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Recent progress on emergy research: A bibliometric analysis

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A R T I C L E I N F O

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A B S T R A C T

Emergy-related studies have been widely conducted worldwide in order to evaluate the total environmental support and sustainability of one system from both natural and economic sides. Aiming to depict the characteristics of emergy-related literatures, recognize global research foci, and forecast future research directions, a complete review on the related research progresses by using a bibliometric analysis approach was performed in this study. H-index is applied to evaluate the influence of most productive journals, countries/territories, and institutions in emergy-related fields. Social network analysis is also performed to evaluate the interaction among different countries/territories and institutions. A holistic picture of the primary performance of emergy-related literatures published from 1999 to 2014 is presented. Co-word analysis reveals that emergy-based sustainability research and the integration of emergy synthesis with other methods (especially life cycle assessment) will be future research directions in emergy-related fields. Results obtained from this study can provide valuable information for researchers to better identify future hotspots in emergy-related fields.

1. Introduction

Human's production and consumption is solely dependent on the continuous support from our natural ecosystem [1]. However, such a system has been seriously damaged by human-dominant activities, especially with rapid economic development and urbanization, and increasing population. In order to identify a feasible pathway on human's future sustainable development, it is necessary to uncover the key problems so that sustainability can be integrated into product design [2,3] and policy making [4,5]. Many evaluation methods have been proposed, such as life cycle analysis (LCA), material flow analysis (MFA), ecological footprint (EF), and input-output analysis. However, these methods mainly focus on individual parameters and therefore cannot provide a complete picture of regional development. Consequently, an innovative evaluation method that can address such concerns should be raised.

Emergy analysis (EMA) is one method that can address these concerns. It is defined as the total amount of available energy needed directly and indirectly to generate a product or service [6,7]. Since solar energy is the original form of all energy, it is commonly used as equivalent to quantify other forms of energy and expressed as solar emjoules, abbreviated as sej. The amount of emergy needed to generate one unit of product or service is defined as UEV and expressed with the unit of sej/unit (i.e., sej/g, sej/J, and sej/$). Measuring all forms of energy, resources, and human services based on solar energy equivalent allows the direct comparison of input and output flows. Correspondingly, a series of emergy-based indicators could be calculated to quantify the economic benefits, environmental impacts, and evaluate the overall sustainability of one system.

Emergy theory was first proposed in the late 1980s and then gradually applied to study natural ecosystem or human-dominated systems. Particularly, with the increasingly mature theoretic progresses, updated emergy transformity (UEV) database, more emergy scholars worldwide, and an international emergy research organization (International Society for the Advancement of Emergy research, ISAER), emergy study has become one hot spot and received more attentions globally. As a useful tool for environmental management and planning policies [8], EMA has been extensively applied in other systems, such as agricultural systems [9–11], industrial systems [12–14], and urban systems [15–17]. Moreover, EMA has been widely applied at micro levels, such as computer production [18], power generation [19,20], construction materials production [21,22], as well as waste treatment [23].

Academically, studies on various aspects of EMA have been published in the international journals. For instance, Amaral et al. [24] addressed the theory, application, and last development of emergy

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research. However, only two emergy-related review papers based on bibliometric analysis have been published until now [25,26], One was published in a peer-reviewed international journal and authored by Chen and his colleagues [25], in which they conducted a bibliometric and visualized analysis to present the performance of emergy-related publications. Another one was published in a Chinese journal and was authored by Liu and her colleagues, in which they summarized the recent progress of emergy study both in China and in other countries. However, no comprehensive emergy-related review papers based on bibliometric analysis have been published. Bibliometric analysis can help search for academic materials and analyze their merit by tracing relationships amongst academic journal citations, guiding readers to better understand the current research progress and future research directions. In order to fill such a research gap, this paper aims to investigate the performance of emergy-related literatures published from 1999 to 2014. Social network analysis (SNA) and co-word analysis are also performed to further provide a holistic picture on emergy-related publications and point out future research direction. The whole paper is organized below. After this introduction section, we first present our research method. We then show our research findings in Section 3 and conduct our discussions in Section 4. Finally, we draw our conclusion in Section 5.

2. Methods

2.1. Bibliometric analysis

Bibliometric analysis is a systematic approach which could quantitatively analyze scientific publications in order to identify particular research phenomena [27]. The application of bibliometric analysis has been extended from the initial area of library and information science to measure scientific progress in various fields [28]. Mathematical and statistical techniques are applied in bibliometric analysis, aiming to investigate the distributed architecture, mathematical regularities, varying patterns, and quantitative management of studied information, and then analyze the structure, features, as well as patterns of the underlying science and technology [29–31].

2.2. Impact factor and h-index

Impact factor was first proposed in Science by Garfield in order to measure the impact a journal receives citations to its papers over time [32,33]. Impact factor is assessed by dividing the total citations of papers from a journal published in preceding two years cited in the Journal Citation Reports (JCR) by the total amount of papers published in that journal in the same previous periods. As a standardized indicator, impact factor has been widely applied to measure the quality of journals, research papers, as well as researchers [28]. In this study, impact factors from 2014 JCR were used to evaluate the influence of different relevant journals.

