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Sustainability and Data Envelopment Analysis: A bibliometric review

Sustentabilidade e Análise Envoltória de Dados: Um estudo bibliométrico

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Authors' notes

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Abstract

Environmental management is important for all nations in terms of sustainable development. Several methods were created to analyze the environmental sustainability, being the Data Envelopment Analysis (DEA) one of the main approaches. However, there is no consensus on the best models and variables to build sustainable indicators. This article aims to map the literature of DEA sustainable indicators through a bibliometric analysis, searching 6,330 articles on the Web of Science. Our main finding revealed 10 clusters and the existence of several authors and journals, although the publications are concentrated on few relevant ones. Also, the DEA models analysis reveals the model CRS stands out, representing 24% of the sample, followed by CRS and VRS with 12%. We also observed that the trend topics "innovation", "empirical evidence" and "urbanization" were the most approached in the last four years. This study provides a platform for future research in Sustainability and DEA.

Keywords: Data Envelopment Analysis, environmental efficiency, indicators, bibliometric review

Resumo

Sustentabilidade e Análise Envoltória de Dados: Um estudo bibliométrico

A gestão ambiental é importante para todas as nações em termos de desenvolvimento sustentável. Vários métodos foram criados para analisar a sustentabilidade ambiental, sendo a Análise Envoltória de Dados (DEA) uma das principais abordagens. No entanto, não há consenso sobre os melhores modelos e variáveis para construir indicadores sustentáveis. Este artigo tem como objetivo mapear a literatura de indicadores sustentáveis da DEA por meio de uma análise bibliométrica, buscando 6.330 artigos na Web of Science. O principal resultado revelou 10 clusters e a existência de vários autores e periódicos, embora as publicações estejam concentradas em poucas revistas. A análise dos modelos de DEA revela que o modelo CRS se destaca, representando 24% da amostra, seguido por CRS e VRS com 12%. Observa-se que os tópicos de tendência "inovação", "evidência empírica" e "urbanização" foram os mais abordados nos últimos quatro anos. Este estudo fornece uma plataforma para futuras pesquisas em sustentabilidade.

Palavras-chave: Análise Envoltória de Dados, eficiência ambiental, indicadores, bibliometria

1 Introduction

Countries face the challenge of promoting economic growth without environmental damage. In this regard, the topic of sustainability has been discussed in several articles (Klewitz and Hansen, 2014; Govindan et al., 2013; Geissdoerfer et al., 2017; Hahn and Kühnen, 2013; Parlasca and Qaim, 2022; Bibri et al., 2024), being also the main topic in meetings between policymakers of several countries and multilateral organizations (United Nations - UN, World Bank, etc.). The Paris Agreement is one of the most recent examples, in which countries declared Intended Nationally Determined Contributions (INDCs) outlining their post-2020 climate actions to limit global warming to 1.5 degrees Celsius (UNFCCC, 2015).

Countries can use an accounting approach of their choice in their INDCs, such as the inclusion of emissions and removals of CO2 related to land use or any other sector, as used by Brazil and the United States of America (Rogelj et al., 2016). The relevance of this theme can also be seen in the Sustainable Development Goals (SDGs), formulated by the United Nations Rio+20 Summit in Brazil in 2012 (UN, 2012). This approach increases public and political support and channels funds effectively to urgent global issues (Griggs et al., 2013).

However, there are many indicators on the subject that have already been created, but there is no organization of this literature to know which communities treat these indicators. In this sense, this article reveals the clusters of this research community, contributing to the organization of the research community by describing our bibliometrics findings. Addtionaly, our bibliometric analysis through the WoS database also contribute to the following aspects:

a) mapping the main sources, documents, authors and the publication growth by year; b) presenting the trend topics of the research community and; c) revealing the research clusters and the DEA models used in the studies.

There are some articles that have been published previously to organize the literature in the area of DEA and sustainability, note that Mardani et al. (2018) shows an overview of the application of DEA models in the fields of environmental and energy economics, Yu and He (2020) introduces an overview of all publications published until 2018 about energy efficiency based on DEA and Zhou et al. (2021) review the literature on DEA applications in sustainability using citation-based approaches. However, our article distances itself from the previous ones because carries out a bibliometric analysis of sustainability in general and describes ten co-citation clusters.

2 Literature Review

2.1 Sustainability

The importance of sustainability stemmed from the depletion of natural resources, concerns about wealth disparity, and pressures on corporate social responsibility (Bocken et al., 2014). Therefore, the broad definition of sustainability guarantees that the use of natural resources and the human cycle does not lead to the minimization of the quality of life of current and future generations (Govindan et al., 2013). To Ahi and Searcy (2013), the definition of sustainability is ambiguous and can be challenging when attempting to apply its principles in practice. Such ambiguity is contextualized by the authors due to the complexity that the theme incorporated, passing through environmental concern and covering today's environmental and social aspects.

According to Dyllick and Hockerts (2002), sustainability can be defined at the institutional level as the management actions of organizations that strive to balance environmental, social, and economic objectives. For the authors, this balance would result in less environmental damage without compromising the economic benefits for society. In the current globalized world, a collaboration between organizations and all their stakeholders is essential to achieve sustainability (Bocken et al., 2014). From the governmental perspective, sustainability is a crucial issue for policymakers and researchers to ensure sustainable performance (Čuček et al., 2012). Glavič and Lukman (2007) emphasize that the definitions of sustainability and its interfaces with other themes are essential to ensure the development of a sustainable society, and so, those interested in sustainability must elaborate a straightforward definition for this theme to face sustainable development challenges.

Linked to the sustainability concept, the rise of the theme of sustainable development can be observed. The concept is interdisciplinary, as is sustainability, and is based on the balance between ecological, economic, and social values (Boons and Lüdeke-Freund, 2013). This nomenclature was registered for the first time at the United Nations Conference on the

Human Environment in 1972. The definitions of sustainable development are divers, however, they are usually similar to the definition given by the Brundtland Commission (1987): 'development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs' (WCED, 1987, Ch. 2, p. 1). It is noteworthy that the political dimensions are a central part of the debate on sustainable development. Consequently, the theme has been receiving the attention of several governments (Glavič and Lukman, 2007). Due to such circumstances, there is a constant concern in actions developed by global institutions, such as the United Nations. Sustainability is a broad field of study that needs to be explored, considering its dimensions and interfaces with other themes. The importance of sustainability in the current context is considered the only way out for an acceptable society.

Another similarity between sustainability and sustainable development is the social, environmental, and economic dimensions called the Triple Bottom Line (TBL) (Govindan et al., 2013). The triple bottom line term was coined by business consultant John Elkington in the mid-90s to show that organizations need to positively impact the environment and society, going beyond the search for economic performance. Therefore, the organization will be assuming its responsibility concerning economic prosperity, environmental quality, and social justice (Bai and Sarkis, 2010; Furlan and Mariano, 2022). Schulz and Flanigan (2016) recognized that is difficult accurately quantify and evaluate all three dimensions of TBL, specially the social and environmental dimensions.

The challenge present in the sustainability approach of transforming an interdisciplinary concept into quantitative measures has an important challenge that is how researchers might translate a complex concept into a single indicator, which must be straightforward and useful for policymakers. In most publications, the indicators are organized around the "triple bottom line" (Roca and Searcy, 2012). For example, Azapagic (2004) points out that sustainability indicators allow sustainable measures to be quantifiable, providing a path for organizations and governments to follow their strategies. The authors conclude that indicators developed for this area need to translate relevant sustainability issues into representative performance measures. Some researchers developed studies that aimed to analyze sustainability quantitatively. For example, Bauler et al. (2007) analyze the sustainability indicators available in the literature and their challenges and approaches. Ness et al. (2007) assessed sustainability in indicators, product-related assessments, and integrated assessment tools.

2.2 DEA and the Environmental Issues

The method called DEA is based on mathematical procedures, such as linear programming, to analyze the weights that expand the efficiency of decision making units

(DMUs). This method allowed the application of several models and extensions, even in research on human development (Mariano et al., 2015). The use of DEA allows the insertion of several inputs and outputs containing a single value. However, there is no need to transform them into a standard measure, and the type of scale return used will characterize the CRS, and Variable Return to Scale (VRS) models (Cooper et al., 2007).

Charnes et al. (1984) developed the model that was the first to analyze constant returns and variable returns to scale. This model allowed the advancement of other methodologies, such as the Slack Based Measure (SBM), Russell Measure (RM), and even another model developed by Charnes et al. (1987), originating from a geometric combination between variables. One of the uses of the DEA is the measurement of sustainable development, allowing the identification of multidimensional efficiency problems, direct interpretations in a single index, and winning the interest of decision-makers (Chaaban et al., 2016). The choice for DEA is justified by allowing the weights to be chosen endogenously (Chaaban et al., 2016).

According to the research carried out by Ferraz et al. (2020), several authors are using the DEA to measure social and environmental issues in their studies. The authors point out that the works of Mahlberg and Obersteiner (2001), Despotis (2005), Tofallis (2013), and Zhou et al. (2010) used the DEA to recalculate the HDI and analyze human and environmental development. Such repercussion is given by the DEA efficiency measures integrated with environmental technology, which have the property of measuring environmental performance (Zhou et al., 2007).

Färe et al. (2004) discussed the environmental performance index which was calculated using DEA tools. The authors used distance functions to formulate the index, allowing them to only attach information on the input and output quantities. The method developed by the academics was applied to a sample of Organization for Economic Cooperation and Development (OECD) countries. Zaim (2004) aimed to develop a new definition of pollution intensity. According to the author, traditional indices do not consider pollution as a by-product of manufacturing activity. Therefore, the research provides a new index using the Malmquist quantity index modification. The index also allows for the comparison of pollution levels over time.

