Circular economy scientific knowledge in the European Union and China: A bibliometric, network and survey analysis (2006-2016)

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Serdar Türkeli[a], René Kemp[a], Beijia Huang[b], Raimund Bleischwitz[c], Will McDowall[c]

a U United Nations University-MERIT, Maastricht University, Boschstraat No. 24 6211 AX Maastricht, the Netherlands (Corresponding Author, e-mail: turkeli@merit.unu.edu)
b University of Shanghai for Science and Technology, 516 Jungong Rd, Yangpu Qu, Shanghai , China
c University College London (UCL), Central House, 14 Upper Woburn Place, London WC1H 0NN, United Kingdom

Abstract
In this article, we analyse the evolution of circular economy (CE) scientific knowledge in the most productive political geographies in the field, namely the European Union (EU) 28 and China by using bibliometric, network and survey analysis. Our objective is to provide a systemic, quantitative, visio-temporal review of the evolution of the CE scientific research field. Using Web of Science (WoS) database and Scopus, we trace the bibliometric characteristics of key research terms, their co-occurrences, publication (co)authorships at multi-level (author, institute, city, region, country), issue journals, literature citations and funding sources. Our findings from co-authorship, citation, co-citation, bibliometric coupling, co-occurrence and network analyses indicate that China and the EU have the highest amount of CE literature published and are each other's primary source of co-authorship. Emerging or reiterated main themes in the joint CE literature between EU and China are emergy analysis, indicators; resource efficiency, food waste, zero waste; eco-cities, lifestyle and governance. There appears a good potential for international cooperation in the sectoral fields of automotive, construction and demolition, critical raw materials; in business, (new) business models, product and services platforms, and from security perspective, resource security, security of supply, given the paucity of co-authorship between China and the EU under these themes. In China; Beijing, Shenyang, Dalian, Shanghai are the most active cities with a central role of Chinese Academy of Sciences at institution level of analysis. The most active EU institute is the Delft University of Technology in South Holland, the Netherlands. In Europe, we observe countries citing CE literature yet with no or few publications. Journal of Cleaner Production is the most important outlet for publications on CE and also for joint publications of CE researchers in both China and EU-28. We conclude our article with future research agendas, and a positive note on existing interests in international cooperation based on our survey participated by highly-cited CE authors.

Keywords: Circular Economy; EU-28; China; Bibliometric and Network Analysis; Regions and Cities; Future Research Directions

1. Introduction

In contrast to a linear ten-step[1] "take-make-dispose" economy, a circular economy (CE) proposes activation of ten loops[2] between the stages of take (e.g. harvesting, mining) and dispose (e.g. landfill) activities. In proposing so, a CE aims to reject or (at least) reduce the take of particular materials (e.g. rare earths, critical raw materials, bio-ingredients) and energy sources (e.g. fossil fuels) from nature at the stages of take and make, and (at least virtually) eliminate the landfill at the disposal, and the airfill (e.g. CO_2, SO_2, NO_x emissions) at all stages of take-make-dispose (Ellen MacArthur Foundation, 2012; World Resources Forum, 2014; Esposito; 2015). Going beyond resource and waste management debates, CE concept gained traction among scholars and policymakers as an overarching concept indeed promising to be able to systematically cope with the historical (e.g. adverse effects of industrial revolution, industrial negative externalities), geographical (e.g. environmental and ecological issues, such as climate change, soil erosion and degradation, reduction in air and water quality, excessive use of rare earths, hazardous materials), political (e.g. energy insecurity, dependency), economic (e.g. fluctuating resource commodity prices, supply insecurity, critical raw materials), technological (e.g. brown and resource inefficient technologies, untapped potential of emerging ICT, (big) data, nanotech or biotechnologies), and social (e.g. unemployment, health risk) issues of the contemporary era we are producing and consuming in.

Yet even after a decade, the growing field of CE scientific knowledge in the realm of CE is still highly pertinent to be analysed from a systematic perspective of CE scientific knowledge production (publication authorship), dissemination (issue journals), use (literature citation), funding (research funding sources), content (key research terms) and cooperation (co-authorship) to inform researchers and policymakers in detail about the evolving characteristics of CE scientific knowledge in the most productive political geographies, namely China and the European Union. An article exclusively dealing with the CE scientific knowledge has not yet been published other than global analyses of the relationship between CE and various other concepts, such as industrial ecology (Saavedra et al., 2017), green and bio-economy (D'Amato et al., 2017), sustainability (Geissdoerfer et al., 2016), big data and internet of the things (Nobre et al., 2017).

In this article, we aim to fill this gap by several research questions exclusively concentrating on the CE scientific knowledge in China and the EU. By doing so, we fill several gaps, especially, 1) temporal (2006-2016), 2) methodological (bibliometric and network analysis of CE scientific publications with the use of an enhanced query, and with a survey of highly-cited CE researchers to gain insights for the future research directions in the CE field), 3) geographical (region and city-level analyses), 4) comparative (Europe Union and China), and 5) content-wise (incumbent, emerging topics) research and empirical gaps, which are related to the history, status and prospects of CE scientific knowledge. Our objective is to provide evidence-based insights for researchers and policymakers who are interested in advancing CE research and its associated policy framework.

Our research questions (RQs) are, thus, 1) Production-related RQs: Which countries, regions/cities, institutes, authors published the CE scientific literature? What are the characteristics of co-authorship networks? 2) Distribution-related RQs: Which journals issued the CE literature and are central? 3) Use (citation)-related RQs: Which countries, regions/cities, institutes, authors use (cite) the CE literature? 4) Financing-related RQs: Which agencies funded the highly-cited CE research? What is the structure of funding behind these highly-cited CE literature? 5) Content-related RQs: Which themes are central and emerging in the field of CE? 6) Cooperation-related RQs: On which key terms are there international cooperation potentials in the field of CE and in future CE research agendas between the EU and China?

The article proceeds as follows: in Section 2, we review earlier bibliometric studies closer to the field of CE (e.g. industrial symbiosis, sustainability and CE, food waste, emergy analysis), and discuss their choices on the selection of citation indexing services as data source and their query construction. Section 3 provides information in detail on the databases, query construction, data, case selection, methods and tools that are used in this article. In Section 4, we present and discuss our findings. Complementary discussions are provided in Section 5, whereas in Section 6, we present the findings from our survey participated by the most highly-cited CE researchers, meaning that CE researchers who received enough citations as of September/October 2017 to place them in the Top 1% of their academic fields, here, CE, based on Web of Science Essential Science Indicators, about the future CE research agendas, the ideas, and the interests in international cooperation.

2. Theoretical and empirical background

With regard to the history, milestones, timeline and the fundamental concepts of CE discussion, several studies have used bibliometric analysis to study the origins of CE by analysing the contributions of several research fields, namely industrial symbiosis (Yu et al., 2013) and industrial ecology (Saavedra et al., 2017), to the CE.

Yu et al. (2013) provide an overview of the development of industrial symbiosis, and distinguish two periods in the evolution of this field. In the second period (2006–2012), the authors observe maturation in theory building about CE and CE-related research. Yet before this period, the authors indicate that in the first period (1997–2005), industrial symbiosis (IS) scientific research held a minority share in the Industrial Ecology (IE) literature, and revolved around a) the concept of IS, b) the assessment of eco-industrial park (EIP) projects, and c) the establishment of waste treatment and recycling networks (Yu et al.,2013). The authors' findings show that IS evolved from practice-oriented research towards coherent theory building through a systematic underpinning and linking of these diverse topics, meanwhile the co-authorship networks show that the academic communities of IS are distributed worldwide, and international collaboration is widespread (Yu et al., 2013). According to Chertow and Park (2016), the field of IS has become more and more diverse, and this diversity is also reflected in the wide range of terminology (Chertow and Park, 2016). Researchers, such as Boons et al., also draw attention to the existence of common building blocks amid diversity which stems from disparate origins regarding IE (Boons et al., 2009). Conclusively, according to Saavedra et al. (2017), evolution of CE would not be possible without the existence of IE concepts and tools, especially with the tools such as Industrial Symbiosis (IS) and Eco-Industrial Parks (EIPs).

Starting from EIPs, in China, initially the research about Chinese EIPs has accumulated plenty of lessons and knowledge to formulate the CE in China yet alongside the research about cleaner production, recycling of industrial waste, and urban planning (Geng and Zhao

2009; Liang et al. 2011 as cited in Yu et al., 2013). Chinese government's CE strategy as part of its 11th 5-Year Plan was an initiator at policy level for the expansion of the applications of CE from individual enterprises to eco-industrial parks (EIPs), and to the cities, provinces, and regions (Zhang et al., 2009). Zhang et al. (2009) provide further structured concepts and information on the infrastructures, preferential policies, CE frameworks, and eco-chains in these EIPs.

Their CE discussions concentrate on the themes of 1) resource efficiency, 2) material efficiency, 3) environmental protection performance, 4) socio-economic performance, and 5) green management (Zhang et al., 2009).

In line with Zhang et al (2009), Zhu Tan, Vice President, Economic and Social Council of Tianjin and Director, Environment and Social Development Research Center at Nankai University at the 4th EU-China Round Table on Recycling Industries, indicated that: "The concept of circular economy took shape in the 1960s in the United States. The term of circular economy appeared in China in the middle of 1990s and it has been explained by scholars from the angles of resource utilization, environmental protection, technology paradigm and economy's growth" (European Economic and Social Committee (EESC), 2008). About China, European Commission (EC) (2011) also reported that "the Chinese Circular Economy Promotion Law from 2008 aims at developing this paradigm across sectors and resources through a core strategic framework, with the purpose of simultaneously raising resource utilization rates, managing waste, protecting and improving environment, and achieving sustainable development" EC(2011).

In the EU, objectives and concepts of the Resource Strategy: *"resource efficiency, sustainable use of natural resources, decoupling, eco-efficiency, life-cycle thinking"* are embedded into many policy initiatives (European Commission, 2005, 2011a, 2011b, 2011c). In line with this argument, an analysis of CE and its building blocks for Europe is demonstrated by Taranic et al. (2016) following a structured review of academic literature, such as Rizos et al. (2015), and grey literature (Accenture, 2015; EMF, 2012; Planing, 2015). The authors report that, after in-depth analysis of several business sources and intensive stakeholder interactions in the context of two EC Framework Programme (FP) 7 funded projects, called NETGREEN and GreenEcoNet, they developed a framework for CE in Europe consisting of eight building blocks:

These fundamental building blocks of CE in Europe are grouped under eight headlines as (1) industrial symbiosis, 2) material resource efficiency, 3) product life-cycle extension, 4) biological products, 5) energy efficiency and renewable energy, 6) the performance economy, 7) the sharing economy and 8) the platform economy (Taranic et al., 2016).

Considering the commonalties and differences in CE policies in China and Europe, McDowall et al. (2017) discuss what both contexts can learn from each other in the field in detail. These aforementioned articles above are highly relevant for CE scientific research field due to the fact that they help to characterize and institutionalize the CE research field in itself with respect to the history, milestones, timelines and the fundamental concepts of CE discussions which are both internal and external to the industrial symbiosis and industrial ecology literature.