Proposed by Hirsch in 2005, h-index is another indicator to evaluate the research achievement of a scholar from both quality and quantity aspects [29,34]. According to Hirsh [34], the definition of the h-index is that a scholar with an index of h has published h papers, each of which has been cited in other papers at least h times. In this study, h-index was employed to assess the influence of journals, countries/territories, authors and institutes.

2.3. Social network analysis

Social network analysis (SNA) is a quantitative approach to evaluate the relationship among the social actors [29]. SNA has been extensively applied due to the development of network theory and computer processing capacities [35]. In this study, SNA was applied to investigate the academic collaboration among the most productive countries/territories and institutes.

2.4. Data sources

The Institute for Scientific Information (ISI) Web of Science (WoS) published by Thomson Reuters are extensively used for searching scientific literatures [36]. As a widely accepted database of different scientific fields, WoS has been regarded as a significant source of data for bibliometric analysis [37,38]. Including more than 100 subjects, WoS could provide more consistent and standardized records compared with other databases such as Scopus [29,39]. Falagas et al. [40] found that detailed information and relative good graphics could be obtained from the citation analysis provided by WoS. Although the subfield database Science Citation Index Expanded (SCIE) and Social Sciences Citation Index (SSCI) include the most influential publications, some publications or “grey” literatures (e.g., report and conference proceedings) are not covered [29]. Therefore, SCI, SSCI, Conference Proceedings Citation Index—Science (CPCI-S), and Conference Proceedings Citation Index—Social Science & Humanities (CPCI-SSH) are all selected as the data sources in this study. “Emergy accounting”, “emergy analysis”, “emergy evaluation”, or “emergy assessment” were selected as the keywords under the “topic” option to search emergy-related literatures published during the period of 1999–2014 in the aforementioned databases. Data analysis was performed based on the data which was obtained on September 7, 2015.

3. Results

Among 722 publications obtained from the abovementioned databases, approximately 98.75% were published in English, followed by Chinese (0.83%) and French (0.42%). Only those literatures published in English (713 publications) were considered in this study since English is the common academic language worldwide. Among them, journal papers (517 publications) and proceeding papers (151 publications) are the major contributions, accounting for approximately 72.51% and 21.18% of the total published English-language literatures, respectively. In addition, other contributions include review papers (4.63%), editorial papers (0.84%), letters (0.70%), and corrections (0.14%), which are insignificant. Therefore, 668 publications (i.e., research papers and proceeding papers) were finally selected for further analysis in this study.

3.1. Primary performance of selected publications

Table 1 presents the primary performance of emergy-related literatures published during the period of 1999–2014. Results show

Table 1
Primary performance of emergy-related publications from 1999 to 2014.

Year	TP	AU/TP	CR/TP
1999	3	3.67	17.00
2000	10	2.30	31.60
2001	15	2.73	24.40
2002	13	2.54	23.08
2003	18	2.78	19.22
2004	27	3.04	23.70
2005	17	3.59	21.18
2006	32	2.94	37.69
2007	33	3.21	35.67
2008	44	3.43	39.52
2009	65	3.57	40.17
2010	65	3.51	39.69
2011	84	3.60	40.52
2012	68	3.60	40.78
2013	85	3.89	44.31
2014	89	4.13	54.12

TP, AU, and CR represent the amount of publications, the amount of authors, and the amount of cited reference, respectively.

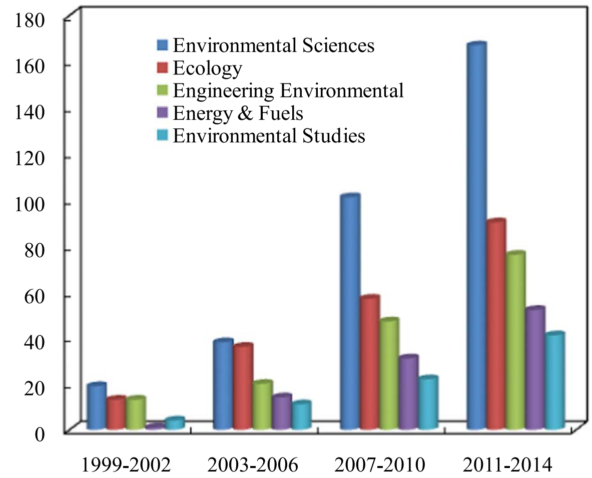

Fig. 1. Top five subject categories.

that the total amount of annual emergy-related papers, the average author numbers for each paper and cited references per paper all increased. For instance, the amount of emergy-related papers increased from 4 in 1999 to 97 in 2014, with an annual increase of 22%, indicating that emergy-related fields received increasing attentions, especially in the last decade. The average author amounts for each publication grew from 3.67 in 1999 to 4.13 in 2014, and cited references for each publication increased from 17.00 in 1999 to 54.12 in 2014. Such figures indicate that more communication and cooperation among the emergy scholars had been significantly enhanced.

3.2. Distribution of subject categories and journals

The 668 publications selected in this study cover 88 subject categories under the aforementioned databases (i.e., SCI, SSCI, CPCI-S, and CPCI-SSH). The first five subject categories include Environmental Sciences (325 publications), Ecology (196 publications), Environmental Engineering (156 publications), Energy & Fuels (98 publications), and Environmental Studies (78 publications). Fig. 1 shows the amounts of published papers on the top five subject categories during different years. The period of 1999–2014 was divided into four stages (each stage covers four years), aiming to better identify the trend of emergy-related researches in different categories. For each category, the amount of publications increased over the time. Results also show that Environmental Sciences category had the most publications, followed by the Ecology category, Engineering and Environmental category. Although the annual amount of total publications fluctuated (shown in Table 1), emergy-related publications in general experienced an increasing trend in the dominant subject categories, particular in the Environmental Sciences category.

