S, 2014; Bjornali & Ellingsen, 2014; J. Chen et al., 2015; Keramitsoglou et al., 2016; Meyskens & Carsrud, 2013), and “renewable energy technology” (Bjornali & Ellingsen, 2014; Brown et al., 2007; Raja & Thomas, 2010) are often used. In recent years, research interest in sustainable technology (Pal & Nayak, 2016; Sjö & Frishammar, 2019; Willaert & Baron, 2004; Yang & Wang, 2015), such as green technology (Annamalai et al., 2018; Wang et al., 2019), clean technology (Yang et al., 2019), environmental technology (Chan et al., 2020; Diana et al., 2017; Ozusaglam et al., 2018; Roshdi et al., 2018), and renewable energy technology (Johansen, 2019; Karooni et al., 2016; Sung, 2019) has increased noticeably. Though, despite a rising number of researches in sustainability and sustainable technology as seen in many disciplines, there is a necessity of analysis demonstrating how sustainable technology studies have evolved and become an emergent research part.

Academically, researches on various aspects of sustainability have been published in the international journals (Cui, 2018; García-Berná et al., 2019; Pang & Zhang, 2019; Tang et al., 2018; Valente et al., 2018). However, no comprehensive review of sustainable technology based on BR has been published. Thus, the core objective of this study is to assess the progress on sustainable technology studies in the sustainability area, and suggest a research agenda. Using BR, this paper does so by examining the literature published in the Web of Science™ (WoS) Core Collection database. The research includes a BR based on 1122 publications on sustainable technology published from 1970 to 2019.

Our contribution detects the most influential authors, leading countries, top leading journals, theoretic grounding, the topics already covered and, subsequently, new lines and viewpoints for forthcoming investigation.

2. Review of the literature on bibliometric review

BR, in earlier times, identified as a statistical analysis of the literature (Cole & Eales, 1917) Thanuskodi, 2010), defined BR as “the application of mathematics and statistical methods to books and other media of communication” (Groos & Pritchard, 1969). BR involves using statistical methods to describe qualitative and quantitative changes in an assumed scientific research theme (De Bakker et al., 2005). This method provides suitable statistics for academics seeking to assess scientific activity (Duque Oliva et al., 2006). BR is founded on the statement that scientists publish their significant results in academic journals and mostly constructed their research on documents before published in related journals (Van Raan, 2003). In evaluative BR, two main techniques have been developed, the performance analysis, based on publication output and received citations and mapping of science (Noyons & Moed, 1999). BR contains different approaches such as content analysis, text analysis, citation analysis, keyword co-occurrence, co-citation analysis, or co-authoring analysis (Dias, 2019).

In this study, we use co-citation analysis. Co-citation analysis is an exclusive method for studying the cognitive structure of science. Co-citation analysis involves tracking pairs of papers that are cited together in the source articles. Documents co-citation is used to conduct searches on similar documents (Surwase et al., 2011). By co-citation analysis, the theoretic foundations of the inquiry field are identified by evaluating the similarities in the cited articles (Boyack & Klavans, 2010). Co-citation is a common method in BR which has been used in many studies (Danvila-del-Valle et al., 2019; Dzikowski, 2018; Gaviria-Marin et al., 2019; P. Kumar et al., 2019; Martínez-López et al., 2019).

3. Method

3.1. Data source and procedure

In BR, the first step is to identify databases that help study (Albort-Morant & Ribeiro-Soriano, 2016). Clarivate Analytics- Web of Science (WoS) database was used to extract the data. Citation data is available for a wide range of publications on ISI Web’s most renowned science academic database, the WoS was suitable for this as one of the main purposes of interdisciplinary literary research and many important bibliometric studies have used this database before (Fetscherin & Usunier, 2012). The WoS database provides extensive coverage of the social sciences, and arts and humanities have previously been used in a wide range of bibliographic research (Danvila-del-Valle et al., 2019; Gurzki & Woisetschläger, 2017; Huang et al., 2019; Mulet-Forteza et al., 2019).

The BR examines a set of publications using numerical analysis methods (Azevedo et al., 2019). As stated (Fahimnia et al., 2015), BR is used to identify emerging topical areas. By identifying clusters or research and researchers show how different areas of thought emerge based on author and institutional characteristics. Also, by identifying the most influential researchers in these clusters, it provides the basis for identifying additional field studies.

There are many bibliometric studies of a wide variety of issues. For example, solar energy technologies and open innovation (De Paulo & Porto, 2017), the supply chain of renewable energy (Azevedo et al., 2019), sustainability in the collaborative economy (Ertz, 2018), open innovation and absorptive capacity (Seguí-Mas et al., 2016).

We decided to use a variety of documents in the database including articles, books, articles related to proceedings, book chapters and other types of documents available in databases. The search terms include all documentation with the terms “Sustainable Technology”, OR “Green Technology”, OR “Clean Technology”, OR “Environmental Technology”, OR “Renewable Energy

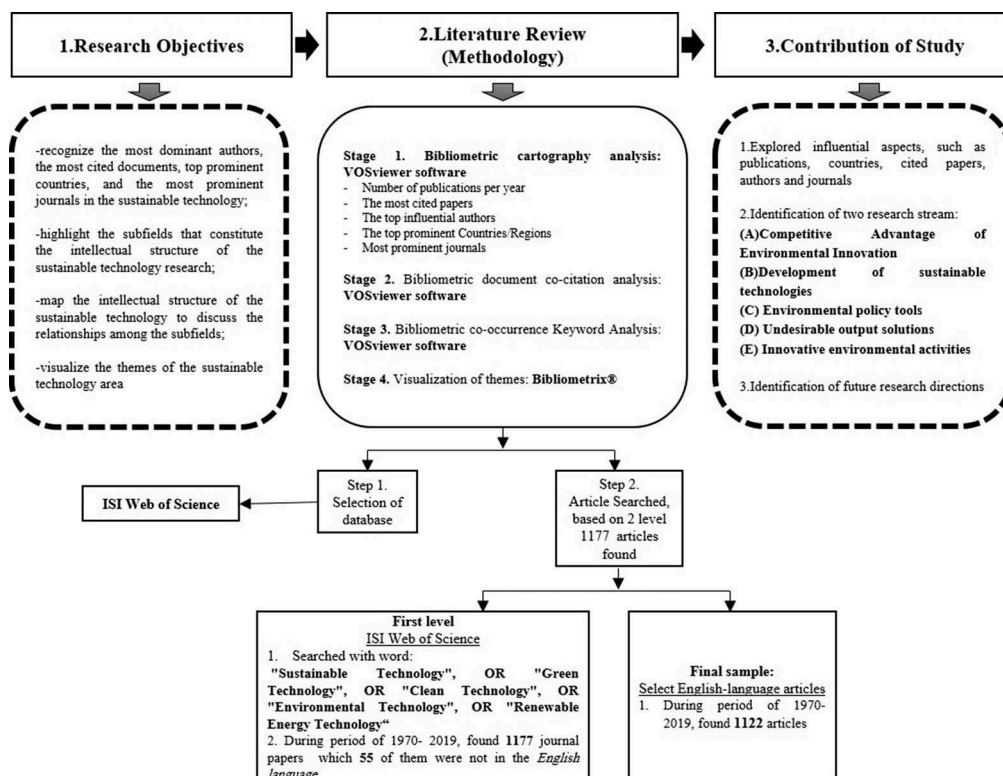
Technology”, as a search for the following sections in their “Title”. To develop complete information about the journals, the “All Year” timeframe has been set, but the first records we obtained from WoS were from 1970.