Zhou et al. (2007) claim that most studies use the DEA technique through radial efficiency models. Thus, the authors developed a non-radial DEA approach to measure environmental performance in their studies, filling a gap in the literature. The model developed by the authors allows for multilateral comparisons of environmental performance and provides a Malmquist environmental performance index. Research by Zhou et al. (2010) also introduces a non-radial DEA methodology and develops a Malmquist CO_2 emission

performance index. These tools allow measuring changes in carbon emission performance over time.

3 Method

In order to map the intellectual territory concerning the use of DEA approach under the sustainability literature, we adopted a bibliometric analysis with quantitative synthesis. Such combination provides a large-scale set of scientific data in a knowledge domain, allowing researchers to establish intellectual connections in the searched field and indicate the main trends. Our articles selection involved only papers from peer-reviewed journals, aiming at a sample of publications with a higher academic impact.

The database used for the collection of bibliographic material was ISI Web of Knowledge, also called WoS, which is internationally recognized among researchers for having high-quality standards (Gaviria-Marin et al., 2019) and indexing a large set of academic studies from highly respected journals all over the world (Gumus et al., 2018). The WoS database has become one of the main tools for researching and evaluating different types of journals and publications (Gaviria-Marin et al., 2019); being used by many notable bibliometric studies (Gonçalves, 2019; Lampe and Hilgers, 2015; Albort-Morant and Ribeiro-Soriano, 2016; Fetscherin and Heinrich, 2015). WoS indexes more than 15,000 journals and 50 million articles (Bonilla et al., 2015). Furthermore, it includes a set of metadata (Gaviria-Marin et al., 2019) to obtain information needed for analyses (Gumus et al., 2018).

For research reproducibility, it should be noted that the data was collected during October 2021. The selection of keywords for the research was based on the preliminary readings of the most recent and cited articles on the subject and published in high-impact journals, we also selected terms linked to the main dimensions of indicators such as environmental performance and ecological footprint. The search terms resulted in the search phrase as shown in Table 1.

Table 1

Keywords

Group	Keywords
Group 1	"Data Envelopment Analysis" OR "DEA"
AND	
Group 2	sustainab* OR environmental* OR "air* qualit*" OR sanitation OR wastewater* OR water* OR freshwater OR "heavy metal*" OR "waste management" OR biodiversity OR habitat* OR "climate change" OR pollut* OR "greenhouse gas" OR agriculture OR biocapacit* OR natur* OR carbon* OR CO2 OR "land use" OR forest* OR pasture* OR fisheries OR energ* OR renewabl* OR emission* OR ecolog* OR "green growth" OR "green development" OR "green innovat*" OR "green product*" OR ecoefficiency OR eco-efficiency OR "eco efficiency"

Source: The authors.

Note that "*" replaces one or more characters of an expression, for instance, "sustainab" includes the expressions "sustainable" and "sustainability".

Some terms were used in Group 1 to exclude articles from other areas such as "desethylatrazine", "diethylamine", and "diethanolamine". In WoS, this search was conducted in the title, abstract and keywords. The results of this search generated an initial set of documents. We excluded those that did not fit the criteria of articles written in English and selected the categories related to this research such as Engineering, Environmental studies, Political science, and Economics.

Subsequently we conducted a quantitative analysis of the data. Aiming to find journals with the highest quantity of publications, authors with the most papers published, the evolution of the number of papers on the theme over the years, and the most cited papers discussing the research topic.

We also carried out an analysis of the citation network with the assistance of the VOS Viewer and Biblioshiny tools, which enabled the formation of a citation network, with the formation of clusters that group papers with more links. The citation analysis allowed a broader perspective of the field of the theme study by viewing works with greater affinity to each other, offering a classification of publications according to their themes. The trend topics analysis also contributes to map themes within the study field, since identifying terms are often used together in articles.

4 Results

4.1 Most Relevant Sources

Firstly, this review investigates the leading journals that published studies related to environmental DEA indicators. We found 1,239 journals with articles in the theme, with only 598 (48%) of these journals contained more than one document. Figure 1 shows the most important journals in the area, with 15 journals with seventy or more articles which represents 34% of the total number of articles in the sample. Beyond the Journal of Cleaner

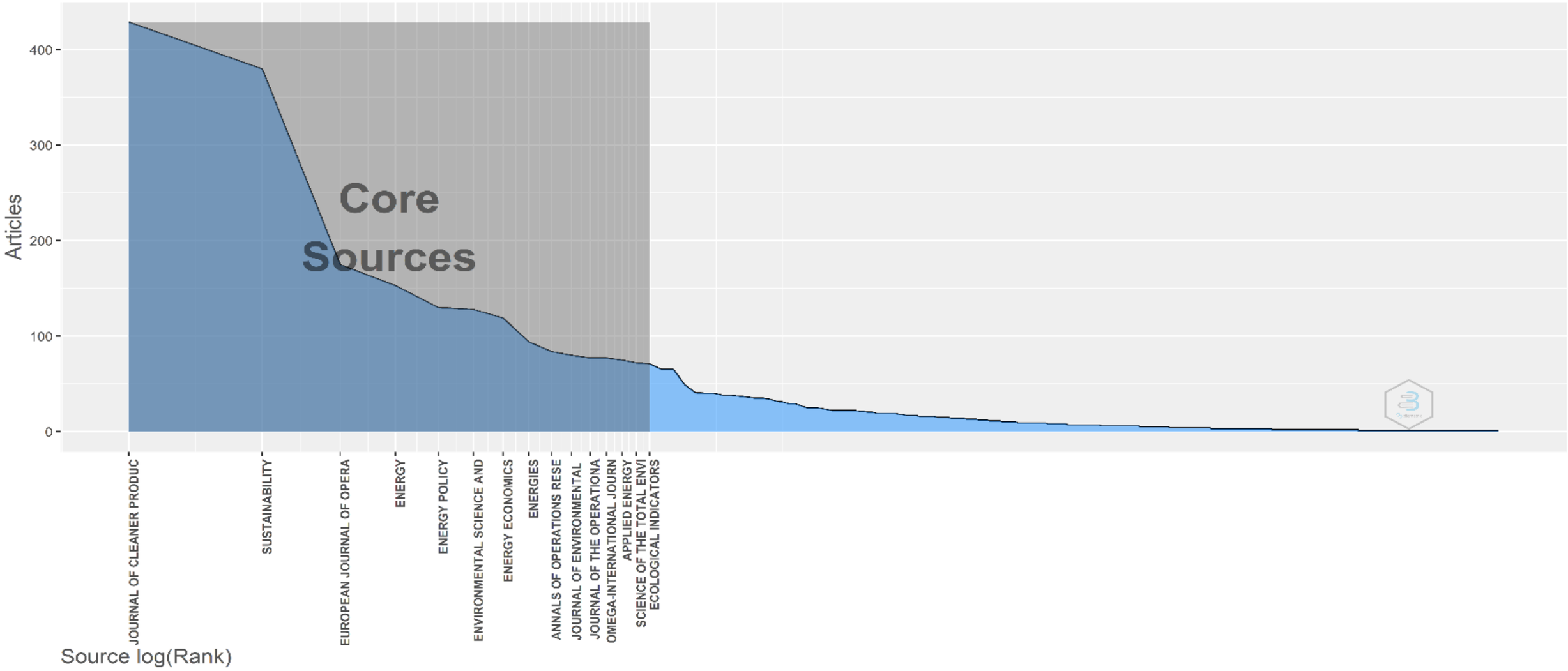
Production with 7% of the articles in the sample and Sustainability with 6% of the articles, other relevant journals for the area are European Journal of Operational Research (3%), and Energy and Energy Policy (2%).

We made an analysis of the most relevant journals over time and figured out that, in 1991, the European Journal of Operational Research published the first paper exploring this subject, entitled 'A Data Envelopment Analytic Model for Assessing the Relative Efficiency of the Selling Function'. Only in 2017, the Journal of Cleaner Production published its first study on the theme and 15 years later, the Journal of Cleaner Production overcame the European Journal of Operational Research in number of publications.

Note that the Journal of Cleaner Production is a recognized scientific journal focused on cleaner production, environmental, and sustainability research and practice. It explores several subject areas, such as energy efficiency, climate change, pollution reduction, eco-efficiency, sustainability indicators. In this sense, our study reveals that studies published on the Journal of Cleaner Production has been using the DEA as one of the most significant methods to measure indicators for the sustainability issue, among others like Stochasctic Frontier Analysis (SFA), life cycle assessment (LCA), multi-criteria decision analysis (MCDA), sustainable business model (SBM), circular economy (CE) model, delphi method, multi-attribute utility model.