Emergy-related publications had been published in 211 types of journals from 1999 to 2014. Table 2 shows the top 10 most productive journals in the emergy-related studies. All of them are mainstream journals in the field of environmental management and economics. Ecological Modeling is the most productive journals since 89 papers were published in this journal. Energy has the highest impact factor (4.844) among the aforementioned top 10 most productive journals, followed by Journal of Cleaner Production (3.844). Also, Ecological Modeling has the highest *h*-index (29), followed by Journal of Cleaner Production (16). In general, Ecological Modeling, Energy, and Journal of Cleaner Production are the most influential journals in emergy-related fields. Other key journals also support such studies, but the total numbers of published papers are relatively less.

Table 2
Characteristics of the top 10 journals from 1999 to 2014.

Journal name	Amount	Percentage	Impact factor	h-index
Ecological Modeling	1 (89)	42.18%	2.321	29
Ecological Engineering	2 (38)	18.01%	2.580	14
Journal of Cleaner Production	3 (31)	14.69%	3.844	16
Ecological Indicators	4 (30)	14.22%	3.444	10
Journal of Environmental Management	5 (25)	11.85%	2.723	13
Energy Policy	6 (24)	11.37%	2.575	9
Communications in Nonlinear Science and Numerical Simulation	7 (20)	9.48%	2.866	14
Energy	7 (20)	9.48%	4.844	13
Resources Conservation and Recycling	9 (13)	6.16%	2.564	7
Agriculture Ecosystem & Environment	10 (9)	4.27%	3.402	7
Ecological Economics	10 (9)	4.27%	2.720	6

3.3. Contribution of countries/territories and institutions

In this study, contributions of dominant countries and institutions were analyzed according to the addresses of various authors. Among the 668 selected publications, six publications lack the author addresses. Thus, finally 662 publications were analyzed. Among these 662 publications, 136 papers (approximately 20.54% of the total studied papers) were published with international collaboration. In total, 49 countries/territories and 395 institutions made their contributions to the development of emergy-related studies during the period of 1999–2014.

3.3.1. Contribution of countries/territories

Fig. 2 presents the global distributions of emergy-related publications from 1999 to 2014, covering 49 countries in total. China (291 papers) published the most papers among the 49 countries, followed by Italy (152 papers), USA (128 papers), Brazil (43 papers), and France (16 papers). Fig. 2 also shows the *h*-indexes of the top 10 productive countries. Italy and USA have the highest *h*-indexes (31), followed by China (28).

Table 3 shows the primary performance of the top 10 most productive countries. China is the most productive country with the highest amount of total emergy-based publications, publications without international collaborations, first-author publications, and corresponding-author publications. The USA is the most active country in terms of international cooperation, with the largest amount of international collaboration publications. The amounts of annual publications of the top 5 most productive countries were further analyzed in Fig. 3. Italy ranked No. 1 from 1999 to 2006, except for 2000, in which USA was the most productive. The total amount of publications from China has increased rapidly since 2003 and become the most productive since 2007. These results indicate that China, Italy, and USA are major contributors to the development and application of emergy studies.

The academic cooperation of the top 25 most productive countries/territories with the rest countries/territories are illustrated in Fig. 4. This figure was made by using Gephi, a software tool for complicated network analysis. The top 3 most productive countries (e.g. China, Italy, and USA) have close international cooperation. The USA is the most active country for emergy-related international cooperation, especially with China (27 papers), Italy (19 papers), and Brazil (5 papers). As the most productive country, China also actively cooperated with other countries, such as Italy (12 papers) and Canada (3 papers). It is common that countries with high academic publications usually tend to have close cooperation with each other since scholars can easily find potential research partners from these countries due to their

