Cross-boundary collaboration in waste management research: a network analysis

Jinying Xu*, Weisheng Lu, Fan Xue, Ke Chen, Meng Ye, Jing Wang, and Xi Chen

Department of Real Estate and Construction, Faculty of Architecture, The University of Hong Kong, Hong Kong

* Corresponding author, email: jinyingxu@connect.hku.hk; Department Real Estate and Construction, Faculty of Architecture, 7/F, Knowles Building, The University of Hong Kong, Pokfulam, Hong Kong.

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Abstract

This paper aims to illustrate the cross-boundary research collaboration (CBRC) landscape of waste management (WM) by various collaboration networks. Through a set of rigorous procedures, a total of 15,396 research papers were extracted from eight subject-related journals published between 1981 and 2016. The author utilized *CiteSpace*, a Java programme that helps visualize and dissect patterns in scientific literature, to evaluate the content through individual, institutional, national, and disciplinary perspectives. The evaluations of three former perspectives revealed a steady rise in CBRC within WM over the last thirty-five years, although the overall intensities proved fairly low. Inter-individual collaboration groups were limited to their respective regions and only loosely connected, but as more and more academic institutions and universities engaged in WM research, the number and quality of the collaborations increased. Developed countries, chiefly in North America and Western Europe, comprised the bulk of the WM research, whilst the mounting contributions from developing countries, China in particular, forecasts greater diversity in the future. Analysis also suggested that the intensity of the interdisciplinary collaboration network declined slightly, however, the intensity proved low to begin with. Previous WM research focused more on "hard" technologies than "soft" measures. Future endeavors to encourage CBRC in WM should promote more innovative research to tackle waste challenges globally in a sustainable way.

Keywords: waste management, cross boundary research collaboration, network analysis, collaboration network, network structure

1. Introduction

Managing waste is a major global sustainability challenge that demands combined efforts from a myriad of public and private stakeholders. Increasingly multifaceted, no single discipline, let alone single researcher, can possess the necessary knowledge to maximize waste management (WM) efficiency. Given the drift towards internationalization and globalization of knowledge creation, a growing number of scholars and research institutions seek to conduct their frontier research outside their immediate surroundings. By sharing workloads, specific expertise and skills, equipment or resources (Altbach and Knight, 2007), research collaboration helps resolve personal research limitations. Research collaboration is defined as researchers working together to produce new scientific knowledge, insights, methodologies, solutions and/or inventions (Katz and Martin, 1997). Research and researchers collaboration can operate in a decentralized manner, supported by user-friendly and expedient online platforms, ranging from email exchange to online manuscript submission systems, e.g., ScholarOne® or EditorialManager®. Cross-boundary research collaboration (CBRC) can provide a platform for researchers to communicate research strategies and innovations across the traditional institution, nation, and disciplinary boundaries. To incorporate the multidisciplinary and multinational nature of WM, research policymakers seem to encourage multi-institutional collaborations in order to develop complex, intellectually diverse projects (Carley, 2006), e.g., the *European Waste Management Cluster* and the *Urban Strategies for Waste Management in Tourist Cities*. Smaller scale, but arguably more active CBRCs materialize more organically, forming through online communication and idea sharing. This is not to say that such CBRCs lack big scale funding as many receive backing from major international bodies like EU agencies, which characteristically insist on cross-boundary collaborations.

Previous studies have tended to understand CBRC by investigating the connections and structures of social networks formed in knowledge innovation (Tortoriello and Krackhardt, 2010) and information sharing (Pardo et al., 2010). Network structure, in a broad sense, concerns the pattern of relationships generated by direct and indirect connections between actors (Hoang and Antoncic, 2003). In CBRC, one of the most significant networks is a co-authorship network. The "explicit product" of a scientific collaboration between two or more authors (Newman, 2004), co-authorship represent a kind of tangible proof that collaboration has occurred. Whenever a scholar publishes a co-authored article, he or she has created an individual co-authorship network (Li et al., 2013). In the meantime, with their institutional, national and discipline information, inter-institutional, inter-national and inter-disciplinary networks have also been created. Modeling CBRC networks provides valuable insight into the patterns of collaborations amongst individuals, institutions, nations and disciplines, the emergence and the propagation of thoughts in academic society (Cross et al., 2002). WM research, where different expertise is required, saw intensive CBRC. However, a definitive analysis of CBRC networks in WM domain has long been overdue. This article seeks to shed light on the cross-boundary collaborative relationships in WM research on four cross-boundary perspectives using a network analysis. It does so by investigating 15,396 relevant research papers extracted from eight highly relevant journals published over the past thirty-five years. This paper is organized as follows, section 2 reviews the prevailing literature of WM research, CBRC in other relevant areas, and analytical tools; section 3 presents the research methods of data collection and analysis; section 4 reports the detailed analysis and results from the four cross-boundary perspectives, namely, individuals, institutions, nations, and disciplines, together with longitudinal analyses of these four aspects respectively; the last two sections discuss in depth the problems and solutions facing global and interdisciplinary collaborations in the WM field and conclude the paper.