Following this perspective, Blomsma and Brennan (2017) indicate that while the emergence of CE is a new framing around prolonging resource productivity, resource life-extending strategies in the waste and resource management debate following three periods: 1960–1985 Preamble Period; 1985–2013 Excitement Period; and 2013-present Validity Challenge Period, the theoretical or paradigmatic clarity regarding the CE concept has yet to emerge (Blomsma and Brennan, 2017). In our analysis, we extend our scope of analysis to the scientific activity over these aforementioned conceptual building blocks and other keywords by co-occurrence analysis of each concept with circular economy while conducting bibliometric and network analysis of CE scientific knowledge in the EU and China (See also supplementary file).

3. Data, research methodology and initial analyses

3.1. Defining the appropriate search terms: "*circular* *econom*"

Query construction is one of the most important decisions in bibliometric research. Researchers have three choices: the literal use of the concept (e.g. "circular economy" Geissdoerfer et al. (2016); Merli et al. (2017)), the use of wildcards to replace one or multiple characters in a query, (e.g. "e.g. circular econom*" Nobre and Tavares (2017)) or using an extended semantic set of keywords related to the research field which is expert-driven yet can be arbitrary. The query we use in this article "*circular* *econom*" can capture phrases such as circular economic, circularity, circular-economy, or "circular bio-economy". In this way, we capture scientific publications e.g. Tong and Tao (2016) on urban *circular economic system*, He et al. (2014) on *circular economic development* of the non-ferrous metal industry, Bocken et al. (2017) on taking the *circularity* to the next level, or Satpute et al. (2017) on *innovative and smart technology in circular bioeconomy*. The precision as such is often overlooked yet our query is a relevant improvement over Geissdoerfer (2016) and Merli et al. (2017) which use "circular economy" as the keyword without a wildcard. Another important issue in query construction is trying to *"capture the publications containing terms and expressions semantically different but with the same meaning/or a subset of CE*" e.g. Nobre and Tavares (2017). Yet the downside of using additional semantic search keywords is to capture -claimed- CE-type studies e.g. cradle-to-cradle, biomimicry, regenerative design, resource recirculation, regenerative econom*, restorative econom* as listed in Nobre and Tavares (2017) and yet the choice of these keywords still cannot comprehensively cover all potential expressions related to the realm of CE, therefore the length of such associated concepts list is questionable. In this article, we concentrate on *pure* circular economy scientific knowledge field with a "*circular* *econom*" query, yet we also control for the scales of publishing and interactions with other semantic keywords of the framework-based assessments (Zhang et al., 2009, Taranic et al., 2016) determined via our literature review, and listed in Section 2. This action provides a broader contextual keyword co-occurrence analysis for CE-type scientific research (See also supplementary file).

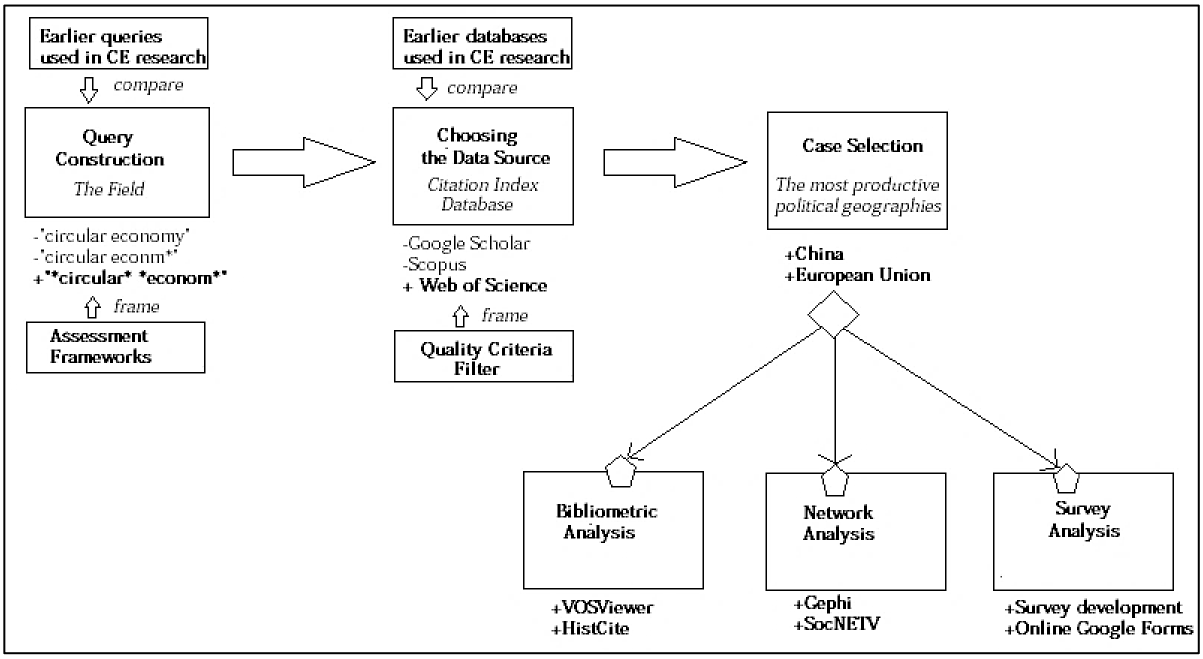
3.2. Choosing the citation index database: Web of Science and Scopus

In bibliometric research, three main data sources are Web of Science (WoS) of Thomson Reuters, Scopus of Elsevier, and Google Scholar of Google Inc. For a structural comparison of these three data sources please refer to Falagas et al. (2008) and Harzing and Alakangas (2015). Between WoS, Scopus and Google Scholar, CE researchers came up with different choices for their bibliometric analyses. For instance, Geissdoerfer et al. (2016) justifies the reason behind choosing WoS as concentrating on the peer-reviewed scientific journal articles in English to ensure the quality of their sample while studying the relation between circular economy and sustainability. Chen et al., 2017a, b, on food waste research, also uses WoS, cites van Leeuwen (2006) that WoS is the most important source of data for scientific bibliometric analysis. Chen et al. 2017a, b, citing Bettencourt and Kaur (2011) and Hou et al. (2015), indicates that WoS could provide more consistent and standardised records compared with other databases such as Scopus, on analysing the recent progress on emergy analysis research. On the other hand, Nobre and Tavares (2017) chooses to use Scopus as they consider it as one of the largest abstract and citation databases of peer-reviewed literature, including scientific journals, books and conference proceedings while aiming to assess the potential between CE, Internet of the Things (IoT) and big data. Merli et al. (2017) choose to merge the results from WoS and Scopus. In analysing the evolution of industrial symbiosis, Yu et al. (2013) considers using Google Scholar yet decides to use Scopus in the final evaluation and benefit from the Google Refine tool for data acquisition and cleaning up their data by various fuzzy-string matching algorithms, which, since October 2nd, 2012, Google is not actively supporting, and is rebranded as OpenRefine, that is now fully supported by volunteers. Thus, the choice of citation index database, namely, the data source, depends on the aim and the scope of the bibliometric CE research.

In this article, we mainly use WoS database after comparing our initial results with Scopus database. The reason why we also use Scopus is to check for and investigate the broader non-English publications and/or conference papers, and to observe whether they make any significant difference. Although this situation initially creates one immediate disadvantage, which is the quality concern for these CE publications, the advantage is the expected retrieval of more information about the local and emerging CE activities that non-English, relatively local journals or conference publications can contain. This aspect is important especially for content, co-occurrence analysis. Thus, we compared the results of WoS and Scopus in the field of CE for content, co-occurrence, after defining and running the appropriate search term (Section 3.1). To be able to capture the broadest range of scientific activity in CE field, our unit of analysis is a scientific publication, which can be an article, a proceedings paper, book review, editorial material, letter, meeting abstract, review, in all languages available. This feature also differentiates our article and its contribution from other studies in the field. Our search criteria for both citation index databases include all scientific publications in all languages available, published at all times available (no publication type, language or chronological restriction regarding to a starting year were employed). The cut-off date is set to December 31st, 2016 to be able to achieve a consistent set of scientific publications, which is stable and robust against the backlog and pipeline (e.g. late, not yet included 2017 published publications) of citation indexing services for the times we conducted our research.

Running our query defined in Section 3.1, from Scopus database, it returned 1,290 scientific publications as of December 31st, 2016, starting from 2001 (3.1 times more than the number of WoS-listed CE publications n: 412). Yet the difference in these numbers is mainly caused by the conference papers (n: 548) listed by Scopus. Scopus database also consists of 147 CE publications in Chinese language (11% of them are conference papers, while for WoS; this is only 1 CE publication in Chinese language). Still the pressing disadvantage of CE publications in Scopus is related to the quality criteria of these publications. As of September 2017, 412 WoS-listed CE publications have received in total 4,585 citations whereas 1,290 Scopus-listed CE publications received only 5,864 citations. Thus, although Scopus lists 3.1 times more CE publications than WoS, quality criterion regarding received citations also guided us towards using WoS database, especially for network analysis (see Fig. 1. selections are in bold fonts). However, we decided to use WoS and Scopus, separately, especially for comparative content, co-occurrences analysis due to the importance of being able to capture integrated local level movements in co-occurrences of key research terms with circular economy.

Fig. 1 Research Design



3.3 Case Selection: The most productive political geographies of CE scientific knowledge

Our initial data reveal that China, in which the Circular Economy Promotion Law was officially legislated in 2008, and adopted in 2009, has the highest number of CE publications in total (n: 142). On the other hand, EU-28, in which the CE package was part of a heated policy debate, has collectively the highest number of CE publications (n: 241). In Europe, the European Commission (EC) issued a communication outlining a strategy for a CE in July 2014 and a revised CE package in December 2015 (EC, 2015), approximately six years after the Circular Economy Promotion Law of the People's Republic of China. Yet these two political geographies are the most productive ones in CE scientific knowledge creation.

Table 1
Initial WoS search results (2006-2016)

Search keyword	Search results (number of CE publications (2006-2016)		
	China	EU-28	EU-China Co-authorship
"*circular* *econom*"	142	241	26

Besides, although the first two co-author source countries for China appear to be the U.S. (n: 25) and Japan (n: 24) at country level, our initial data suggest that the EU-28 collectively is the first co-author source for China (n: 26) for CE scientific publications (Table 1 and Fig. 1).

3.4 Type of analyses and tools

3.4.1. Bibliometric analysis

Bibliometric methods include co-authorship analysis (White, 1990), citation analysis (Garfield, 1979; Pilkington and Meredith, 2009); co-citation analysis (Kessler, 1963). Each method of analysis reveals different aspects of the data at hand. Co-authorship analyses help investigating the relatedness of authors, institutes, countries which is determined by their number of co-authored publications. Co-occurrence analyses help to scrutinise the relatedness of keywords based on the number of publications in which they occur together. Citation analysis, on the other hand, is associated with the relatedness of items which is based on the number of times they cite each other. In bibliographic coupling: the relatedness of items is determined by the number of references, the authors or countries, depending on the unit of analysis, they share. In co-citation analysis, the relatedness of the units of analysis is determined by the number of times they are cited together. These analyses and visualisations are performed by using VOSViewer (van Eck and Waltman, 2017). Total Local Citation Score (TLCS) which represents the total citations to the publications within the CE collection and Total Global Citation Score (TGCS) which shows the total citations to all publications (WoS citations) are calculated by using HistCite (Garfield, 1979; 2009).