The data set encompasses 1177 documents which 55 of them were not in the English language. Meanwhile, various journals publish only in English, the majority of the articles (95.32%) were published in that language. There are also some papers in German (34), Swedish (6), Spanish (4), Croatian (2), Polish (2), Portuguese (2), Chinese (1), Czech (1), French (1), and Korean (1), which are not included in this study. Finally, a total of 1122 documents have been published in 850 sources (journals, books, etc.). This sample, based on the WOS database, contains publications in various research fields. Most of the documents were published in environmental sciences (262), engineering environmental (142), green sustainable science technology (135), engineering chemical (128), environmental studies (113), and energy fuels (107). Also, economics (94), management (64), business (58) were the most productive area of the WoS category. The key organizations in the sample are “University of California System” (20 records), “Indian Institute of Technology System IIT System” (12), “United States Department of Energy Doe” (12), “Murdoch University” (11), “UNIVERSITI TEKNOLOGI Malaysia” (11), “Council of Scientific Industrial Research CSIR India” (9), “UNIVERSITI SAINS Malaysia” (9), and “Harvard University” (8).

3.2. Analytical methods and software

Based on data exported from the WoS database, VOSviewer software was used to establish special relationships with networks and maps. VOSviewer is a permitted software program established by Van Eck and Waltman (Van Eck & Waltman, 2009) developed to create, visualize, and explore bibliographic maps (Castillo-Vergara et al., 2018; H. Wang & Yang, 2019). One of the main advantages of this software is that it focuses on graphical representations of maps. This is especially suitable when visualizing large maps, is easy to interpret and is most commonly used to create maps based on network data (Jeong et al., 2016). The research method is summarized in Figure 1.

Figure 1. Methodological approach (Author’s Presentation).



4. Results

This section contains the overall results; the number of documents per year, the most cited articles, the most prominent authors, the most cited journals, and the highest efficiency countries. Besides, this investigation runs networks of cited references and their particular groups. Since the purpose of this study is to gain an overview of the evolution of sustainable technology research, it encompasses all available publications and countries.

4.1. Overall consequences

The study recognizes 564 articles, 345 proceeding papers, 46 review, 9 books, and 95 editorial materials and other categories. 1122 documents were published by 2768 authors in 850 journals and 84 countries.

4.2. Total studies by year

This section shows the core outcomes found in BR in the WoS database for the sustainable technology documents from 1970 to 2019 (October) (Table 1). The rising pattern of sustainable technology investigation between 1970 and 2019, and Figure 2 shows the growing trend of sustainable technology publishing. As mentioned earlier, the first publications in this field were in the year 1970.

4.3. Most cited studies

The top-ranking of publications in terms of the highest number of citations publications have received in WoS. The analysis contains papers with at least 100 citations (see Table 2). The results showed that the total citation of the articles was 12,864 and the average citation rate per year was 1,464 citations. The article “Ionic liquids for clean technology” (Seddon, 1997) is the most cited paper in the WoS database, with 1,725 citations. In this article, the principles of designing ionic liquids as clean technology at room temperature, some of their properties and the rational reason for using these solvents are discussed. The second most-cited article in the collection is “Natural deep eutectic solvents as new potential media for green technology”, accounting for 569 citations (Dai et al., 2013). Freemantle is the author of the third most-cited studies “Designer solvents—ionic liquids may boost clean technology development”, accounting for 566 citations (Freemantle, 1998). This article also discusses ionic liquids as clean technology that may boost the development of clean technology, and the fourth most-cited paper in the WoS database is “Biocatalysis in ionic liquids—advantages beyond green technology”, accounting for 524 citations (Park & Kazlauskas, 2003).

4.4. Top influential authors

In this study, Table 4 identifies the most influential authors. The number of published documents from any author and the sum of citations given to each author indicates the most influential

Figure 2. Total studies by Year.

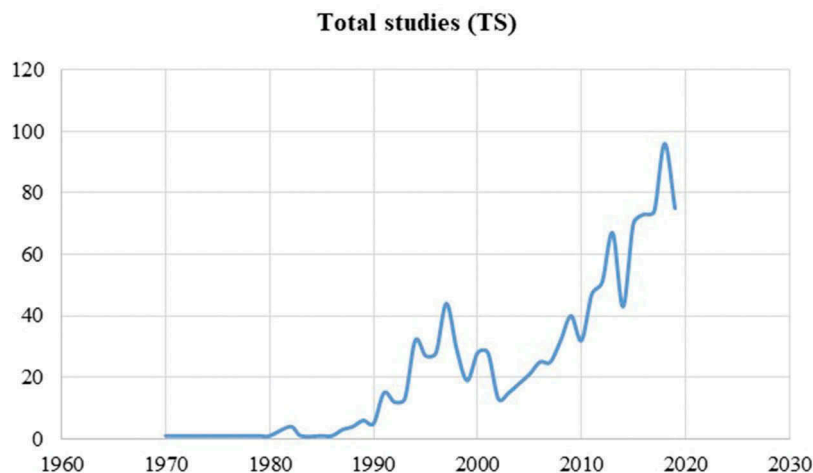


Table 1. Number of studies published in sustainable technology between 1970 and 2019