2. Literature review

2.1 Why WM demands joint efforts

WM includes all the activities and actions required to manage waste from inception to final disposal (Division, 1997), such as waste collection, transport, treatment by thermal or biological processes, disposal, monitoring, and regulation to name a few. WM exemplifies a global sustainability dilemma that calls for the efforts of governments, private sector, research institutions, scientists and the general public (Vithanage et al., 2014). In the age of economic globalization, traditionally local WM activities, e.g., waste collection, can impact another continent's environment, e.g., the US-China recycling trade. Meanwhile, the economic development in emerging countries has triggered an exponential increase of waste generation. For example, China's municipal solid waste amounted to 148 million tons in 2006, of which 91.4% became landfill, 6.4% incineration, and 2.2% compost (Zhang et al., 2010). Similarly, India suffers from the massive pileup of e-waste stemming from its high speed economic and technological growth (Sinha-Khetriwal et al., 2005), along with that of more typical urban waste. WM concerns escalate as cities and countries develop, but global joint research in parallel with urbanization can enable knowledge sharing, informed response and innovation exchange in order to amend WM performance in developed and less developed countries.

Research is the action of creating and sharing new knowledge to guide practices (Appleton, 1993). Numerous researchers have entered the field of WM, exploring both hard and soft approaches. “Hard” approaches denote scientific and technological means of reducing, reusing, and recycling abandoned resources. For example, researchers have spent countless time and effort exploring the reuse of solid waste in order to replace natural resources, e.g., reusing waste iron as a partial substitute for sand in concrete (Ismail and AL-Hashmi, 2008a), plastic waste as an aggregate replacement to mix concrete (Ismail and Al-Hashmi, 2008b), and converting fly ash into construction materials, fertilizer and other geotechnical applications (Ferreira et al., 2003). They have also endeavored to find treatments to remove pollutants or collect biogas from wastes (Kamala and Rao, 2012). While soft approaches represent economic or managerial measures, for instance estimating overall waste generation (Lu et al., 2017), designing from waste (Osmani et al., 2008), public policies (Goorhuis et al., 2012), economic analysis (Lu et al., 2015), and management strategies (Shen et al., 2004). CBRC plays a crucial role in devising hard and soft approaches, tackling the global issue, and developing opportunities for mutual WM learning and idea sharing (Berkes, 2009). However, how and to what extent the global body of researchers of this field conduct CBRC is still under-researched.

Research collaboration can take various forms. Examples range from online sharing of data and sources, correspondence by mail, presentations at workshops and conferences, visits to foreign laboratories, to the exchange of papers. The most obvious and easily measured form of collaboration is the writing and publication of research findings (Laudel, 2002). One can study the collaboration of an article publication from different aspects to understand the CBRC patterns between individual researchers, institutions, nations and disciplines. Such activities automatically generate networks comprised of nodes, e.g., authors, and relationships, e.g., co-authorship (Borgatti et al., 2013). A practical way to demonstrate and visualize the CBRC is to draw the networks of article collaboration and analyze their outcome variables and structures, then attempt to reveal some characteristics from the network analyses.

2.2 Cross-boundary research collaboration (CBRC) networks

A boundary signifies the demarcation of activities that marks the limits of an area. This area can take concrete and non-concrete forms, such as geographical, social, cognitive, relational, cultural, temporal, spatial, divisional, occupational, organizational, disciplinary, knowledge, and tasks (Hsiao et al., 2012, Cummings and Kiesler, 2005). A CBRC network constitutes a reflection of research collaboration, in which valuable resources are shared as information understanding and knowledge through a social interaction (Newman, 2004). The importance of networking in research has long been emphasized. By sharing resources and working goals, collaboration in networks advances knowledge creation, transfer, distribution, and redistribution (Li et al., 2013). Networks that span multiple communities of practice can convey complex ideas to diverse audiences (Reagans and McEvily, 2003), so as to exchange and transfer knowledge from developed countries or regions to the less developed. CBRC networks are usually examined from individual, institutional, national and disciplinary levels in order to investigate collaborative patterns and relationships amongst researchers.

The primary concerns in CBRC usually involve the study of co-authorship networks and citation networks. A co-authorship network is a documented collaboration between two or more authors working towards a common research aim, such as the publication of a paper or securing of a patent (Melin and Persson, 1996). A typical co-authorship network can be drawn as nodes connected by lines. Nodes indicate the authors, while lines the relationships among the authors (Xie et al., 2016). The co-authorship network has been proffered as a critical indicator of CBRC, with the authors' affiliation information, inter-institutional and inter-national research collaboration also capable of being investigated. It not only implies the research trends and popular topics within a domain, but more importantly, the patterns of research collaboration and the subsequent thoughts and their development, which in turn support and call for substantial future collaboration (Leydesdorff et al., 2013).

