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Exploring the global scientific literature on urban metabolism

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Abstract. Urban ecosystems can be conceptualized like living organisms supported by material and energy flows that allow the generation of ecosystem structures and functions and the production of goods and services. Urban metabolism accounts for the flows of materials, energy, resources, food, and people in cities, providing a framework for the study of the interactions between natural and socio-economic systems. In this paper, the global scientific literature on urban metabolism was explored to identify knowledge gaps and emerging research areas over the last decades. A bibliometric network analysis was implemented to generate maps based on network data of scientific publications displaying relationships among scientific journals, researchers, countries, and keywords. The total number of publications on urban metabolism from 1990 to 2019 resulted in 498 documents. USA and China resulted the first countries publishing on urban metabolism while among the journals, the Journal of Industrial Ecology and Journal of Cleaner Production resulted the first in the ranking. The co-occurrence network map of keywords showed that, over the last decade, the main focus of research on urban metabolism has shifted from environmental issues to environmental accounting and socio-economic aspects. Considering the importance of urban systems for the achievement of local and global sustainability goals, it is likely that the scientific literature on urban metabolism will continue growing over the next years. Being cities characterized by complex relationships between natural and socio-economic systems, it is desirable that future studies will explore the multidimensional features of urban metabolism through multi-criteria assessment frameworks.

Keywords: Urban metabolism, VOSviewer, bibliometrics, social network analysis.

1. Introduction

Urban ecosystems can be conceptualized like living organisms supplied by material and energy flows supporting ecosystem structures and functions, and the production of goods and services (Nikodinoska et al., 2018; Russo et al., 2014). Urban metabolism accounts for the flows of materials, energy, resources, food, and people in cities, providing a framework for the study of the interactions between natural and human systems. The sustainable management of cities is based on the sustainable exploitation of natural capital stocks delivering a large set of ecosystem services vital for human economy and well-being (Häyhä and Franzese, 2014). The interplay of environment, economy, and resources taking place within urban ecosystems can be explored and monitored over time using different environmental accounting methods (Franzese et al., 2008). These methods can help understanding how cities use raw and processed resources supplied from larger environmental systems.

According to Kennedy et al. (2007), urban metabolism can be defined as "the sum total of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste".

It consists of a model that describes and quantifies the main input and output flows (e.g., materials and energy) processed by a city system. In this way, urban metabolism also represents a powerful analysis, planning, and management tool for accelerating the transition to a circular economy (Levoso et al., 2020).

1.1. Linear accounting models

The metabolism of many cities worldwide has been investigated by several researchers developing different models of urban metabolism focusing on the assessment of different variables. Wolman (1965) in his pioneering article "The metabolism of cities" applied material flow analysis by conceptualizing the operation of an urban system based on the analogy between urban metabolism and living systems. Haberl (2001) developed an energetic metabolism model of societies and urban systems. Odum (1996) developed an emergy-based accounting framework including natural flows, human labor, and economic services measured in solar energy equivalents. Other energy-based urban metabolism models were based on exergy, which represents the amount of useful work that can be performed by exploiting an energy flow (Zhang, 2013). Another input-output accounting method to explore urban metabolism was based on ecological footprint (Dakhia and Berezowska-Azzag, 2010).

1.2. Circular accounting models

Ulgiati et al. (2011) proposed Life Cycle Assessment (LCA) to investigate the metabolism of socio-economic systems. Rugani and Benedetto (2012) stressed that the LCA is more focused on downstream impacts and does not account for human labor and ecosystem services. Other studies tried to face these limitations by integrating LCA with Emergy accounting (Buonocore et al., 2019; Reza et al., 2014; Skaf et al., 2019; Ulgiati et al., 2010; Viglia et al., 2013).

Girardet (1990) proposed a cyclical urban metabolic model to overcome the limitations of the linear carbon metabolism approach not capable of accounting for the negative feedback of human impacts on natural ecosystems and their ability to provide ecosystem services such as, for instance, carbon sequestration. Thus, an ecosystem perspective was adopted to reduce the dependence of cities on natural ecosystems by increasing their internal cycling. The extension of this perspective was then employed both from a management (Huang et al, 2007) and from a metabolic activity viewpoint (Zhang et al., 2006). More recently, Goldstein et al. (2013) coupled urban metabolism and LCA applying an integrated model to the five cities of Beijing, Cape Town, Hong Kong, London, and Toronto, allowing a more comprehensive assessment of recycling processes within cities and environmental impacts beyond their boundary.