Publication Years	Total Studies (TS)	Total citation (TC)	TC/TS	% Of 1122	Publication Years	TS	TC	TC/TS	% of 1122
2019	75	57	0.76	6.684	1994	32	110	3.44	2.852
2018	96	208	2.17	8.556	1993	13	59	4.54	1.159
2017	74	477	6.45	6.595	1992	12	41	3.42	1.070
2016	73	706	9.67	6.506	1991	15	40	2.67	1.337
2015	70	512	7.31	6.239	1990	5	0	0.00	0.446
2014	43	601	13.98	3.832	1989	6	2	0.33	0.535
2013	67	1517	22.64	5.971	1988	4	1	0.25	0.357
2012	51	386	7.57	4.545	1987	3	14	4.67	0.267
2011	47	414	8.81	4.189	1986	1	0	0.00	0.089
2010	32	139	4.34	2.852	1985	1	0	0.00	0.089
2009	40	235	5.88	3.565	1984	0	0	0.000	0.000
2008	32	358	11.19	2.852	1983	1	0	0.000	0.089
2007	25	686	27.44	2.228	1982	4	3	0.75	0.357
2006	25	521	20.84	2.228	1981	0	0	0.000	0.000
2005	21	207	9.86	1.872	1980	1	2	2.00	0.089
2004	18	548	30.44	1.604	1979	1	0	0.000	0.089
2003	15	742	49.47	1.337	1978	0	0	0.000	0.000
2002	13	198	15.23	1.159	1977	1	0	0.000	0.089
2001	28	171	6.11	2.496	1976	0	0	0.000	0.000
2000	28	865	30.89	2.496	1975	0	0	0.000	0.000
1999	19	40	2.11	1.693	1974	0	0	0.000	0.000
1998	29	777	26.79	2.585	1973	1	0	0.000	0.089
1997	44	2070	47.05	3.922	1972	0	0	0.000	0.000
1996	28	74	2.64	2.496	1971	0	0	0.000	0.000
1995	27	80	2.96	2.406	1970	1	3	3.00	0.089

Table 2. The 17 most cited studies in sustainable technology discipline based on WoS

Rank	Title	Authors	Journal	Year	TC	Citations Per Year
1	Ionic liquids for clean technology	Seddon, Kr	Journal of chemical technology and biotechnology	1997	1725	75
2	Natural deep eutectic solvents as new potential media for green technology	Dai et al.,	Analytica Chimica acta	2013	569	81.29
3	Designer solvents—ionic liquids may boost clean technology development	Freemantle, M	Chemical & engineering news	1998	566	25.73
4	Biocatalysis in ionic liquids—advantages beyond green technology	Park, S; Kazlauskas, Rj	Current opinion in biotechnology	2003	524	30.82
5	The politics and policy of energy system transformation—explaining the german diffusion of renewable energy technology	Jacobsson, S; Lauber, V	Energy policy	2006	462	33
6	The diffusion of renewable energy technology: an analytical framework and key issues for research	Jacobsson, S; Johnson, A	Energy policy	2000	420	21
7	Transforming the energy sector: the evolution of technological systems in renewable energy technology	Jacobsson, S; Bergek, A	Industrial and corporate change	2004	328	20.5
8	Modified silicas for clean technology	Price et al.,	Journal of the chemical society-dalton transactions	2000	280	14
9	Fostering a renewable energy technology industry: an international comparison of wind industry policy support mechanisms	Lewis et al.,	Energy policy	2007	257	19.77
10	Sustainable technology—green chemistry	Pollakoff, Martyn; Licence, Pete	Nature	2007	220	16.92
11	Decision-making in energy planning. Application of the electre method at regional level for the diffusion of renewable energy technology	Beccali et al.,	Renewable energy	2003	213	12.53
12	Deep-ocean mineral deposits as a source of critical metals for high- and green-technology applications: comparison with land-based resources	Hein et al.,	Ore geology reviews	2013	193	27.57
13	Supercritical fluid extraction of vegetable matrices: applications, trends and future perspectives of a convincing green technology	De Melo et al.,	Journal of supercritical fluids	2014	168	28
14	Environmental taxes and the choice of green technology	Krass et al.,	Production and operations management	2013	148	21.14

(Continued)

Table 2. (Continued)

Rank	Title	Authors	Journal	Year	TC	Citations Per Year
15	Use of experience curves to analyse the prospects for diffusion and adoption of renewable energy technology	Neij, L	Energy policy	1997	112	4.87
16	Geochip 4: a functional gene-array-based high-throughput environmental technology for microbial community analysis	Tu et al.,	Molecular ecology resources	2014	106	17.67
17	Phytoremediation: current views on an emerging green technology	Flathman, Pe; Lanza, Gr	Journal of soil contamination	1998	102	4.64

Table 3. Top influential authors publishing sustainable technology documents between 1970 and 2019

Rank	Authors	TS	TC	TC/TS	h-index
1	Park, Sangsung	8	569	71.13	4
2	Ariwa, Ezendu	6	1	0.17	1
3	Jun, Sunghae	6	33	5.50	2
4	Kumar, Mohit	6	7	1.17	2
5	Zahnd, Alexander	6	0	0.00	0
6	Marinova, Dora	5	3	0.60	1
7	Raja, Robert	5	186	37.20	4
8	Song, Malin	5	90	18.00	5
9	Thomas, John Meurig	5	181	36.20	3
10	Wang, Shuhong	5	100	20.00	5

authors. About 50 of the authors have published the above three papers. The analysis includes authors with at least five articles. Therefore, based on the results, “Park”, “Sangsung”, “Raja”, “Robert”, “Jun”, “Thomas”, and “John Meurig” are the most influential authors (see Table 3).

4.5. Top prominent Countries/Regions

In this section, as in the other sections, the most prominent countries in the field of sustainable technology that you see in Table 4 are shown documents published in each country and the number of citations (Figure 3). Despite contributing from 84 countries, the largest number of articles is published by authors from the “USA”, the “Peoples R China”, “England”, “India”, “Germany”, “Malaysia”, “Canada”, “Japan”, “Australia”, and “South Korea”, and come from a wide array of organizations. The USA is the first place in the ranking, with the largest number of publications and total citations. Canada is the most dominant country within sustainable technology, with 26.1 citations per document. Next is England, with 22.68 and Germany, with 11.40 citations per document.

4.6. Top most prominent journals

In this study, 1,122 documents were published in 850 journals. The total prominent available in each journal and the total citations determine the most effective journals in the field of sustainable technology (see Table 5). The investigation contains journals with at least 9 documents.

The statistics disclose that the “Journal of Chemical Technology and Biotechnology” is the most dominant journal, with 154.00 citations per document. “Energy Policy” with 87.12 citations per

Table 4. Top prominent Countries/Regions publishing sustainable technology documents

Rank	Countries/Regions	TS	TC	TC/TS	h-index
1	USA	271	2389	8.82	25
2	Peoples R China	124	796	6.42	15
3	England	85	1928	22.68	19
4	India	80	467	5.91	12
5	Malaysia	46	225	4.90	6
6	Germany	43	490	11.40	9
7	Canada	40	1044	26.1	12
8	Japan	36	244	6.78	7
9	Australia	35	123	3.51	4
10	South Korea	31	232	7.48	9

Figure 3. Map of countries that publish sustainable technology documents.