Analysis of interdisciplinary collaboration logically follows analysis of co-authorship networks. In recent years, as CBRC in academia increased, a wealth of research examining collaboration between various disciplines did as well. By searching and tallying paper keywords, one could identify research collaboration between different WM related disciplines (Xie et al., 2016). Li et al. (2013) suggested this as a promising direction to focus cross-boundary collaboration features of interdisciplinary research, and different social capitals generated by intra- and inter-disciplinary co-authorship networks. However, former inter-disciplinary collaboration research was done through the survey of researchers in an institution (Van Rijnsoever and Hessels, 2011), or the investigation of the citation index of a database (Leydesdorff, 2007), or at journal level (Waltman and Eck, 2012). More in-depth understanding of interdisciplinary collaboration from a micro level (e.g., publications) is highly desired.

Analyzing collaboration networks offers rich information that probes CBRC in a specific research field. Network analysis concerns the structure and pattern of relationships over time, as well as the exploration of network relationships within a social system (Parsons, 1951). A research community or knowledge domain describes large and complex social networks of individual researchers interacting, developing, and exchanging new knowledge through a collaborative research process. Network analysis provides a new linguistic and mathematical terminology to understand the development of a specific knowledge domain and the involved collaborations (Wasserman and Faust, 1994). The past decade has witnessed network analysis increasingly employed in specific research communities or knowledge domains (Girvan and Newman, 2002) to portray research collaboration among individuals, institutions, countries, and disciplines (Newman and Girvan, 2004). To investigate the collaboration development trajectory in WM research, which requires multifaceted expertise, co-authorship networks can better describe the collaborations cross individual, institutional, national and disciplinary boundaries.

3. Methodology

To collect comprehensive, representative and authoritative data for CBRC analysis in WM, a pilot study was conducted to identify which journals most concern the WM domain. Using Thomson Reuters' *Web of Science (WoS) Core Collection Database*, judged one of the most comprehensive and reliable sources (Hoekman et al., 2010), and the Elsevier's *Scopus Database*, the pilot gathered a list of papers with titles containing keywords pertaining to waste management. This helped reveal a fairly accurate and comprehensive picture of the scholarly WM work available (Meho and Yang, 2007). The deliberately chosen timespan, 1981-2016, followed the introduction and universalization of the Internet (Leiner et al., 1997), the main enabler of cross-boundary research collaboration (Wagner and Leydesdorff, 2005). The selected document types were then narrowed down to research journal articles, the sentiment being that such work demands more profound collaboration than conference or proceeding papers, letters, and notes (Zheng et al., 2016). Books were also omitted as search results identified editors rather than the chapter authors responsible for the research. As a result, the search found 3,830 and 6,133 research articles and reviews from *WoS* and *Scopus* respectively.

By comparing the top fifty cited journals in both databases, eight journals (i.e., *Environmental Science &Technology*, *Journal of Cleaner Production*, *Journal of Environmental Management*, *Journal of Hazardous Materials*, *Resources, Conservation and Recycling*, *Waste Management*, *Waste Management & Research*, and *Water Science and Technology*) were identified as the most relevant and representative of the WM field.

Afterwards, an advanced search was conducted in *WoS* focusing on the eight journals. The following retrieval codes were used in the *WoS Core Collection Database*: TS = waste AND (manag* or reduc* or mitag* or hazadou* or emmis* or develop* or equip* or recyc* or solid or landfill* or special) and SO = "*Name of the identified journal*". TS stands for paper topic; "waste AND (manag* or reduc* or mitag* or hazadou* or emmis* or develop* or equip* or recyc* or solid or landfill* or special)" indicates the paper concerns both *waste* and one of the keywords, while disregarding word order. These keywords selected based on the authors' research experience, are mostly used and related to waste management. The * in the condition means a fuzzy search (e.g., manag* hunts for management, managing, or any terms starting with *manag*). SO is publication name. Again, search results had to be published between 1981 and 2016 and primarily in English. Table 1 shows the search results.

Table 1. Top eight journals most relevant to WM and their corresponding quantity of papers.

Journal title	Year of first Volume	2016 Impact Factor	Quantity of Papers Collected	h-index	Average citations per item	Sum of Times Cited	Without self citations
Journal Of Environmental Management	1973	4.01	910	54	17.31	15748	15392
Resources, Conservation And Recycling	1988	3.313	1200	67	21.59	25910	23974
Journal Of Cleaner Production	1993	5.715	1364	58	15.8	21549	19475
Waste Management & Research	1983	1.803	1537	49	10.85	16680	15110
Environmental Science &Technology	1967	6.198	1839	127	44.77	82327	80355
Journal Of Hazardous Materials	1976	6.065	2555	111	32.74	83651	81096
Water Science & Technology	1970	1.197	2918	72	14.1	41152	39720
Waste Management	1983	4.03	3073	83	21.2	65140	58201

Data source: "Year of first Volume" and "2016 Impact Factor" are collected from the official website of the journals; "h-index", "Average citations per item", "Sum of Times Cited" and "Without self-citations" were collected from Web of Science when searching for the papers about WM on Nov, 13 2017, this data is based on the searched papers.

