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Global Research Trends in Emergy and Wastewater Treatment: A Bibliometric Analysis

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This research reports a bibliometric analysis using the bibliometrix package with information from the SCOPUS database. A descriptive analysis was performed to provide an overview of the countries, institutions, authors, journals and keywords of 80 manuscripts published between 1997 and 2022 in the field of study of emergy and its application in wastewater treatment. The results showed 2 sources with the highest h and g impact index (Ecological Engineering and Journal of Cleaner Production) with a significant growth since 2009. The most cited keywords were "emergy" and "wastewater", and the countries with the most important scientific networks were China, Japan, Saudi Arabia, USA, Brazil, Colombia and Italy. In addition, it shows that collaborative groups among the authors from China and USA are the ones that consolidate the main research network, as well as the largest scientific production with the most cited articles in the field of study of emergy in wastewater treatment. Therefore, the application of the emergy method in wastewater treatment requires extensive research in different types of treatments. This type of analysis would allow the development of a new approach in the application of wastewater treatment in terms of sustainability and the introduction of Latin American countries in this emerging field.

Keywords: emergy, sustainability, wastewater, clean production.

Introduction

Water pollution is a real problem in water resources management (Issakhov et al., 2021), in industrial (Jeong et al., 2021) and urban activities (Hachi et al., 2022). This is what is really important to treat wastewater from different activities using technology. Furthermore, it is necessary to apply some environmental management instruments to quantify the activities of humans that cause direct and indirect effects on the environment, to enable decision-makers to track and measure progress towards sustainability goals and outcomes (Ciobanu et al., 2022). Some of these instruments could be Life Cycle Assessment (LCA) (Bonton et al., 2012; Raghuvanshi et al., 2017), water footprint (Huang et al., 2022; Johnson and Mehrvar, 2019; Romeiko, 2019), exergy analysis (Li et al., 2021) and emergy analysis (Ciobanu et al., 2022; Liu et al., 2022). Each of these methods have their own field of application. A method that is suitable from the sustainable development perspective has to consider all interactions between environmental, social, and economic impacts of wastewater treatment systems. Emergy could provide a holistic approach and a unified measurement for sustainability evaluation (Ciobanu et al., 2022).

The term "emergy" refers to the energy memory or the total energy embodied in any product or service (Odum, 1996). Also, it is defined as the sum of all energy inputs required directly or indirectly through a transformicity (solar equivalent joules, seJ) necessary to manufacture any product or service (Odum, 1974).

The emergy accounts for all forms of energy of materials, converting them into equivalents of one form of energy (Pulselli et al., 2008). Emergy analysis is a technique that allows the determination of the value of nature for the human economy (Odum, 1988). This technique makes it possible to analyze the relationships between the components of anthropogenic systems and the natural resources necessary to maintain sustainability in a system, while allowing the calculation of environmental and economic indices (Almeida et al., 2007). Emergy is also widely used to measure energy flow, logistics, information flow and money flow, thus assessing the health of ecosystems where some activity takes place, enabling the management of complex ecological systems and assessing sustainable development (Chen et al., 2017).

The emergy method has been developed over the last five decades by Odum (Odum, 1974, 1976, 1988, 1994a, 1994b, 1995, 2000) but the application of emergy analysis in wastewater treatment is reported from the early 2000s, for example, in the research of Grönlund et al. (2001) and Geber and Björklund (2001).

Wastewater treatment plays an irreplaceable role in reducing pollutants and reusing water. Nonetheless, it also consumes resources and releases environmental emissions during treatment processes (Shao et al., 2014). In recent decades, research has been developed on the emergy approach in wastewater treatment (Vassallo et al., 2009). For example, Alizadeh et al. (2020) assessed the sustainability of two actual wastewater treatment plants using the eco-efficiency index based on emergy and LCA; Chen et al. (2009) assessed the emergy, resource consumption and environmental support contained in a constructed wetland as a kind of ecological treatment engineering through different relative emergy-based indices; Lu et al. (2014) assessed an integrated water quality, emergy and economic evaluation of the three treatment systems that was performed based on the observed changes in biomass (*Ipomoea aquatica, Misgurus anguillicaudatus, Rhodopseudomonas palustris*), water quality, and other natural and economic inputs and outputs. Also, Zhang et al. (2014) conducted the analysis of an integrated livestock wastewater treatment system to assess the environmental performance due to their resources consumption and emissions impact; Moss et al. (2014) compared two anaerobic digestion (AD) systems to determine their relative sustainability.

Recently, articles have been published more frequently in terms of water treatment and emergy, and have included new applications. For example, the research of Liu et al. (2022) assessed the performance of wastewater treatment plants before and after their improvement using emergy evaluation combined with economic analysis; Praveen et al. (2022) assessed the remediation of mine acid drainage through the application of microalgae using emergy and carbon footprint; and Shao et al. (2022) assessed the recovery of nitrogen (N) and phosphorus (P) from wastewater by ceramsite in the model that is compared with other two approaches (i.e., landfill and incineration). Due to the growth and new applications that have been arising in recent years regarding emergy and wastewater treatment, it is important to understand dynamics, evolution and origin of this field of research.

Bibliometric analysis has been used in various disciplines and fields, including environmental sciences due to their different advantages such as data visualization, quantitative analysis and knowledge discovery. Furthermore, bibliometric helps researchers to start understanding a new topic and helps to identify current research trends, provides information on specific and general aspects over time, and contributes to the development of important areas (Virú-Vásquez et al., 2022). In this sense, the aim of this research is to carry out a bibliometric analysis, through quantitative and qualitative analysis, and to identify trends in scientific literature, explore its future direction in specific scientific fields, analyze the state of research in detail, identify research hotspots, and build an international cooperation network between countries, institutions or important authors.

Methods

Bibliometric analysis

To carry out the bibliometric analysis, the steps described in Zupic and Čater (2014) were followed. These steps are study design, data collection, data analysis, data visualization, and interpretation. They are explained as follows.

For the study design, the following terms were introduced in the advanced search of Scopus: (TITLE-ABS-KEY (emergy) AND TITLE-ABS-KEY (wastewater AND treatments) OR TITLE-ABS-KEY (municipal AND wastewater) OR TITLE-ABS-KEY (treatment AND plants). Only the Scopus database was considered to carry out the bibliometric analysis. Furthermore, articles, conference papers, conference reviews, and reviews were taken into consideration for analysis.

For data collection, the data obtained with the keywords was extracted in a csv format from excel, then the data were uploaded to biblioshiny, which is a shiny app providing a web-interface for bibliometrix in R studio.

For data analysis, all the articles downloaded in a csv format were processed qualitatively and quantitatively. For data visualization, R studio was used to show analysis, describing the most important authors with a number of documents and through different indices (H index and G index), where a set of papers has an h-index if h of these papers has at least h citations (Hirsch, 2005), and a set of papers has a g-index, if an academic has published at least g articles that combined have received at least g^2 citations (Egghe, 2013). Also, other analyses were carried out, for example, on most relevant affiliations, corresponding author's country, most cited countries and authors productivity using Lotka's law.

Lotka's law of scientific productivity shows the number of authors against the number of contributions made by the authors plotted on a logarithmic scale (Kawamura et al., 2000), and it is represented by the following Equation 1 (Bookstein, 1977; Simont, 1955):

$$A_N = A_1 / N^C \quad (1)$$

Where: A_N is the number of authors publishing N papers; A_1 is the number of authors publishing one paper; C is a parameter to estimate depending on the data. N: 1, 2, 3, ... n.

For sources, the most relevant sources (number of documents) and source impact (through the h and g indices) are shown, as well as the dynamics of the sources, that is, how they change over the years versus the number of occurrences. Finally for this section, Bradford's law was analyzed, which is a pattern first described by Bradford (1934) to estimate the exponentially diminishing returns of searching for references in science journals. One formulation is that journals in a field are sorted by the number of articles into three groups, each with about one-third of all articles. Bradford's law is explained below with the following Equation 2:

$$k = (e^{y} \cdot Y_m)^{1/P} \quad (2)$$

Where: γ is 0.57,772, Y_m is equal to the maximum productivity of the first magazine, P is the number of groups (Andrés, 2009).

For documents, the most cited documents and the Spectroscopy of the Year of Reference Publication (SYRP) are shown. SYRP is a bibliometric method which can be used to analyze the historical origins of research fields or researchers. This method analyzes the cited references and especially the referenced publication years of a publication set (Glänzel et al., 2016). Moreover, a keyword map tree is illustrated, where the distribution of keywords is shown in terms of percentage (%).