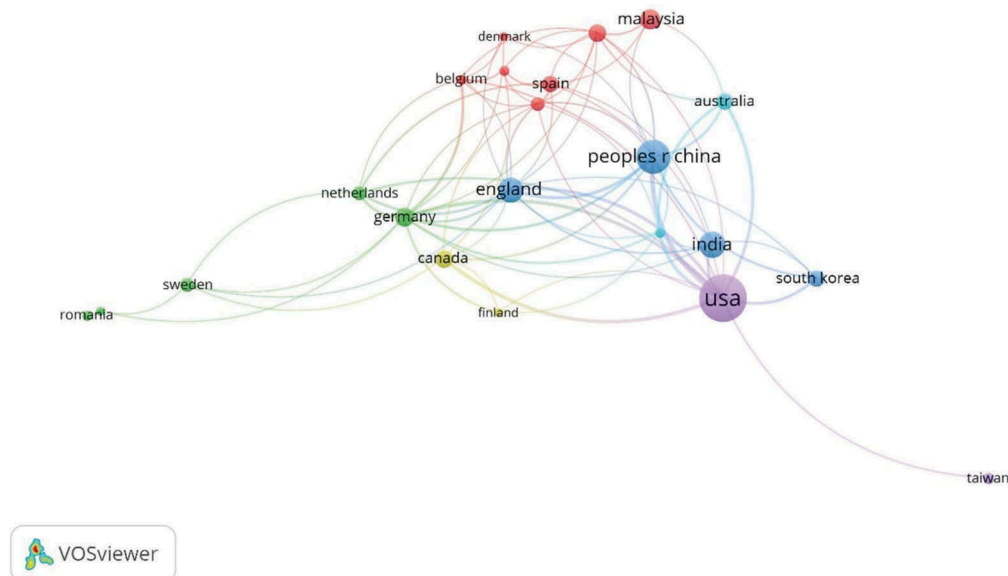


Table 5. Top most prominent journals publishing sustainable technology documents

Rank	Source Titles	TS	TC	TC/TS	h-index
1	Journal of Cleaner Production	31	419	13.52	14
2	Abstracts of papers of the American Chemical Society	30	0	0.00	0
3	Sustainability	21	78	3.71	5
4	Energy Policy	17	1481	87.12	11
5	Clean Technologies and Environmental Policy	15	54	3.60	4
6	Journal of Chemical Technology and Biotechnology	12	1848	154.00	8
7	Advanced Materials Research	9	4	0.44	1
8	AIP Conference Proceedings	9	10	1.11	2
9	Elgar Original Reference	9	14	1.56	2
10	Renewable Sustainable Energy Reviews	9	186	20.67	8

document, and the “Renewable sustainable energy reviews” with 20.67 citations per document are the most cited journals. On the other hand, journals with the highest number of documents consist of the “Journal of Cleaner Production”, with 31 articles; “Abstracts of papers of the American Chemical Society”, with 30 articles; and “Sustainability”, with 20 articles.

4.7. Document co-citation analysis

Document co-citation analysis, with cited references, was done to better understand the theoretical foundations of the 1,122 documents in the sample. The initial sample of 25,965 cited references was reduced to publications with at least 7 citations, resulting in 35 publications (see Table 6).

Figure 4 shows the bibliometric network based on document co-citation analysis which consists of five clusters.

4.7.1. Cluster A: Competitive advantage of environmental innovation

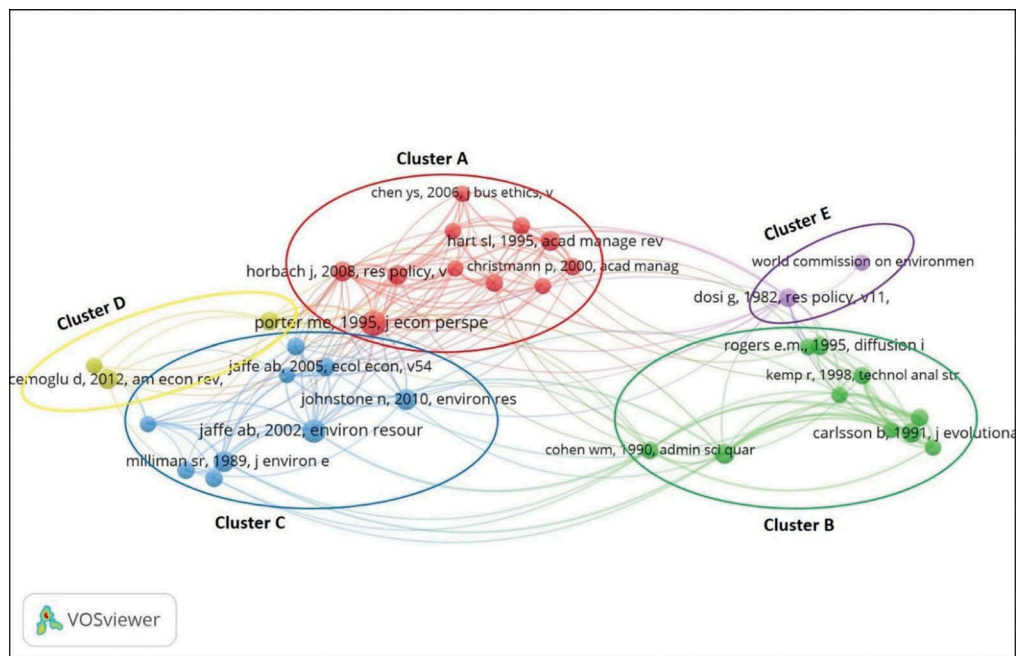
Cluster A includes 9 articles and 2 book publications, labeled as “Competitive Advantage of Environmental Innovation”. Commonly, the publications in this cluster examine the impact of