In total, the journals sourced 15,396 relevant articles, from which this paper's analysis of CBRC in WM is based. Figure 1 shows the numbers of research articles published each year. The data showed the number of waste management papers in the 1980s to be relatively small, while the 1990s experienced a considerable rise, publishing 36 papers in 1990 to 239 in 1999, if somewhat of a drag in sustained growth. Not until 2004 did a takeoff in WM research occur, ultimately plateauing in 2009. Although the following three years witnessed slight decreases, WM researchers appeared to regain their enthusiasm and recent years show a spike in collaboration.

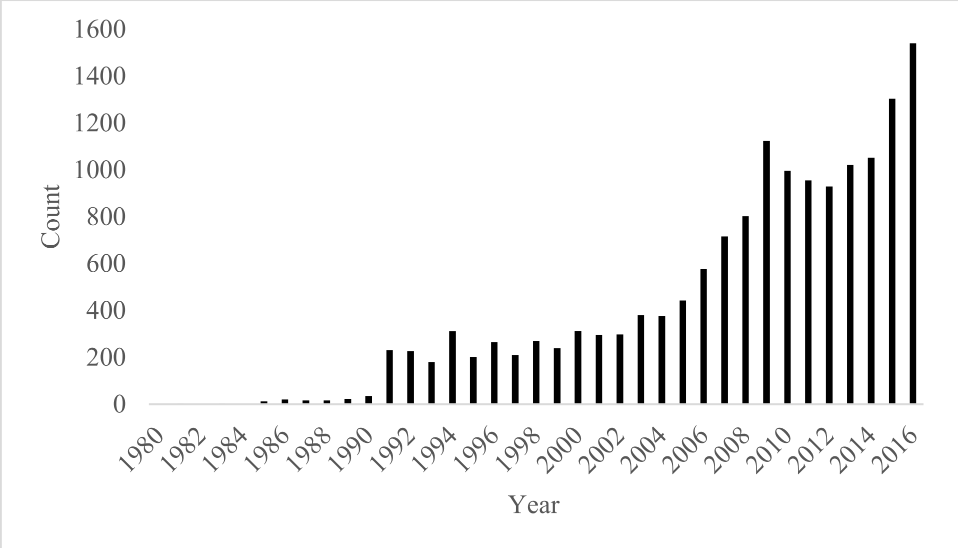

Figure 1. The quantity of papers published from 1981 to 2016.

All details of the 15,396 papers were carefully extracted and examined with *CiteSpace*, a professional scientific literature software widely used for visualizing patterns, emerging trends and dynamics in scientific knowledge domains and their corresponding intellective base (Chen et al., 2010, Zhao, 2017, Chen, 2006). *Citespace*, having been broadly used to analyze networks of different aspects in scientometrics (Zhao et al., 2018), is a good choice for CBRC network analyses. Specifically, *CiteSpace 5.1. R1 SE* was used to analyze the CBRC in WM from four perspectives: (a) inter-individual research collaborations; (b) inter-institutional research collaborations; (c) inter-national research collaborations; and (d) inter-disciplinary research collaborations.

4. Analysis, results, and findings

4.1 Inter-individual research collaboration network

Co-authorship of paper constitutes an inter-individual collaboration between two or more authors. Such collaborations form an 'inter-individual collaboration network'. To understand the collaboration between individual scholars in the WM domain, an author collaboration network was drawn in *CiteSpace* using data of the authors with top fifty levels of publication number from every year of 1981 to 2016. Top fifty levels of most occurred items each year will cover almost all the authors since each level may include multiple qualified nodes and an author is incapable of publishing fifty articles in one year. As shown in Figure 2, the nodes represent the specific authors; the lines linking the nodes, paper co-authorship; and the different blocks of authors, different collaboration groups. Node colors change from blue to green, then yellow, orange and finally red as time passes from 1981 to 2016. The bigger the node, the more productive the author is. The bigger the node label, the more papers the author has published, like Christensen TH with ninety-three papers and Barlaz MA with thirty-six. The thicker the line, the more often the authors at either end collaborated with one another. For example, Christensen TH collaborated a lot with other researchers, particularly Astrup TF early on. The inter-individual collaboration network consists of 3,427 nodes and 3,074 links, clearly demonstrating the co-authorship in WM research.