1.3. Network accounting models

Zhang et al. (2009) proposed the ecological network analysis as a tool to explore urban metabolism and used the emergy method to account for different types of natural and huma-driven flows (materials, energy, and money flows) exchanged within the urban metabolic system.

Li et al. (2010) developed an ecological network model of societal metabolic system displaying the internal environmental effects due to the exploitation of natural resource flows in China. Liu et al. (2010) performed an extended exergy analysis of the urban metabolic system of the Chinese city of Beijing. Chen et al. (2010) emphasized the theoretical capability of the emergy and exergy approaches to add eco-flows within an urban metabolic system, despite the difficulties in their practical adaptability.

More recently, some studies advocated the return to the input-output analysis due to its usefulness in portraying the emissions of socio-economic systems at different scales. In this regard, Li et al. (2018) used ecological input-output analysis to analyze the utility of the direct and indirect carbon flows in urban metabolic system. Sovacool and Brown (2009) focused on the analysis of carbon-related metabolic processes to account for the impact of urban metabolism on global climate change. Other studies focused on the social and economic sources of carbon emissions while ignoring the carbon sequestration from natural compartments (Kennedy et al., 2010; Ye et al., 2011). The ecological network analysis as a tool to study urban carbon metabolism was applied by Chen and Chen (2012) to study carbon emissions in the city of Vienna (Austria). Previous studies mostly investigated the vertical direction of carbon emissions and carbon sequestration, namely flows from land to atmosphere and vice versa (Zhang et al., 2016).

Many studies, among which Zhao et al. (2014), Lu et al. (2015), and Lu and Chen (2015), accounted for the socio-economic carbon sinks while ignoring the impact of land-use and cover changes on the carbon emissions and sequestration (Zhang et al., 2016). The ecological network analysis allowed to connect the vertical carbon flux (Zhang et al. 2016) with the horizontal emissions among economic sectors and a single "environment" compartment. Li et al. (2018) used ecological network analysis to account for monetary input-output flows and convert them to embodied carbon dioxide flows among sectors. The spatial analysis of urban carbon metabolic network based on land use and cover change (LUCC) performed by Xia et al. (2016) allowed to connect the natural and artificial components of an urban ecosystem based on their roles in the city's carbon metabolism. This approach can support the sustainable management of the spatial pattern of urban carbon metabolism and an adaptation to the low-carbon spatial design scenarios (Zhang et al. 2016). Consequently, Chen et al. (2010) suggested that the information indices of network analysis (ascendency and overhead) should be integrated into the assessment methodology of urban metabolic systems to evaluate the sustainability of urban development in terms of system efficiency and stabilizability. The different approaches to the study of urban metabolism are summarized in Table 1.

In this paper, we review the global scientific literature on urban metabolism to identify knowledge gaps and emerging research areas over the last decades. A bibliometric analysis was conducted to generate maps based on network data of scientific publications displaying relationships among scientific journals, researchers, and countries. Finally, a keywords analysis was performed to review the co-occurrence of different terms connected to the research on urban metabolism.

2. Materials and Methods

2.1. Data Collection

The keyword "urban metabolism" was used as a search input to explore the global scientific literature on the topic. The time frame was set to include all available publication years in the Web of Science Core Collection (WSCC) database set from 1990 to 2019. All data was saved as "Tab-delimited (Mac)" files which contained "Full Record" and "Full Record and Cited References" content. The "Full Record" and "Full Record and Cited References" content were respectively used for co-authorship and co-occurrence analyses (e.g., network maps of authors, countries, and keywords) and citations analysis (e.g., network map of scientific journals).

2.2. Bibliometric Network Analysis

Bibliometric network analysis is an effective tool combining bibliometrics and social network analysis (SNA) to investigate specific fields of science (Reuters, 2008; Zou et al., 2018). SNA and maps based on network data allow for the application of systems thinking in bibliometric science. In particular, such analysis allows for the construction of network maps based on the relationships among countries, journals, organizations, authors, and keywords related to the investigated topic (Chen et al., 2016; Buonocore et al., 2018; Pauna et al., 2018, 2019; Skaf et al., 2020).

VOSviewer (version 1.6.12) software was used to perform the bibliometric analysis. This software allows for the creation, visualization, and exploration of maps based on bibliometric network data. The output results are displayed in clusters to allow for a clear visualization of the existing connections among the bibliometric data. Table 2 summarizes the main technical terms used by the software.

Table 1. Approaches to the study of urban metabolism.