Figure 1

Bradford's Law



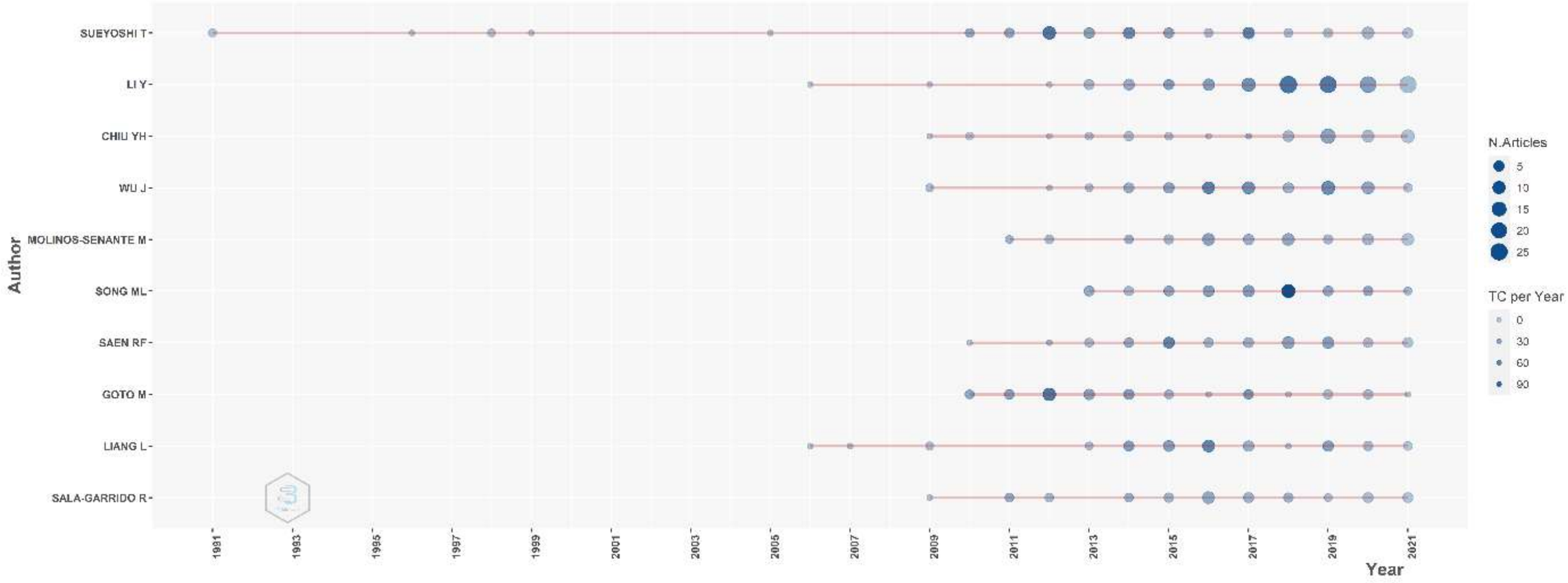
Source: The authors.

4.2 Authors Production

We identified the authors with the more published studies over time from the sample based on the theme. This is important to map the main authors and the most renowned scientists that discuss the theme with their H index. Figure 2 illustrates the authors' production (in terms of the number of publications and total citations per year).

Figure 2

Top Authors' Productivity over the time



Source: The authors.

Toshiyuki Sueyoshi dedicates himself to studies on solid-state physics, spectroscopy, physical chemistry, and catalysis (Research Gate, 2022). He published 2 articles in 1991, which received 47 citations. After a five-year hiatus, he published again in 1996. Since then, 2012 has been the year he published the most, with 11 articles and 817 citations in total, putting his H index at 38. His first publication, entitled 'A literature study for DEA applied to energy and environment' summarizes previous research efforts on DEA applied to energy and the environment, including concepts and methodologies on DEA environmental assessment.

Yi Li is a researcher at the University of California, Los Angeles, United States. His research focuses on materials science, chemistry, physics and astronomy, computer science, engineering, and mathematics. His research is of unique relevance to several studies, including research on the carbon-polymer nanotube bilayer electrode (SCOPUS, 2022). His works received numerous citations, constituting an H index of 19. Another important researcher is Yung Ho Chiu, who is a professor at Soochow University in Taiwan. He is dedicated to research in energy savings, quantitative social research, microeconomics, and industrial organization (Research Gate, 2022). The author has about 545 citations between 2009 and 2021 and an H index of 12.

Researcher Jie Wu is a management science and engineering professor at the University of Science and Technology in China. His research focuses on decision analysis and DEA (Google Scholar, 2022). The author has been cited around 1,760 times since 2009, the number of citations being higher each year. His H-index is 23. Maria Molinos Senante is a professor at the Pontifical Catholic University of Chile. Her studies are about DEA, sewage system and Metaborder (Google Scholar, 2022), the author is cited about 1,157 times, with an H index of 20. The Table 2 presents the most local cited article of these authors and its main contributions.

Table 2

Main contributions

Author	Document	Contribution to the research area
Toshiyuki Sueyoshi	SUEYOSHI T, 2017, ENERG ECON	To summarize studies on DEA applied to energy and environment in the last fourty years and discusses three issues as future research tasks.
Yi Li	LI Y, 2013, ENERG POLICY	To model three internal factors (economic structure, energy consumption structure, and technological progress) to compare the impact of each factor on energy intensity, and then discuss the effects of technological progress using the DEA-Malmquist method.
Yung Ho Chiu	CHIU YH, 2015, ENERG SOURCE PART B-a	To find a comparatively fair and efficient allocation method, using a zero sum gains DEA model to explore the allocation of emission allowances.
Jie Wu	WU J, 2016, TRANSPORT RES D-TR E	Measure the energy and environment performance of transportation systems using DEA with the goal of sustainable development.
Maria Molinos Senante	MOLINOS-SENANTE M, 2014, CLEAN TECHNOL ENVIR	To estimate an efficiency scores for each input involved in the operation of WWTPs, a non-radial DEA model has been applied, identifying cost-saving opportunities.

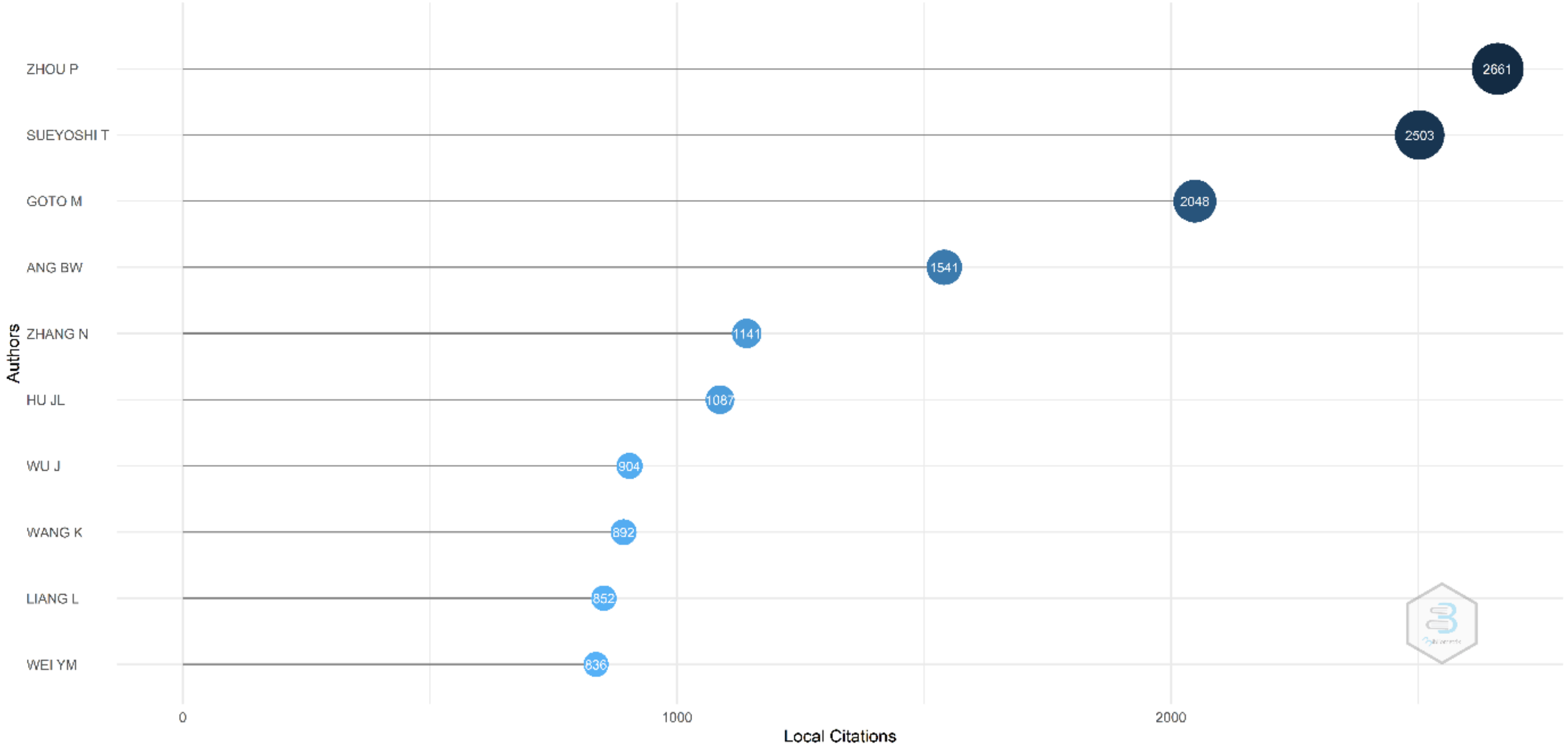
Source: The authors.

Figure 3 illustrates the 10 most cited local authors, who are (1) Peng Zhou (2646), (2) Toshiyuki Sueyoshi (2466), Mika Goto (2018), Beng Wah Ang (1532), Ning Zhang (1134), Jin-Li Hu (1087), the rest did not pass of 898 citations. 11872 authors and 56,8% received 1 or 0 citations.

Peng Zhou contributes to the theme by studying non-radial function modeling energy and CO2 emission performance (non-radial DEA approach to measuring environmental performance), Malmquist CO2 emission performance index for measuring changes in total factor carbon emission performance over time, measuring the carbon emission performance, defining an energy index, decomposing the change of aggregate CO2 emissions over time, DEA models for measuring economy-wide energy efficiency performance, index with higher discriminating power for modeling economic-environmental performance and estimating the impacts of environmental regulations.