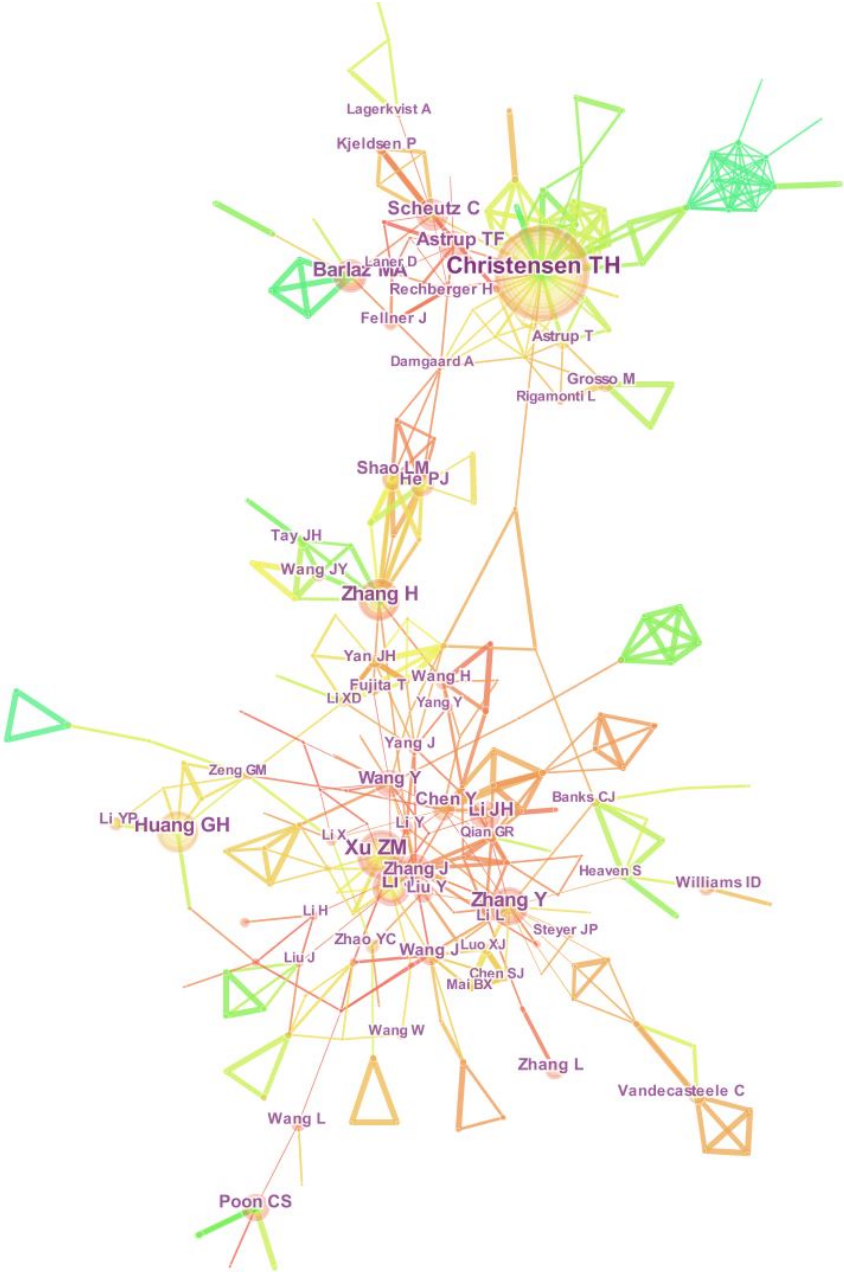

Figure 2. Inter-individual research collaboration network from 1981 to 2016.

Note: Some minor clusters and nodes of the network were too small to be highlighted in the figure, only authors with ten or more articles are labeled in the figure.

The *density*, the actual number of ties in a network divided by the maximum possible number of ties, of a network describes the intensity of the interconnection between nodes of the network. The inter-individual collaboration network, as shown in Figure 2, scored only 0.0005 in network density as calculated by *CiteSpace*. This suggests a more modest overall international collaboration between WM researchers. The *modularity*, comparing actual with expected tie values, measures the strength of network divisions into modules, also called groups, clusters or communities. In this case, the modularity, 0.9014, indicates dense connections within research groups, but sparse connections between groups. Network *homogeneity*, indicating the tendencies toward homophile of different categories, measured by the mean silhouette (an indicator of consistency within clusters of data) of 0.5215, is relatively low, implying the network is somewhat diverse. *Centrality*, specifically, betweenness centrality in *CiteSpace*, is a very crucial parameter to identify the most important node within a network. It uses the number of times a node lies on the shortest path between other nodes to measure which nodes influence the flow around a system. A high centrality could indicate someone holds authority over collaboration controls between clusters in a network. In the inter-individual research collaboration network, each author's the centrality is very low, denoting the lack of any obvious important central researchers within the network. Generally, the international collaboration in WM research is relatively decentralized. Many of the collaboration groups in the field appear to be relatively small and disconnected from each other. There are many small groups, exploring a certain niche of the field, without any connections with others. This suggests many scholars are exploring different topics individually.

Regarding collaboration, several research subnets thrive within the network according to cluster analysis in Figure 2. The largest subnet was comprised of 136 scholars, mainly focused on waste management problems in China. More than 90% of the 136 authors in the largest subnet hail from China. Of the remaining 10%, notably Steyer JP, Abanades S and Flamant G, most are from France. Based on the color of the nodes and lines, this subnet is relatively new. The second largest subnet, consisting of ninety-three researchers overwhelmingly all from Europe, such as Christensen TH, Scheutz C, Astrup TF from the Technical University of Denmark, Rechberger H and Fellner J from Vienna University of Technology and Grosso M from Politecnico di Torino, mainly worked on greenhouse gas and landfill related topics. Since some of the nodes and lines are green, this subnet proved an older collaboration network. The third largest subnet, concerned with regional integrated solid WM, includes Zhang H, Wang H, Yan JH and Li YP, who are also Chinese academics. This third subnet formed at the time between the first and the second ones.