Approaches	Advantages	Disadvantages
Linear	Allows to decrease resource dependency by decreasing the consumption of the imported resources while substituting them by local resource supplies.	Stress imposed on local resources leads to the high dependency on imported ones. In other words, the city brings a low contribution to economy while causing a huge environmental impact.
Circular	Accounting for recycling and reuse of wastes allows to reduce the dependence on the imported resources, thereby decreasing their demand and an overall environmental impact of a socio-economic system.	The unknown internal sources of environmental impacts and constraints (or their absence) on resource use in cities that trigger the continuous self-organization process of urban ecosystems may lead to the long-term mismanagement.
Network	Allows to optimize the structural properties (e.g., cycling) to retain the resources on pathways and adjust the relationships among the economic sectors and external environment towards mutualism to minimize the harm (pollution and competition) between the sectors.	The ecosystem is considered as a "single compartment" that interact with a socio-economic system's compartments and direct and indirect effects between social and ecological compartments are unknown. The urban socio-ecological carbon flux model was able to open the "black box".

Co-authorship, co-occurrence, and citation analyses (Table 3) were conducted to create network maps showing: (1) the co-authorship among researchers and countries, (2) cited scientific journals, and (3) the co-occurrence of keywords. Each network map that resulted from the analyses contains nodes with size determined by "total link strength", and lines connecting the nodes with thickness based on "link strength" (Table 2).

The amount of clusters visualized in the network maps is determined by the resolution parameter. The higher its value, the higher the level of details. This value can be set to visualize an appropriate number of clusters in the maps (Van Eck and Waltman, 2019). In this study, the resolution was set to 1 for all the analyses.

3. Results and discussion

The total number of publications on "urban metabolism" from 1990 to 2019 resulted in 498 documents. Figure 1 shows the trends based on the number of publications and cumulative citations. Both trends show an exponential growth since 2009. This outcome can be due to the effects of the Europe 2020 strategy enacted in legislation in 2009 and calling for smart, sustainable, and inclusive growth.

Applying the social network analysis to this set of publications, five network maps were generated (Figures 2-6). For each network map, the five items with the highest weight in terms of total link strength and citations were reported in Tables 4-7.

3.1. Co-authorship authors network

The co-authorship authors analysis is based on documents with a maximum of 25 authors per document, resulting in 1165 authors. Moreover, only author with a minimum of 5 documents published on the topic were selected, resulting in a total number of 24 authors. The final network map shows only 12 authors grouped into 4 main clusters and characterized by a higher level of connection (Fig. 2). The top 5 authors ranked by number of documents are shown in Table 4. Yan Zhang, with 32 documents and 861 citations, resulted the main author contributing to the growth of the research on urban metabolism using the ecological

Table 2. Main terms in VOSviewer software (Van Eck and Waltman, 2019).

Term	Description
Items	Objects of interest (e.g., publications, researchers, keywords, authors).
Link	Connection or relation between two items (e.g., co-occurrence of keywords).
Link Strength	Attribute of each link, expressed by a positive numerical value. In the case of co-authorship links, the higher the value, the higher the number of publications the two researchers have co-authored.
Network	Set of items connected by their links.
Cluster	Sets of items included in a map. One item can only belong to one cluster.
Weight attribute: Number of Links	The number of links of an item with other items.
Weight attribute: Total Link Strength	The cumulative strength of the links of an item with other items.

Table 3. Description of VOSviewer analyses used in this study.

Type of Analysis	Description
Co-authorship	In co-authorship networks, researchers, research institution, or countries are linked to each other based on the number of publications they have authored jointly.
Co-occurrence	The number of co-occurrences of two keywords is the number of publications in which both keywords occur together in the title, abstract or keyword list.
Citation	In citation networks, two items are linked if at least one cites the other.