3.4.2 Network Analysis

VOSViewer is used for calculation of network statistical metrics, and network analysis which consists of calculation and interpretation of centralities, e.g. in author or keyword networks, such as association strength (van Eck and Waltman, 2017) or eigencentrality. Eigencentrality is a measure of the influence of a node in a network: connections to high-scoring entities contribute more to the score of the entity than connections to low-scoring entity (e.g. author, paper, country) in a network, Wasserman and Faust (1994). Our network analysis in this article in based on the data gathered from WoS.

3.4.3 Survey analysis on future research agendas and opportunities for collaboration

To consolidate the ideas on potential future research agendas and opportunities relating to international collaboration in the field of CE, using Google Forms, we implemented an online survey of 10 questions to the first authors of the most highly-cited CE articles, meaning that these CE researchers received enough citations as of September/October 2016 to place them in the Top 1% of their academic fields, here, CE, based on Web of Science Essential Science Indicators. In total, 24 articles from China or EU-28 satisfied this quality criterion, 11 CE researchers participated into our survey implemented between June 2017 and September 2017. Survey questions are provided in the supplementary file.

3.5 Limitations

Bibliometric analysis is too sensitive to the construction of the search query, selection of data source, and is actually exploratory in nature (Narin, 1976; Van Leeuwen, 2004; 2006). Network analysis is, in general, temporally agglomerative, and can hide e.g. researchers' mobility. Thus, they both have limited use in predicting future research agendas. This is the main reason why we implemented a survey of 10-questions, to cope with these limitations. Yet the general limitation of survey analysis is the representativeness and the number of participants. Our sample is rather a homogenous group, Top %1 CE Researchers, based on Web of Science Essential Science Indicators. Methodologically, Guest et al., 2006 indicate that 6 to 12 observations are sufficient in cases of a scientific inquiry with a rather homogenous sample. Purposive samples are the most commonly used form of non-probabilistic sampling, and their size typically relies on the concept of saturation (Guest et al., 2006). In this regard, we assess that our sample is representative within this purposive frame. In other words, self-selection bias does not significantly influence our findings and conclusions, which do not claim generalizability yet strong contextual insights on the future research agendas and opportunities for international collaboration, provided by the most highly-cited CE researchers who are in the Top 1% of their academic fields, here, CE, based on Web of Science Essential Science Indicators.

4. Analysis and discussions

4.1. Bibliometric Analysis

4.1.1 Core content of circular economy scientific knowledge

Table 2 below presents the core articles of circular economy scientific literature based on citation (cited-reference) analysis. Publication years range from 2000 to 2013. The main finding is that other than Chertow (e.g. in the U.S., Yale University, which has a long historical relationship with China (app. 170 years), with sponsorship from China's State Council and National School of Administration is an important university relating to CE scientific research (see Supplementary file for multi-level multi-domain, and international co-funding characteristics behind the most cited CE publications)) and Jacobsen, core CE literature is formed by the authors from China.

Table 2.
Core literature of CE – 10 articles

Title of the Cited Reference	First Author	Year	No of WoS Cit.	Total Link Strength	Journal	DOI
The Circular Economy: A New Development Strategy in China	Yuan ZW	2006	46	103	j ind ecol	http://dx.doi.org/10.1162/108819806775545321
Industrial symbiosis: Literature and taxonomy	Chertow MR	2000	41	114	annu rev energ env	http://dx.doi.org/10.1146/annurev.energy.25.1.313
Developing the circular economy in China: Challenges and opportunities for achieving 'leapfrog development'	Geng Y	2008	36	91	int j sust dev world	http://dx.doi.org/10.3843/susdev.15.3:6
Implementing China's circular economy concept at the regional level: a review of progress in Dalian, China	Geng Y	2009	36	98	waste manage	http://dx.doi.org/10.1016/j.wasman.2008.06.036
"Uncovering" Industrial Symbiosis	Chertow MR	2007	32	109	j ind ecol	http://dx.doi.org/10.1162/jiec.2007.1110
Towards a national circular economy indicator system in China: An evaluation and critical analysis	Geng Y	2012	32	69	j clean prod	http://dx.doi.org/10.1016/j.jclepro.2011.07.005
A review of the circular economy in China: Moving from rhetoric to implementation	Su B	2013	29	61	j clean prod	http://dx.doi.org/10.1016/j.jclepro.2012.11.020
Industrial Symbiosis in Kalundborg, Denmark: A Quantitative Assessment of Economic and Environmental Aspects	Jacobsen NB	2006	24	97	j ind ecol	http://dx.doi.org/10.1162/108819806775545411
Developing country experience with eco-industrial parks: a case study of the Tianjin Economic-Technological Development Area in China	Shi H	2010	24	88	j clean prod	http://dx.doi.org/10.1016/j.jclepro.2009.10.002
Industrial Symbiosis in China: A Case Study of the Guitang Group	Zhu QH	2007	24	94	j ind ecol	http://dx.doi.org/10.1162/jiec.2007.929

Source: WoS, selected between 16361 cited references. Criteria: being cited 22 times or more times, meaning that every year at least 2 citation received on average in the last 11 years (2006-2016). WoS Cit: Citations received from WoS listed publications. Total link strength: total link strength of the co-citation links with other cited references. Citation count, backlog coverage until March 10, 2017.

Table 3 below demonstrates 67 keywords studied within CE and their distribution in the EU and China (coverage of these keywords counts for ~%95 of all CE publications). In terms of revealing the differences (the rightmost column), in 28 topics, EU is consistently leading in both WoS and Scopus with respect to both % of publications and number of publications consisting these keyword co-occurrences. In 11 topics, China leads. This analysis reveals the focal differentiation points among two contexts. For CE scientific knowledge in China, these focal differentiation points are sustainable development; construction; pollution; environmental protection; eco-industrial (parks); low carbon; low carbon economy; emergy; emergy analysis; ecological civilization; harmonious society, which reveal the issue-based (e.g. pollution), meso/macro-level (e.g. eco-industrial parks, low carbon economy), technical (emergy, emergy analysis) and societal focus (e.g. ecological civilization; harmonious society) of CE research and scientific knowledge. For CE scientific knowledge in the EU, we initially observe *Waste* other than *Pollution*, which is followed by sustainability (instead of sustainable development); impact; bio*; waste management; water; critical (raw materials); climate (change); food; raw materials; end-of-life; business model* terms which reveal different issue-based (e.g. waste), sectoral (e.g. bio, water, food), environmental (e.g. impact, climate change, raw materials) and market-based focus (e.g. business model) of CE research and scientific knowledge.

For differences in primary co-occurring keywords with CE, *Waste* is the primary co-occurring keyword in the EU (~55% in WoS, ~69% in Scopus) and *Resource* is the primary co-occurring keyword in China (~57% in WoS and ~68% in Scopus). These findings are in line with waste as resource approach in the EU (e.g. EEA, 2014), and resource utilization approach in China (e.g. Zhongfu et al., 2016). Mix topics indicate the local movements if a context lead only in Scopus but not in WoS. These findings are in line with McDowall et al. (2017).

Table 3.
Results of different co-occurrences of terms with CE (terms in vertical axis):

Term of interest	EU WoS NoP	Percent in Total (EU WoS)	China WoS NoP	Percent in Total (China WoS)	EU Scopus NoP	Percent in Total (EU Scopus)	China Scopus NoP	Percent in Total (China Scopus)	Leading in both indices & % and NoP
Automotive	5	2.16%	2	1.42%	31	8.20%	11	1.47%	EU
Bio*	53	22.84%	15	10.64%	176	46.56%	120	16.02%	EU
Business Model*	10	4.31%	0	0.00%	58	15.34%	2	0.27%	EU
Cleaner Production	7	3.02%	12	8.51%	173	45.77%	147	19.63%	Mix
Climate	17	7.33%	7	4.96%	104	27.51%	41	5.47%	EU
Climate Change	13	5.60%	6	4.26%	79	20.90%	32	4.27%	EU
Competition	4	1.72%	3	2.13%	21	5.56%	28	3.74%	Mix
Competitive	9	3.88%	1	0.71%	45	11.90%	23	3.07%	EU
Competitiveness	5	2.16%	1	0.71%	31	8.20%	20	2.67%	EU
Construction	15	6.47%	16	11.35%	68	17.99%	215	28.70%	China
Consumption	42	18.10%	35	24.82%	125	33.07%	177	23.63%	Mix
Cradle	7	3.02%	0	0.00%	52	13.76%	3	0.40%	EU
Cradle-to-cradle	5	2.16%	0	0.00%	46	12.17%	1	0.13%	EU
Critical	25	10.78%	14	9.93%	126	33.33%	49	6.54%	EU
Critical Raw Materials	3	1.29%	0	0.00%	30	7.94%	0	0.00%	EU
Demolition	6	2.59%	0	0.00%	19	5.03%	5	0.67%	EU
Eco-industrial	15	6.47%	25	17.73%	33	8.73%	113	15.09%	China
Ecological civilization	0	0.00%	0	0.00%	1	0.26%	16	2.14%	China
Emergy	4	1.72%	11	7.80%	9	2.38%	34	4.54%	China
Emergy Analysis	2	0.86%	9	6.38%	5	1.32%	20	2.67%	China
End-of-life	23	9.91%	2	1.42%	76	20.11%	14	1.87%	EU
Environmental protection	6	2.59%	10	7.09%	45	11.90%	153	20.43%	China
Food	27	11.64%	6	4.26%	97	25.66%	48	6.41%	EU
Food waste	11	4.74%	1	0.71%	27	7.14%	4	0.53%	EU
Green economy	5	2.16%	1	0.71%	22	5.82%	17	2.27%	EU
Harmonious society	0	0.00%	1	0.71%	3	0.79%	11	1.47%	China
Impact	66	28.45%	29	20.57%	190	50.26%	138	18.42%	EU
Indicator	19	8.19%	22	15.60%	79	20.90%	128	17.09%	Mix
Industrial metabolism	0	0.00%	2	1.42%	8	2.12%	10	1.34%	Mix
Industrial symbiosis	23	9.91%	22	15.60%	42	11.11%	54	7.21%	Mix