In the conceptual structure, the factorial analysis is shown, this analysis groups the research topics in different research clusters. Also, the two-dimensional thematic map, which presents four zones: i) niche themes, ii) motor themes, iii) emerging or declining themes and iv) basic themes. The social structure is analyzed, it shows the collaboration between authors and countries through collaboration networks. Visualization is shown through graphs and tables and the interpretation was carried out through bibliometric articles in the Scopus database. Finally, an analysis of the most cited documents for different periods on the recent trends and evolution of the topics related to emergy and wastewater treatment is discussed.

Result and discussion

Descriptive analysis

Fig. 1 shows that the annual scientific production had a slight increase from 1997 to 2022 with an annual global rate of 8.09%. It is interesting to note that the increase is temporary and intermittent, e.g., 1997 to 2001, 2007 to 2010, 2012 to 2014 and then maintained until 2021. This indicates that some of the authors are not constantly publishing or are publishing seasonally. Furthermore, *Fig. 1* shows an intermittent number of citations from 1997 to 2011 and then an increase from 2012 to 2022. There is a prolific increase in both total and average citations since 2012. It is often accepted that the higher the number of citations, the greater the impact. Therefore, it could be affirmed that the impact of the research increased from 2012 to 2022.

Table 1 illustrates the main information. A total of 80 documents were taken into consideration for bibliometric analysis: 68 research articles, 8 conference papers, 2 conference reviews and 2 reviews. The review articles were taken into consideration since they summarize the theme and show research trends as well.

Fig. 1. *Annual scientific production (1997–2022)*

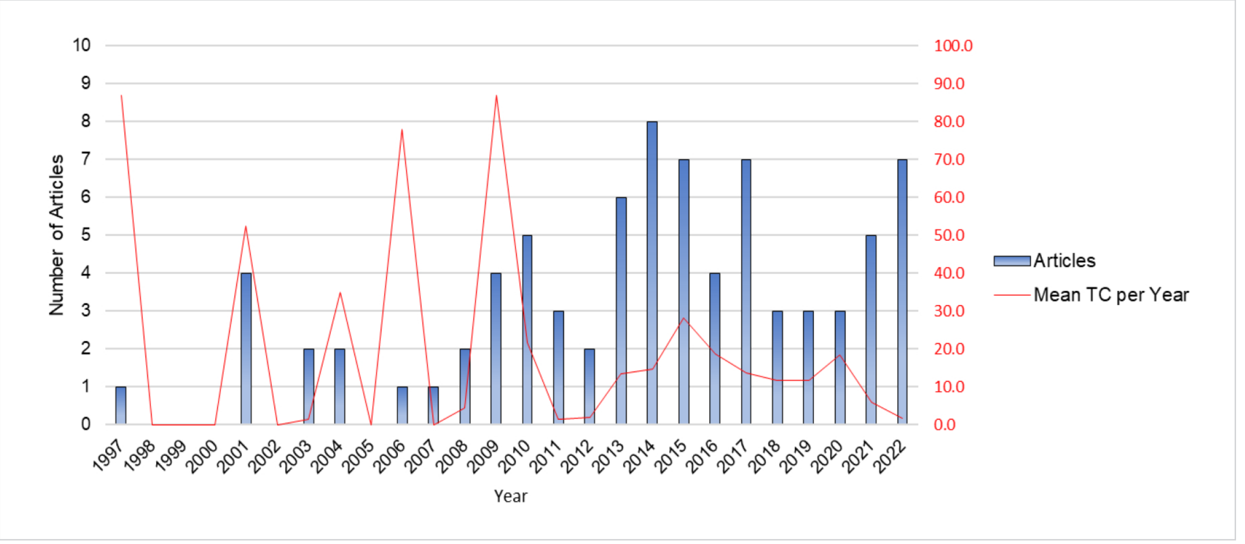


Table 1. *The main information of the research*

Description	Results
MAIN INFORMATION ABOUT DATA	
Timespan	1997:2022
Sources (Journals, Books, etc)	46
Documents	80
Annual Growth Rate %	8.09
Document Average Age	8.31
Average citations per doc	20.65
References	3567
AUTHORS' COLLABORATION	
Single-authored docs	3
Co-authors per doc	4.06
International co-authorships %	28.75
DOCUMENT TYPES	
Article	68
Conference paper	8
Conference review	2
Review	2

Authors

Fig. 2 shows information about the number of documents (frequency %) in the research field of emergy analysis in wastewater treatment. *Fig. 2* shows the 10 authors with the highest scientific production, including all types of authorship (first author, co-authorship, etc.). Giannetti BF leads the distribution percentage of publications with a value of 8.6%, followed by Almeida CMVB and Zhang X with a percentage of 7.4% (6 documents), Chen GQ and Zhang Y with a percentage of 6.2% (5 documents), Agostinho F and Wu J with a percentage of 4.9% (4 documents), and finally Bastianoni S, Bonilla SH and Cano NA with a percentage of 3.7% (3 documents).

Developing a time evolution analysis to examine the scientific productivity of the top 20 authors over time allows us to understand the research that was published between 1997 and 2022. *Fig. 3* shows that 18 out of 20 authors have started publishing since 2008. This indicates better organization, emergence of research networks and increased collaboration for these authors. This also explains previous findings on the substantial increase in citations from 2012 onwards considering a stronger collaborative organization.

It is worth noting that there is a production gap in the field of the research from 2004 and 2008. Similarly, it is worth mentioning that Bastianoni S published

Fig. 2. *The most relevant authors*

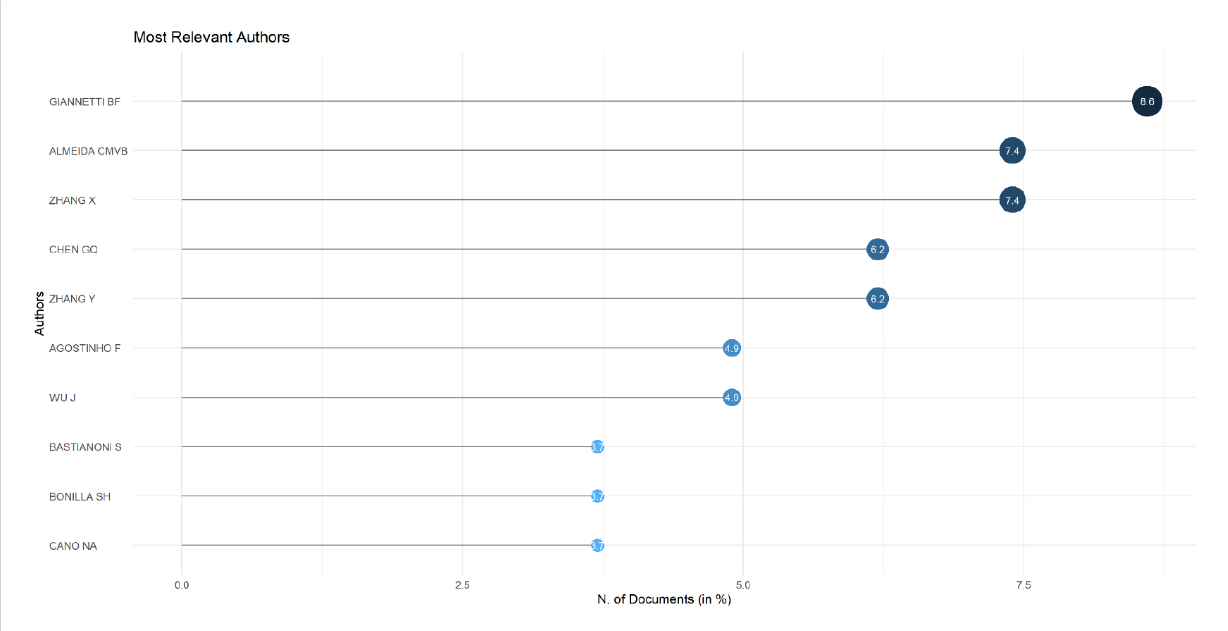
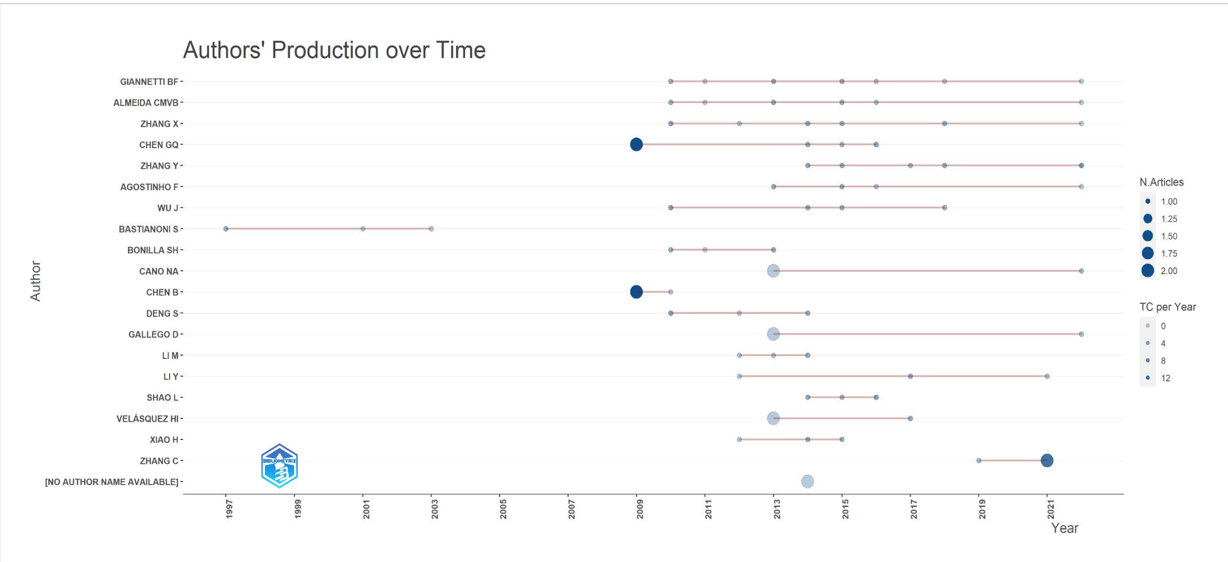