Table 6. Co-citation network of cited references in sustainable technology

Clusters	Reference	Research areas/topics
Cluster A: Competitive Advantage of Environmental Innovation	(Brunnermeier & Cohen, 2003)	General factors that drive environmental innovation: - Environmental laws and regulations - Environmental policies - complementary assets such as resources and technical capabilities of the company
	(Y. S. Chen et al., 2006)	
	(Christmann, 2000)	
	(Hart & Hart, 2013)	
	(Horbach, 2008)	
	(Kemp, 1997)	
	(Porter & Van der Linde, 1995)	
	(Porter & Van der Linde, 1995)	
	(Rennings, 2000)	
	(Schiederig et al., 2012)	
(Shrivastava, 1995)		
Cluster B: Development of sustainable technologies	(Carlsson & Stankiewicz, 1991)	The factors that influence the development of sustainable technologies: - Creating innovation systems - Creating technological systems - Enhancing absorption capacity - Designing strategic niche management
	(Cohen & Levinthal, 1990)	
	(Davis, 1989)	
	(Geels, 2002)	
	(Hekkert et al., 2007)	
	(Jacobsson & Johnson, 2000)	
	(Kemp et al., 1998)	
	(Lundvall, 1992)	
	(Rogers, 2003)	
	(Rogers, 1995)	
Cluster C: Environmental policy tools	(Dixit et al., 1994)	Incentives to use advanced pollution abatement technologies: - direct control - Emission subsidies - Emission taxes - Free marketable permits - Auctioned marketable permits - Performance standards Policy tools for renewable energy sources: - R&D programs - Investment incentives - Tax incentives - Preferential tariffs - Voluntary programs - Quantitative obligations, tradable certificates
	(Jaffe et al., 2002)	
	(Jaffe et al., 2005)	
	(Johnstone et al., 2010)	
	(Jung et al., 1996)	
	(Krass et al., 2013)	
	(Milliman & Prince, 1989)	
	(Popp et al., 2010)	
	(Requate & Unold, 2003)	
Cluster D: Undesirable output solutions	(Acemoglu et al., 2012)	Methods to eliminate undesirable outputs such as pollution: - Endogenous changes - Malmquist-luenberger index
	(Chung et al., 1997)	
	(Jaffe & Palmer, 1997)	
Cluster E: Innovative environmental activities	(Dosi, 1982)	Innovative environmental activities depend on three factors: - Technology push - Market pull - Institutions Role
	(WCED, 1987)	

green and environmental innovations on firms' competitive advantage. Table 5 provides an overview of the 36 publications, their theoretical contributions, and the implications of sustainable technology research the publications of this cluster, highlight the effect of environmental innovation on the competitive advantage of companies. All of these publications emphasize the positive relationship between environmental innovation and organizations' competitive advantage.

Figure 4. Co-citation network of cited references in sustainable technology documents.



One of the most important issues in the field of competition and economics is the natural environment. Ecological issues lead to both competitive chances and restraints, and in many manufacturing change the competitive landscape (Shrivastava, 1995). Ecofriendly innovation, measured by the number of successful ecofriendly patents in the industry (Brunnermeier & Cohen, 2003), has a slight difference with green innovation, eco/ecological innovation, sustainable innovation (Schiederig et al., 2012). In the past, most executives thought that investing in ecological safety activities was harmful to industries. If industries were eager to invest in environmental protection, most of their incentives were to take on public duty or be forced to do so. Due to strict global rules and agreements in the field of environmental protection and the increase of environmentalists and activists, this has created challenges for companies all over the world. Industries can not only rise resource productivity over green innovation but also design and develop green products that allow them to make higher earnings (Chen et al., 2006). Environmental innovation reduces the costs spent on environmental pollution, however, and supervisory and enforcement activities reduce the incentive to innovate. According to studies, environmental innovations occur in industries that are internationally competitive (Brunnermeier & Cohen, 2003).

By reviewing the publications in this cluster, the factors that affect environmental innovation and in turn the competitive advantage of companies include:

- Environmental laws and regulations
- Improve resources and technical capabilities of the company
- Environmental policies

Protecting the environment requires extensive laws and regulations because everyone wants a viable planet, but there has long been a belief that environmental regulation destroys competition. In their view, commerce has two dimensions; on the one hand, social benefits stem from rigorous environmental standards; on the other hand, the private costs of preventive and clearing industries that lead to higher prices and lower competition (Porter & Van der Linde, 1995), but Porter believes that if environmental standards are properly designed, it can stimulate innovation

that offsets part or more of the costs of compliance. This “innovation cost compensation” can not only decrease the net cost of enforcing ecological regulation, but it also can initiate total advantages over external firms that are not subject to similar regulations. Compensating for innovation costs is common because reducing trash often results in improved resource efficiency and thus offsets the cost of innovation. Briefly, firms benefit from well-designed environmental regulations than competitors in other countries. By creating innovation, stricter environmental rules can increase competition (Porter & Van der Linde, 1995), and by properly managing environmental variables can gain a competitive advantage (Shrivastava, 1995). Of course, the best environmental management practices generally do not lead to a competitive advantage for all companies. There are doubts about the best environmental management practices that are meant to protect the environment and increase competition. Studies also indicate that firms must have complementary assets, including capabilities and abilities to implement innovation, to create a competitive advantage. Therefore, it is important to utilize the environmental strategies, resources, and capabilities of the company (Christmann, 2000). As econometric estimates show, improving technology capabilities (“knowledge capital”) by research and development leads to an innovation environment. Environmental regulations, environmental management tools, and general organizational change also encourage environmental innovation (Horbach, 2008).

Eco-friendly technologies at the company level provide new opportunities for competitive advantage. Environmental technologies at the industry level affect basic costs such as resource use, energy consumption, production efficiency, waste disposal, and pollution reduction. At the company level, these technologies enable businesses to generate new commodity marketplaces and change customer demand in current markets. As a result, environmental technologies are a tool for influencing market share. By creating environmental concerns, companies can attract new customers, improve customer loyalty, and expand demand for all products. As environmental technologies reduce the environmental impacts of the manufacturing process and increase the competitiveness of firms, it identifies the fundamental orientations of management processes (Shrivastava, 1995). Also, three interconnected environmental strategies (pollution prevention, product stewardship, and sustainable development) will lead to sustainable competitive advantage for companies (Hart & Hart, 2013). Environmental policies such as (emission standards, pollution taxes, marketable quotas, and subsidies), on the technical changes of corporations (Kemp, 1997) and technology push such as (product quality, raw material efficiency, etc.) affect environmental innovations (Rennings, 2000), these are themselves the key to achieving sustainable development (Kemp, 1997).

4.7.2. Cluster B: Development of sustainable technologies

Cluster B includes 8 articles and 2 book publications, labeled as “*Development of sustainable technologies*”. In this cluster, publications are about the aspects that impact the development of sustainable technologies. These include: creating innovation systems (Carlsson & Stankiewicz, 1991; Hekkert et al., 2007), enhancing absorption capacity (Cohen & Levinthal, 1990), designing strategic niche management (Kemp et al., 1998).