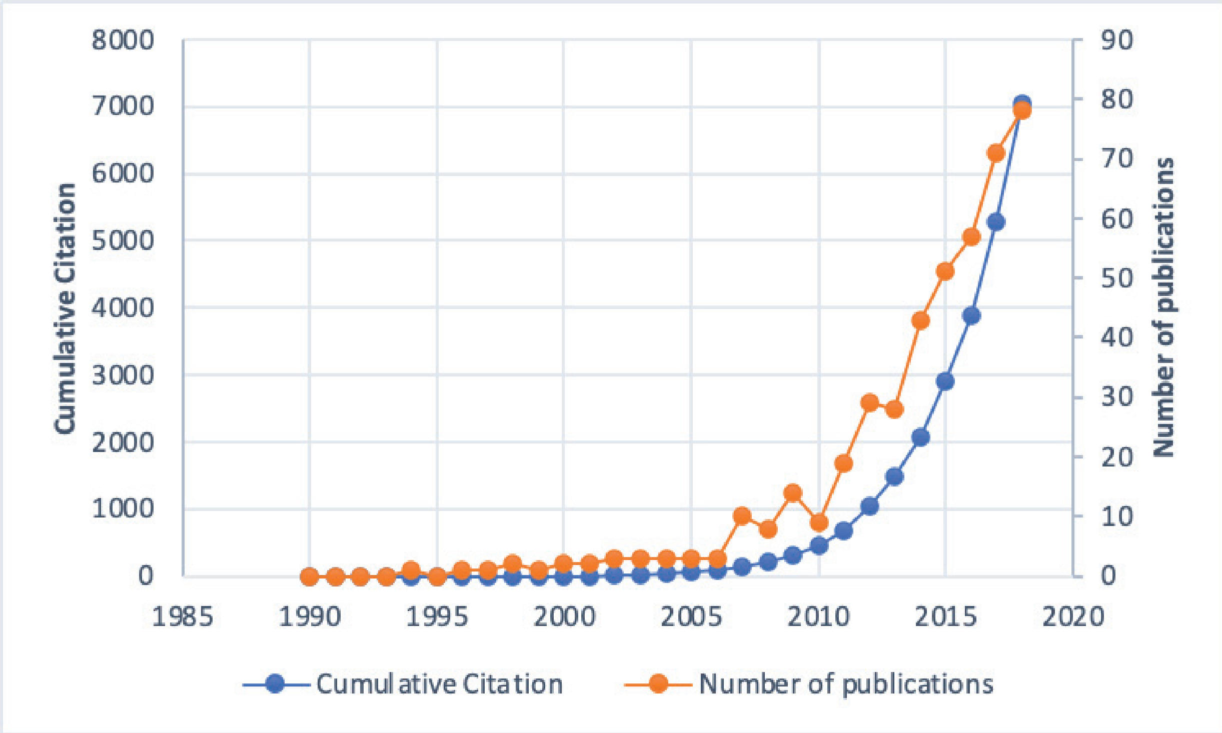

Figure 1. Temporal trends of documents published from 1990 to 2019.

Table 4. Top 5 authors ranked by number of documents.

Author	Specialization	Total link strength	Link	Documents	Citations
Zhang, Yan	Industrial Ecology	61	9	32	816
Chen, Bin	Industrial ecology, Systems Ecology	25	7	23	391
Yang, Zhifeng	Urban Ecology, Water Management	50	10	19	622
Liu, Gengyuan	Urban Ecology, Systems Ecology	38	10	12	239
Fath, Brian D.	Systems Ecology, Ecosystem Ecology	29	9	12	280

network analysis methodology. Four out of five authors are Chinese, highlighting the considerable attention that the Chinese scientific community pays on the subject. The major focus on this research subject is most probably due to the critical environmental conditions characterizing Chinese cities, determining the need for facing and solving these environmental problems towards more sustainable cities.

The results in Table 4 also reveal that the topic of urban metabolism is mostly investigated by authors specialized in “industrial ecology” and “system ecology”, confirming the need for investigating urban metabolism thorough the study of the complex metabolic linkages among industrial, urban, and natural systems by means of a unified framework.