Fig. 3. *Production by author over time*



between 1997 and 2003. Furthermore, *Fig. 3* shows that while the circle is bluer, it means that there is a greater total citation (TC) per year, while for a larger circle, it means that there is a greater number of articles (N. Articles) (Virú-Vásquez et al., 2022). It is illustrated that, for 2009, Chen GQ and Chen B obtained a citation per year of 16.57 with two documents only. On the other hand, it can be observed that Giannetti BF, Almeida CMVB and Zhang X maintain a similar long-term production. In the case of Giannetti BF and Almeida CMVB, it is because they collaborate together.

Lotka's law is shown in *Fig. 4*. Lotka's law represents the number of authors against the number of contributions made by the authors plotted on a logarithmic scale (Kawamura et al., 2000). It is illustrated that at least 198 authors (81%) contributed with 1 article, 27 authors (11%) with less than two articles, 12 authors (5%) with 3 articles, 2 authors with 4 articles, and 1 (0.4%) author with 7 scientific articles.

The different impact indices are proportional to the productivity of the respective authors. *Fig. 5* shows h-index and g-index. It shows that the authors with the highest number of publications have the highest total citation (TC) and have the highest academic impact in the field of emergy analysis in wastewater treatment. According to *Fig. 5*, it can be noticed that there are 3 groups of authors differentiated by the h-index. The first group is with the h-index of 5 (Chen GQ, Zhang Y), the second group – with the h-index of 4 (Almeida CMVB, Giannetti BF, Wu J, Zhang X) and the third group (Agostinho F, Chen B, Deng S, Li M) is with the

Fig. 4. *Authors' productivity using Lotka's law*

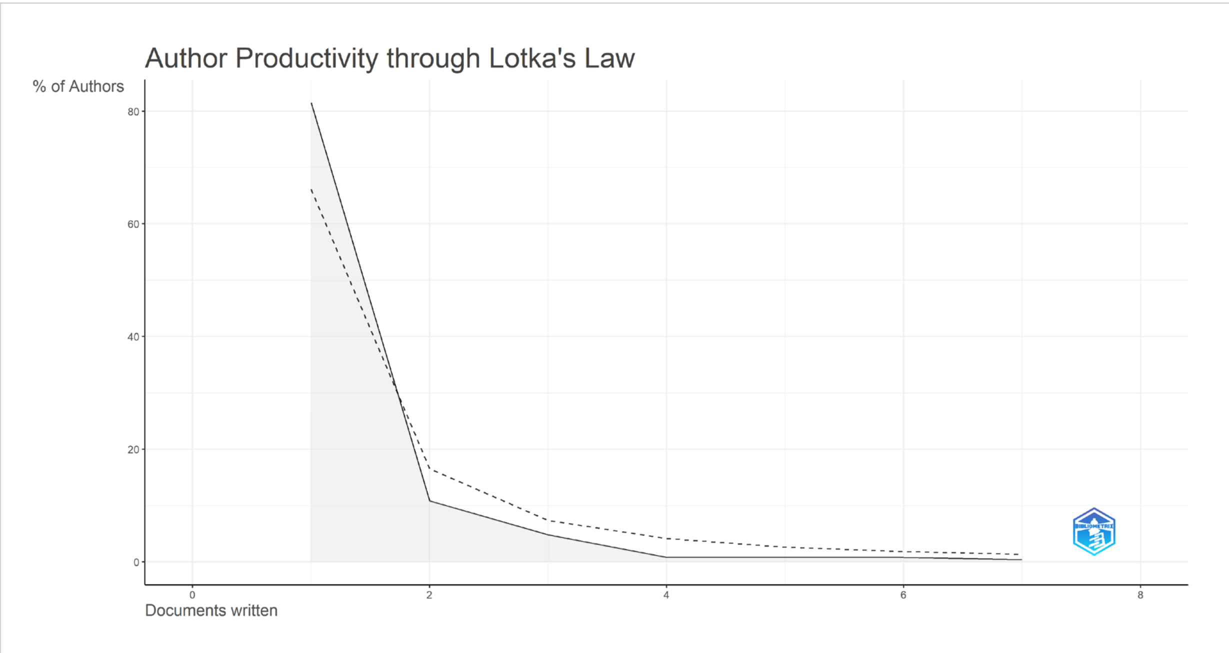


Fig. 5. *Author's impact*

h-index of 3. It should be noted that the contribution of authors to the foundations of the emergy theory, such as Odum HT, Odum B and Brown MT, is limited, despite the fact that they were the founders of research about emergy; on the contrary, more recent authors, such as Chen B and Chen GQ, have the highest total indices (TC). Scientific productions are generally the result of institutional collaborative activities. *Fig. 6* shows the most relevant affiliations. According to the figure, the universities leading the field research of emergy in wastewater treatment are Asian universities such as Sichuan Agricultural University (China), Sichuan Agricultural University Chengdu – campus (China), Peking University (China). Latin American universities are also included: Universida de Paulista (Brazil), University of Florida (USA) and Universidad Nacional de Colombia Sede Medellin (Colombia).

The country of the corresponding author is shown in *Fig. 7*. It illustrates that China has the largest number of corresponding authors. China has a total of 33 publications, of which 24 were single country publications (SCP), and 9 multiple country publications (MCP). In the second place, there is the USA with 8 publications (2 MCP and 6 SCP). The third place is taken by Italy with only SCP (6 publications). Furthermore, China is the country with the most total citations (606), followed by Italy (225), Sweden (217), USA (202) and other countries with less than 150 citations. *Table 2* shows the most cited countries, with the total citation (TC), and the average article citations.

Table 2. *Most cited countries*

Country	TC	Average Article Citations
China	606	18.36
Italy	225	37.50
Sweden	217	54.25
USA	202	25.25
Brazil	132	26.40
United Kingdom	65	65.00
Iran	32	10.67
France	26	26.00
Luxembourg	15	15.00
Mexico	15	15.00