Innovation	21	9.05%	10	7.09%	139	36.77%	144	19.23%	Mix
Institution	8	3.45%	3	2.13%	53	14.02%	24	3.20%	EU
Low carbon	6	2.59%	11	7.80%	36	9.52%	74	9.88%	China
Low carbon economy	2	0.86%	2	1.42%	10	2.65%	40	5.34%	China
Metabolism	7	3.02%	9	6.38%	31	8.20%	46	6.14%	Mix
Metal*	23	9.91%	7	4.96%	109	28.84%	86	11.48%	Mix
Method	28	12.07%	39	27.66%	157	41.53%	292	38.99%	Mix
Plastics	11	4.74%	3	2.13%	52	13.76%	17	2.27%	EU
Policy	64	27.59%	55	39.01%	218	57.67%	260	34.71%	Mix
Pollutant	5	2.16%	11	7.80%	29	7.67%	45	6.01%	Mix
Pollution	16	6.90%	30	21.28%	85	22.49%	208	27.77%	China
Production	85	36.64%	46	32.62%	279	73.81%	318	42.46%	Mix
Raw Materials	31	13.36%	5	3.55%	92	24.34%	33	4.41%	EU
Recycl*	76	32.76%	40	28.37%	229	60.58%	329	43.93%	Mix
Recycle	73	31.47%	39	27.66%	34	8.99%	77	10.28%	Mix
Recycling	73	31.47%	39	27.66%	221	58.47%	283	37.78%	Mix
Reduce	38	16.38%	25	17.73%	46	12.17%	62	8.28%	Mix
Reduce AND Recycl*	19	8.19%	12	8.51%	36	9.52%	1	0.13%	Mix
Reduce AND Recycle	17	7.33%	11	7.80%	8	2.12%	1	0.13%	Mix
Reduce AND Reuse	7	3.02%	8	5.67%	14	3.70%	1	0.13%	Mix
Reduce AND Reuse AND Recycle	4	1.72%	7	4.96%	5	1.32%	0	0.00%	Mix
Remanufacturing	10	4.31%	4	2.84%	43	11.38%	28	3.74%	EU
Resource	102	43.97%	79	56.03%	285	75.40%	505	67.42%	Mix
Resource Efficien*	31	13.36%	10	7.09%	119	31.48%	21	2.80%	Mix
Resource Security	0	0.00%	0	0.00%	11	2.91%	2	0.27%	Mix
Reuse	25	10.78%	18	12.77%	85	22.49%	75	10.01%	Mix
Reuse AND Recycl*	15	6.47%	11	7.80%	73	19.31%	12	1.60%	Mix
Security of supply	1	0.43%	0	0.00%	1	0.26%	0	0.00%	EU
Sustainability	67	28.88%	26	18.44%	223	58.99%	120	16.02%	EU
Sustainable development	27	11.64%	41	29.08%	168	44.44%	373	49.80%	China
Symbiosis	30	12.93%	31	21.99%	44	11.64%	58	7.74%	Mix
Transport	9	3.88%	2	1.42%	45	11.90%	39	5.21%	EU
Vehicle	6	2.59%	4	2.84%	40	10.58%	18	2.40%	Mix
Waste	127	54.74%	52	36.88%	260	68.78%	259	34.58%	EU
Waste hierarchy	3	1.29%	0	0.00%	13	3.44%	1	0.13%	EU
Waste management	39	16.81%	10	7.09%	149	39.42%	94	12.55%	EU
Water	34	14.66%	22	15.60%	128	33.86%	138	18.42%	EU

Source: Authors' calculation based on WoS and SCOPUS data, as of 31st December 2016, Percentages refer to the proportion of articles mentioning the circular economy that also mention the term of interest in the title, abstract or in keywords. NoP: Number of Publications

From Table 4, in terms of co-authored scientific publications by researchers in the EU and China, we observe that the co-occurrence of the term *Policy, 57.69%* is the most common in WoS-listed scientific publications. This finding reveals the importance of policy, and research efforts in understanding policy among contexts in the field of CE. For Scopus-listed scientific publications, this finding about *Policy* is still robust (70.83%), yet we have two more dominant co-occurring terms which are Resource (75%) and Production (75%). This finding reveals the common economic (environmental and industrial, respectively) focus of co-authored scientific CE publications by researchers in the EU and China. These two findings together justifies the political (e.g. policy) and economic (e.g. environmental, industrial) coverage and reach of CE scientific research and knowledge.

Table 4.

Co-occurrences in EU-China co-authorships

Term of interest	EU-China Co-authorship WoS NoP	Percentage in Total EU-China WoS	EU-China Co-authorship Scopus NoP	Percentage in Total EU-China Scopus

Production	7	26.92%	18	75.00%
Resource	11	42.31%	18	75.00%
Policy	15	57.69%	17	70.83%
Pollution	7	26.92%	16	66.67%
Sustainability	9	34.62%	15	62.50%
Waste	9	34.62%	14	58.33%
Waste management	3	11.54%	12	50.00%
Cleaner Production	2	7.69%	11	45.83%
Recycl*	6	23.08%	11	45.83%
Recycling	6	23.08%	11	45.83%
Sustainable development	11	42.31%	11	45.83%
Bio*	1	3.85%	10	41.67%
Consumption	5	19.23%	10	41.67%
Impact	6	23.08%	10	41.67%
Method	5	19.23%	10	41.67%
Water	5	19.23%	10	41.67%
Critical	4	15.38%	8	33.33%
Environmental protection	1	3.85%	8	33.33%
Climate	1	3.85%	7	29.17%
Emergy	4	15.38%	7	29.17%
Food	2	7.69%	7	29.17%
Indicator	4	15.38%	7	29.17%
Eco-industrial	5	19.23%	6	25.00%
Innovation	3	11.54%	6	25.00%
Low carbon	3	11.54%	6	25.00%
Industrial symbiosis	4	15.38%	5	20.83%
Resource Efficien*	3	11.54%	5	20.83%
Symbiosis	8	30.77%	5	20.83%
Climate Change	1	3.85%	4	16.67%
Emergy Analysis	2	7.69%	4	16.67%
Green economy	1	3.85%	4	16.67%
Metabolism	2	7.69%	4	16.67%
Reuse	2	7.69%	4	16.67%
Construction	1	3.85%	3	12.50%
Metal*	0	0.00%	3	12.50%
Plastics	0	0.00%	3	12.50%
Pollutant	1	3.85%	3	12.50%
Recycle	6	23.08%	3	12.50%
Reduce	2	7.69%	3	12.50%
Reuse AND Recycl*	2	7.69%	3	12.50%
Transport	0	0.00%	3	12.50%
Competition	2	7.69%	2	8.33%
End-of-life	0	0.00%	2	8.33%
Food waste	1	3.85%	2	8.33%
Reduce AND Recycl*	1	3.85%	2	8.33%
Remanufacturing	0	0.00%	2	8.33%
Competitive	0	0.00%	1	4.17%
Cradle	0	0.00%	1	4.17%
Harmonious society	0	0.00%	1	4.17%
Industrial metabolism	0	0.00%	1	4.17%
Institution	0	0.00%	1	4.17%
Low carbon economy	1	3.85%	1	4.17%
Raw Materials	0	0.00%	1	4.17%
Reduce AND Recycle	1	3.85%	1	4.17%
Reduce AND Reuse	1	3.85%	1	4.17%
Reduce AND Reuse AND Recycle	1	3.85%	1	4.17%
Vehicle	0	0.00%	1	4.17%
Waste hierarchy	0	0.00%	1	4.17%
Automotive	*0*	*0.00%*	*0*	*0.00%*
Business Model*	*0*	*0.00%*	*0*	*0.00%*
Competitiveness	1	3.85%	0	0.00%
Cradle-to-cradle	*0*	*0.00%*	*0*	*0.00%*
Critical Raw Materials	*0*	*0.00%*	*0*	*0.00%*
Demolition	*0*	*0.00%*	*0*	*0.00%*
Ecological civilization	*0*	*0.00%*	*0*	*0.00%*
Resource Security	*0*	*0.00%*	*0*	*0.00%*
Security of supply	*0*	*0.00%*	*0*	*0.00%*

Product and Service Platform	*0*	*0.00%*	*0*	*0.00%*

Source: Author's work based on WoS and Scopus (31st December 2016).

Further analysing Table 4, we argue that there is still room for co-authorship cooperation between the EU and Chine, especially in the sectoral fields of automotive, construction and demolition, critical raw materials; in business, (new) business models, product and services platforms, and from security perspective, resource security or security of supply, over which no co-authorship exists between China and the EU (Table 4, please see the last rows given in *italic* and underlined).

4.1.2 Core science categories of circular economy scientific knowledge in different contexts

Context is an important structure for scientific research. In the field of CE, main common science categories, building blocks, for China and the EU-28 are *Environmental Sciences, Environmental Engineering, Green Sustainable Science Technology, Energy Fuels, and Environmental Studies* (Table 5). Yet initial differentiating science categories for China is Management, Operations Research and Mathematics; for the UK, Geography, Biotech and Agriculture; for the Netherlands, Water Resources, Urban Studies, Soil Science; for Italy Economics, Transportation and Toxicology, and finally for Germany, Construction and Building Technology (Table 5). These findings indicate the importance of context-specific sensitivity of CE research, diversity of research approaches (e.g. Operations Research, Mathematics in China), and prioritisations (e.g. Water for the Netherlands, Construction and Building Technology for Germany, Management for China).

Table 5.
Rank of science categories and bodies of knowledge in different contexts

R	China	UK	The Netherlands	Italy	Germany
1	ENVIRONMENTAL SCIENCES	ENVIRONMENTAL SCIENCES	ENVIRONMENTAL SCIENCES	ENVIRONMENTAL SCIENCES	ENVIRONMENTAL SCIENCES
2	ENGINEERING ENVIRONMENTAL	ENGINEERING ENVIRONMENTAL	ENGINEERING ENVIRONMENTAL	GREEN SUSTAINABLE SCIENCE TECHNOLOGY	ENGINEERING ENVIRONMENTAL
3	GREEN SUSTAINABLE SCIENCE TECHNOLOGY	GREEN SUSTAINABLE SCIENCE TECHNOLOGY	GREEN SUSTAINABLE SCIENCE TECHNOLOGY	ENGINEERING ENVIRONMENTAL	GREEN SUSTAINABLE SCIENCE TECHNOLOGY
4	ENERGY FUELS	ENVIRONMENTAL STUDIES	***WATER RESOURCES***	ENVIRONMENTAL STUDIES	ENVIRONMENTAL STUDIES
5	ENVIRONMENTAL STUDIES	ENERGY FUELS	ENVIRONMENTAL STUDIES	ENERGY FUELS	***CONSTRUCTION BUILDING TECHNOLOGY***
6	***MANAGEMENT***	***GEOGRAPHY***	***URBAN STUDIES***	***ECONOMICS***	METALLURGY METALLURGICAL ENGINEERING
7	ENGINEERING CHEMICAL	***BIOTECHNOLOGY APPLIED MICROBIOLOGY***	***SOIL SCIENCE***	MULTIDISCIPLINARY SCIENCES	MATERIALS SCIENCE MULTIDISCIPLINARY
8	***OPERATIONS RESEARCH MANAGEMENT SCIENCE***	***AGRICULTURAL ENGINEERING***	PLANNING DEVELOPMENT	ENGINEERING CHEMICAL	MATERIALS SCIENCE COMPOSITES
9	METALLURGY METALLURGICAL ENGINEERING	PLANNING DEVELOPMENT	MATERIALS SCIENCE MULTIDISCIPLINARY	***TRANSPORTATION***	MATERIALS SCIENCE CHARACTERIZATION TESTING

10	ENGINEERING INDUSTRIAL	MULTIDISCIPLINARY SCIENCES	ENGINEERING MANUFACTURING	TOXICOLOGY	ENGINEERING CIVIL
11	BIODIVERSITY CONSERVATION	ENGINEERING INDUSTRIAL	ENGINEERING INDUSTRIAL	PLANNING DEVELOPMENT	ENGINEERING CHEMICAL
12	THERMODYNAMICS	ENGINEERING CHEMICAL	ENGINEERING CHEMICAL	METALLURGY METALLURGICAL ENGINEERING	ENERGY FUELS
13	MULTIDISCIPLINARY SCIENCES	ECONOMICS	ENERGY FUELS	MANAGEMENT	BIODIVERSITY CONSERVATION
14	MINING MINERAL PROCESSING	CHEMISTRY MULTIDISCIPLINARY	CHEMISTRY PHYSICAL	GEOGRAPHY	
15	***MATHEMATICS INTERDISCIPLINARY APPLICATIONS***		CHEMISTRY MULTIDISCIPLINARY	CHEMISTRY PHYSICAL	
16	ENGINEERING MANUFACTURING		BIOTECHNOLOGY APPLIED MICROBIOLOGY	CHEMISTRY APPLIED	
17	CHEMISTRY PHYSICAL		AUTOMATION CONTROL SYSTEMS	BUSINESS	
18	CHEMISTRY MULTIDISCIPLINARY		AGRICULTURAL ENGINEERING	BIOTECHNOLOGY APPLIED MICROBIOLOGY	
19	BIOTECHNOLOGY APPLIED MICROBIOLOGY			AGRICULTURAL ENGINEERING	
20	WATER RESOURCES				
21	URBAN STUDIES				

Source: Authors' calculation based on WoS data, as of 31st December 2016, excluding backlog. R: Rank Order based on number of publication in the research field.