Figure 3

Most Local Cited Authors



Source: The authors.

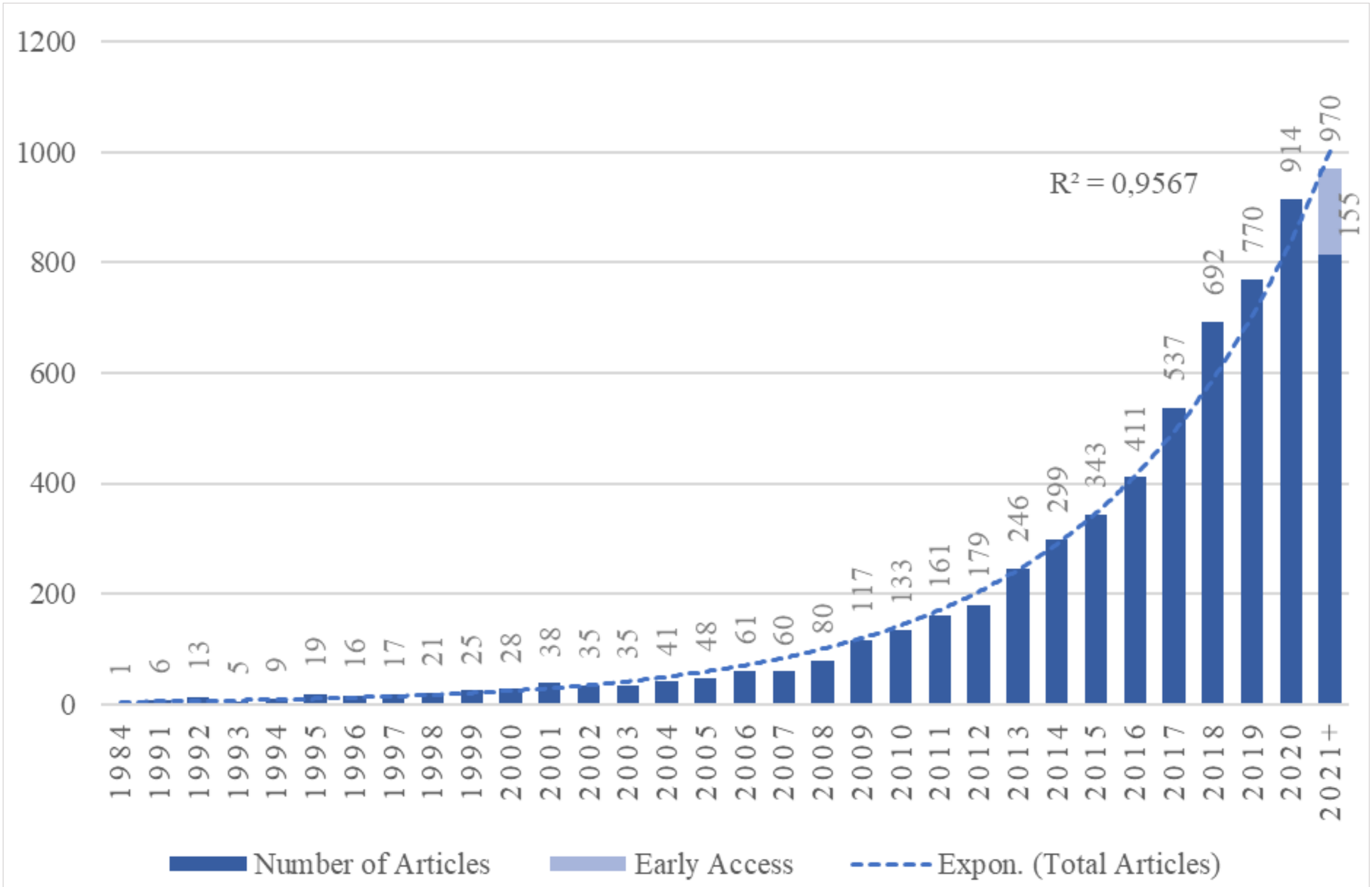
4.3 Most Relevant Documents

Figure 4 presents the evolution of publications over time. The articles are dated between 1984 and 2021 (about 37 years) and show exponential growth over time (the adjustment to a natural exponential function has an R2 of 96%). When analyzing the annual accumulated percentage, the last 10 years account for 87% of the sample. We can see that 155 articles are Document Type Early Access

.

Figure 4

Publication Growth



Source: The authors.

The Publication Growth graph allows us to analyze the distribution of articles published over the years, in this way it is possible to observe the growing number of publications on the theme. Note the importance of observing the graph together with the events of society. In 1972, the Stockholm Conference was held, being the first world conference seeking environmental issues (Mauss, 1972). The Vienna Conference was held in 1985 its established the principles for protecting the ozone layer (Slaper et al., 1996). In 1987, the Brundtland report was published, being the first document that conceptualized the term sustainable development (Keeble, 1988). After this series of events, one can observe the emergence of the first studies on DEA and sustainability, illustrating the emerging need for environmental concerns. Later, in 1992, Rio-92 took place, with the launch of Agenda 21 (Sánchez and Croal, 2012). Then, in 1997, the Kyoto Protocol took place, such protocol established goals and deadlines for countries to reduce their greenhouse gas emissions (Freedman and Jaggi, 2005). At the beginning of the 21st century, in 2000, the United Nations Millennium Summit was organized, the event resulted in the launch of the Millennium Goals (Summit et al., 2000). The compound annual growth rate from 1991 to 2008 is 16%, suggesting that all these events had a positive effect on boosting publications on the subject.

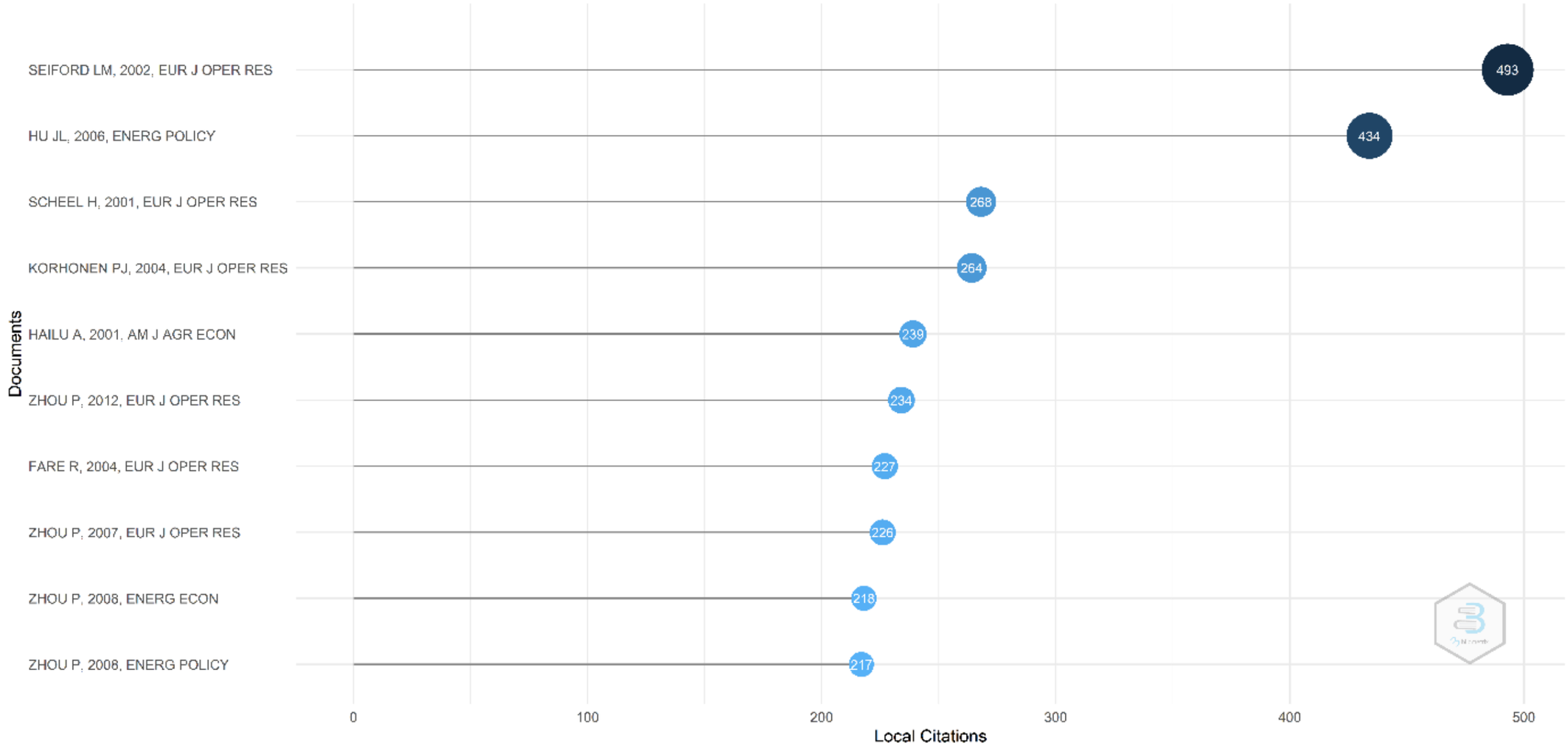
Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report, released in 2007, has its main activity to provide an assessment of the state of knowledge on climate change based on peer-reviewed and published scientific/technical literature. From 2008 to 2009, the graph shows a change in the level of annual publications, with a 46% growth from one year to the next, showing that the topic has gained relevance for academia.