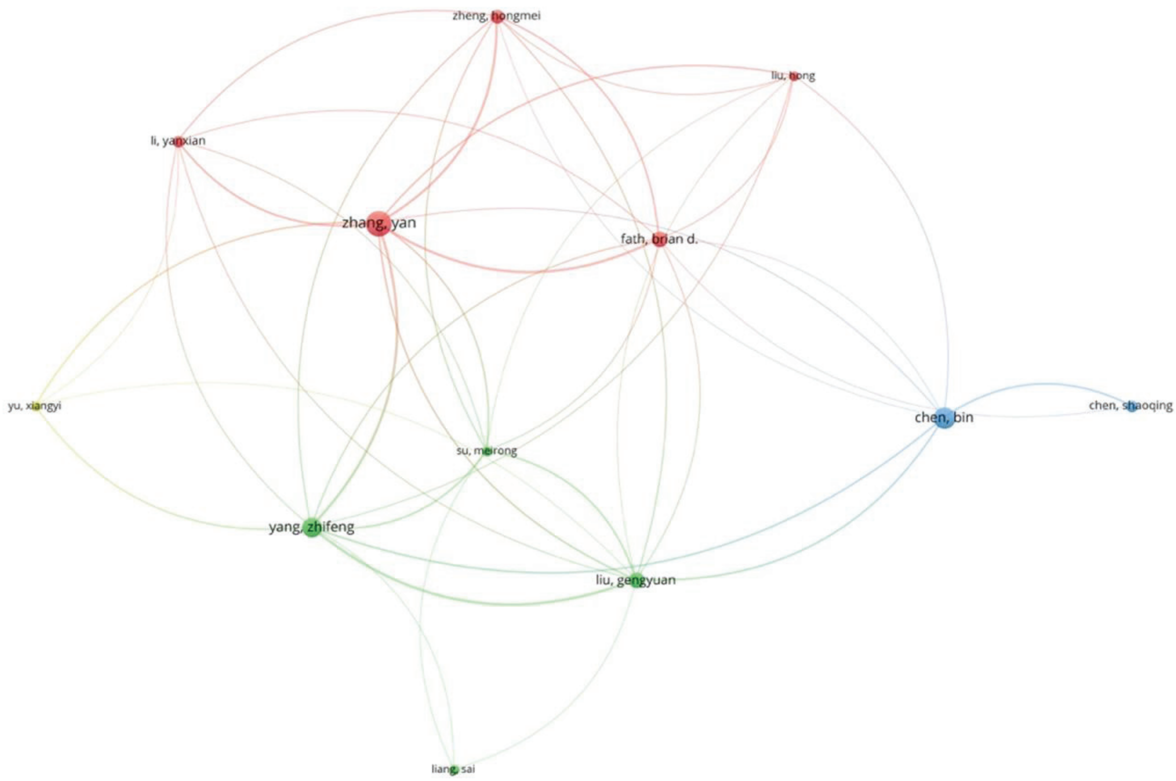

Figure 2. Network map of authors based on number of documents.

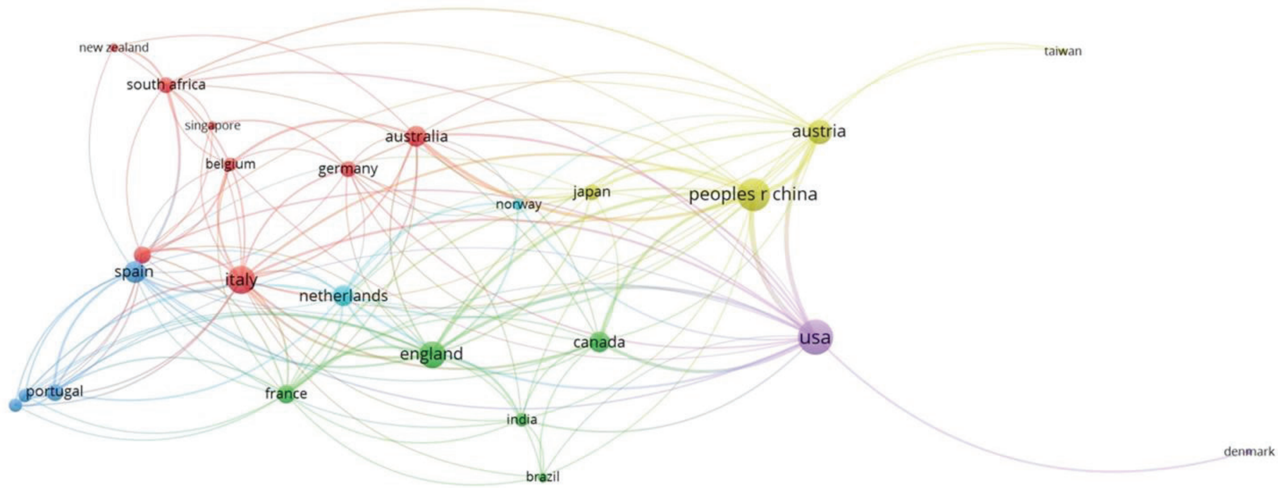

Figure 3. Co-authorship countries network map based on total link strength.

Table 5. Top 5 countries ranked by total link strength

Country	Total Link Strength	Links	Documents	Citations
USA	83	19	112	2,287
Peoples Republic of China	77	14	130	2,088
Italy	53	21	37	436
England	48	18	38	795
Austria	43	15	25	641

3.2. Co-authorship countries network

The analysis resulted in 60 countries publishing on urban metabolism. Documents co-authored by more than 25 countries were excluded. Out of the total number of countries, only 26 countries met the threshold of minimum 5 documents. The network map shows 6 main different clusters (Fig. 3). It is interesting to note that most clusters include different countries belonging to different geographic areas. For instance, the cluster in red color includes countries located in Europe, Asia, South Africa, New Zealand, and Australia. These results highlight the existence of a very diversified global network of researchers committed on urban metabolism studies.