Carlsson and Stankiewicz argue that the development potential of countries has an impact on their economic growth and is a function of technological systems (Carlsson & Stankiewicz, 1991). The technology system is a dynamic network of factors that interact with one another in a definite fiscal and manufacturing zone, under a specific institutional infrastructure, and participate in the production, distribution, and exploitation of technology. Technological systems are defined as the flow of knowledge and competence. Such networks lead to synergies between companies and technologies and create new job opportunities. In this way, Cohen and Levinthal introduced the concept of absorption capacity. Absorption capacity, meaning, dynamic capabilities and supplements (Cohen & Levinthal, 1990). The ability of a company to recognize the value of external and new information; the ability to absorb that information; and to exploit this information during decision making. Also, organizational capability is required to adopt innovation. Hekkert et al. also, recognize innovation systems as crucial determinants of technological change and provide

a framework for innovation systems' function in sustainable technology development (Hekkert et al., 2007). The "functions of innovation systems" framework, focuses on the most important processes in the system to successfully lead to technology development and technology diffusion. It is like having an innovation system for certain technologies such as renewable energy technologies that will lead to the success of disseminating these technologies by studying the competition between different ways of energy supply (Jacobsson & Johnson, 2000).

Sustainable technologies that can meet the basic needs of the user in terms of efficiency and cost are not available in the market, or these technologies are not attractive to the market (Kemp et al., 1998). According to Rogers' findings, innovations must have 5 features to be noticed and used. These features include relative advantage, compatibility, complexity, observability, and trialability so that users can exploit them (Rogers, 2003). As a result, Kemp proposes a strategic niche management approach to exploit sustainable technologies and produce such technologies by manufacturers (Kemp et al., 1998).

4.7.3. Cluster C: Environmental policy tools

Cluster C includes 8 articles and a book publication, labeled as "Environmental policy tools". For the past ten years, the relationship between technology developments and environmental policies has been the focus of policymakers. Approximately most research on the relationship between environmental policy and technology change is tied to two realities: First, the environmental impacts of social activities are largely influenced by the rate and direction of technological change. Second, their environmental policy interventions create new constraints and incentives that influence the process of technological progress (Jaffe et al., 2002). Milliman and Prince provide five incentives to use advanced pollution abatement technologies: direct control, emission subsidies, emission taxes, free marketable permits, and auctioned marketable permits (Milliman & Prince, 1989). According to studies by to Milliman and Prince approximating emission taxes on emissions and auctioned permits is the company's highest incentive to promote technological change. Free permits and direct controls provide the least relative incentives for technology upgrades. Another comprehensive study by (Jung et al., 1996) is that in addition to those mentioned by Milliman and Prince performance standards have also been added to environmental policy tools for the development and adoption of advanced pollution abatement technologies in various industries (Milliman & Prince, 1989). These standards vary between companies before adopting technology to minimize pollution control costs. In these two articles, the authors conclude that environmental policy tools can be ranked as follows: (1) auctioned permits, (2) taxes and subsidies, (3) free permits, and (4) emission standards. Requate and Unold re-examined the ratings of the two articles above and found that taxes are stronger incentives than permits, auction and free permits provide the same incentives, and standards may be stronger incentives than permits (Requate & Unold, 2003). Contrary to Requate and Unold remarks on taxation that give companies greater incentives to use clean technologies. Krass et al. (2013), has found that corporate responses to taxation are not the same. Their study shows that different levels of taxation can have different reactions from companies. High levels of taxation may even cause more pollution than clean technology. Tax levels that lead to social welfare can simultaneously lead to the choice of clean technology and reduce this gap. However, different levels of taxation have different effects on the corporate response (Krass et al., 2013).

Johnstone et al., explored different types of policy tools for renewable energy sources. Their empirical results indicate that public policy has had a significant impact on the development of new technologies in the field of renewable energy between 1978-2003. In OECD countries, significant changes have been made in the public policy framework to use renewable energy. These policies initially include R&D programs, investment incentives, tax incentives, preferential tariffs, voluntary programs, and ultimately, quantitative obligations, tradable certificates. Interestingly, different policy instruments have different impacts on renewable energies. Therefore, understanding these differences is important for government policy. For example, investment incentives are effective in supporting innovation in solar and waste technologies, tariff structures for biomass,

obligations and tradable certifications in support of wind technology are effective in supporting innovation in solar and waste technologies. Volunteer programs also help with waste-energy innovations. In general, in the field of energy innovation, tax incentives alone have a widespread impact on the innovation for many renewable energy sources (Johnstone et al., 2010).

4.7.4. Cluster D: Undesirable output solutions

Cluster D includes 3 articles and labeled as “*Undesirable output solutions*”. The output and the end product of any industry include desirable marketable goods and undesirable products such as pollution. To eliminate such an undesirable output, Chung et al. have introduced an index called Malmquist-Luenberger, which solves the problem of co-producing desirable and undesirable outputs and provides a practical management tool (Chung et al., 1997). Acemoglu et al., on the other hand, proposes endogenous changes in his studies to eliminate undesirable output (Acemoglu et al., 2012). For example, if one part uses dirty machinery, the output will also be affected, so one of the endogenous changes could be to improve the machinery technology of each part. As can be seen in the articles, environmental laws and regulations are driving innovation in industrial enterprises. Porter and Van Der Linde has also argued that if a country adopts stricter environmental regulations than its competitors, the increase in innovation in that country will make it an exporter of new and more developed environmental technologies (Porter & Van der Linde, 1995). This view is known as “Porter’s Hypothesis”. According to Porter and Van Der Linde, environmental laws and regulations stimulate innovation in the organization and, as a result, create environmental innovations, resulting in the company’s competitive advantage over foreign competitors. Environmentalists, like Michael Porter, argue that stricter environmental laws and regulations are one of the incentives for firms to create new ways of production and lower-cost ways to reduce pollution. This will ultimately reduce production costs (Porter & Van der Linde, 1995). Jaffe and Palmer by examining Porter’s hypothesis stated that spending on environmental adaptation has a positive and significant relationship with R&D spending. The results of their research in the manufacturing industry show that R&D expenditures also increase shortly after rising costs of environmental compliance (Jaffe & Palmer, 1997).