4.1.3 A Multi-level bibliometric analysis of CE field

Status and characteristics of circular economy scientific knowledge at city level have not been yet made available in the CE literature. In this subsection we address this gap (Table 6). In Beijing, we observe a high level of activity by Chinese Academy of Sciences and Tsinghua University. The most active international partner is the National Institute of Environmental Studies from Tsukuba, Ibaraki, Japan. From public institutes, National People's Congress, Environment and Resources Commission, Ministry of Environmental Protection (MEP) and Ministry of Transport are also involved in CE scientific knowledge production activities. This indicates a multi-domain characteristic of CE in China. Private sector participations from big corporations are such as Coca Cola Co., Japan Environmental Safety Corporation, CCID Consulting Co. Ltd., Baosteel Group, VAST, Towa technologies supports the idea of multi-actor involvement in the field of CE (Fig. 6).

Table 6

Production and content performance of CE publications at city level around the world (33 cities)

City	No_A	No_I	No_C	No_KW	No_P	No_J	No_CR	No_CRS	No_CRA
Beijing	166	83	19	155	49	24	1789	965	1408
Shenyang	55	32	8	67	26	14	854	434	631
Shanghai	87	42	11	75	23	11	854	413	645
Tsukuba	70	47	15	55	20	9	714	321	526
Delft	51	21	6	77	17	10	914	529	733

Dalian	26	15	5	50	15	12	616	341	475
Rome	44	38	17	44	10	8	600	377	477
Jinan	24	5	<3	31	9	6	202	99	177
Helsinki	38	20	7	36	8	6	592	384	455
Leeds	23	13	10	16	8	4	347	224	310
Brussels	34	28	14	26	8	8	196	156	143
Nanjing	24	7	<3	25	8	7	165	128	144
Bologna	23	14	3	32	7	6	509	347	416
Barcelona	28	15	3	24	7	6	441	242	383
Tianjin	34	11	4	34	7	5	298	173	270
Milan	14	11	4	25	6	4	554	340	477
Naples	13	16	6	19	6	5	526	334	416
Stockholm	17	5	<3	35	6	3	461	270	385
Oxford	30	3	<3	27	6	5	348	227	286
New Haven	14	6	3	25	6	5	343	252	279
Lund	12	9	7	24	6	3	315	251	253
London	34	25	13	30	6	4	283	208	218
Hefei	19	4	<3	27	6	5	148	77	117
Wuhan	28	9	4	20	6	6	146	117	125
Changsha	10	3	<3	30	6	6	144	116	136
Potsdam	20	14	4	20	5	4	303	193	265
Berlin	36	26	13	24	5	4	292	202	252
Hague	13	14	7	21	5	4	276	237	219
Wageningen	23	17	7	28	5	4	267	207	217
Rotterdam	15	8	3	19	5	3	225	124	180
Waterloo	11	7	4	13	4	4	113	80	86
Xuzhou	12	7	<3	17	4		104	82	93
Chongqing	17	9	5	15	4	4	79	66	71

Source: WoS Authors' work, selected cities (4 or more publications) , at least one affiliated in a given city No_A (number of authors); No_I (Institutions), No_C (Countries), No_KW (Keywords); No_P (Publications); No_J (Journals), No_CR(Cited references), No_CRS (Cited Reference Journals) No_CRA (Cited references Author) Citation count, backlog coverage until March 10, 2017

However, we cannot see the same performance in the received citations in Beijing. In terms of citation performance, Shenyang is the leading city (Table 7) yet still with CAS Shenyang branch.

Table 7

Production and citation performance of CE publications at city level in China (13 cities)

City	Region	NoP	SotTC	SoTCwSC	CA	CAwSC	ACpI	h-index
Beijing	**Beijing**	**49**	**429**	**401**	**332**	**319**	8.76	**13**
Shenyang	**Liaoning**	**26**	**635**	**580**	**425**	**404**	**24.42**	**15**
Shanghai	**Shanghai**	**23**	275	265	263	256	11.96	5
Dalian	**Liaoning**	15	**465**	**440**	**355**	**343**	31	**9**
Jinan	**Shandong**	9	48	48	41	41	5.33	5
Nanjing	**Jiangsu**	8	166	165	151	150	**20.75**	3
Tianjin	**Tianjin**	7	199	199	189	189	**28.73**	5
Changsha	**Hunan**	6	15	13	12	11	2.50	2
Wuhan	**Hubei**	6	8	8	8	8	1.33	2
Hefei	**Anhui**	6	105	98	95	91	17.50	4
Changchun	**Jilin**	4	49	49	49	49	12.25	2

Chongqing	**Chongqing**	4	14	14	14	14	3.55	3
Xuzhou	**Jiangsu**	4	3	3	3	3	0.75	1

Source: WoS Authors' work, selected cities (4 or more publications) , NoP: Number of Publications, SotTC: Sum of the Times Cited, SoTCwSC: Sum of Times Cited without self-citations, CA: Citing Articles, CAwSC: Citing Articles without self-citations ACpI: Average Citations per Item, h-index: h articles received at least h citations (Hirsch, 2005). Citation count, backlog coverage until March 10, 2017

In the EU, the leading city is Delft in South Holland, the Netherlands. Delft University of Technology and TNO have central roles in CE scientific knowledge creation (Table 8).

Table 8

Production and citation performance of CE publications at city level in EU-28 (13 cities)

City	Region/ Country	NoP	SotTC	SoTCwSC	CA	CAwSC	ACpI	h-index
Delft	**South Holland/ Netherlands**	**17**	**184**	**180**	**164**	**160**	10.82	**6**
Rome	**Lazio/ Italy**	**10**	96	94	87	85	9.60	**4**
Brussels	**Brussels-Capital Region/ Belgium**	**8**	24	24	24	24	3	1
Helsinki	**Uusimaa/ Finland**	**8**	28	27	28	27	3.50	2
Bologna	**Emilia-Romagna/ Italy**	7	22	21	21	20	3.14	2
Barcelona	**Catalonia/ Spain**	7	25	24	25	24	3.57	3
Leeds	**Yorkshire and the Humber/ UK**	**8**	**264**	**264**	**261**	**261**	**33.00**	3
Naples	**Campania/ Italy**	6	**133**	127	114	110	**22.17**	3
Milan	**Lombardy/ Italy**	6	128	**127**	**122**	**121**	**21.33**	**4**
Stockholm	**Södermanland and Uppland/ Sweden**	6	26	26	24	24	4.3	2
Oxford	**South East England/ UK**	6	16	15	15	14	2.67	2
London	**Greater London/ UK**	6	46	46	45	45	7.67	2
Lund	**Scania/ Sweden**	6	16	16	15	15	2.67	2

Source: WoS Authors' work, selected cities (6 or more publications) , NoP: Number of Publications, SotTC: Sum of the Times Cited, SoTCwSC: Sum of Times Cited without self-citations, CA: Citing Articles, CAwSC: Citing Articles without self-citations ACpI: Average Citations per Item, h-index: h articles received at least h citations (Hirsch, 2005). Citation count, backlog coverage coverage until March 10, 2017

Being the most productive country, in China, 18 regions and 26 cities are active in producing WoS-listed CE publications. Beijing (northern China) is the most active city in this (n: 49). It is followed by the cities of Shenyang (n: 26) and Dalian (n: 15) (which are both in *Liaoning region*, at the northeast China). Shanghai (n: 23), Jinan (n: 9) and Nanjing (n: 8) follow these cities as far as number of CE publications is concerned (Fig 2).

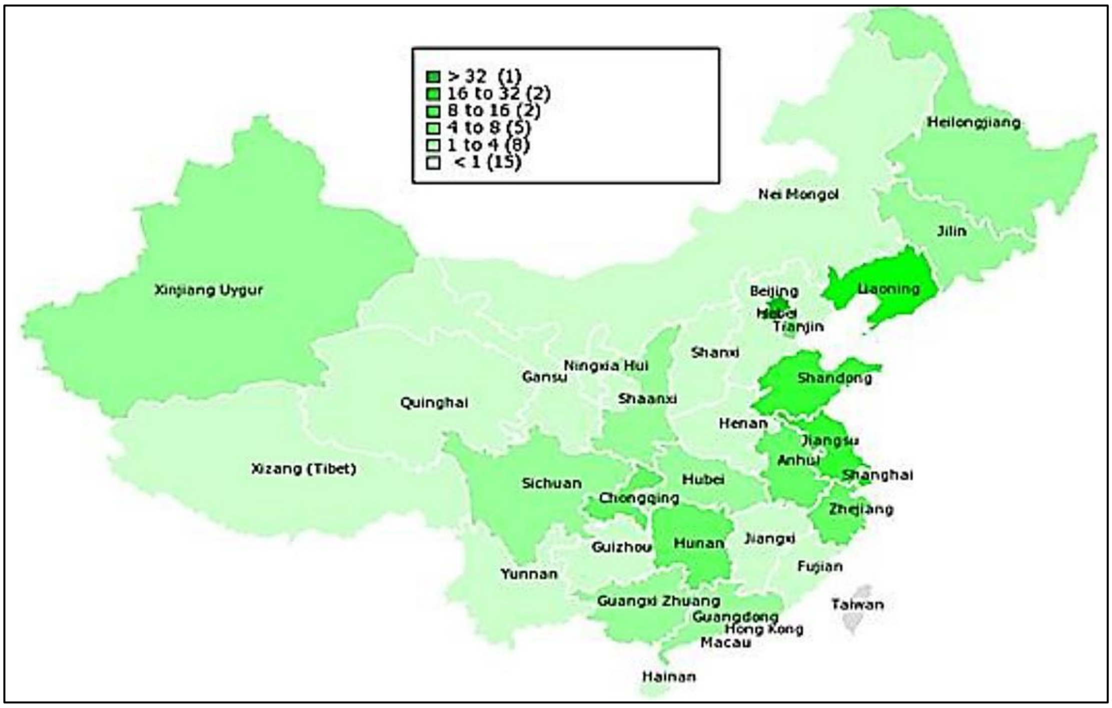


Fig. 2 China – Regional-level CE Scientific Knowledge Production (WoS, 2006-2016)

Researchers in China produce the highest number of CE publications in total (n: 142 WoS; n: 755 Scopus). China is also the leading country in temporal breakdown, e.g. in 2015 (n: 28) and in 2016 (n: 35) publications (Fig. 3), yet researchers in the EU-28 as a supranational entity reach to 241 WoS-listed CE publications (n: 407 in Scopus). The UK (n: 55), the Netherlands (n: 40) and Italy (n: 40) are the most productive top 3 countries in the EU. Top 3 countries do not change in Scopus, yet we capture more publications from France and Eastern European countries. Even after a decade, EU Member States such as Croatia, Bulgaria, Luxemburg and Malta have not produced a CE publication (Table 9).