In 2013 we can observe a change of level being 37% more voluminous than the previous year, on the other hand, we observe the realization of Rio+20, in 2012, with the main focus on eradicating poverty (Mische, 2014). In 2015 two important moments stand out, the COP 21, whose main result was the Paris Agreement (Rhodes, 2016), and the 2030 Agenda and the Sustainable Development Goals (Liu et al., 2016). Therefore, given the context of studies about environmental concern in society, it is justified, as shown in the figure 4, the growing increase in the analysis of DEA measurement and sustainability in this period.

Figure 5 illustrates the 10 articles most local cited.

Figure 5

Most Local Cited Documents



Source: The authors.

We analyzed the 25 most local cited articles, and we mapped the most used DEA models as seen in Figure 6 that presents that the majority research has an emphasis on quantitative modeling DEA methods.

Table 3

Most Local Cited Articles

No	Document	Year	Local Citations	Global Citations	LC/GC Ratio (%)	Method	DEA Model
1	Seiford LM, 2002, Eur J Oper Res	2002	493	820	60.12	Quantitative	N/A
2	Hu JL, 2006, Energ Policy	2006	434	773	56.14	Quantitative	CRS
3	Scheel H, 2001, Eur J Oper Res	2001	267	475	56.21	Quantitative	CRS
4	Korhonen PJ, 2004, Eur J Oper Res	2004	264	380	69.47	Quantitative	VRS
5	Hailu A, 2001, Am J Agr Econ	2001	239	382	62.57	Quantitative	N/A
6	Zhou P, 2012, Eur J Oper Res	2012	233	411	56.69	Quantitative	N/A
7	Fare R, 2004, Eur J Oper Res	2004	227	347	65.42	Quantitative	CRS
8	Zhou P, 2007, Eur J Oper Res	2007	225	316	71.2	Quantitative	N/A
9	Zhou P, 2008, Energ Econ	2008	217	324	66.98	Quantitative	CRS/ VRS
10	Zhou P, 2008, Energ Policy	2008	216	317	68.14	Quantitative	CRS
11	Zhou P, 2006, Ecol Econ	2006	209	283	73.85	Quantitative	N/A
12	Zhang B, 2008, Ecol Econ	2008	209	300	69.67	Quantitative	CRS/ VRS
13	Zhou P, 2010, Energ Econ	2010	194	366	53.01	Quantitative	N/A
14	Shi GM, 2010, Energ Policy	2010	194	276	70.29	Quantitative	CRS/ VRS
15	Dyckhoff H, 2001, Eur J Oper Res	2001	191	266	71.8	Quantitative	CRS
16	Kuosmanen T, 2005, J Ind Ecol	2005	189	304	62.17	Quantitative	N/A
17	Choi Y, 2012, Appl Energ	2012	171	353	48.44	Quantitative	SBM/CRS/VRS
18	Reinhard S, 2000, Eur J Oper Res	2000	170	316	53.8	Quantitative	N/A
19	Chang YT, 2013, Energ Policy	2013	168	248	67.74	Quantitative	SBM/CRS
20	Tyteca D, 1996, J Environ Manage	1996	165	326	50.61	Quantitative	N/A
21	Hu JL, 2007, Energ Policy	2007	165	274	60.22	Quantitative	CRS
22	Wang K, 2013, Math Comp Model	2013	164	235	69.79	Quantitative	VRS
23	Kuosmanen T, 2005, AmJAgr Econ	2005	157	276	56.88	Quantitative	N/A
24	Sueyoshi T, 2017, Energ Econ	2017	157	198	79.29	Theoretical	N/A
25	Fried HO, 2002, J Prod Anal	2002	154	340	45.29	Quantitative	N/A

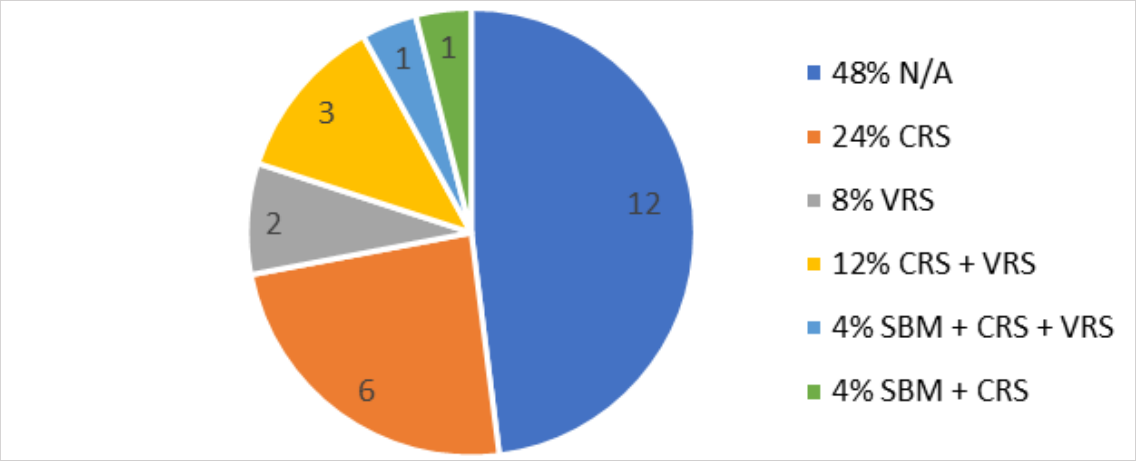
Source: The authors.

Table 3 shows these articles, using data from WoS citation count as shown. Column 5 shows the global citation (GC), which is the number of citations of a paper. Meanwhile, column 4 shows the local citation (LC) of each paper. While GC can be interpreted as the overall influence of the document across scientific disciplines, LC is the influence of a paper on the examined pool of documents, showing the overall influence of the paper on the literature on the theme.

Figure 6 summarizes the DEA Model of the 25 selected articles.

Figure 6

DEA model analysis

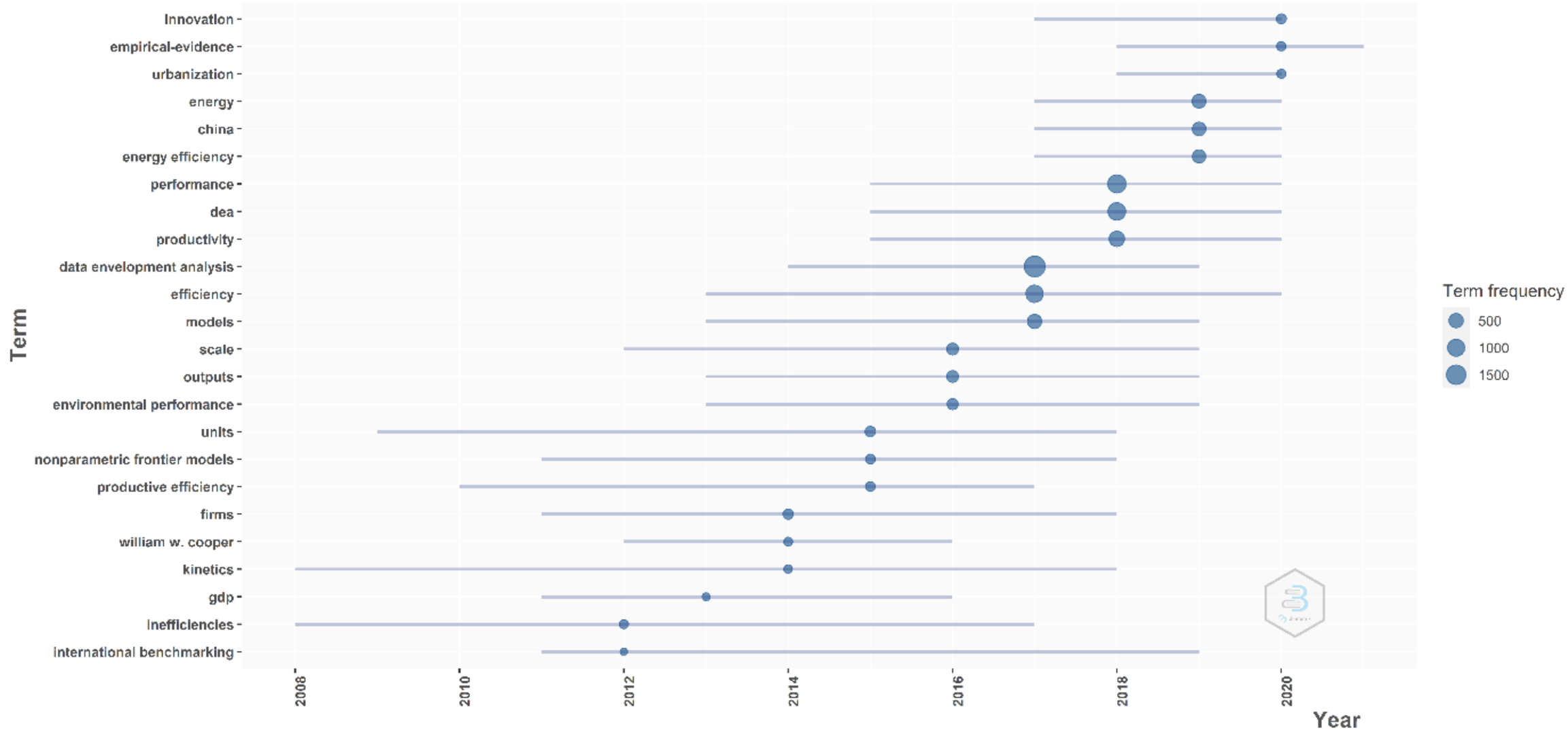


Source: The authors.

Figure 7 shows the trend topics of this literature. This analysis shows that research related to "innovation" was more commonly performed since 2017, with the highest concentration being in 2020, and the term "data envelopment analysis" was more commonly performed since 2014 with the highest concentration in 2017.