4.7.5. Cluster E: Innovative environmental activities

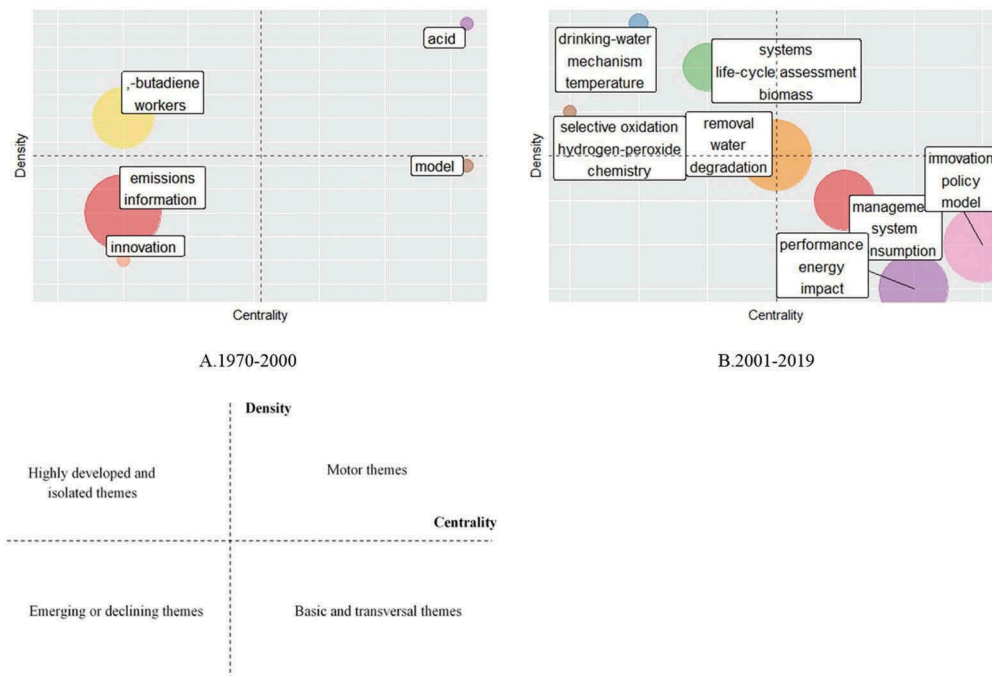
Cluster E includes an article and a report and labeled as “*Innovative environmental activities*”. As noted in cluster B, innovation systems were introduced to create and implement environmental innovations, and Dosi and Nelson argue that the rate and direction of innovative activities depend on technology push, market pull, and the role of institutions (Dosi & Nelson, 2016). On the other hand, they point out that there is a serious relationship between innovative activities and economic growth. As discussed in cluster A, the competitive and economic advantages of innovative environmental activities, the WCED also emphasizes sustainable development as a holistic approach that promotes development in ways that do not harm the environment or endanger natural resources as they become available in the future. The report adds that these conditions are not only compatible with environmental policies, but also with economic and social policies (WCED, 1987).

5. Intended of themes

It seems unlikely that many keywords that appear only a few times will have a major impact on the core themes of *sustainable technology*. To focus on the main themes, only keywords that have been repeated at least twice have been included in the analysis. To identify the most prominent sustainable technology topics for each sub-period (1970–2000 and 2001–2019), strategic charts were created using *Bibliometrix*®, which is illustrated in Figure 5.

Highly related keywords are grouped in clusters and the subject is named by the keyword with the highest rank (Wang, Qu, et al., 2019). According to Colon et al. (Callon et al., 1991), parts A and B of Figure 4 represent four quadrants containing several types of themes (Cobo et al., 2011). The theme of the first quarter is a *motor theme*. The themes are highly concentrated and have good inner and external relations. The theme of the second quarter is *highly developed-and-isolated*. In

Figure 5. Strategic diagrams in sustainable technology.



this quarter, the themes are low-concentration and high-density, indicating good internal links between themes and external links are very important. The third quarter has the theme of *emerging-or-declining*. In this quarter, the themes are both low concentration and low density, indicating weak internal and external relationships. The fourth quarter of the *basic-and-transversal* theme contains themes of high concentration and low density that represent themes with weak internal links but important external links (Cobo et al., 2011).

The analysis of the drawn strategic map shows that the themes with the highest number of documents and citations fall into the first or fourth quarters. Considering Table 7, in 1970–2000, acid with two total studies and 361 total citations were in the first quarter (*motor theme*) and the model with two total studies and 83 total citations in the fourth quarter (*basic and transverse themes*). In 2001–2019, “management”, “system”, “consumption” were placed in the fourth quarter (*Basic and transversal themes*) of the strategy map due to the high number of publications and citations.

In any given time, the number of keywords is not the same. Keywords evolve to describe the content of sustainable technology documents. Over time, with the emergence of new topics in this field, the related keywords appear and previous keywords disappear. Some of these keywords will remain unchanged and will be addressed in later periods. For example, innovation, the model, but other themes such as butadiene, workers, information, and emissions were only in the previous period and disappeared in the new period. And some themes, such as policy, management, system, performance, Consumption, energy, impact, life cycle assessment, biomass, removal, water, degradation, chemistry, drinking-water, mechanism, Temperature, selective oxidation, hydrogen-peroxide are new themes that have only emerged in the new era, reflecting the emergence of new topics in technology.

6. Discussion

The purpose of the present study is to conduct a BR to gain a better understanding of sustainable technology. Due to the increasing trend of publishing and citing articles in this field, the analysis of our sample in the present study will lead to an increased interest in this research topic.

Table 7. Themes in sustainable technology from 1970 to 2019

Theme name	1970–2000				2001–2019			
	TS	TC	TC/TS	Theme name	TS	TC	TC/TS	
Emissions	3	435	145	Management	23	222	9.7	
Information	2	36	18	System	15	119	7.9	
Acid	2	361	180.5	Consumption	11	151	13.7	
Model	2	83	41.5	Design	11	100	9.1	
Innovation	2	26	13	Climate-change	8	74	9.3	
1,3-butadiene	2	3	1.5	Models	8	90	11.3	
Workers	2	3	1.5	Drinking-water	5	142	28.4	
				Mechanism	4	21	5.3	
				Temperature	4	91	22.8	
				Escherichia-coli o157-h7	3	16	5.3	

This research has three main contributions. Primary it shows the number of sustainable technology publications per year, and then detects the influence of particular authors, journals, countries, and articles on sustainable technology. This profile of literature provides a comprehensive introduction to sustainable technology literature for future researchers. Secondary, this paper, using document co-citation analysis, classifies five main focus parts that present sub-domains of the extended sustainable technology research. These five clusters include environmental innovation as a competitive advantage, development of sustainable technologies, environmental policy tools and incentives to exploit renewable technologies, innovation for the undesirable outputs of industrial enterprises, and Innovative environmental activities.