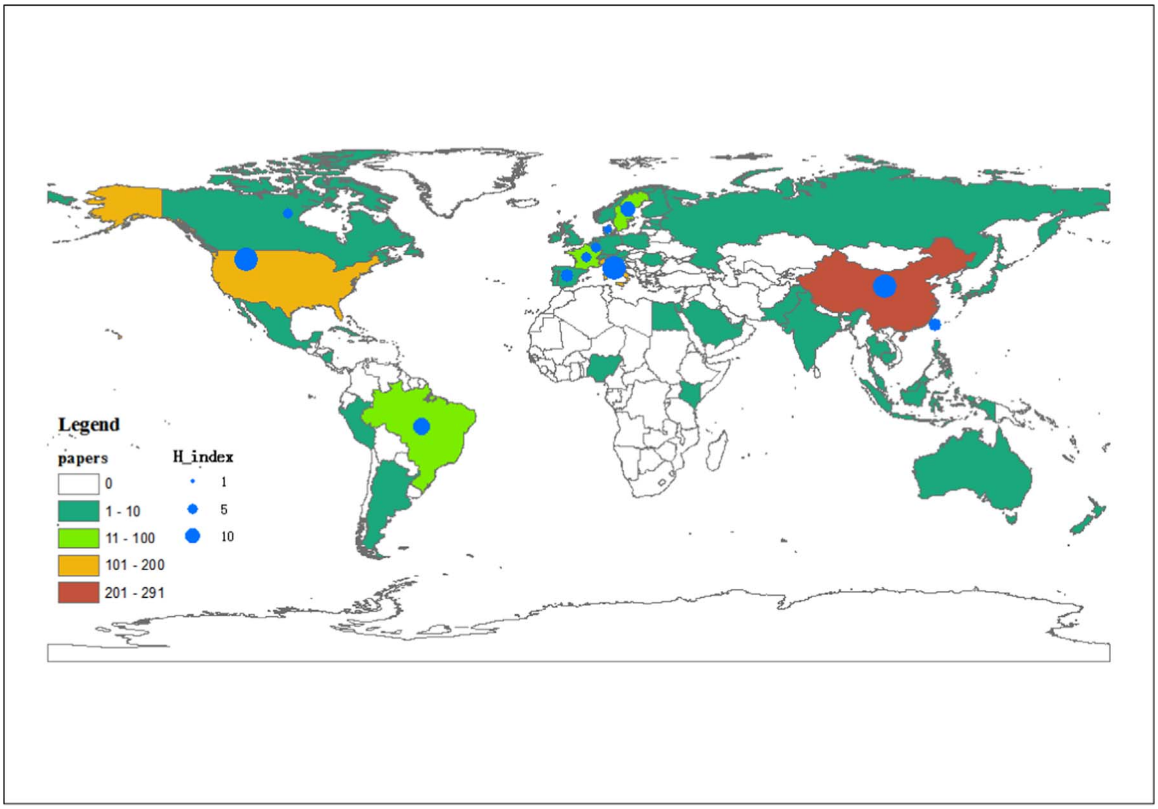

Fig. 2. The global distribution of emergy-related publications.

Table 3
Characteristics of the top 10 productive countries.

Country	TP	TP R (%)	SP (%)	CP (%)	FP (%)	RP (%)
China	291	1 (43.96)	35.95	8.01	43.66	43.50
Italy	152	2 (22.96)	16.31	6.65	19.49	19.49
USA	128	3 (19.34)	9.06	10.27	12.08	12.08
Brazil	43	4 (6.50)	4.68	1.81	5.59	5.74
France	16	5 (2.42)	1.21	1.21	1.51	1.66
Sweden	14	6 (2.11)	0.91	1.21	1.21	1.21
Taiwan (China)	14	6 (2.11)	1.66	0.45	1.96	1.96
Luxembourg	13	8 (1.96)	0.30	1.66	1.36	1.21
Denmark	11	9 (1.66)	0.60	1.06	0.91	1.06
Spain	10	10 (1.51)	0.45	1.06	0.76	0.91
Canada	10	10 (1.51)	0.76	0.76	0.91	0.91

TP: The total publications of a country from 1999 to 2014.
TP R (%): Rank and the percentage of the total publications from 1999 to 2014.
SP (%): The percentage of publications of a country without international collaborations.
CP (%): The percentage of publication of a country with international collaborations.
FP (%): The percentage of first-author country publications.
RP (%): The percentage of corresponding-author country publications.

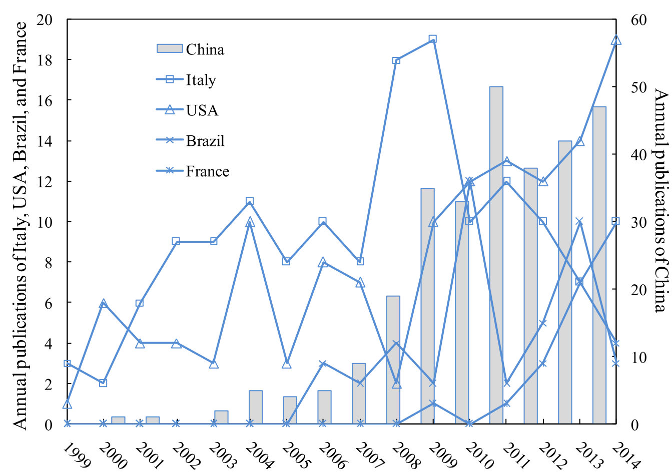

Fig. 3. Annual publications of the top 5 most productive countries.

similar research interests. Essentially, such international cooperation enhanced their research abilities and improved the development of emergy studies.

3.3.2. Contribution of institutions

Table 4 illustrates the primary performance of the top 10 most productive institutions in emergy-related research from 1999 to 2014. University of Siena in Italy is the most productive institution with the largest amount of total publications, first-author publications, and corresponding-author publications, followed by Beijing Normal University in China, Chinese Academy of Sciences, and Peking University in China. University of Siena also has the highest *h*-index among the top 10 most productive institutions, followed by Beijing Normal University, Peking University, University of Florida, Parthenope University of Naples, US Environmental Protection Agency (EPA), and Chinese Academic of Sciences. Moreover, Ohio State University, China Agricultural University, and University of Maryland, are also key contributors to the development and application of emergy-related studies.