The top 5 countries based on the total link strength are shown in the Table 5. USA ranks the first by the number of citations and total link strength, while China ranks the first by the number of documents. In addition, it is interesting to note that Italy ranked first by the number of links but has a relatively small number of documents, confirming that this country is an emerging international player in the field of urban metabolism.

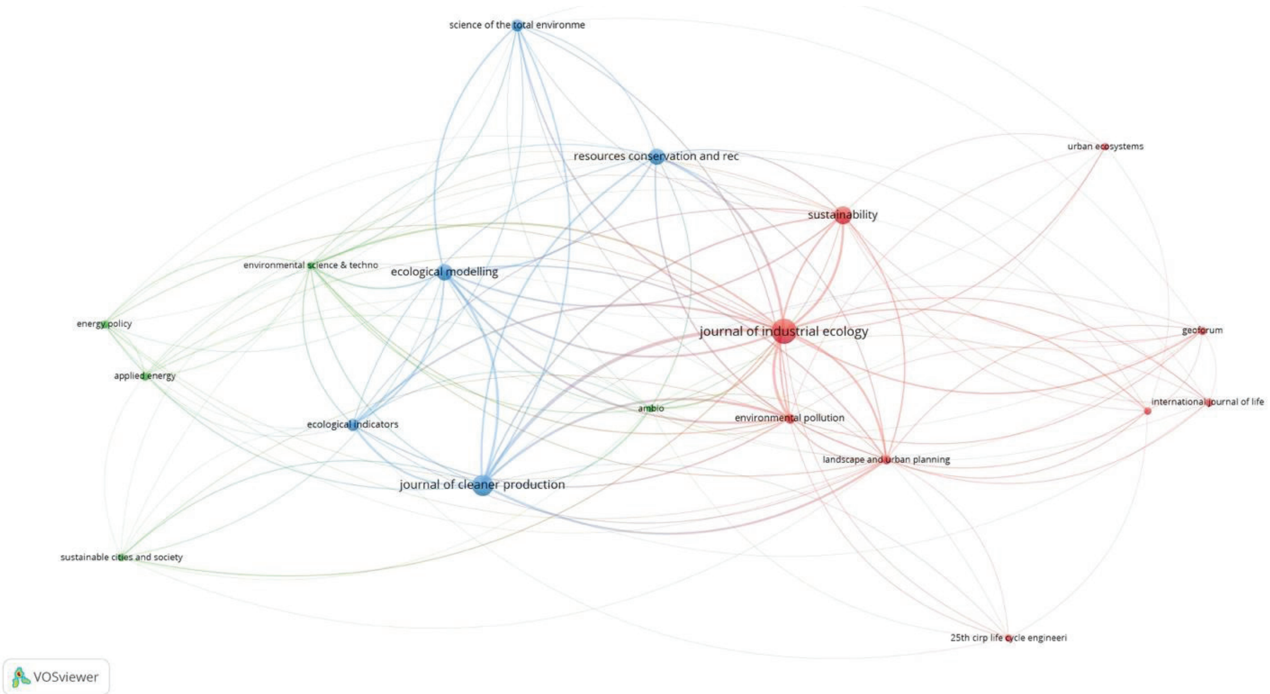

Figure 4. Network map of citations analysis of journals based on total link strength

3.3. Citation analysis of journals

The citation analysis resulted in a network map including 19 items out of 171 journals publishing on urban metabolism that met the threshold of having at least 5 publications on the topic. The network map shows 3 main clusters (Fig. 4). The top 5 journals ranked by total link strength are shown in Table 6. The Journal of Industrial Ecology and Journal of Cleaner Production are the first ranked in terms of total link strength and number of documents. Despite its relatively recent foundation in 1996, the Journal of Industrial Ecology is ranked first, showing the high commitment of its scientific community on the topic of urban metabolism.

3.4. Co-occurrence keywords network

The analysis of keywords resulted in 1940 items. Applying a threshold of a minimum number of 5 occurrences, a total number of 167 keywords was generated. The network map shows 7 main clusters (Fig. 5). The top 5 keywords are ranked in Table 7 based on the total link strength.

The network map in Figure 5 shows that “cities” and “energy” have a close relationship to urban metabolism, confirming the importance of the energy issue and of city structures and functions in relation to urban metabolism studies. The keyword “sustainability” highlights the relevance of cities for the achievement of local and global sustainability goals. In fact, considering that about 55% of the world’s population lives in urban settlements (UN, 2018), understanding the metabolism of urban systems is crucial for the achievement of the 2030 Agenda for Sustainable Development Goals. It is also noteworthy that China is included among the top 5 keywords related to urban metabolism. In the last decades, China has experienced rapid urbanization and industrialization processes leading to critical environmental problems such as resources depletion, atmospheric pollution, and waste generation (Tian et al., 2017). In this context, finding solutions for sustainable urban development has become a notable research interest in the Chinese scientific community and urban metabolism has been used as an effective approach for analyzing the structure and functioning of urban systems. In addition, Fig. 5 also shows that the topics of “industrial ecology” and “ecological network analysis” play an important role in the context of urban metabolism studies.