Fig. 6. *Most relevant affiliations*

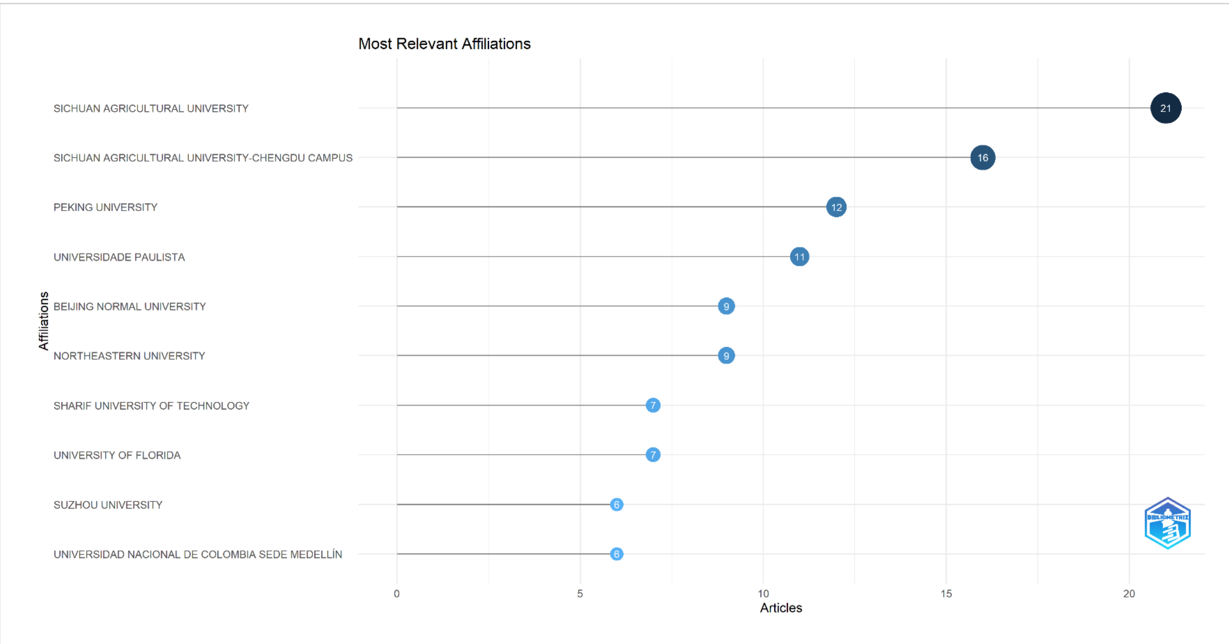
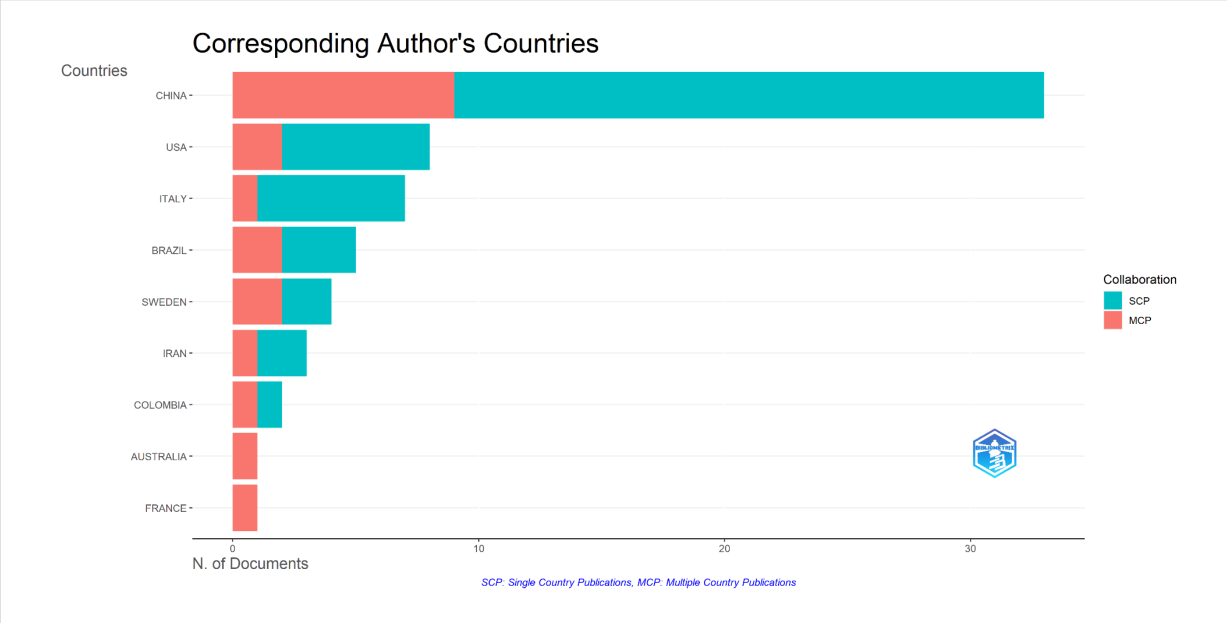


Fig. 7. *Corresponding author's country*

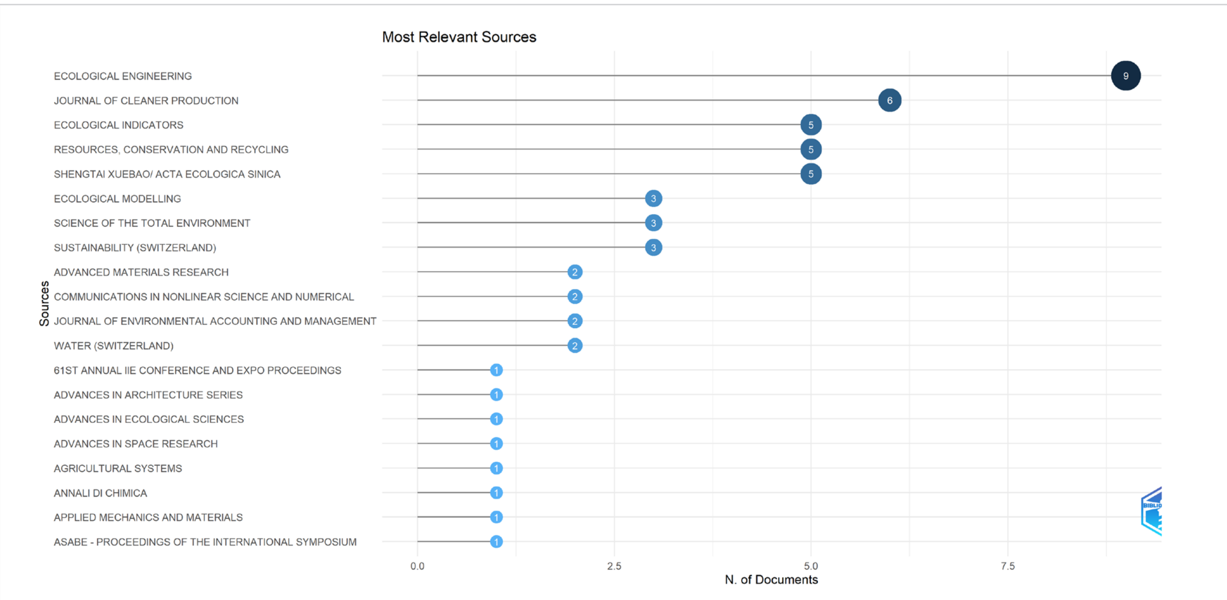


Sources

In bibliometric research, another common unit of analysis is the sources in which the scientific output is published. *Fig. 8* shows that Ecological Engineering, Journal of Cleaner Production, Resource Conservation and Recycling and Shengtai Xuebao/Acta Ecologica Sinica are the main journals.

From the perspective of publication sources, it was found that only four journals position themselves as the main sources of publication in the area of emergy and wastewater treatment. Bradford's Law is one of the methods for determining core journals in a given subject over a set period of time.

Fig. 8. *Most relevant sources*



According to Bradfords Law, relevant journals can be split into three groups in any field of interest and each group contributes around one-third of all articles (Kilicoglu and Mehmetcik, 2021). As shown in *Fig. 9*, Ecological Engineering, Journal of Cleaner Production and Resources Conservation and Recycling and Health Economics are the most relevant journals.

The journal impact factor was created with the aim of determining the most important articles in a given field. *Fig. 10* lists the journals according to their impact indices (h-index and g-index) as well as according to the TC count. There are some differences with the list of top journals according to Bradford's law. The total citation index shows "Ecological Engineering and Journal", "Communications in Nonlinear Science and Numerical Simulation" and "Resources, Conservation and Recycling" as the most cited sources. This is due to the fact that, in recent years, these journals have become a publication platform for research on the analysis of emergy in wastewater treatment. According to the data, sources started publishing as shown: Ecological Engineering and Journal in 2001, Journal of Cleaner Production in 2015, Resources, Conservation and Recycling in 2001, Ecological Indicators in 2014, and Communications in Nonlinear Science and Numerical Simulation in 2009.