The academic cooperation among different institutions is also analyzed by using Gephi. Fig. 5 shows the corresponding cooperation network of the top 10 most productive institutions. Beijing Normal University and University of Florida are the most active cooperation institutions in the emergy-related research. Beijing Normal University and Peking University in China are the most active cooperation partners (23 joint papers) among the top 10 institutions, followed by Chinese Academy of Sciences with US EPA (13 joint papers), and Beijing Normal University with Parthenope University of Naples (10 joint papers). Such facts indicate that Chinese institutions have been

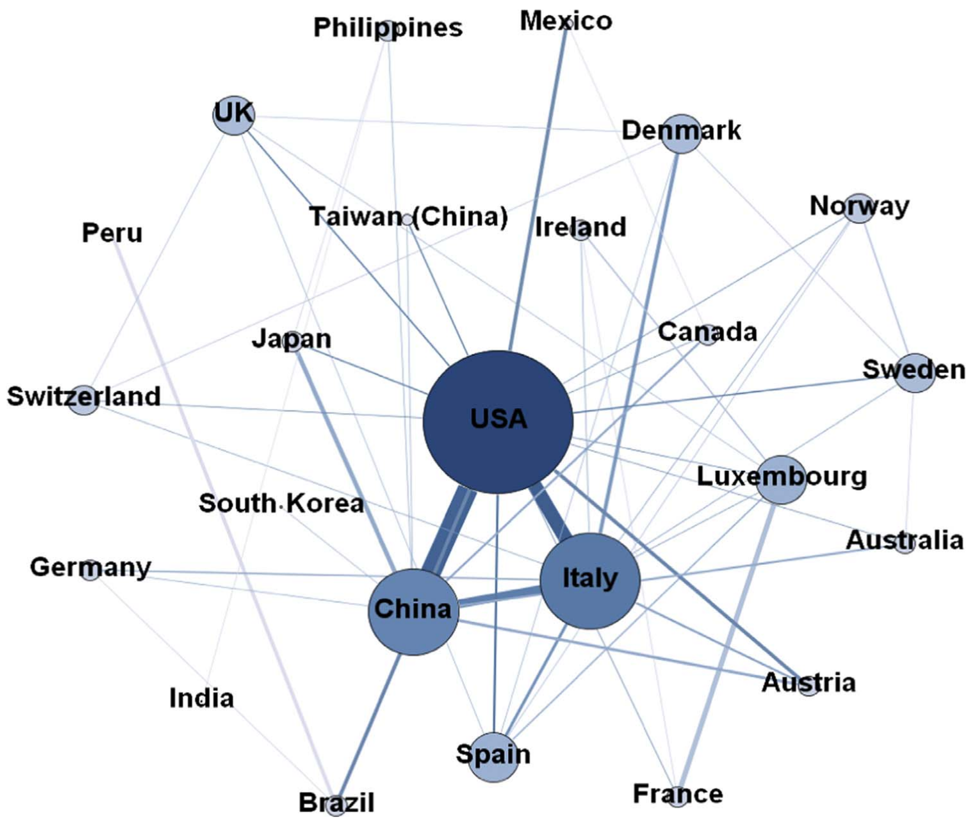

Fig. 4. The cooperation network of the top 25 most productive countries/territories.

Table 4
Characteristics of the top 10 productive countries.

Institution	TP	TP (%)	FP (%)	RP (%)	h-index	Country
University of Siena	98	14.80	11.48	11.33	24	Italy
Beijing Normal University	82	12.39	10.57	9.82	23	China
Chinese Academy of Sciences	50	8.01	6.19	6.34	13	China
Peking University	49	7.40	4.08	5.14	22	China
University of Florida	34	5.14	3.63	3.17	18	USA
Parthenope University of Naples	33	4.98	0.91	1.06	15	Italy
US EPA	33	4.98	2.11	2.27	14	USA
Ohio State University	17	2.57	1.81	2.11	12	USA
China Agricultural University	15	2.27	1.66	1.81	8	China
University of Maryland	14	2.11	1.36	1.36	6	USA

TP: The total publications of an institution from 1999 to 2014.
TP R (%): Rank and the percentage of the total publications from 1999 to 2014.
FP (%): The percentage of first-author institution publications.
RP (%): The percentage of corresponding-author institution publications.

very active in terms of international cooperation.

4. Research hotspots

4.1. The most frequently cited papers

Although several miscounting citations may occur, variation of annual citations can be used to evaluate the academic influence of publications [28,41]. Fig. 6 shows the total citations and annual citations of the most frequently cited publications in each year from 1999 to 2014. It is clear that the total citations of papers published in the last few years are lower than those published in the previous years, which is very sensible since these papers may not address adequate attentions due to their shorter publication time. But they will receive more citations with the rapid development of emergy research. Therefore, comparing with the total citations of one publication, the analysis of annual citations of one publication may provide more rational explanations.