In general, in most documents, sustainable technology innovation is emphasized as a competitive advantage (Porter & Van der Linde, 1995). Various factors were identified to stimulate innovation in the field of sustainable and environmental technology. Environmental laws and regulations (Horbach, 2008), complementary assets such as resources and technical capabilities of the company (Christmann, 2000), next is environmental policies that lead to innovation and policy tools that are used as incentives for the use of sustainable and environmental technologies in organizations. Different categories of these tools have been developed by the authors. Some of them are mentioned: 1) emission standards, pollution taxes, marketable quotas and subsidies (Kemp, 1997, p. 2) direct control, emission subsidies, emission taxes, free marketable permits, and auctioned marketable permits (Milliman & Prince, 1989, p. 3) auctioned permits, emissions taxes, and subsidies, issued marketable permits, performance standards (Jung et al., 1996), and some of the public policies developed in OECD countries for the use of renewable energies, such as R&D programs, investment incentives, tax incentives, preferential tariffs, voluntary programs, and ultimately, quantitative obligations, tradable certificates (Johnstone et al., 2010).

Organizations need to consider several factors for the creation and development of sustainable technologies. These factors include enhancing absorption capacity (Cohen & Levinthal, 1990), designing strategic niche management (Kemp et al., 1998), creating innovation systems (Carlsson & Stankiewicz, 1991; Hekkert et al., 2007), and creating technological systems (Carlsson & Stankiewicz, 1991). Dosi and Nelson (2016) have also stated that technology push, market pull, institution's role has a significant impact on creating innovative activities within the organization. Some researchers have also proposed two ways to prevent undesirable outcomes such as contamination with organizations. These two methods are Malmquist-Luenberger index, endogenous changes (Acemoglu et al., 2012; Chung et al., 1997).

In addition to the articles reviewed in the areas mentioned, some recent articles on sustainable technologies, green technologies, clean technologies, renewable energy technologies and environmental technologies have also been studied, topics discussed in recent articles involves, evaluating the efficiency of such technologies using the Malmquist-Luenberger index (Feng & Wang, 2018; Luo et al., 2019; Mardani et al., 2017), examining the impact of green innovations on materials use (Wendler, 2019), exploring ways to reduce pollution and waste (Bruscato et al., 2019), toxic and organic micro-pollutants (Jankovic et al., 2019), the need to use sustainable technologies such as carbon capture in the oil and coal exploitation process to reduce pollution (Sarkodie & Ozturk, 2020), and also, the need to use low-carbon technologies to meet international climate change agreements (Romano & Fumagalli, 2018), optimizing green technologies (Kumar et al., 2019), investigating the effects of government policies such as emission taxes on green innovation (Langinier & Ray Chaudhuri, 2019), reviewing optimal green technology innovation strategies in local governments and companies (Deng et al., 2019), investing in green technologies (Zhou et al., 2019), and R&D investments in green technology to develop these technologies (Lee et al., 2015), the amount of sustainable technologies consumed and the importance of training in adopting these technologies (Ninh et al., 2019).

Recent articles, such as those considered in clusters, show that companies are still concerned about investing in these technologies, innovating and using them more to reduce pollution and

waste. Recent articles also point to the various policies and incentives governments use to make the most of their companies by using sustainable technologies and green and environmental innovations. Given the content of these articles, although recent articles overlap with the cited articles in the clusters under study, some of the new issues in the field of sustainable technologies have been overlooked, including issues of converting solid waste to energy (Mukherjee et al., 2020), the issue of commercialization of emerging green technologies that are essential to improving the sustainability of industrial processes (Tan et al., 2019), how to commercialize renewable energy technologies (Shakeel et al., 2017), how governments support commercialization and the drivers and barriers to commercialization (Meijer et al., 2019), and of course funding the development of new technologies as a serious obstacle to their commercialization (Tan et al., 2019), modernizing the energy sector towards the use of renewable resources and the deployment of “green technologies” that require large quantities of raw materials, some of which are at high risk for supply (Valero et al., 2018). Investigations in clusters have mentioned investment in this area, but little attention has been paid to uncertainty as one of the most important factors in investment decisions (Romano & Fumagalli, 2018).

The third main contribution is the analysis of strategic keyword diagrams. This diagram illustrates the evolution of the literature on sustainable technology in 1970–2000 and 2001–2019 shows that some keywords in the basic and transversal themes are due to a large number of publications and some of them fall into the motor themes due to a large number of citations. It also shows that some of the words that existed in the literature on sustainable technology in 1970–2000 disappeared in the years 2001–2019, reflecting the evolution of literature in this field. Several other words have also recently appeared in 2001–2019 period and some have remained unchanged during these two periods.

7. Conclusion

This study investigates sustainable technology research between 1970 – 2019 using bibliographic analysis. In this study, the performance of publications of authors, journals, and countries is evaluated. This paper presents a BR of sustainable technology research to identify areas within which scholars are studying sustainable technology, the trend of total documents from year to year, the language of publication, the most cited and prolific authors of sustainable technology and the most appropriate journals for literature review. Furthermore, this paper analyzed the co-citation networks of the cited references. This study provides insights by reviewing the literature and summarizing existing research.

The BR of sustainable technology research documents collected from the WOS database. The most common language for the document is in English (1122 documents), the area with most published documents is environmental sciences (262 documents). The first record about sustainable technology appears in 1970, but only after 2003 the concept attracted researchers and since that time the number of publications in this field has been increasing reaching 1122 documents published in 2019 (October). The country that has done a lot of sustainable technology research is the USA (271 publications). The journal that has published the most on sustainable technology research is the “Journal of Cleaner Production” (31 documents), which has an impact factor of 6.395. The most productive sustainable technology author is Park, Sangsung (8 documents and 569 citations). This review shows that the co-citation network of references revealed five clusters; environmental innovation as a competitive advantage, development of sustainable technologies, environmental policy tools and incentives to exploit renewable technologies, innovation for the undesirable outputs of industrial enterprises, and innovative environmental activities.

8. Limitations and future research direction

Our research has some limitations. One of the limitations is the use of the WoS database. Although the WoS database is very comprehensive and valid, it is better to use other databases, including Scopus or Google Scholar. Another limitation is that our research includes publications in English, and it is recommended that future research include documents published in other languages. In

reviewing articles, authors, journals, countries, most prominent and most influential were screened and arranged according to the number of publications; then, publications with only one document but with high citations may be overlooked. In future research, it is suggested to be arranged and examined based on the number of citations.

Funding

The authors received no direct funding for this research.

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Citation information

Cite this article as: A bibliometric study of sustainable technology research, Morteza Akbari, Maryam Khodayari, Mozhgan Danesh, Ali Davari & Hamid Padash, *Cogent Business & Management* (2020), 7: 1751906.

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