Fig. 9. *Bradford's law and the basic journals*

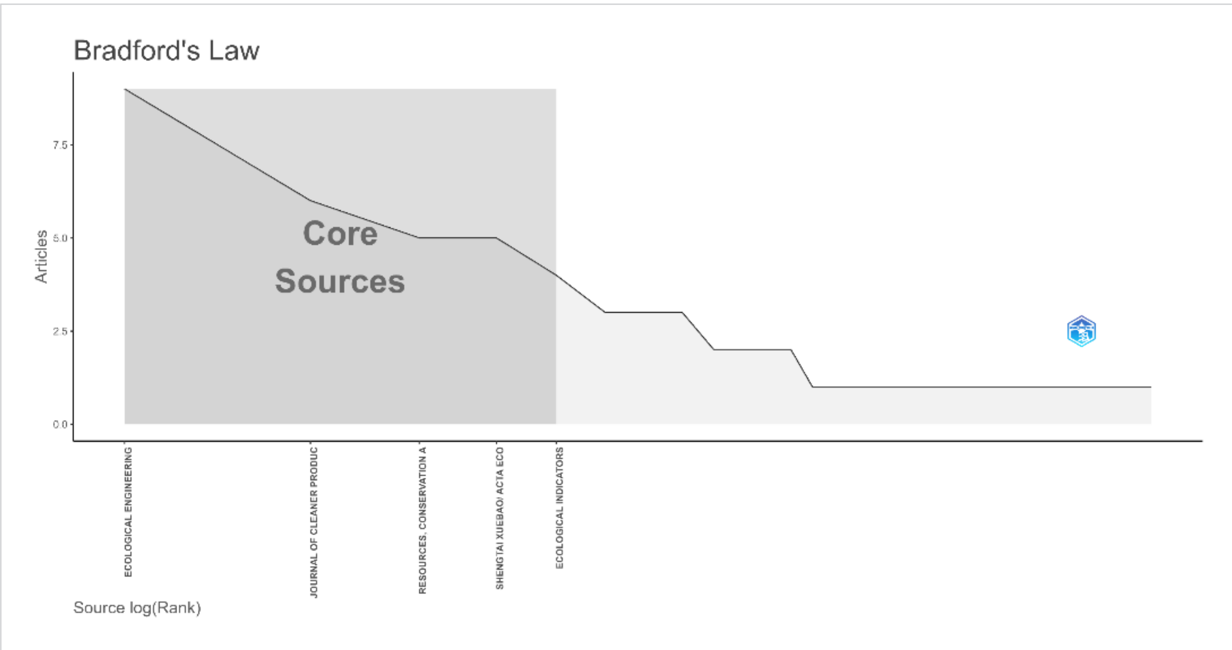


Fig. 10. *Source impact*

Fig. 11 shows an increasing publication trend for almost all major journals in different magnitude in the field of emergy research in wastewater treatment. Interestingly, the strong increase in publications of the journal "Ecological Engineering" started around the 2000s. Overall, the trend indicates an increased interest of journals to publish articles that consider aspects of environmental management or resource conservation.

Documents

In bibliometric research on emergy analysis in wastewater treatment, it is useful to consult the most cited documents. *Table 3* shows the most cited papers. It is observed that 8 of the 10 most cited documents correspond to the period before 2010 and only two were published after 2015. Research reports emergy analysis in different scenarios: constructed wetlands (Arias and Brown, 2009; Chen et al., 2009; Siracusa and la Rosa, 2006; Zhou et al., 2009), municipal wastewater (Björklund et al., 2001; Ciobanu et al., 2022), organization system (Bastianoni and Marchettini, 1997) and specifically water treatment with microalgae (Grönlund et al., 2004).

Recently, the technique of reference publication year spectroscopy (RPYS) has been introduced, which is based on the analysis of the frequency with which references are cited in publications in a specific research field (Glänzel et al., 2016). In *Fig. 12*, the black line shows the distribution of the number of references cited over the years of publication, and the orange line shows the absolute deviation of the number of references cited in one year from the median number of references cited in the previous two years. From 1970 onwards, research was published giving theoretical support to emergy, and it was not until 2001 that applications of emergy analysis in wastewater treatment began to be carried out, with a constant growth until 2008, reaching its maximum in 2012 and then decreasing until 2022. This is corroborated by the red line that shows that the median of the number of quotes from previous years is higher than the current ones because the graph starts to decrease.

The keywords used by the authors in research related to emergy in wastewater treatment are shown in *Fig. 13*. Statistical analysis of the keywords could provide research directions, which can be a useful way to deepen the development of scientific output.

Fig. 11. *Source dynamics*

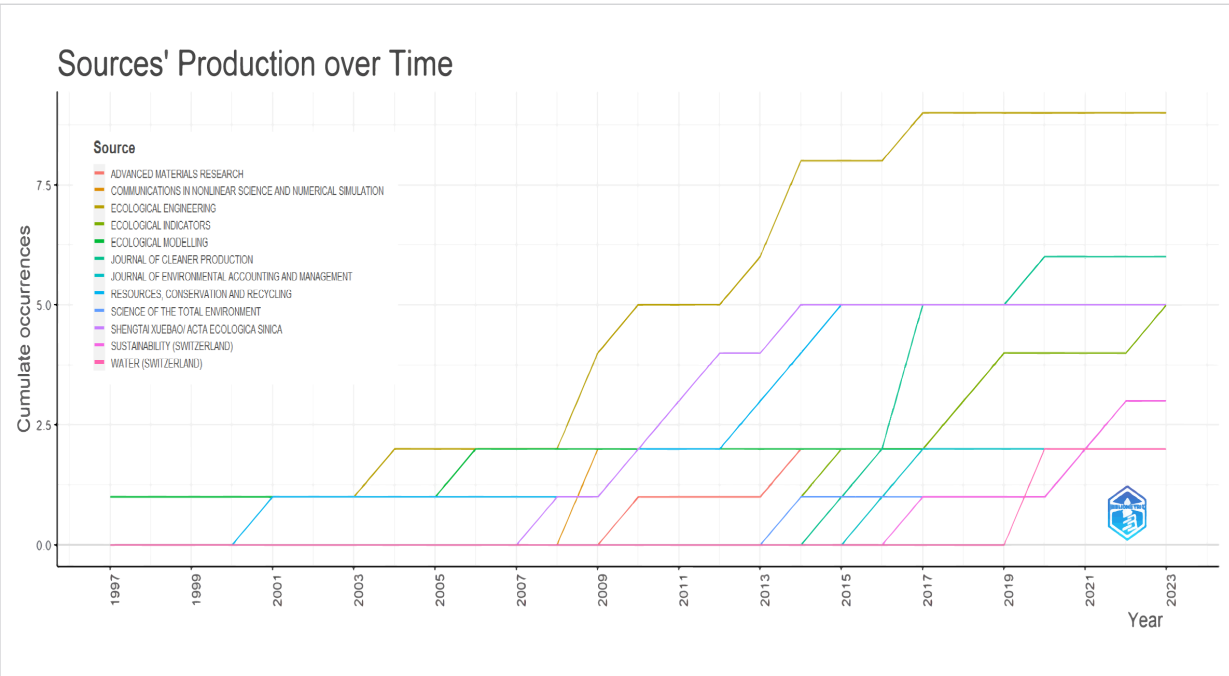


Table 3. *Most cited documents*

Item	Tittle	Journal	Keywords	Citations	TC per Year	Reference
1	Emergy evaluations for constructed wetland and conventional wastewater treatments	Communications in Nonlinear Science and Numerical Simulation	Emergy; Constructed wetland; Wastewater treatment; Systems ecology	117	8.36	Zhou et al., 2009
2	Emergy as embodied energy based assessment for local sustainability of a constructed wetland in Beijing	Communications in Nonlinear Science and Numerical Simulation	Emergy as embodied solar energy; Sustainability; Constructed wetland; Wastewater treatment	115	8.21	Chen et al., 2009
3	Emergy analysis of municipal wastewater trea`tment and generation of electricity by digestion of sewage sludge	Resources, Conservation and Recycling	Emergy; Wastewater treatment, Biogas, Resource use; Energy analysis	115	5.23	Björklund et al., 2001
4	Emergy/exergy ratio as a measure of the level of organization of systems	Ecological Modelling	Emergy; Exergy; Efficiency of ecosystems; Self-organization	87	3.35	Bastianoni and Marchettini, 1997
5	Design of a constructed wetland for wastewater treatment in a Sicilian town and environmental evaluation using the emergy analysis	Ecological Modelling	Emergy analysis; Natural capital; Environmental accounting; Constructed wetlands, First - order plug - flow model	78	4.59	Siracusa and la Rosa, 2006
6	Sustainability of wastewater treatment with microalgae in cold climate, evaluated with emergy and socio-ecological principles	Ecological Engineering	Sustainability; Microalgae; Wastewater treatment; Emergy; Socio-ecological principles; Cold climate	69	3.63	Grönlund et al., 2004
7	"Living off the land": resource efficiency of wetland wastewater treatment	Advances in Space Research	Not found	65	2.95	Nelson et al., 2001
8	Feasibility of using constructed treatment wetlands for municipal wastewater treatment in the Bogotá Savannah, Colombia	Ecological Engineering	Municipal wastewater; Emergy; Developing countries; Appropriate technology	60	4.29	Arias and Brown, 2009
9	Critical insights for a sustainability framework to address integrated community water services: Technical metrics and approaches	Water Research	Water services; Sustainability; System analysis; Integrated water management; Environment	59	7.38	Xue et al., 2015
10	A sustainability analysis of a municipal sewage treatment ecosystem based on emergy	Ecological Engineering	Sewage treatment ecosystem; Emergy based indicator; Reclaimed water; Sludge; Sustainability	57	4.38	X.H. Zhang et al., 2010