Figure 7

Trend Topics



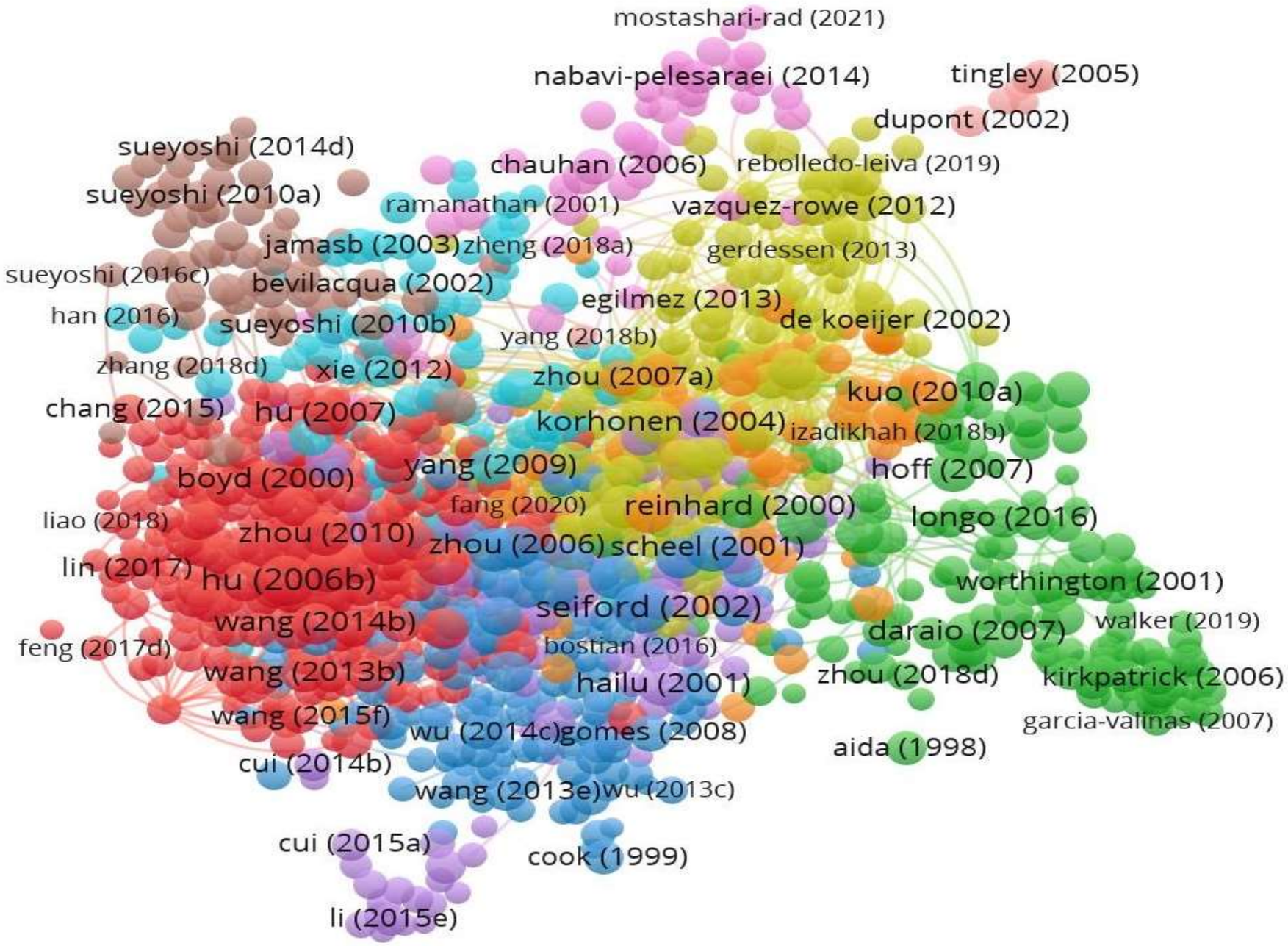
Source: The authors.

4.4 Citation Network

To better understand how the studies published on the theme relate with each other, we carried out a citation network analysis using the VOSviewer software. The citations clusters achieved by those documents is shown in Figure 8. Van Eck and Waltman (2017) elucidate that the VOSviewer clustering technique determines the relatedness of publications based on direct citation relations. In this case, a citation link is a link between two items where one item cites the other. Publications are assigned to clusters by maximizing a quality function. In order to maximize the quality function, the VOSviewer clustering technique uses the smart local moving algorithm introduced by Van Eck and Waltman (2013).

Figure 8

Citation Network



Source: The authors.

We identified 10 clusters in the network analysis and we analyse the 30 most important articles used in the indepth analysis to explore each one, exposing the most relevant articles and their main contributions to each field/cluster.

Cluster 1 – Energy Efficiency and Pollution

The first cluster analyzes issues pertaining to "Energy efficiency and Pollution". This cluster is significant because it analyzes the issue of energy efficiency and pollution (Pao and Tsai, 2011; Omer, 2008; Al-Mulali et al., 2013; Mikayilov et al., 2018). Note that the energy issue is relevant to both pollution and sustainable development goals (Sharma et al., 2021; Yuksel and Kaygusuz, 2011). Over a third of the global energy-related CO2 emissions is caused by electricity generation, but energy supply is invaluable for economic growth (Zhou et al., 2012). Therefore, the efficiency of energy consumption must be simultaneously promoted so that redundant energy consumption is eliminated. There are various definitions of the term energy efficiency, among which "the ratio of energy services to energy input" is a popular one. A general definition given in the Directive 2006/32/EC of the European Council and the Parliament on energy efficiency and energy service is "a ratio between an output of performance, service, goods or energy, and an input of energy". Indicators used to monitor changes in energy efficiency can yield very different results and policy implications (Zhou, 2008).

In this sense, the main article of this cluster, named "Total-factor energy efficiency of regions in China", constructed a new index of energy efficiency defined as the ratio of the target energy input that the DEA suggests to the actual energy inputs in a region (Hu and Wang, 2006). Among the main articles, we can see "Linear programming models for measuring economy-wide energy efficiency performance" that developed three alternative energy efficiency performance indexes to evaluate energy efficiency within a joint production framework of both desirable and undesirable outputs (Zhou, 2008). One of the top articles, which created several performance indexes for measuring energy and CO2 emission performance in electricity generation is titled "Energy and CO2 emission performance in electricity generation: A non-radial directional distance function approach" (Zhou et al., 2012).

Hu and Wang (2006) pointed out that a more detailed analysis can be conducted by referencing each region's root causes at a deeper level, and that industrial structure, energy policies, energy consumption type, and treatments from local governments can be further incorporated together. Zhou et al. (2012) did their empirical study based only on data from 2005, but further research may be carried out using time-series data or the data from for a more recent year. They also pointed out that the proposed approach can be directly applied to measure energy and environmental performance of electricity generation at factory level if

the needed data is available. In cases where there are more input and output variables, the proposed non-radial directional distance function approach can also be easily adapted.

In accordance with what has been exposed, the understanding that energy efficiency and pollution are relevant topics and, consequently, should be considered in this research is notorious. Still, it is necessary to emphasize the possible paths for this theme, as evidenced in the suggestions for a future research agenda by the authors Fenerich et al. (2017), who consider that a research agenda in energy efficiency can be the path to solutions aimed at reducing energy consumption in industries.

Cluster 2 - DEA and Economic Sectors Analysis

The second cluster analyzes issues pertaining to "DEA analysis for economic sectors (agriculture, fisheries, and airports)". There is a strong scientific consensus that climate change may affect both the quantity and quality of available water and energy resources. Wastewater treatment plants (WWTPs) are energy-intensive facilities contributing in some measure to climate change (Plósz et al., 2010). This energy consumption is expected to grow considerably in the near future, due to a higher expected volume of water being treated, as well as the adoption of new technologies aimed at yielding higher quality effluents (Hernández-Sancho et al., 2011). This cluster defines environmental efficiency as the ratio of minimum feasible to observed use of multiple environmentally detrimental inputs, conditional on observed levels of output and the conventional inputs.

In this sense, the main article of this cluster, "A survey of DEA applications", classifies a set of DEA papers into methodological and non-methodological works and then further segments the theoretical works based on real world problems that are discussed, tested, and validated within each work. Among the main articles, we found "Environmental efficiency with multiple environmentally detrimental variables; estimated with SFA and DEA" that revealed the strengths and weaknesses of the Stochasctic Frontier Analysis and DEA methods for estimating environmental efficiency scores (Reinhard et al., 2000). This article is important because it shows SFA and DEA based on its facility to incorporate their fulfilment of theoretical restrictions, the possibility of testing these restrictions, and the effects of statistical noise.

Moreover, the article titled "Energy efficiency in Spanish wastewater treatment plants: A non-radial DEA approach" is also among the top articles, which analyzes the efficiency behavior of a sample of WWTPs and identifies several variables that can explain differences between the energy plants. It also quantified the savings in CO_2 emissions and economic costs that could be obtained if plant efficiencies were improved (Hernández-Sancho et al., 2011).