Figure 3 shows the results of a further investigation into the cited-authors. The links of these networks are denser and the lines thicker. It is worth noting that many of the authors being cited are not individuals, but institutions like the American Public Health Association (APHA), European Commission, United States Environmental Protection Agency (US EPA), European Commission, Intergovernmental Panel on Climate Change (IPCC), Organisation for Economic Co-operation and Development (OECD), United Nations Environment Programme (UNEP) and International Organization for Standardization (IOS). This finding indicates that in WM governmental and non-governmental organizations have considerable influence through published report and the policy design. Some scholars, prominnet in the inter-individual research collaboration network, also pervade the cited author network, for example, Finnveden G, Christensen TH, Chang NB, Barlaz MA and Poon CS. This phenomenon of certain authors being both frequently published and frequently cited implies that long-term research ventures in the WM domain is crucial for developing influence. Given the clustered color distribution of Figure 3, the change in cited authors as time passes appears to be organized. At the bottom right part are the latest most cited authors.

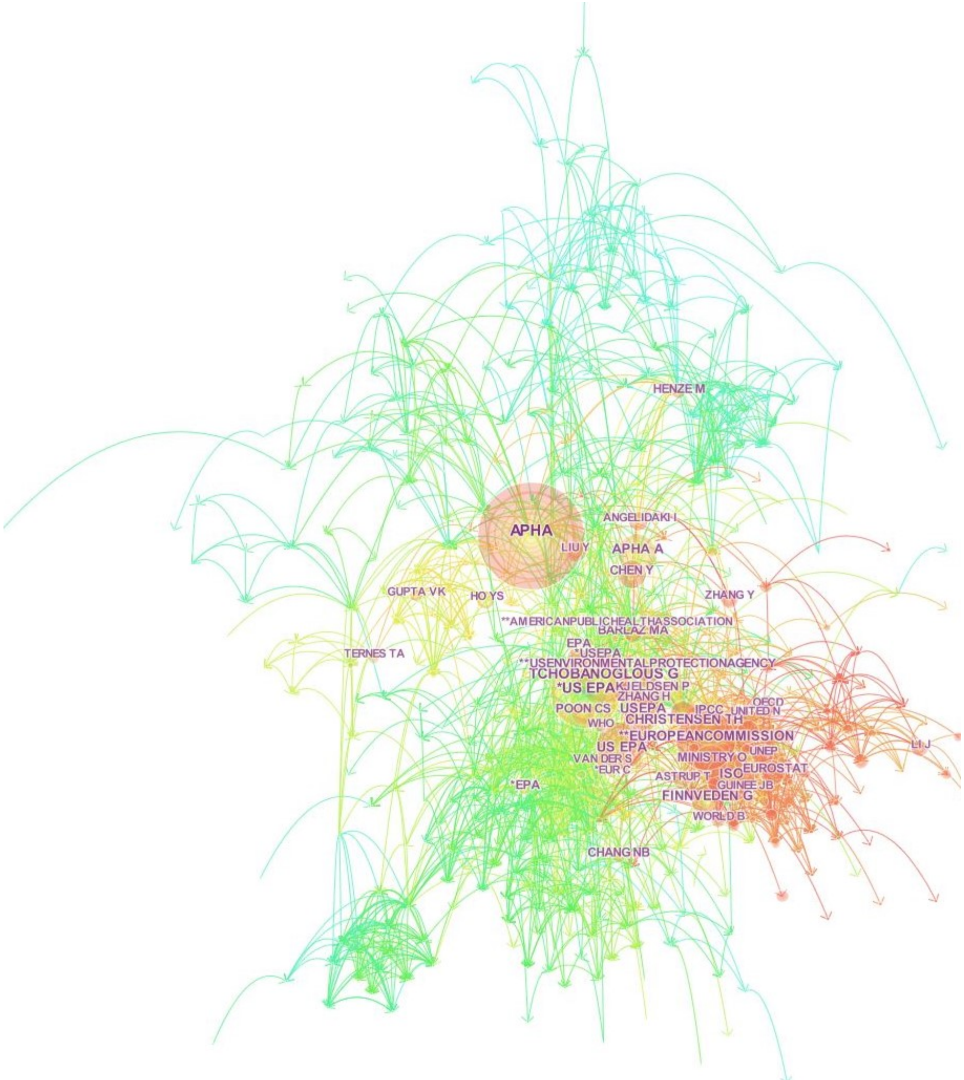

Figure 3. A network of cited-authors

In order to further examine the longitudinal change of inter-individual research collaboration networks, the years between 1992 and 2016, when the vast majority of network generation occurred, were divided into five year intervals and gaged by their number of network nodes, links, and densities. Figure 4 shows the results. The x-axis represents the timeline inspected every five years, while the meanings of nodes, links, and densities remain the same as defined above (i.e., the nodes represent authors; the links, co-authorship; and the densities, the intensity of the inter-individual collaboration). The y-axis on the left-hand side tallies the number of nodes and links; while the right one, the network density. Figure 4 displays the number of authors and their collaborations increasing steadily until 2006, while the density curve achieved the opposite. More and more researchers entered the WM field while collaborations were in a period of relative slackness, evidenced by the longitudinal collaboration networks as shown in the upper part of Figure 4. In the past decade, 2006 to 2016, the number of researchers in the WM field decreased slightly, while also becoming more productive as interpreting Figure 4 in conjunction with Figure 1 implies. It is also reasonable to conclude that the inter-individual collaborations over the past decade have intensified, resulting in a greater number of publications in WM research. Notably, from 2012 to 2016, a larger concentrated research collaboration subnet formed though there were still many small subnets exploring different topics.