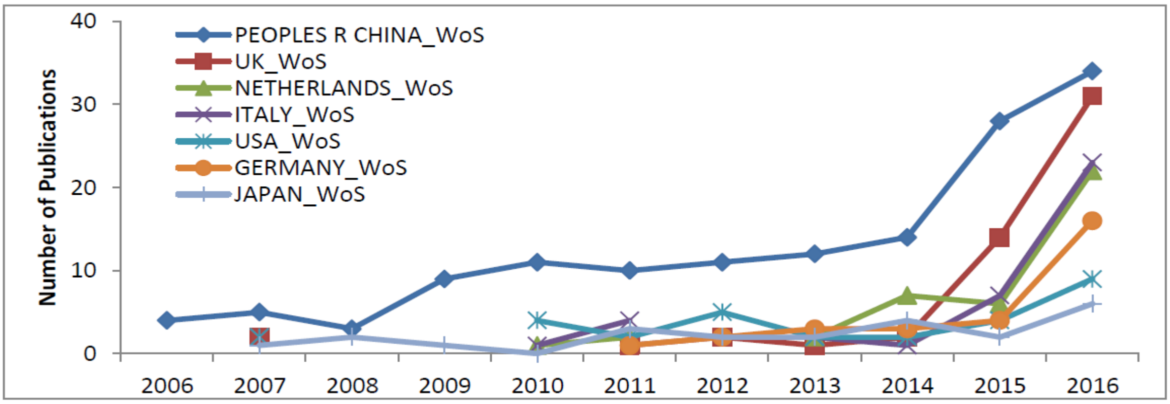


Fig. 3 - CE - The growth trends of the 7 most productive countries

Here, the important findings are that the take-up trends for the use of "circular econom*" in Fig. 3 are in line with the policy introductions in China after 2008 and the EU after 2014. In the EU, EC issued a communication outlining a strategy for a circular economy in July 2014 and in December 2015 a revised circular economy package, approximately 6 years after the Circular Economy Promotion Law of China which is entered into force as of January 2009.

Table 9.

EU and China - Citing the CE literature (number of CE citing articles without self-citations)

Countries/Territories	NoP	CAwSC	CAwSC/NoP
PEOPLES R CHINA	142	797	5.61
ENGLAND	47	301	6.40
ITALY	38	105	2.76
NETHERLANDS	40	96	2.40
SPAIN	16	82	5.13
GERMANY	29	78	2.69
SWEDEN	19	59	3.11
AUSTRIA	6	42	7.00
DENMARK	14	39	2.79
FRANCE	14	39	2.79
BELGIUM	19	31	1.63
FINLAND	16	21	1.31
PORTUGAL	2	19	9.50
GREECE	10	18	1.80
ROMANIA	3	17	5.67
HUNGARY	0	11	-
WALES	6	11	1.83
SCOTLAND	5	9	1.80
IRELAND	2	8	4.00
POLAND	8	8	1.00
LUXEMBOURG	0	5	-
LITHUANIA	1	4	4.00
CZECH REPUBLIC	1	4	4.00
SLOVENIA	0	4	-
LATVIA	0	3	-
ESTONIA	1	2	2.00
CYPRUS	1	1	1.00
CROATIA	0	1	-
NORTH IRELAND	0	1	-

NoP: Number of publications, CAwSC records: Citing articles without self-citation, citing publications as of March 2017

Table 9 provides EU countries (e.g. Hungary, Romania, Portugal, Austria, Luxemburg) citing many CE literature but publishing few in the field, indicating the presence of interest in CE literature, and international cooperation potential within the EU.

4.2. Network Analysis

4.2.1 Core Content

Analysis of the core literature of CE reveals the networked citation connections with Industrial Symbiosis literature (Chertow, 2000; Jacobsen, 2006; Zhu et al., 2007). Main aspects of CE as a new and leapfrog development strategy (Yuan et al., 2006; Geng and Zhao, 2009) with a contextual focus on China, yet with regional level (Geng and Zhao, 2009; Shi et al., 2010) and sectoral level research focus (Zhu et al., 2007) come forward. Quantitative assessment (Jacobsen, 2006) and indicator system research are also fundamental part of the core CE literature (Geng, 2012).

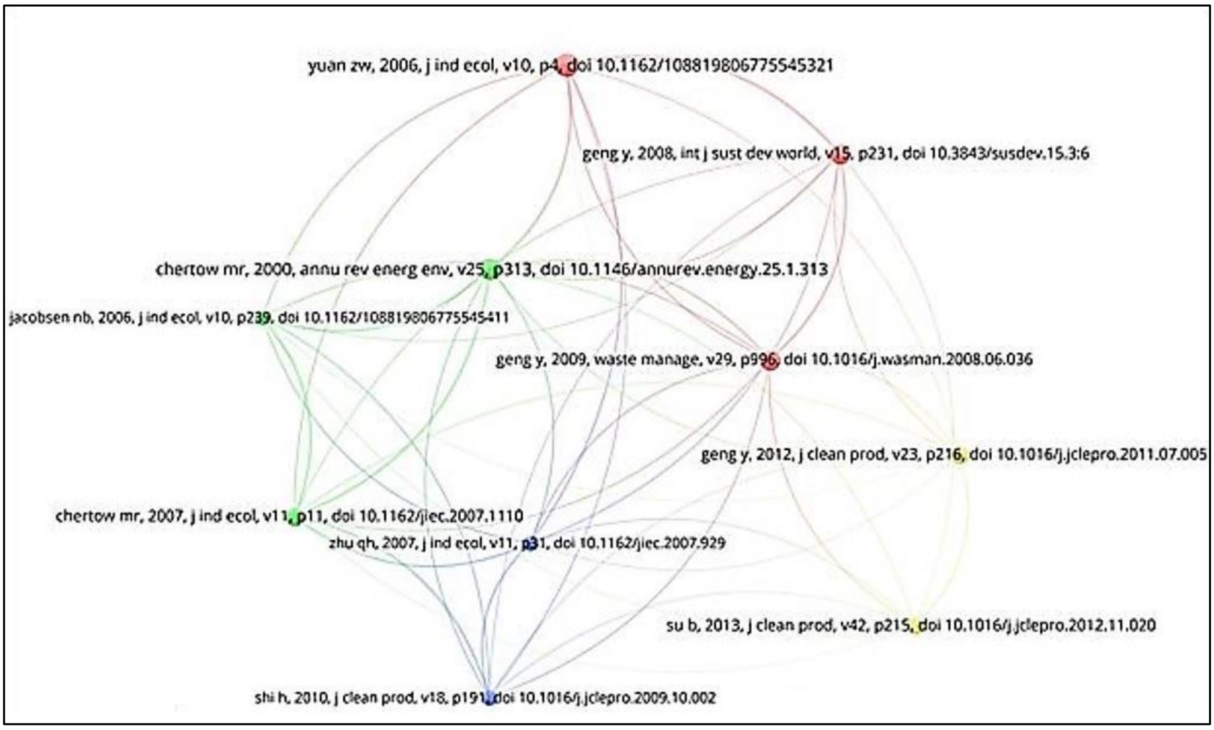


Fig.4 – Four clusters of the core CE Literature

Fig. 4 above represents four connected clusters of the core CE literature. IS literature (green), CE introductory-literature (red), CE regional/sectoral level literature (blue), CE implementation/measurement-related literature (yellow). The latter two core clusters indicate CE's regional/sectoral and measurement (needs) focus. Core CE literature analysis reveals a network of four important themes in CE research: IS background, CE as an emergent concept, regional and sectoral applications, and implementation, measurement related needs to move towards a CE.

4.2.2 Co-joint publications, emerging content

Fig. 5 reveals the temporal centrality of China as a consistent context of CE research. This temporal network analysis also reveals that 3R (reduce, reuse and recycle) and international comparison provided a common starting point for joint publications (~2011) and recycling and sustainable development related themes and publications (~2013) supported the co-authorship. Following, industrial symbiosis, eco-industrial parks, sustainable urban development, eco-transformation topics (~2015), lately, co-joint publications are emerging in *emergy analysis*, *sustainability indicators*, *green finance*, *resource efficiency*, *food waste*, *zero waste*, *eco-cities*, *lifestyle and governance*, as themes of co-operation, on average they are published in 2016. These findings indicate the diffusion of CE research towards not only specific issue areas (e.g. food waste) and specific measurement-related topics (e.g. emergy analysis, sustainability indicators), but also towards broader realms such as social (e.g. lifestyles and governance), financial (e.g. green finance) topics.