Table 5 presents the primary features of the most frequently cited papers by analyzing the annual citations of one paper. These papers mainly focused on the development of emergy theory (e.g., Hau and Bakshi [42], Brown and Ulgiati [43], Brown and Ulgiati [44], and Brown et al. [19]) and the application of emergy (e.g., Chen et al. [45], Shao et al. [46], and Liu et al. [15]). Among all the papers, the one authored by Ness et al. in 2004 [47] is the most cited emergy-related publication, followed by papers authored by Carraretto et al. [48] and Chen et al. [49]. The one with the highest annual citations (25.8) is titled *"Categorising tools for sustainability assessment"*. This paper was published in Ecological Economics in 2007 and received 206 total citations. The main contribution of this paper is to provide an EMA framework for the categorization of sustainability assessment tools, in which they highlighted that EMA was an advanced method by considering both the quality and quantity of energy. The paper with the second highest annual citations (19.4) is titled *Biodiesel as alternative fuel: experimental analysis and energetic evaluations*. This paper was published in Energy in 2004 and received 213 total citations. The major contribution of this paper is to investigate the potentialities of biodiesel as an alternative fuel on the basis of strategic considerations and field experiences in boilers and diesel engines, in which the global environmental support for biodiesel production was accounted by using EMA. The paper with the third highest annual citations is titled *Ecological input-output modeling for embodied resources and emissions in Chinese economy 2005*. This paper was published by Communications in Nonlinear Science and Numerical Simulation in 2014 and received 75 total citations. Their contribution is to present a new approach on how to investigate the natural resources consumption and environmental emissions based on the multi-scale input-output model, which is helpful to evaluate the emergy

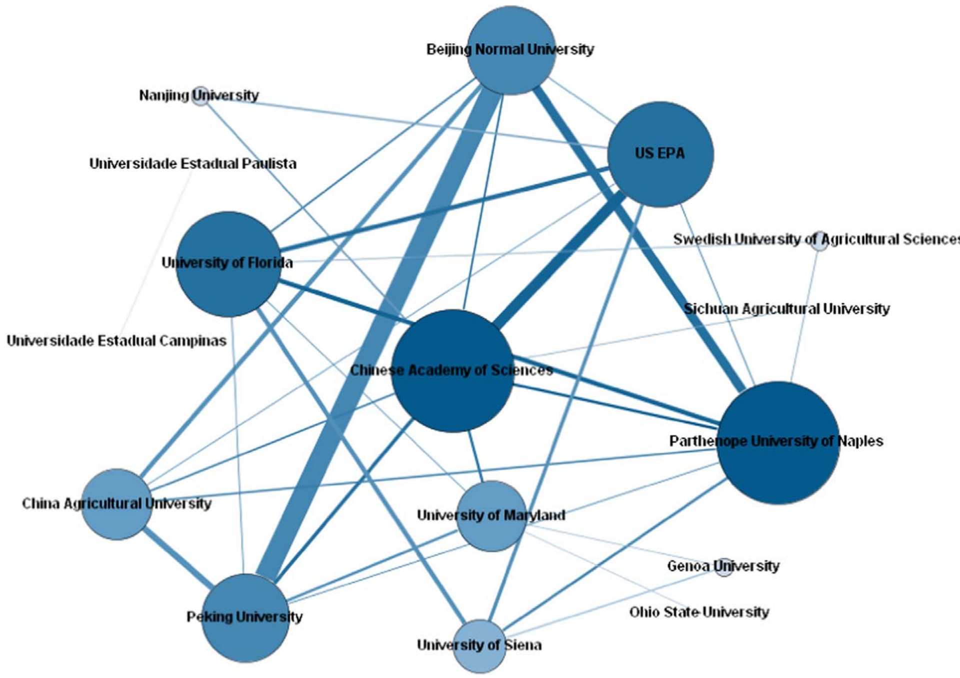

Fig. 5. The cooperation network of the top 20 most productive institutions.

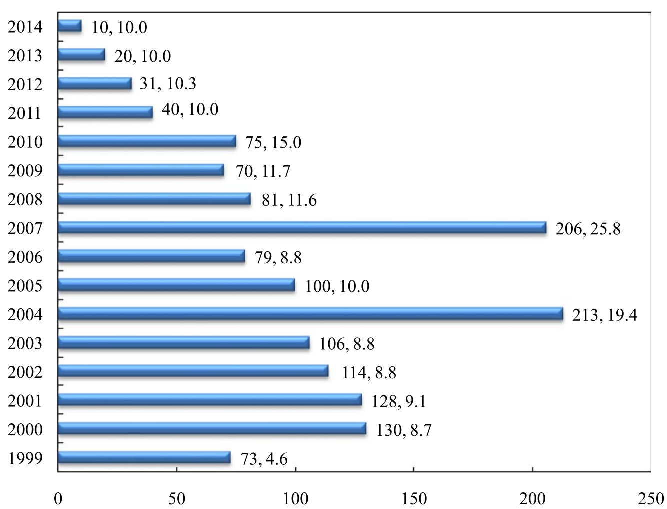

Fig. 6. The total citations and annual citations of the most frequently cited publications from 1999 to 2014.

intensity at the national scale. The implications of these three papers reflect that topics on sustainability assessment, environmental impact assessment from ecological perspectives, integrated assessment on human-dominated industrial ecosystems, and the combination of EMA and other methods are hotspots in emergy-related studies. It is also interesting that China, Italy, and USA published 6, 6, and 4 of those most frequently cited papers, reconfirming that these three countries have become the leaders for the development of emergy studies.

4.2. Main research fields

In this study, keywords of emergy-related publications were analyzed because keywords can identify the research focus of one paper [29]. Among the analyzed 668 publications, 599 publications had keywords, of which the total amount is 2821. The average amounts of key words for each publication range from 4 to 5. Considering that some keywords have very slight differences, such as "emergy analysis" and "emergy accounting", "life cycle assessment" and "life cycle analysis", "emergy indices" and "emergy indicators", these similar keywords are unified in a standard form for further study. With such a treatment, a total amount of 1367 individual keywords were obtained for further analysis. Results show that most keywords were only occasionally used. Keywords with only one use account for approximately 80% of all the keywords, while keywords used more than 10 times account for less than 1.5%. Table 6 presents the dominant topics and subtopics of emergy-related publications from 1999 to 2014. Fig. 7 illustrates the network of the most frequently emerged keywords.