Fig. 12. *Spectroscopy of the year of reference publication*

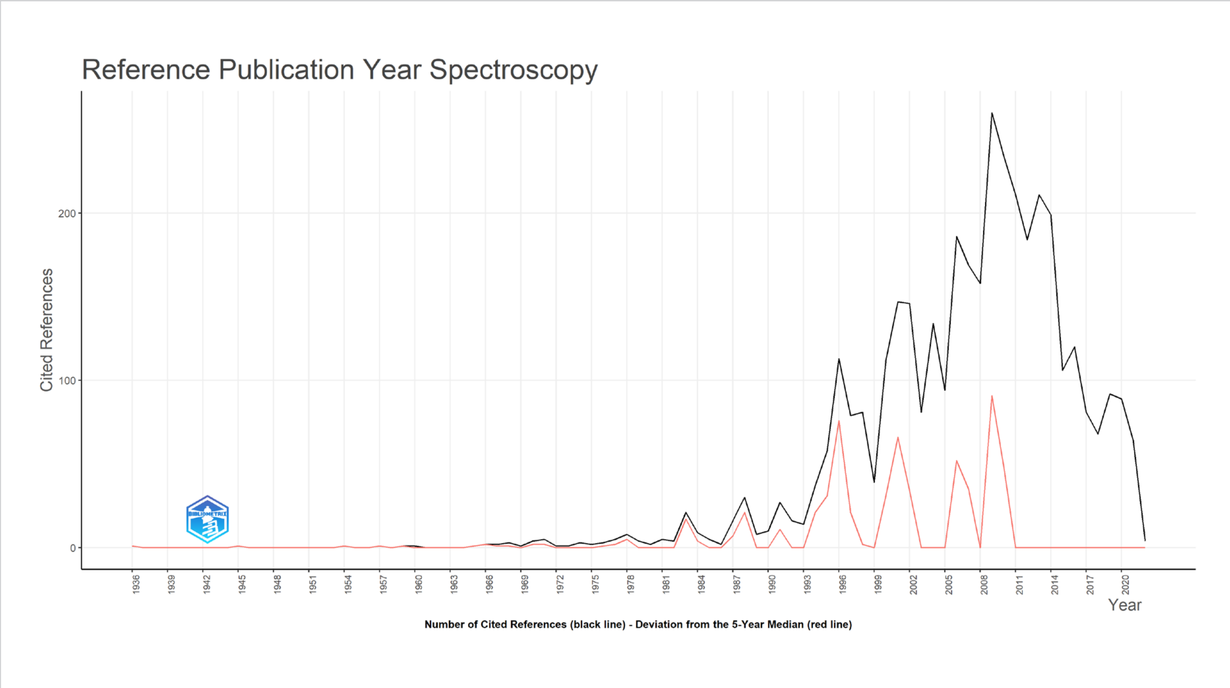
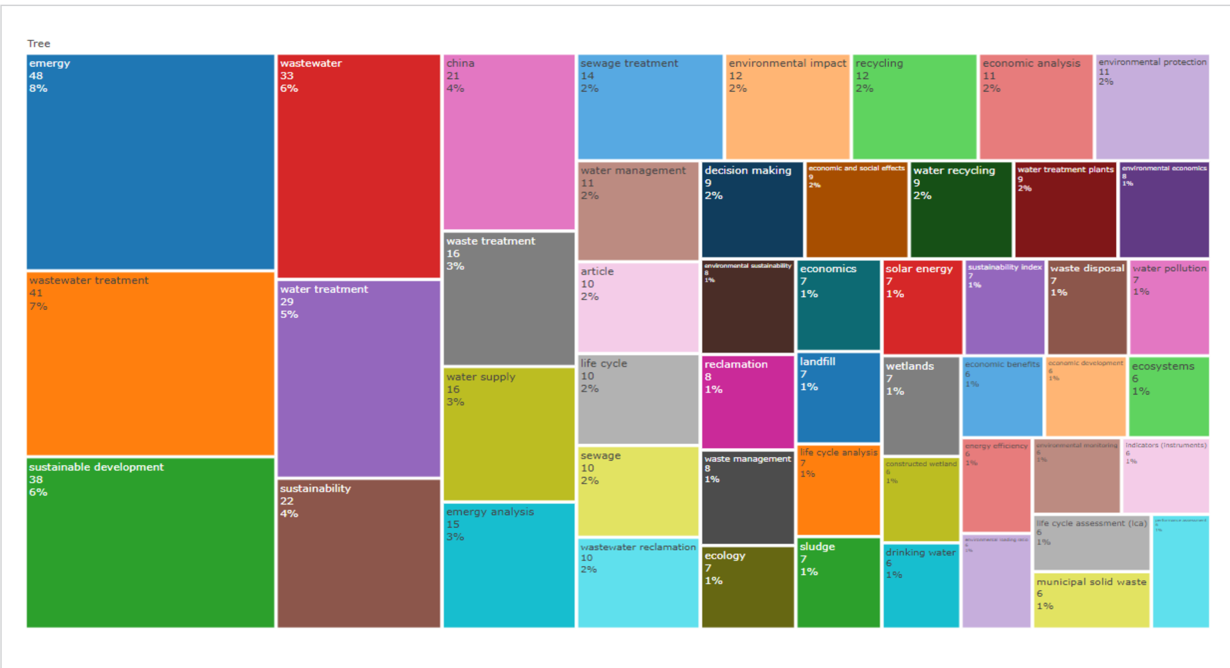


Fig. 13. *Keyword map tree*



The 50 most frequently used keywords in the publications are illustrated in a word tree map (*Fig. 13*). The most frequently used keywords are emergy (8%), wastewater treatment (7%), sustainable development (6%), wastewater (6%) and water treatment (5%) among the top 5 words.

Conceptual structure

Multiple correspondence analysis (MCA) was carried out to understand the conceptual structure of the research. The main research groups in the area of interest were identified. The two-dimensional graph of the keywords organized into clusters is shown in *Fig. 14*. The occurrences of keywords were analyzed by the correspondence method through a conceptual structure map. This indicates that the words covering the field of study of emergy in wastewater treatment can be organized into 4 main groups, which represent the intellectual structure of the research topics addressed by the academics concentrating on the related aspects.

The first group (red color) with a total of 4 keywords which includes the terms "environmental sustainability", "solar energy", "life cycle", and life cycle analysis" could be associated with articles that emphasize the methodology of emergy and life cycle analysis. The second group includes the terms "emergy", "sewage treatment", "China", "recycling", "reclamation", "water treatment", "environmental protection", "sustainability", "environmental impact", "wastewater treatment", "wastewater", "economic and social effects", "sustainability index", "decision making", "ecology", "sustainable development", "emergy analysis", "wetlands", "environmental economics", "economics", "waste treatment", and "economic analysis". They could be associated with articles that emphasize the application of emergy. The third group has the terms "wastewater reclamation" and "water recycling". They could be linked to recovery and recycling. The fourth group includes the terms "water treatment plants", "water management", "water supply" and "sewage". These words are more linked to water management.

The themes were also analyzed according to a two-dimensional strategic diagram of four quadrants based on the four sections as shown in *Fig. 15*: (1) upper right quadrant: main-issues; (2) lower right quadrant:

Fig. 14. *Factorial analysis: conceptual structure map*

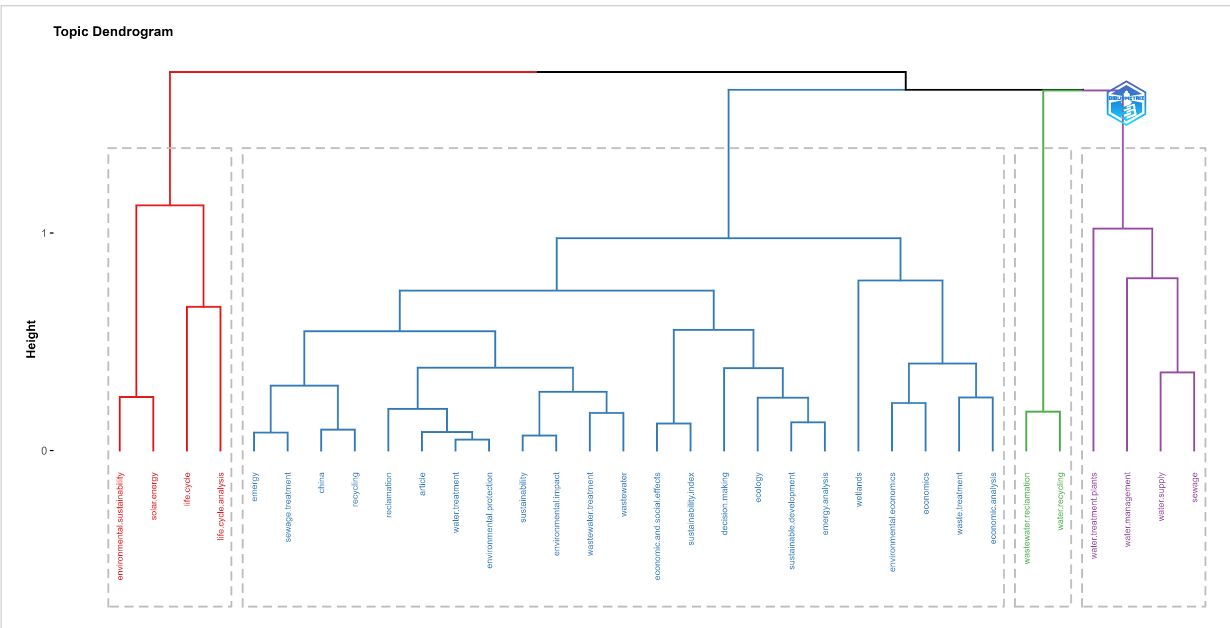
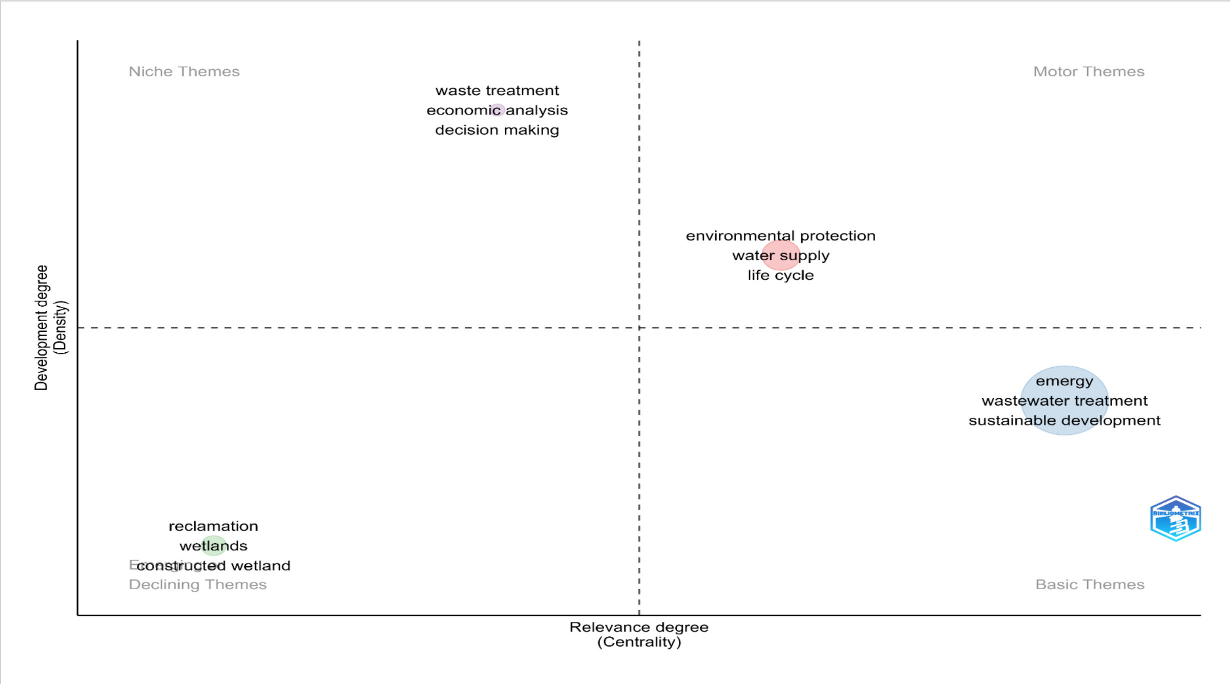


Fig. 15. *Two-dimensional thematic map*



basic issues; (3) lower left quadrant: emerging or disappearing issues; (4) upper left quadrant: highly specialized issues (Niche themes). Niche themes are waste treatment, economic analysis, decision making; motor themes are environmental protection, water supply and life cycle; declining topics include the keywords "wetlands" and "constructed wetlands", and finally, the basic themes are emergy wastewater treatment and sustainable development.

Social structure

Collaborative networks show how authors, affiliated institutions and countries relate to each other in a specific field of research. *Fig. 16* shows different collaboration groups where different authors and their collaboration can be observed. The predominant ones are Zhang X, Xiao H, Wu J, Zhang Y, Mu H, Liu Z, Pan H, Wei Y, Deng S, Liu J, Li M, Li Y, Qi H (red color). There are also collaborations between Giannetti BF, Agostinho F, Bonilla SH, Agustini CAD and Almeida CMVB (blue color).

In *Fig. 17*, different clusters that group countries in terms of their collaboration are shown. A stronger collaboration is observed between China, Japan, Germany, Canada, Saudi Arabia, Pakistan, Philippines, and USA. Other clusters are also shown: Norway, Kenya, Sweden (green color); Brazil, Colombia, Italy, Iran, Romania (red color); Switzerland, Thailand (brown color); India and Australia (orange color); Luxembourg and France (purple).

Fig. 16. *Collaboration network (co-authorships)*

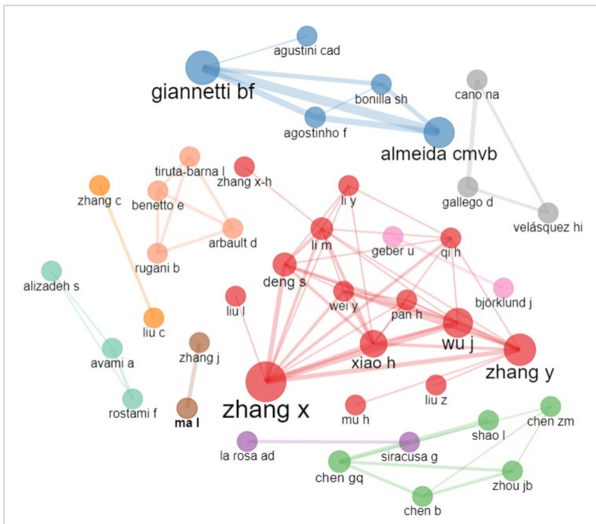
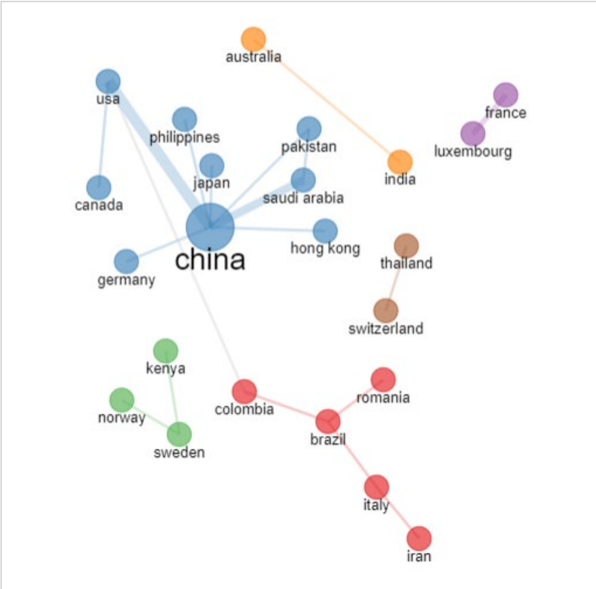


Fig. 17. *Country collaboration network*



Recent trends

In addition, the most significant research areas are shown in *Fig. 18*, as well as how topics related to the study area have evolved and merged. *Fig. 18* illustrates 4 research periods and how the keywords have been changing over time. The periods identified are from 1997 to 2007 (first period); 2008 to 2014 (second period); 2015 to 2020 (third period); 2021 to 2022 (fourth period). In addition, in *Table 4*, the most cited articles for each period are shown.

In the first period, they use indicators with numerical transformations. These include transformations in raw material (electricity, concrete, plastic, oil, etc.), purchased inputs (copper, insulation) (Björklund et al., 2001). In the second period, some indices began to appear and use some mathematical equations, such as Transformity (Tr), Emergy Yield Ratio (EYR), Emergy Investment Ratio (EIR), Environmental Loading Ratio (ELR) and Environmental Sustainability Index (ESI) (Ren et al., 2013). This analysis was carried out in constructed wetlands (Arias and Brown, 2009; Chen et al., 2009). Despite the use of traditional indices, they began to apply and perform others, as in the study by Zhou et al. (2009), which uses the Index of Ecological Waste Removal Efficiency (EWRE), which means indicators referring to removal such as Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD) and phosphorous and total nitrogen.