Fig. 5 - Visio-temporal Content network of already established EU-China cooperation in CE and emerging keywords

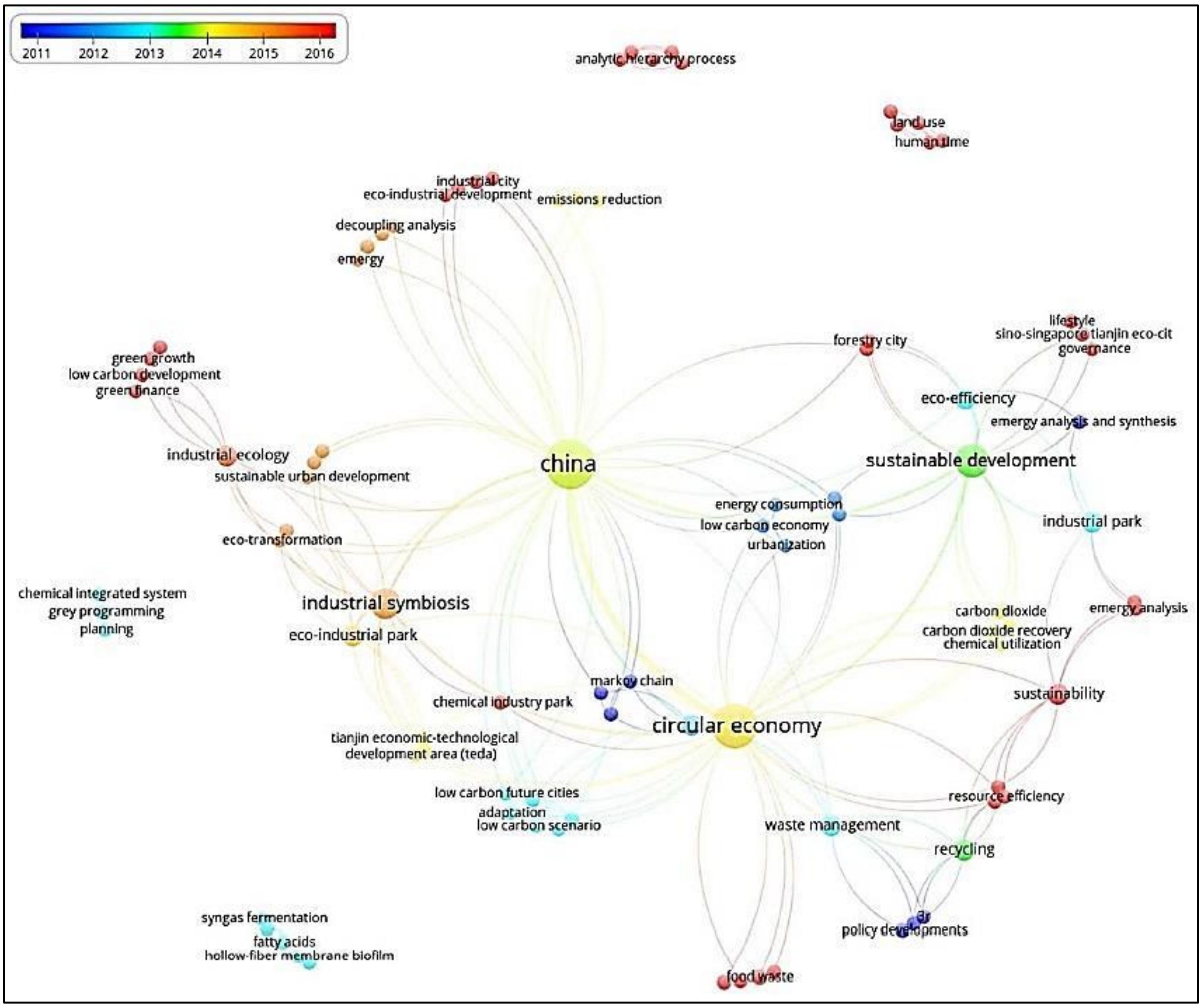


Table 4 above had demonstrated the initial topics of co-authorships. Although Cradle-to-cradle (EU), Ecological civilization (China) could be context-dependent terms (Jin, 2008), *emergy analysis, sustainability indicators, green finance, resource efficiency, food waste, zero waste, eco-cities, lifestyle and governance* apply to both contexts as emerging or reiterated main themes in the joint CE-literature (Fig. 5).

4.2.3 A Multi-level network analysis of CE field

Geng Y., Zhu QH and Fujita T. are the central authors of CE literature written in China, while in the EU-28, Ulgati S., Lieder M., Cialani C. have the highest centrality (Fig. 6). At institutional level, the central role of Chinese Academy of Sciences, Dalian University of Technology and, lately Shanghai Jiao Tong University in producing CE scientific knowledge is revealed, while in the EU-28, the central roles of Delft University of Technology, NL and KTH Royal Institute, Sweden are observable. EU-28 collectively is the first co-authorship source for China (n: 26) in strictly peer-reviewed CE publications from WoS. At national level, the Netherlands and Italy (both n:7) are two primary co-authorship source countries for China (Fig. 6). CE research can benefit from further international co-authorship cooperation among these authors, their research teams, institutions and countries.

In overall network, we observe England as the most influential country, with respect to eigencentrality (which is a measure of the influence of a node in a network by connections to high-scoring countries that contribute more to the score of the country than connections to low-scoring countries). England engaged in co-authorships with 26 countries, whereas China, with 22 countries (Table 10). This finding indicates the importance of differentiating co-authorship portfolios at national level with the countries which are leading in CE research and scientific knowledge to strengthen a central position in the knowledge flow.

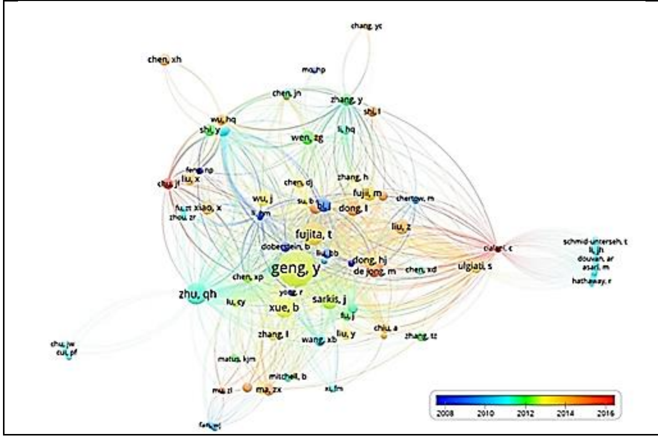
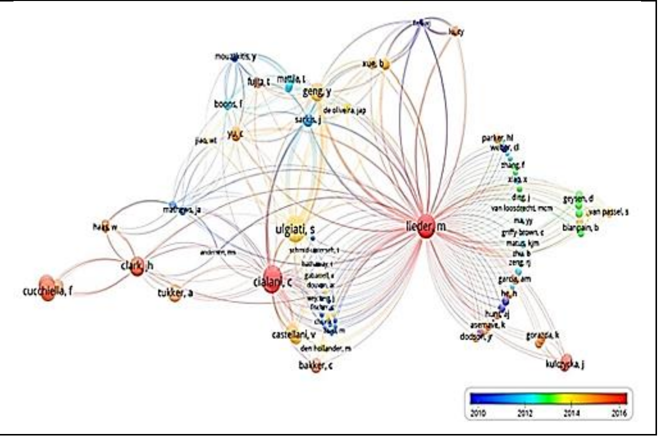
Table 10
Influence of a country in CE co-authorship network (2006-2016)

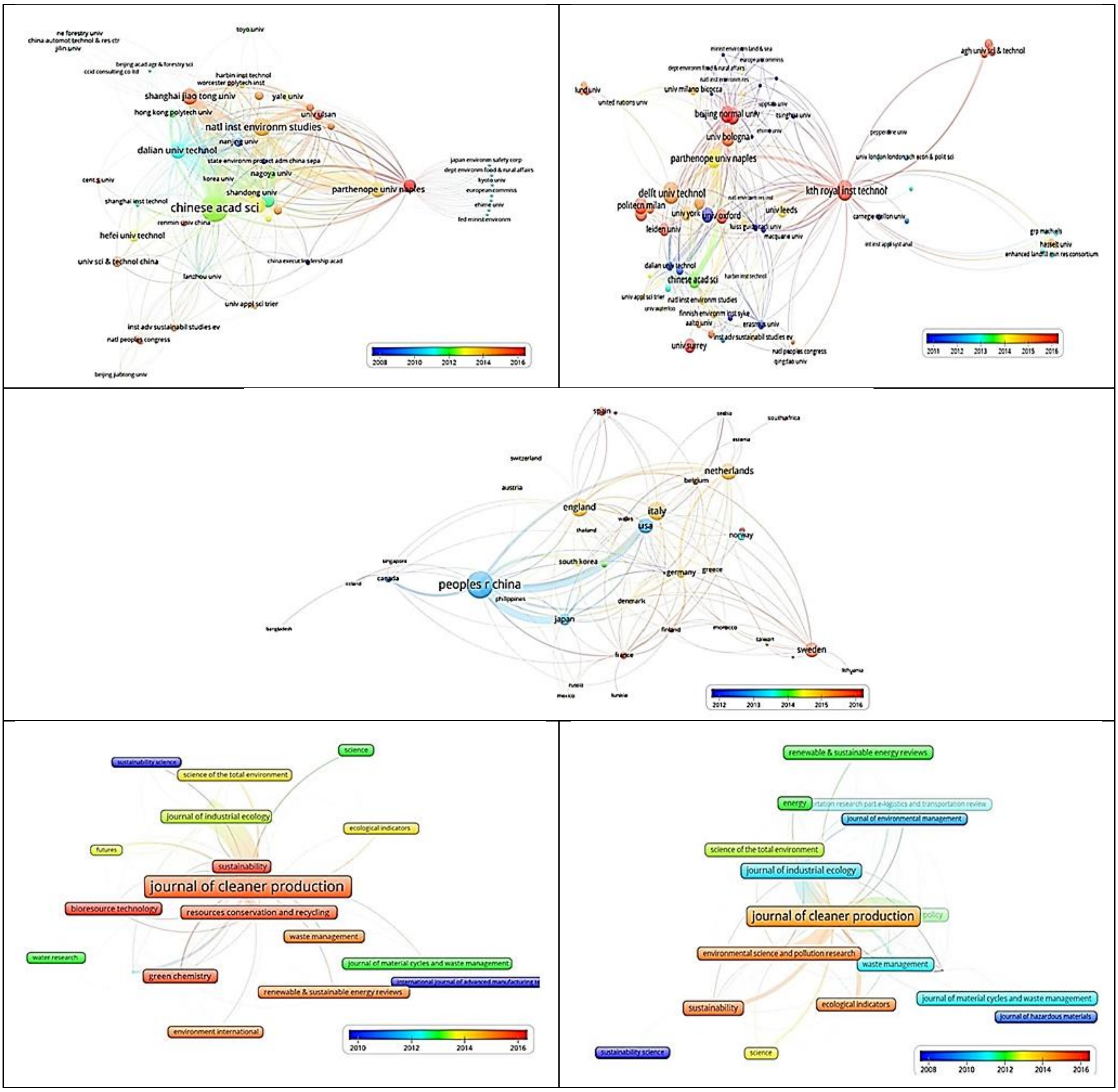
Network metric	England	China	Italy	Germany	Belgium	Sweden	Netherlands	Denmark
eigencentrality	1	0.91	0.88	0.86	0.82	0.80	0.79	0.79

Source: Authors' calculation.

Finally, bibliographic coupling of journals reveals that Journal of Cleaner Production is the central journal for researchers in both EU and China. Publications from China lately couple with journals, such as Environmental Science and Pollution Research, Ecological Indicators and Sustainability, which supports issue-based (e.g. pollution) and technical (e.g. indicators) nature of CE research in China (Table 3), while in the EU-28, publications lately couple with journals, such as Sustainability, Bioresource Technology, Resources Conservation and Recycling, Green Chemistry, Waste Management, Renewable and Sustainable Energy Reviews and Environment International (Fig. 6).

Fig. 6 - Multi-level (author, institute, country, journal) comparison of China and EU-28

China	EU-28
	



4.3 Survey Analysis: Future research directions and international cooperation

82% of the respondents (n:11) who authored one of the top-cited CE publications indicate that *they are involved in research collaboration with researchers based in another world region* (Q1). In research collaborations, major world regions are represented, Europe ~89%, followed by Asia (~67%), North America (~45%), Central and South America (~11%) and Africa (~11%) (Q2). This finding indicates that top-cited CE research possesses an international collaboration dimension.