Results show that emergy is the most used category (533 times), followed by sustainability (238 times), energy (163 times) and analytical method (113 times). A further analysis indicates that "emergy analysis" (sub-category) is the most frequently used keywords in emergy-related studies. This reflects that scholars involved in emergy-related studies regard EMA as one key research method. In addition, emergy indicators are frequently used in order to quantify the sustainability of one system since many other assessment methods cannot measure the contribution of natural ecosystem to economic development [54]. Such a reality reflects that scientific assessment on sustainability is one key area since many stakeholders want to pursue sustainable development. For instance, to develop eco-cities has become a key strategy for many urban managers, thus, urban metabolism or urban ecosystems have been widely investigated by emergy scholars since they believe that EMA can accurately uncover the key driving forces of urban development. Other frequently used keywords also related with such a topic, but at different levels and with different specific concerns.

Other analytical methods (e.g., LCA, EF, and exergy analysis) were also frequently used in those emergy-related papers. Although EMA has several advantages over other assessment methods since other methods do not account for local ecosystem services or the value of existing natural capital, other than in monetary terms and always call for policies optimizing an individual resource or flow, these methods have their advantages and can better fill the gap that emergy cannot fill by itself. For instance, LCA can effectively measure downstream environmental burden, e.g., the impact of emissions in the production chain. EF can be used for evaluating regional sustainability by comparing the production capacity with the absorption capacity of a

Table 5
Characteristics of the most frequently cited publications.

Year	Annual citations	Article	Journal	Author	Country	Reference
2007	25.8	Categorising tools for sustainability assessment	Ecological Economics	Ness et al.	Sweden, Estonia, Denmark	[47]
2004	19.3	Biodiesel as alternative fuel: Experimental analysis and energetic evaluations	Energy	Carraretto et al.	Italy	[48]
2010	15.0	Ecological input-output modeling for embodied resources and emissions in Chinese economy 2005	Coummunications in Nonlinear Science and Numerical Simulation	Chen et al.	China	[49]
2010	12.4	Updated evaluation of exergy and emergy driving the geobiosphere: a review and refinement of the emergy baseline	Ecological Modeling	Brown and Ulgiati	USA, Italy	[44]
2009	11.7	Emergy as embodied energy based assessment for local sustainability of a constructed wetland in Beijing	Coummunications in Nonlinear Science and Numerical Simulation	Chen et al.	China	[45]
2008	11.6	A critical review of reductionist approaches for assessing the progress towards sustainability	Environmental Impact Assessment Review	Gasparatos et al.	UK	[50]
2004	11.4	Promise and problems of emergy analysis	Ecological Modeling	Hau and Bakshi	USA	[42]
2004	10.6	Energy quality, emergy, and transformity: HT Odum's contributions to quantifying and understanding systems	Ecological Modeling	Brown and Ulgiati	USA, Italy	[43]
2012	10.3	On boundaries and 'investments' in emergy synthesis and LCA: A case study on thermal vs. photovoltaic electricity	Ecological Indicators	Brown et al.	USA, Spain, Italy	[19]
2014	10.0	Emergy-based dynamic mechanisms of urban development, resource consumption and environmental impacts	Ecological Modeling	Liu et al.	China, Italy	[15]
2013	10.0	Embodied energy assessment for ecological wastewater treatment by a constructed wetland	Ecological Modeling	Shao et al.	China	[46]
2011	10.0	Greenhouse gas emissions and natural resources use by the world economy: Ecological input-output modeling	Ecological Modeling	Chen and Chen	China	[51]
2010	10.0	Resources use and greenhouse gas emissions in urban economy: ecological input–output modeling for Beijing 2002	Communications in Nonlinear Science and Numerical Simulation	Zhou et al.	China	[52]
2005	10.0	Emergy and exergy analyses: Complementary methods or irreducible ideological options?	Energy	Sciubba and Ulgiati	Italy	[53]

Table 6
The analysis of publications by dominant topic and subtopic.

Dominant category	Dominant sub-category	TP 1999–2002	TP 2003–2006	TP 2007–2010	TP 2011–2014	TP 1999–2014
Emergy	Emergy analysis	20	55	137	212	424
	Emergy indices	0	1	11	23	35
	Unit Emergy Value	1	5	5	16	27
Sustainability	Sustainability analysis	9	17	44	46	116
	Sustainable development	0	4	10	18	32
	Sustainability indicators	0	4	11	7	22
Analytical method	Life cycle assessment	2	2	11	26	41
	Ecological footprint	0	3	10	19	32
	Exergy analysis	3	3	13	12	31
Ecosystem	Ecosystem services	4	1	4	16	25
	Agricultural ecosystem	1	2	1	9	13
Environment	Environmental accounting	1	4	8	8	21
	Environmental impact	1	1	3	12	17
Energy	Energy analysis	6	5	11	14	36
Urban	Urban metabolism	0	1	6	10	17
	Urban ecosystem	1	0	3	7	11