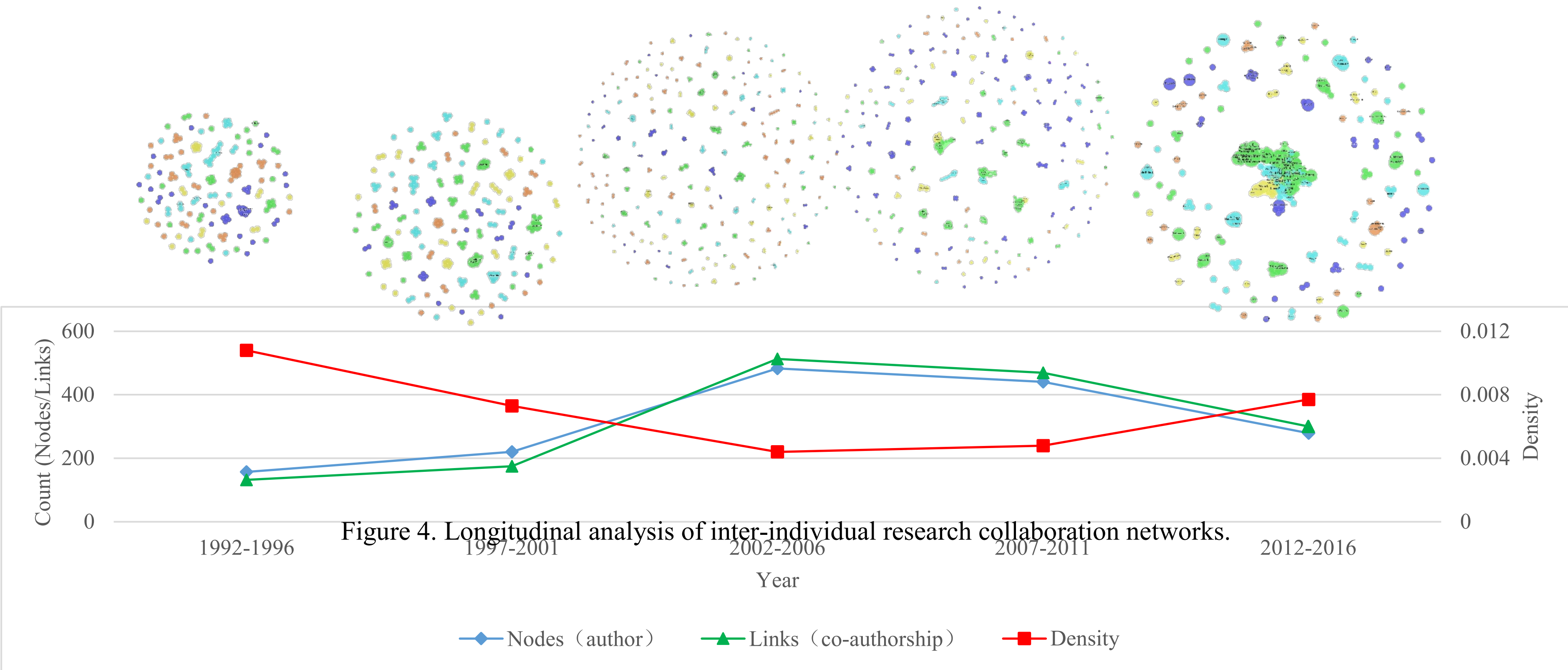

Figure 4. Longitudinal analysis of inter-individual research collaboration networks.

4.2 Inter-institutional research collaboration network

The CBRC as evidenced by the 15,396 papers was further examined using *CiteSpace* by shifting focus from individual researchers to institutions. The contributions of institutions and their impacts are displayed in Figure 5, labeling nodes with seventy or more publication counts. The density of the network, 0.0035, comprised 546 nodes and 516 links, implying a moderate overall international collaboration amongst institutions. It is understandable that the indicators are larger than their counterparts in the inter-individual research collaboration networks, as researchers from the same institution will be aggregated into a single entity for calculation purposes. The Chinese Academy of Science (CAS) proved the largest contributor of WM publications, followed by the Technical University of Denmark. Other major institutions included China's Tsinghua University, Tongji University, and Zhejiang University with more than a hundred articles published each. These Chinese institutions have close research collaboration with one another. It is also found that the US's University of Florida showed connections with multiple Chinese institutions. Although the findings corroborated WM research transpiring in numerous universities from all over the world, many of the institutions highlighted were non-university research organizations or environmental protection agencies (e.g. the CAS, Spanish National Research Council (CSIC), French National Institute for Agricultural Research (INRA), Council of Scientific & Industrial Research, India (CSIR), and National Research Council, Italy (CNR)). This emphasizes how WM is not just an academic issue, but a practical one as well, attracting the close attention of policy and research agencies. However, as evidenced by their low centralities in the collaboration networks, no principal institution stood out. This phenomenon indicates that despite WM enjoying pluralistic research competition and diversification, no single institution plays a leading or unifying role within the research domain.