The main keyword related to urban metabolism are also shown in the overlay map (Fig. 6) providing a temporal perspective for the interpretation of the co-occurrence network map of keywords. The map is based on the average year of publication of documents they occur in, on a color gradient from blue (older publications), to green (publications equally distributed across the timespan), to yellow (more recent publications). The distribution of the keywords along a temporal gradient allowed to understand the evolution of the scientific research on “urban metabo-

Table 6. Top 5 journals ranked by total link strength

Journal	Total link strength	Links	Documents	Citations
Journal of Industrial Ecology	396	18	51	1638
Journal of Cleaner Production	309	15	38	447
Ecological Modelling	223	16	23	593
Environmental Pollution	217	18	8	545
Resources Conservation and Recycling	150	15	23	346

Table 7. Top 5 keywords based on the total link strength.

Keywords	Occurrences	Total link strength	Link
Cities	178	1104	160
Energy	111	742	150
Sustainability	90	600	144
Metabolism	65	396	122
China	57	378	115

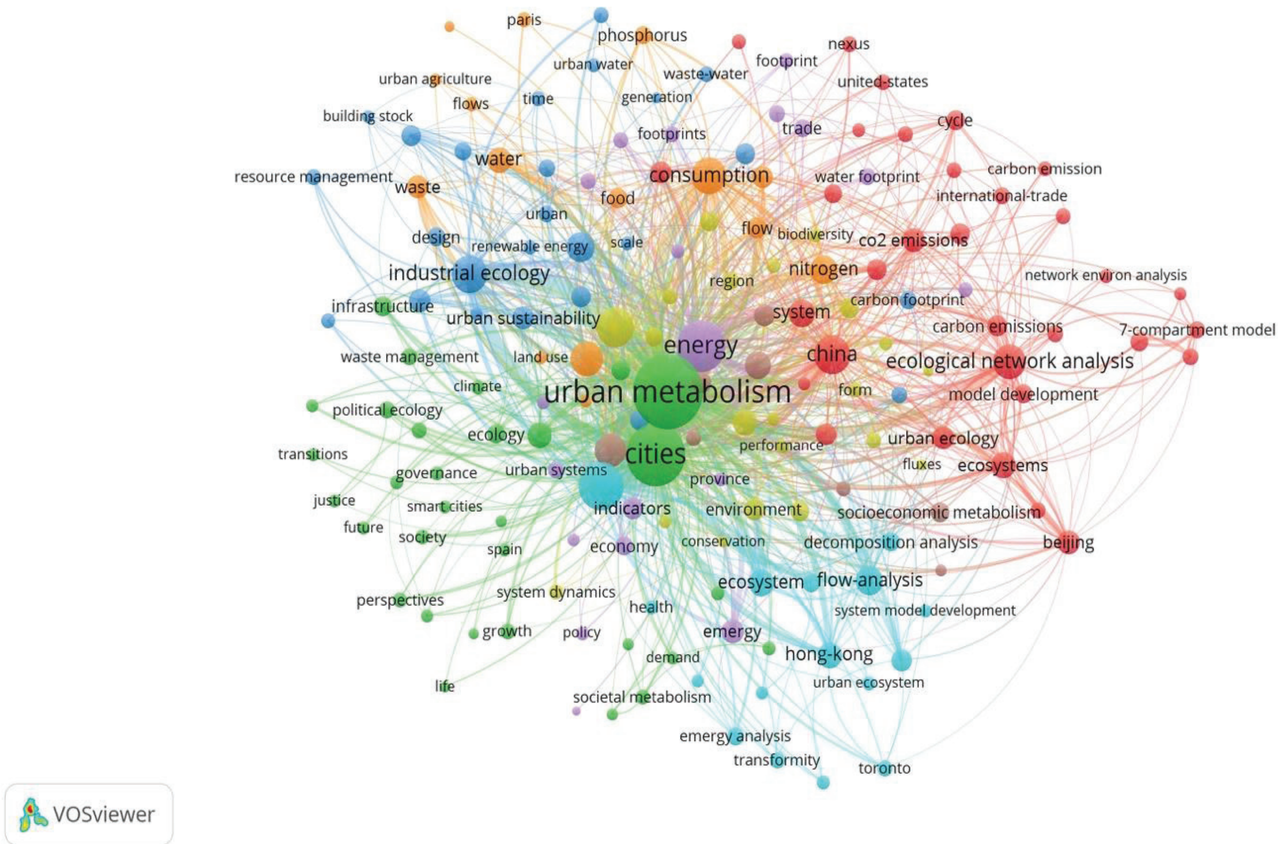

Figure 5. Network map of keywords co-occurrence based on total link strength

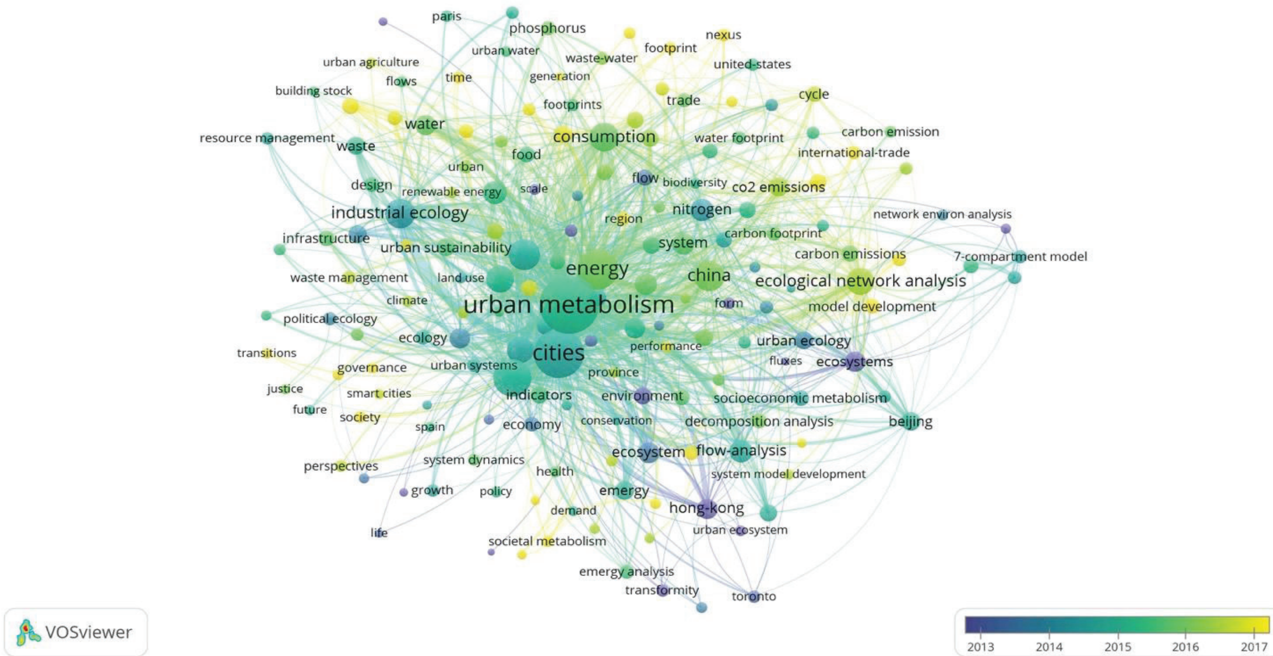

Figure 6. Overlay visualization of the co-occurrence network map of keywords

lism", identifying the most recent topics and main research pathways. The overlay visualization map shows a shift from older studies more focused on environmental aspects (e.g., "ecosystems", "environment", "nitrogen") to a recent focus on the importance of environmental accounting tools (e.g., "water footprint", "emergy analysis") and socio-economic aspects (e.g., "international trade", "governance") showing the awareness on the importance of studying environmental, social, and economic aspects of the sustainability of urban systems.

4. Conclusions

In this study, the global scientific literature on urban metabolism was explored through bibliometric network analysis. The results of this study provided an overview on the main aspects characterizing the topic of urban metabolism and allowed the investigation of the relationships occurring among authors, journals, countries, and keywords. The temporal analysis of publications showed that the scientific research on urban metabolism has experienced an exponential growth over the last ten years. The temporal development of the scientific research on urban metabolism was also investigated, capturing a main shift of focus from environmental issues to environmental accounting and socio-economic aspects.

Considering the importance of urban systems for the achievement of local and global sustainability goals, it is expected that the scientific literature on urban metabolism will continue increasing over the next years. Being cities characterized by complex relationships between natural and socio-economic systems, it is desirable that future studies will explore the multidimensional features of urban metabolism through the development and application of multi-criteria assessment frameworks.

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