Fig. 18. *Thematic evolution*

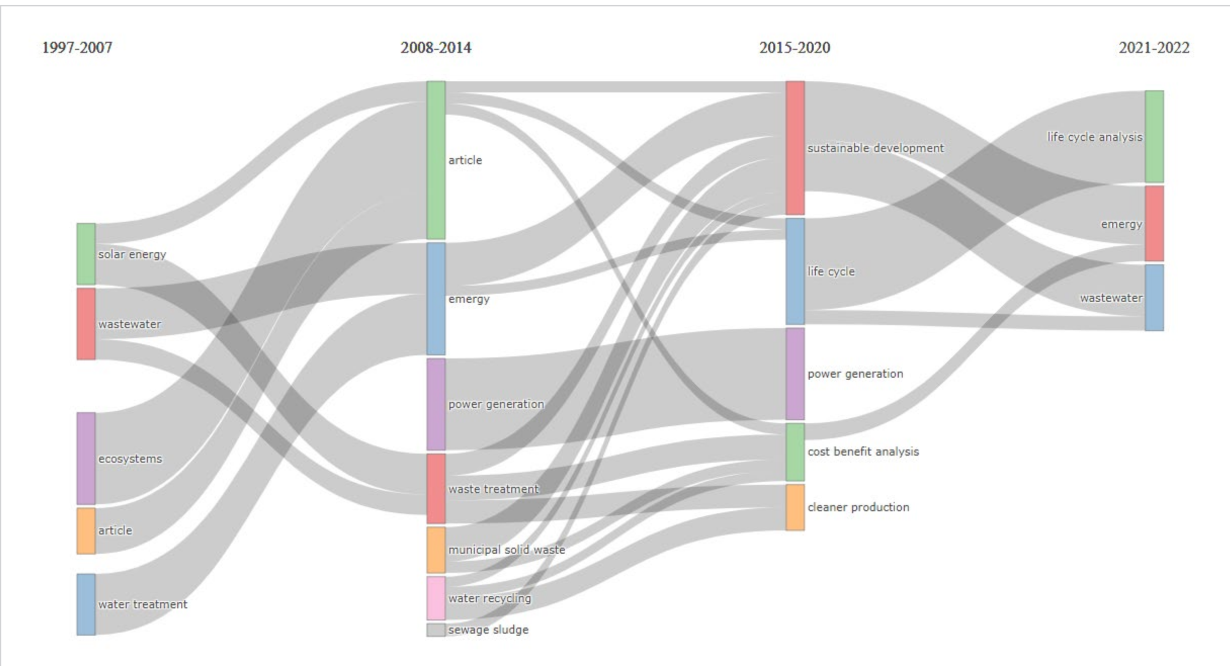


Table 4. *Research about emergy through the years*

Keywords	Focus topic	Method	Indicators	TC	Reference
Wastewater; Eco-environmental damage; Economic development; Emergy	Eco-environmental damage from wastewater (31 provinces)	Emergy analysis	– Eco-environment damage of waste-water per unit land area (EDW-LA) – Eco-environment damage intensity of wastewater per unit GDP (ED-IW-GDP)	31	C. Liu et al., 2021
Phosphorus; Nitrogen; Ceramsite; Recycling; Emergy analyse	Wastewater valorisation by ceramsite	Emergy analysis	– Emergy yield ratio (EYR) – Environmental load ratio (ELR) – Emergy sustainable index (ESI)	9	Q. Shao et al., 2022
Eco-efficiency; Emergy analysis; Life cycle analysis; Sustainability; Wastewater treatment	Wastewater treatment plants (two plants)	Emergy and life cycle analysis	– Emergy yield ratio (EYR) – Environmental load ratio (ELR) – Emergy sustainable index (ESI) – Eco-efficiency index based on emergy – analysis (EE_{EM}) – Eco-efficiency index based on life cycle assessment (EE_{LCA})	30	Alizadeh et al., 2020
Sewage treatment; Cleaner production; Emergy; Indicator	Performance changes of the largest sewage treatment plant	Emergy and money-based indicators	– Treatment ratios – Cost ratios – Emergy ratios	27	X. Zhang et al., 2015
Emergy; Constructed wetland; Wastewater treatment; Systems ecology	Constructed wetland (CW) and conventional wastewater treatments	Emergy analysis	– Index of ecological waste removal efficiency (EWRE)	117	Zhou et al., 2009
Emergy as embodied solar energy; Sustainability; Constructed wetland; Wastewater treatment	Constructed wetland	Emergy analysis	– Emergy yield ratio (EYR) – Environmental loading ratio (ELR) – Emergy investment ratio (EIR) – Emergy sustainability index (ESI)	115	B. Chen et al., 2009
Municipal wastewater; Emergy; Developing countries; Appropriate technology	Constructed wetland for municipal wastewater treatment	Cost analysis and an emergy evaluation	– Treatment ratios – Cost ratios – Emergy ratios	60	Arias and Brown, 2009
Emergy; Wastewater treatment; Biogas; Resource use; Energy analysis	Municipal wastewater treatment and generation of electricity by digestion of sewage sludge	Emergy analysis	– Raw material – Service – Direct environmental inputs – Purchased inputs	115	Björklund et al., 2001
Wastewater treatment; Resource use; Emergy analysis; Ecosystem services; Area demand; Wetlands	Constructed wetland, conventional three-step treatment, treatment in a natural wetland	Emergy analysis	– Total emergy use – Local renewable emergy – Purchased inputs	29	Geber and Björklund, 2001

On the other hand, in order to assess sustainability in different ways, different methodologies are proposed for comparison or integration. Such is the case of emergy and LCA (Alizadeh et al., 2020; Ren et al., 2013), which are integrated methodologies that have been used in parallel or in a hybrid way in many product or regional system sustainability assessments (Arden et al., 2019). Finally, over the years in the fourth period, much more specific and complete research is observed. Such is the case of the application of emergy to give a value to residual sludge and comparing them under other ways of disposing of them (Shao et al., 2022), as well as the complex and dedicated work of Liu et al. (2021) that analyzes the emergy for water treatment in 31 provinces of China. This shows that the research tends to be more specific, complete, complex and tends to compare it with other methodologies such as cost-benefit analysis (Gao et al., 2021) and exergy (Malboosi et al., 2021).

Conclusions

This bibliometric research developed an analysis of publications related to emergy analysis in wastewater treatment that are available in the SCOPUS database. An analysis of 80 publications between 1997 and 2002 was carried out to visualize the overview of authors, sources, documents, conceptual structure, social structure and recent trends. These indicators are intended to make it easier for researchers to analyze the existing literature in order to improve the direction of research into a better scientific contribution.

For author-level metrics, the most prolific authors and their collaboration and citation networks were identified along with their impact. In the article-level metrics, citation counts, reference lists, and networks between different articles were evaluated. Annual scientific output, top articles by number of citations, most productive researchers, most productive countries, average citation per country, most relevant sources (journals) and most applicable keywords were also identified. In the journal level metrics, the main journals in which research on the emergy analysis in wastewater treatment is published were identified, highlighting 5 journals with the highest impact index.

One of the most interesting findings of descriptive statistics is that several authors continue to contribute to the field of research and a group of Asian researchers have recently joined the field and have increased the importance of the research topic since 2009 reaching many more impacts in terms of publication records and citation counts. The most frequently used keyword terms are emergy (8%), wastewater treatment (7%), sustainable development (6%), wastewater (6%) and water treatment (5%). Relevant institutions in the field were identified as the University of Geoscience and Peking University.

China and the USA were found to be the leading countries in the ranking according to the number of publications on this topic, while the collaboration of France and Luxembourg indicates a potential area for research and development in the field of wastewater treatment and emergy in these regions. Leading institutions working on this topic were identified, which can help researchers to identify potential sites for knowledge exchange activities, joint research, study tours, postdoctoral research, etc.

In terms of networks, the research field of emergy analysis in wastewater treatment does not have a very dynamic structure identifying 3 major research networks. In terms of authorship, co-authorship and institutions, emergy in wastewater treatment is slightly pluralistic and is motivated by a logic of multiple collaboration when it comes to publication and academic interaction.

Critical research points were identified on the basis of this bibliometric research, especially after analyzing the keywords. Emergy analysis in wastewater treatment has been found to be an emerging field of research. The application of the emergy method in wastewater treatment requires specific research in the different types of industrial or municipal treatments and applications. These types of analyses would allow the development of a new treatment approach in terms of sustainability and the introduction of Latin American countries in this emerging field. Finally, it was found that over the years new emergy indices have been developed, combining the evaluation of water treatment plants with other methodologies, such as LCA, exergy, cost benefits and economic analysis. In addition, recent studies show complexity and specificity in very particular cases based on different realities of water treatment.

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