given land. Energy analysis accurately measures commercial energy cost of a product. MFA can measure mass degradation in a process. Consequently, it will be rational for emergy scholars to integrate EMA with other methods. Such emergy-inclusive circular economy indicators can provide a more holistic picture on examining the complete characteristics of one complicated system. In this regard, Dong et al. [55] proposed that the combination of EMA and EF can provide valuable suggestions for the improvement of local bio-capacity and urban sustainability. Also, the emergy "supply-side" evaluation system focuses on nature's investment, not only the economic value or the mass of resources supplied to the economic system, reflecting the space, time, and natural activities needed for resource production [56]. Consequently, the combination of EMA with other assessment methods will be the long term direction of future emergy-related studies. Although some early efforts were made, particularly with LCA (mainly due to the fact that the combination of EMA and LCA can help solve the problems of the lack of standardization and relatively lower accuracy during accounting procedure if only exclusive EMA is conducted) [56–58], further efforts that link EMA with other methods (such as EF, MFA, input-output analysis, etc.) are still expected so that more accurate outcomes can be generated for enhancing emergy theories.

In addition, innovative tools are essential to the successful application of emergy theories since they can help researchers and policy makers to identify the space, time, and natural activities needed for resource production and consumption. Consequently, it will be necessary for emergy scholars to explore how to adopt these tools, such as

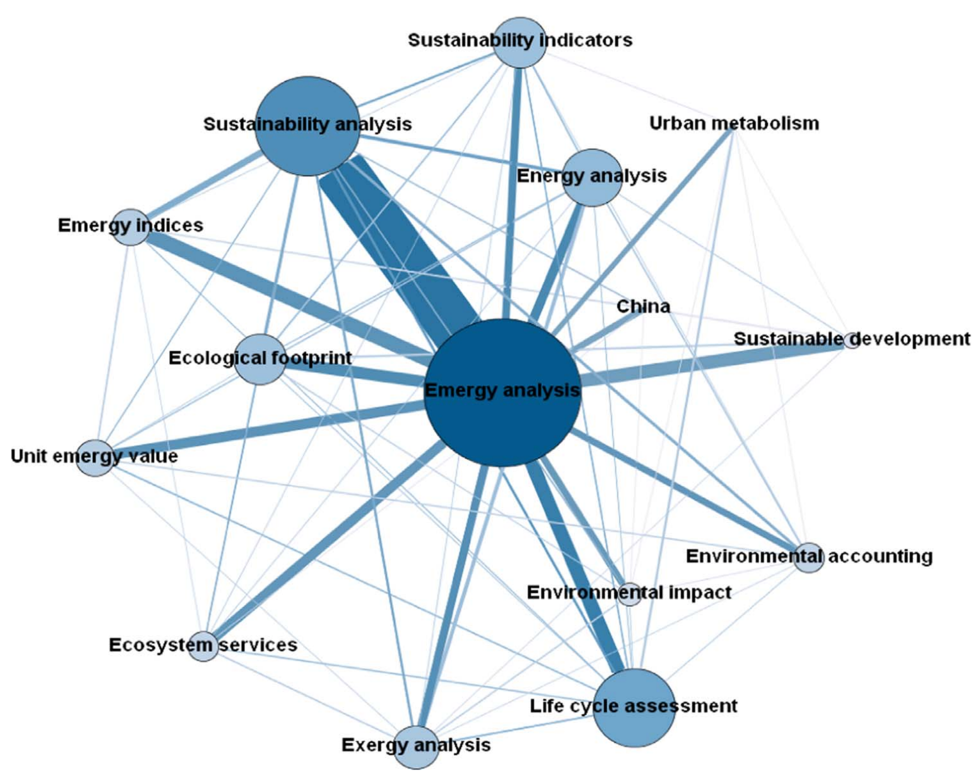

Fig. 7. The network of the most frequently used 15 keywords in emergy-related research from 1999 to 2014.

geographical information system (GIS), remote sensing (RS), and global positioning system (GPS), so that the complex networks or diversity and environmental quality of various resource flows within one system can be specially investigated and system optimization can be achieved.

5. Conclusions

With rapid economic development and increasing ecological concerns, it is critical to assess one system's overall sustainability so that appropriate long term development strategies can be raised. Emergy theories received more attentions due to their unique features and research perspectives. In order to summarize the existing research outcomes and provide future research directions, a comprehensive analysis of emergy-related literatures published from 1999 to 2014 was conducted to depict the characteristics of emergy-related literatures, recognize the global research foci, and forecast future research directions. Results show that most emergy-related studies focus on the field of Environmental Sciences and Ecology. Ecological Modeling, Energy, and Journal of Cleaner Production are the most influential journals. Moreover, the most dominant emergy contributors (i.e., China, Italy, and USA) have close academic collaboration. Particularly, University of Siena and Parthenope University of Naples in Italy contributed greatly to the development of emergy; Beijing Normal University, Peaking University, and Chinese Academy of Sciences are the major Chinese emergy research institutions; and University of Florida and US EPA are the key US emergy research institutions. Also, emergy-based sustainability assessment and the integration of emergy synthesis with LCA have become the key hotspots in emergy-related fields. In general, this paper provides a holistic picture of emergy-related literatures and future research directions, such as the combination of emergy and other methods, as well as the combination of emergy with some innovative tools. These results will be helpful to provide references for future emergy-related studies.

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