Liu et al. (2013) pointed out the following limitations of his study. First, the dataset is from the WoS database and does not include all DEA papers published in academic journals. Second, these papers are categorized manually by one of the authors; some errors in judgment may occur, but this should be reduced to a minimum. Third, application studies discussed herein include application-centered and theory-together-with-empirical-data papers; some of them may not be accurate. Furthermore, they may also be duplications of previous studies where the data is used to illustrate a new method as opposed to a new application. Fourth, the results of the main path analysis are subject to citation noise, which is a general limitation of the citation analysis. Finally, each application area is treated as one broad research area. Some of the application areas may be heterogeneous in nature, such that certain development streams of the area are left out by the main path method. Reinhard et al. (2000) pointed out that the DEA is deterministic, and is unable to identify whether the environmentally detrimental variables suit the model. Liu et al. (2013) suggested that theoreticians should attempt to make their models operational and available by providing standalone software or an add-in to existing commercial software such as DEA Frontier and DEA-Solver. This will attract practitioners to use the model, offer feedback on issues of the model, and eventually turn the development process into virtuous cycles.

After this brief contextualization of the literature on DEA and the analysis of economic sectors, it is noted, therefore, the significance of this field of study for this research. As evidenced in Liu et al. (2013) the DEA methodology evaluates the individual efficiency or performance of a decision-making unit, thus contributing to the analysis of economic sectors. Given this interface between the fields of study, the construction of this second cluster is justified.

Cluster 3 – DEA methodological issues

The third cluster analyzes “DEA issues (i.e., undesirable outputs and radial model)”. DEA has frequently used in environmental performance measurement because it can provide some standardized environmental performance index. Most studies mainly deal with the developments and applications of radial DEA-based models (Zhou et al., 2007). Efficiency measurement is usually based on the assumption that inputs have to be minimized and outputs have to be maximized. In many applications, however, undesirable outputs are incorporated into the production model which have to be minimized (Scheel, 2001).

In this sense, the main article of this cluster, named “Modeling undesirable factors in efficiency evaluation”, develops an alternative approach to improve the performance via increasing the desirable outputs and decreasing the undesirable outputs in DEA (Seiford, 2002). Among the main articles, we can see “Undesirable outputs in efficiency valuations” that discussed several approaches for treating such outputs in the framework of DEA and the

resulting efficient frontiers are compared, then, new radial measures are introduced which assume that any change of the output level will involve both undesirable and desirable outputs (Scheel, 2001). The article titled "A non-radial DEA approach to measuring environmental performance" is also among the top articles, it created a non-radial DEA approach to measuring environmental performance and applied in a case study of OECD countries from 1995 to 1997 (Zhou et al., 2007).

Seiford (2002) pointed out that the new approach can also be applied to situations when some inputs need to be increased to improve the performance. Scheel (2001) argued that the universally efficient DMUs which even cannot improve the "ratio" of desirable and undesirable outputs may be of special interest for benchmark selection, which is an important topic in management applications.

As shown, this cluster demonstrates an alternative to maximize performance, which is possible by increasing desirable inputs and decreasing undesirable outputs in the DEA methodology (Scheel, 2001; Seiford, 2002). Thus, it appears that this alternative is of significant importance for the DEA methodology and, consequently, for this research.

Cluster 4 – DEA for Eco-efficiency measures

The fourth cluster analyzes "DEA for eco-efficiency measures" issues. Eco-efficiency is an instrument for analyzing sustainability, it represents the efficiency of economic activity in relation to nature's goods and services (Dyllick and Hockerts, 2002). Given its possible contribution to academia and society, the correct measurement of eco-efficiency can be obtained through the DEA, as analyzed in the articles found, therefore, it is essential to analyze the cluster of this theme.

Tyteca (1996) carried out a literary review on the measurement of the environmental performance of organizations. The study proposes a discussion about the nature and causes of environmental inefficiencies, analyzes the relationship between environmental performance and the global effect of industrial activities on health and the environment, in addition to considering the DEA method for measuring the environmental performance of organizations. Korhonen and Luptacik (2004) carried out the analysis of the eco-efficiency of power plants. According to the authors, the DEA can help in the measurement and evaluation if used as an efficiency measure. The authors applied their approaches in 24 European plants. Zhang et al. (2008) focused on the eco-efficiency analysis of the industrial system in China using DEA-based models. The study aims to illustrate the possibilities of measuring the eco-efficiency of a region by selecting appropriate indicators, in addition provides insights into the causes of eco-inefficiency.

As a topic for future research, the following suggestions can be inferred from this cluster: Korhonen and Luptacik (2004) advise introducing environmental standards in their

models to assess the impact of environmental policy for the measurement of efficiency, in addition to performing multilateral comparisons of productivity between organizations from all over the planet. Zhang et al. (2008) point out that future research involving the DEA should cover the integration of the non-linear structure, as the increase in of insights into the impacts of production will probably lead to a circular production model. They also consider that the following studies should acknowledge consider the relative weight restrictions, including them in the DEA model.

In this way, this cluster contributes to a satisfactory measure of eco-efficiency, given the importance of analyzing sustainability nowadays (Lu et al., 2022). Once the synergy between the themes is identified, the construction of this fourth cluster is justified, in this way, the contributions of this research are relevant to society and literature.

Cluster 5 - DEA measures for Agriculture

The fifth cluster analyzes "DEA measures for Agriculture" issues. The fifth cluster analyzed focuses on the issue of DEA measurement for agriculture, which is of considerable importance, given that agriculture represents a significant part of the global economy and is indispensable for life (Tilman et al., 2011). The DEA method consists to compare the revealed efficiency with the benchmarks of DMUs (Cooper et al., 2007).

When analyzing the main studies of this cluster, we found that the following statements as main results: Hailu and Veeman (2001) dedicated themselves to understanding the Canadian pulp and paper industry. The authors carried out studies to find the modifications of the nonparametric Varian–Banker–Maindiratta models extended by Chavas and Cox. The results show that researchers must recognize the limitations of the results of analyzes based only on DEA methods. Kuosmanen and Podinovski (2009) carried out a study in order to analyze how non-disposable technology can be modeled so that non-uniform reduction factors can be applied. The authors found a limitation in the literature regarding the conventional specification of disposability in the analysis of activity. Färe et al. (2004) constructed an environmental performance index based on distance functions. The index developed by the authors consists of a formal environmental performance index calculated through the DEA and allows for the measurement of how a company managed to simultaneously yield good production and account for reductions in bad productions.

The studies in this cluster illustrated some limitations regarding theme and research suggestions, such as: empirical estimates of efficiency ratings or productivity growth generated exclusively from analyses done by the DEA (internal limit) do not provide reliable data (Hailu and Veeman, 2001). Another limitation is pointed out in the conventional specification of disposability in activity analysis, and the main drawbacks of this limitation are pointed out (Kuosmanen and Podinovski, 2009). Färe et al. (2004) suggest that the index

built by them be explored in future studies. According to the authors, this would allow for finding more direct evidence on the relationship of the environmental Kuznets curve.

Thus, it is observed that the DEA contributes significantly and positively to agriculture, as pointed out by Hailu and Veeman (2001) and Tilman et al. (2011) DEA measurement for agriculture is of significant importance. Note that there are gaps in DEA measurement, such as the lack of studies that analyze empirical estimates of efficiency indices and about the conventional specification of disposability in the analysis of activities. Consequently, it is noted that, although the DEA measurement is considerable, it still has gaps in its literature, emphasizing the importance of studies in the area and the proper analysis of the interfaces with agriculture.

Cluster 6 - Power plant generation and Energy

The sixth cluster analyzes "Power plant generation and Energy" issues. In this cluster DEA was important to apply power plant generation and, also, energy. Then, a use of DEA was proposed by many researchers in energy economics (Sueyoshi et al., 2017). Also, in performance measurement of power industry, DEA has gained much popularity (Bi et al., 2014).

Yang and Pollitt (2009) built six DEA-based performance evaluation models, using a sample of coal-fired power plants located in China. This effort was a reflection of the lack of studies that, according to the authors, assess undesirable outputs and uncontrollable variables. The authors consider that the findings of this research have implications for both measurement methodology and policies from the power sector to Chinese coal. Bi et al. (2014) analyzed whether environmental regulation affects energy efficiency in China's thermal power generation. To fulfill the objective, the researchers analyzed the relationship between fossil fuel consumption and the environmental regulation of thermal energy generation. Among the research findings, three stand out: 1- Both energy and environmental efficiency were low, 2- Both efficiencies have considerable variations depending on the analyzed location, 3- The characteristics of both efficiencies can be defined on account of the geography. Sueyoshi et al. (2017) summarized the application of DEA measurement applied to energy and the environment. They concluded, therefore, that the use of the DEA maximizes the mitigation of problems due to climate change and environmental pollution.

When looking at this cluster, it is necessary to point out the following propositions for future research: the literature on the DEA should focus on three main issues, namely: technological heterogeneities and time lag, statistical inference, applications for China (Sueyoshi et al., 2017). Bi et al. (2014) consider that the literature should focus on the Malmquist productivity index, the use of the two-stage DEA approach to analyze the energy

conservation and emission reduction performance of the Chinese government and measurement comparisons with other methodologies.

To end the construction of the sixth cluster, note the favorable relationship of the DEA measurement applied in the generation of power plants and energy, observing the popularity of the adoption of the DEA measurement in these cases. There are also gaps in the literature, such as the lack of studies on energy conservation performance and comparisons with other measurement methodologies. It appears that the themes have points in common and that the construction of this cluster is fundamental for the present research.

Cluster 7 - DEA and production systems

The seventh cluster analyzes "DEA and production systems" issues. This cluster analyzes how the DEA can favor the measurement of production systems. Production systems are understood as the process used in the production of products and services (Cassman, 1999).