On a positive note, 91% also declared that *they have a wish to collaborate more with researchers in other world regions*, which is a high percentage, revealing that the top-cited authors are content with the earlier collaboration experience, yet half of the respondents informed us about the conditions for such a collaboration (e.g. *if the understanding and perspectives on CE are aligned, if the collaboration and the research is consistent for both* *parties, if presence of similar interests and research areas, and if complementary research and funding opportunities are accessible*) (Q3). All of which re-emphasise the need for context-specific relevance of CE-related research and scientific knowledge production.

Among our respondents, 78% considers *the level of public funding as poor that they are constantly looking for funding* to do research (Q4), of which 67% also indicated that *there is a need for large multidisciplinary projects on CE (Q6).* These findings indicate the presence of a funding gap which could be filled by international, multi-domain funding (e.g. co-funding by different domain-specific funding agencies, ministries, of different countries).

Overall 82% of the participants stressed *the need for large multidisciplinary projects on CE* (Q6). One concrete suggestion for such a project is: a *large-scale pilot (demonstrator) to research the feasibility of (for instance) the leasing and subsequently refurbishing of a consumer product, involving OEMs (new business models), product design/engineering, consumer research, policy & regulations, reverse supply chain management and refurbishment/recycling industry.* This suggestion comes from an author collaborated within Europe. As a consumer and market-oriented suggestion with an emphasis on the role of policy and regulation, this suggestion is in line with our findings in Section 4.1.1. (Table 3) about the CE research in the EU. On the other hand, collaborators with Asia indicate a different profile on the characteristics of large multidisciplinary projects, which involves issue-based topics (e.g. carbon emissions for metals and construction minerals), industrial (WEEE, circuits models, 3R); technical (impact assessment for new business models, financial models), and societal (e.g. employment effects, energy access/poverty dynamics, consumption). These findings are also in line the findings provided in Section 4.1.1 (Table 3) and emphasise the focal differentiation points of CE research in China.

The opportunities for international cooperation are assessed by 55% as very good, by 27% as reasonable good and by 18% as very poor. Barriers to international cooperation are being associated with *not only the lack of funds but also the lack of open research opportunities in the area and too much focus on the definite work-packages that limit the much-needed trans-disciplinarity in the current CE research paradigm* (Q8). This is an important finding that stresses the complementary role of open research opportunities (e.g. potentially wider thematic co-programming among contexts) other than just financing.

Fig 7. demonstrates percentage share (100%=1) of responses for the assessment of the contribution of 15 research fields to the transition to a circular economy (Q5). New business models, product life-cycle extension and political economy are seen as extremely important research fields. The findings are in line with the findings of Section 4.1.1. on economic (e.g. industrial, environmental) and political (e.g. policy) coverage and reach of CE research and scientific knowledge.

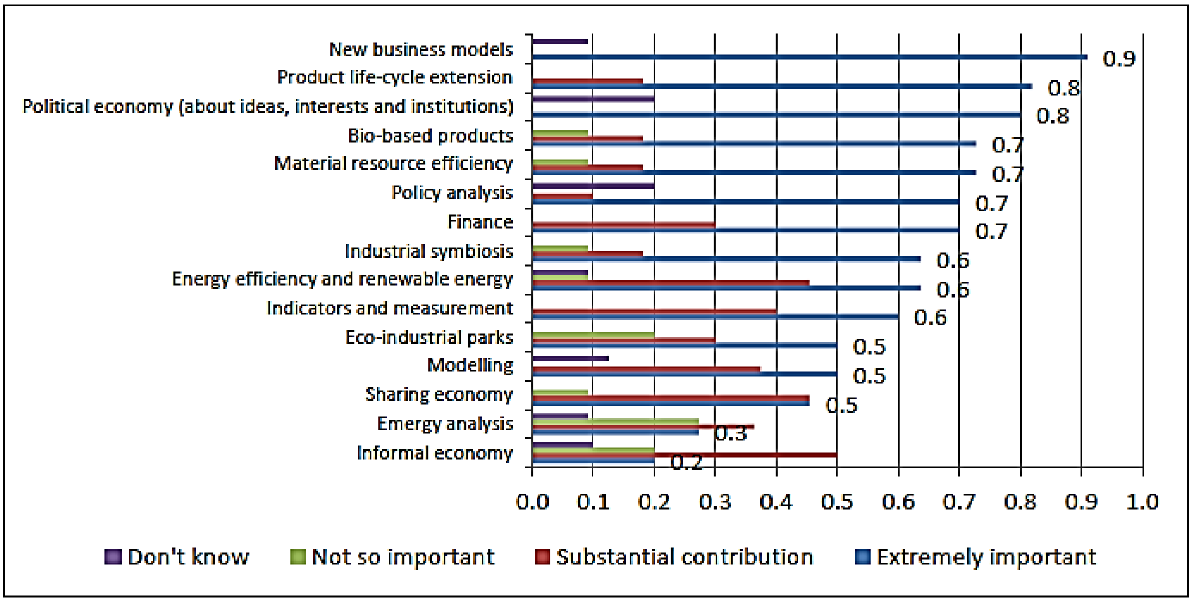


Fig. 7 - Assessment of the contribution of 15 research fields to the transition to a circular economy

Other than these 15 research fields, we also provided an "other category" to capture more information. Roughly from micro to macro level, respondents also think that i) product design and engineering (including product-service-system design); ii) advances in life cycle assessment; iii) sustainable biomass use; iv) systems perspective and systems thinking; v) governance of transition to a CE (at local, regional and global levels) through appropriate supporting mechanisms and incentives; vi) supportive low carbon development strategies; vii) institutional contexts, particularly in emerging/developing market economies, viii) history of materials constraints, ix) conducting research on the linkages between CE and sustainability, climate change, labour/employment and current economic frameworks are also extremely important.

Finally, authors' expert opinions on the most important future research directions (Q9) to enhance the scientific knowledge base required for transition to a CE reflect a similar situation for the case of energy transition, which is *how to create a policy sense of urgency*. CE is considered to be challenged without presence of supporting policies. Concrete research outcomes expected include: benchmarks *(for reuse, refurbish, remanufacturing) to raise expectations in the areas in which embodied energy and materials make an important contribution)* and three types of indicators to: (1) *guide and support circular product design methodology to assist product designers and engineers in capture circular value over multiple use cycles in a CE context,* (2) *guide various innovations for transition towards a CE;* and (3) *assess the performance of CE in a global sustainability context.* With these responses, we can observe the multi-level characteristics and measurement needs of CE research starting and ranging from product designers/designs to various innovations towards a CE at system level, and from various innovations towards a CE in different systems, to sustainability in a global context.

5. Concluding Remarks

In the field of CE scientific knowledge production, China is clearly a leading country in the number of CE publications produced per year and at aggregate level by 2016. This is partly a result of the prominence of the term "circular economy" in China (McDowall, et al., 2017). In Europe, the term "circular economy" is more commonly used in publications of EU researchers after the introduction of EC (2014) communication titled "*Towards a circular economy: A zero waste programme for Europe"*. This finding reveals that researchers in both contexts are highly in tune with the policy developments, and scientific CE research is responsive to these policy developments.

Reflecting on our findings, CE scientific research field is highly international and local; thus international co-authorships, international co-funding and policy co-programming are highly relevant for policy options and agendas. In Beijing, Chinese Academy of Sciences (CAS) and Tsinghua University are the leading institutions. In the EU, Delft is the most active city, with Delft University of Technology and TNO as the most important institutes. The UK emerges as a country which has the most central position in CE co-authorship networks, leading with cooperation with 26 countries, at country level. This finding stresses the importance of diversity creation in the co-authorship portfolio of countries. In the U.S., Yale University, which has a long historical relationship with China (app. 170 years), with sponsorship from China's State Council and National School of Administration, is an important university relating to CE scientific research. This kind of sponsorship can be also applied between Chinese and the EU institutes to accelerate the transition towards a circular economy.

Researchers in the EU and China publish jointly mainly in 14 journals; Journal of Cleaner Production is the main hub and the distributor. Other journals include Science of the Total Environment, Journal of Material Cycles, Waste Management, International Journal of Advanced Manufacturing Technology, Ecological Indicators, Resources Conservation and Recycling, Habitat International, Water Research, and Population and Environment, which are the journals of increased attention by CE researchers in both contexts. These journals could be made more accessible and visible to the starting researchers by their institutes in China and the EU.

EU countries citing many CE literature but publishing few scientific publications in the field, are Hungary, Romania, Portugal, Austria, Cyprus, Croatia, Bulgaria, Luxemburg and Malta. In Brazil and India, we also observe many citations to the CE literature (India (n: 60), Brazil (n:58) in WoS) yet very little contribution to the CE literature. This disparity between citations and publication of CE scientific publications suggest potential opportunities for international cooperation exist with these countries for the EU and China. Policymakers from China and EU could act upon these opportunities by mobilizing relevant funds and incentivizing CE researchers.

Differences exist in terms of focal differentiations of CE research in European and Chinese contexts, yet new topics of cooperation between EU and China also emerge, such as *emergy analysis, sustainability indicators, green finance, resource efficiency, food waste, zero waste, eco-cities, lifestyle and governance.* These findings indicate the diffusion of CE research towards not only specific issue areas (e.g. food waste) or specific measurement-related topics (e.g. emergy analysis, sustainability indicators), but also towards broader realms such as social (e.g. lifestyles and governance, eco-cities) and financial (e.g. green finance) topics. Thus, CE scientific knowledge can further benefit from multi-domain, multi-level co-funding. Policy makers could scan potential international partners for co-programming to fund CE-related research.

Finally, reflecting on our survey, CE is an overarching field which embraces many fields of knowledge domains, including also the fields of politics, finance and economics. We intellectually support the idea that several respondents also expressed: *the need for doing more research also on the societal aspects of CE, including social innovation and alternative economies.* We also value the ideas that future research should focus more on the global sustainability rather than only focusing on the economic and material efficiencies, and also should account for rebound effects and other critical feedbacks in the political economic systems. To support an evidence-based CE policy, framework, CE implementation by various industries, and acceptance by society, conducting transdisciplinary research on developing, supporting sustainable business model practices, and on creating consumer acceptance should also be welcomed to contain both supply and demand side of CE transition in both contexts, namely, China and the EU-28.

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Endnotes

[1] 1) Harvesting/collecting or mining, 2) Manufacturing materials or parts, 3) Manufacturing products, 4) Providing retail 5) Providing services, 6) Consuming or use, 7) Fixing/maintenance, 8) Collecting the waste, 9) Incineration, 10) Landfill

[2] 1) Repair 2) Reuse/Redistribute 3) Refurbish/Remanufacture 4) Repurpose 5) Recycle for technical materials, 6) Generic cascading for biological materials, 7) Extraction of biochemical feedstock 8) Anaerobic digestion/composting for biogas 9) Anaerobic digestion/composting for soil restoration for biological materials, 10) Energy recovery/retrieval from both materials before/instead of landfill