The following most relevant results can be inferred: Fried et al. (2002) developed a technique to incorporate environmental effects and statistical noise into producer performance evaluation using the DEA. According to the study, when using the DEA through three stages, being: stage one based on conventional inputs and outputs, stage two based on regression and the third stage based on conventional outputs and adjusted inputs, it is possible to obtain a more accurate measurement. Kuo, Wang and Tien (2010) analyzed the integration of artificial neural networks and MADA methods for the selection of green suppliers. The authors conclude that the ANN-MADA hybrid method surpasses the ANN-DEA and ANP-DEA hybrid methods, it is also concluded that the ANN-MADA model stands out in discrimination and insensitivity to noise in the evaluation of the performance of green suppliers. Mavi, Saen and Goh (2019) focused on understanding the joint analysis of eco-efficiency and eco-innovation with common weights in the DEA two-stage network. The model proposed by the authors allows decision makers to fully classify the DMUs. Therefore, the model becomes attractive to those who seek to objectively maximize the relationship between products and inputs.

Regarding the limitations of the subject, it is noteworthy to emphasize that the measurement by the DEA for production systems has limitations because it is deterministic and disregards environmental variables (Fried et al., 2002). Therefore, we have studies such as those by Kuo, Wang and Tien (2010) and Mavi, Saen and Goh (2019) that allow mixed measurement methods. However, it is noteworthy that the literature lacks studies in this field and that future research should delve deeper into the DEA linked to other methodologies.

As stated above, it can be understood that the DEA measurement has an interface with the production systems. It highlighted the possible contributions between the themes as

punctuated by the authors Fried et al. (2002), Kuo, Wang and Tien (2010) and Mavi, Saen and Goh (2019) and the absence of studies that carry out this analysis jointly was emphasized. Therefore, the choice of this cluster is justified, given its importance for the literature and given its possible contribution to the measurement of production systems.

Cluster 8 - DEA and Manufacturing

The eighth cluster analyzes "DEA and Manufacturing" issues. Manufacturing problems encompass all events that negatively interfere with the design of the final product or service. Such events can be characterized by the failure of a certain item to function or even environmental damage caused by the production chain (Gill et al., 2001). Therefore, the measurement of these problems in the manufacturing process is essential for prevention and for corrective measures, and the DEA, as justified by the articles in this cluster, is a way to accomplish this task.

Zaim (2004) focused on measuring the environmental performance of state-owned manufacturing through changes in the intensity of pollution using the DEA. According to Zaim, pollution is a by-product of manufacturing, and therefore a consequence of it. The index constructed by the author consists of a variant of the Malmquist quantity index, satisfying the established axiomatic properties. Sueyoshi and Goto (2012) made a comparison between the Japanese electricity industry and manufacturing industries. For this, the DEA environmental assessment was used to measure weak and strong disposability versus natural and managerial disposability. The study allows us to conclude that manufacturing companies outperform electric power companies under natural disposability, however, in managerial disposability, the opposite occurs. Another study by Sueyoshi and Goto (2012) focused on DEA for environmental assessment, comparing public and private ownership in the oil industry. The authors consider that the measurement by the DEA should classify the results of the productive system in desirable and undesirable products, for that the study is composed of three types of unification for environmental evaluation. The first being the decrease in the input vector with the decrease in the direction vector of undesirable outputs, the second consists of the decrease in an input vector with the decrease in the vector of undesirable outputs and the third considers an increase in the input vector but a decrease in the vector of undesirable outputs.

For future research, we found suggestions such as those of Sueyoshi and Goto (2012) who consider that for more robust results of the constructed index it is necessary to increase the sample of manufacturing companies and electric energy companies. The authors also point out that the natural and managerial disposability should be linked to game theory, in addition to considering that future studies should explore the economic and managerial characteristics of the RTS/DTS measurement.

This cluster contributes substantially to this research because, as listed in the development of the analyses, the DEA measurement is positively related to manufacturing. Important contributions can be found in this cluster, such as the DEA being used to measure the environmental performance of manufacturing as well as measuring its disposability (Zaim, 2004; Sueyoshi and Goto, 2012). Thus, the contribution of this cluster is of mutual importance between the fields of study, then justifies being part of the present research.

Cluster 9 - DEA and Energy efficiency

The ninth cluster analyzes "DEA and Energy efficiency" issues. Energy efficiency has, at its core, improved the use of energy sources, rather, it is concerned with efficiently using energy to carry out any industrial, agricultural or service activity (Greening et al., 2000). Consequently, the DEA can favor the correct measurement for energy efficiency, providing real data on energy use. In this way, the cluster analyzed here is responsible for observing the interfaces between both themes.

Yu and He (2020) developed a bibliometric study for the DEA applied to energy efficiency to assess future trends and challenges. After analyzing the articles, the authors concluded that the DEA contributes positively to studies applied to energy efficiency, indicating an interface between the themes that must be analyzed more deeply. Chauhan, Mohapatra and Pandey (2006) used the DEA to improve energy productivity in rice field production through benchmarking. The study separated efficient from inefficient farmers, in addition to identifying unnecessary energy uses. As a result, about 11.6% of energy could be saved if farmers followed the model recommended by this study. Nassiri and Singh (2009) analyzed the energy use efficiency for rice cultivation with the DEA. The authors observed a strong correlation between the energy ratio and technical efficiency and identified a correlation coefficient between specific energy and inverse technical efficiency.

For future research in this field of study, we have the observations of Yu and He (2020), which point out that the DEA should be analyzed with other analytical tools, such as life cycle assessment analysis. The authors also advise research that analyzes the reversal phenomenon in the assessment of energy efficiency. Chauhan, Mohapatra and Pandey (2006) suggest that for future research the sociocultural and economic aspects of the group of more efficient farmers are compared with those of relatively inefficient farmers, the analysis of agricultural practices and yields collected at different times and locations, and the use of the DEA to analyze energy input in various operations with time and duration. Nassiri and Singh (2009) recommend that future studies analyze the CCR and BCC models used to calculate technical efficiencies.

In accordance with what has been exposed, this cluster fulfills its objective by exploring the interfaces between DEA measurement and energy efficiency. In this way, the

contributions between the fields of study are well known, in addition to the notes for future research. It is concluded, therefore, that cluster nine is essential for the development of this research and the current literature.

Cluster 10 - DEA and Fisheries efficiency

The tenth cluster analyzes “DEA and Fisheries efficiency” issues. The issue of fishing efficiency refers to operations that guarantee greater results in fishing activities. Therefore, the DEA methodology can help to measure this efficiency, such a conclusion can be obtained by reading the articles that make up this cluster and which are presented in the following paragraph.

Dupont et al. (2002) investigated measures of capacity utilization and overcapacity in privatized fisheries using the DEA. The results that were accounted for provide useful information for decision makers interested in using market-based approaches to improve their efficiency. Tingley et al. (2005) studied the factors that affect technical efficiency in fisheries using the DEA. Among the conclusions of the authors, we can highlight that the DEA can be used as an alternative to SPF (Stochastic Econometric Production Frontier) techniques. Yang and Fukuyama (2018) used the DEA to measure Chinese regional production potential. Through this study, the authors make some suggestions for Chinese policy makers, since the identification of excess capacity was identified in four provinces, namely: Tianjin, Liaoning, Shanghai and Zhejiang.

Regarding the interface presented by this cluster, we have as suggestions for future research the notes of Yang and Fukuyama (2018). The authors point out that spatial econometric studies should be considered and that they allow the formulation of public policy suggestions.

Note that, after the developed analyses, the DEA measurement can be related to fishing efficiency. Although studies are found that are based on this joint analysis, they are scarce, requiring the development of research that punctuate the two fields of studies synergistically. Consequently, the development of cluster ten is essential for this research to contribute to academia and society.

5 Conclusion

This article presents a bibliometric study revealing a rapidly expanding theme that has been addressed since 1984, with a notable surge in activity since 2009, which underscores the significance of conducting a literature review to enable researchers to map out the existing research and gain insights into the methodologies employed in prior studies. By understanding the historical evolution of a given research area and the ways in which it has been approached in the past, researchers can identify gaps in knowledge, develop new

approaches, and build on the findings of previous studies. Therefore, this study highlights the value of conducting a bibliometric analysis in promoting a deeper understanding of a given research topic and informing future research directions.

There are two articles that stand out in terms of local citations. The article Seiford L.M., 2002, European Journal of Operational Research focused on emphasizing that to increasing the desirable outputs and decreasing the undesirable outputs the DEA model can be used and Hu J.L., 2006, Energy Policy titled "Total-factor energy efficiency of regions in China" are the top two and can be considered as mandatory references in their themes. Additionally, we verified the existence of several journals, however, the publications are concentrated on few relevant ones, such as: (1) Journal of Cleaner Production (with 7% of the articles); (2) Sustainability (6%); (3) European Journal of Operational Research (3%); (4) Energy; (2%) and (5) Energy Policy (2%). The same happened with the most relevant authors. When the great importance for the development of this research field is considered from the point of view of the volume of publications, author Sueyoshi T., Li Y., and Chiu YH. can be highlighted. From the point of view of the number of citations (local impact), author Zhou P., Sueyoshi T., Goto M. can be considered as main references in the field.

When analyzing the DEA models most used in 25 articles with the greatest local impact (local citations), the model CRS stands out, representing 24% of the sample, followed by CRS+VRS with 12%. As the most current trend topics, "innovation", "empirical-evidence", and "urbanization" appear as timeless themes, which over the last 4 years have always been approached. Although it is an extensive literature, we can see the formation of 10 research clusters and articles that can be considered pillars in each cluster.

Despite these contributions, we have pointed out the following limitations. The search for articles was limited to the WoS database, suggesting that material from other databases may offer different results. Although we cover a wide range of words related to sustainability, it is always possible that related articles have not used these terms in the title, abstract and keywords. Another limitation is the range of words related to sustainability not covering the entire academic production on the matter. This bibliometric mapping is just a starting point, the deeper analysis of the clusters and the content of the most relevant articles are important continuities.

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