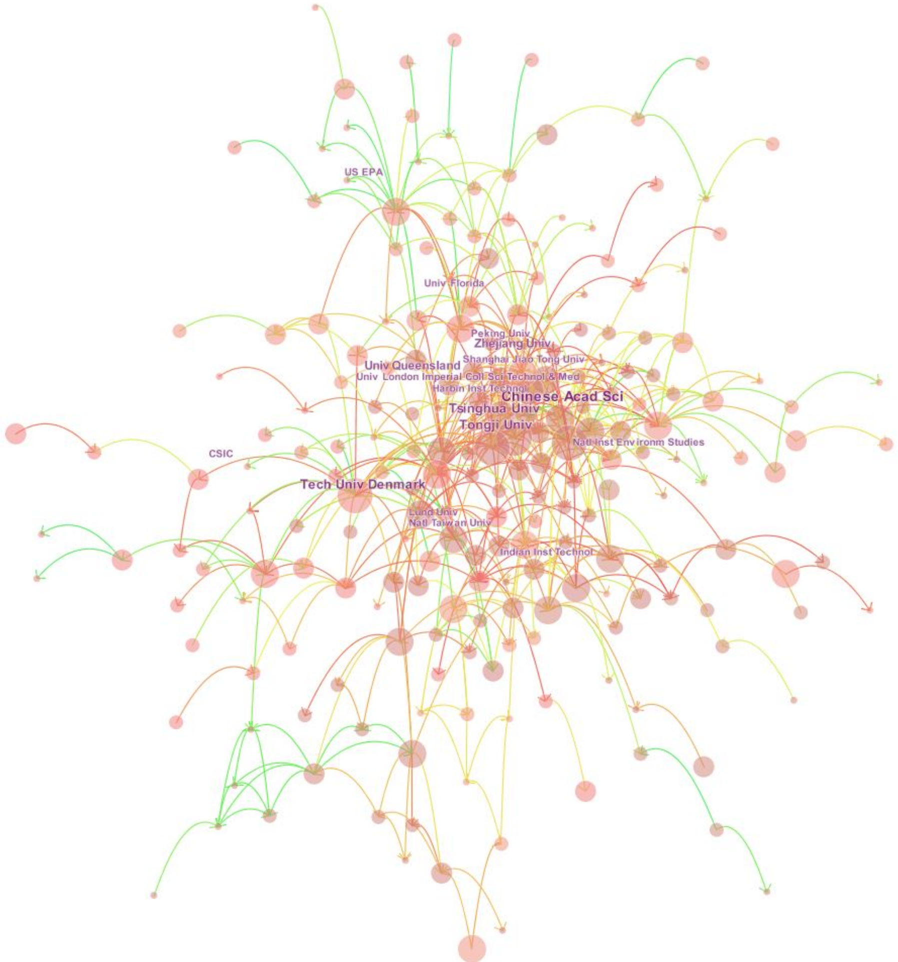

Figure 5. Cluster view of inter-institutional research collaboration network.

This section further analyzes the longitudinal change of the inter-institutional research collaboration networks calculated every five years from 1992 to 2016. Results are shown in Figure 6. The meanings of the x- and y-axis mimic that of Figure 4, while the nodes represent institutions; the links, the collaborations between institutions; and the density , the intensity of the inter-institutional collaboration network. Figure 6 signifies that some of the institutions withdrew from the WM research field. Interpreting this in conjunction with Figure 4, it can be assumed that the remaining institutions self-organized (Prigogine et al., 1984) and appointed more researchers. In parallel with this self-organization, inter-institutional collaborations steadily increased, as substantiated by the links, the densities and the graphical longitudinal networks shown in Figure 6. As for the influence of institutions, which can be extracted by the centrality of nodes, no definitive leader emerged between 1992 and 2001. However, Nanyang Technology University and Kyoto University proved relatively more influential than others while other institutions, such as Technical University of Denmark began to burgeon between 2002 and 2006. CAS gained the most conspicuous presence from 2007 to 2016, exhibiting by far the highest centrality. Meanwhile, other significant institutions from 2007 to 2011 included the University of London's Imperial College of Science, Technology and Medicine, National Taiwan University, and Hong Kong Polytechnic University, while amongst the leading institutions from 2012 and 2016, Delft University of Technology, Technical University of Denmark, Tsinghua University, University of Queensland, and Zhejiang University. It can also be noticed that from 2007 to 2016, there were some big nodes at the outer ring of the networks, and they collaborated more as time went by, indicating that some big institutions didn't enter the focused main network but kept independent or built their own small networks.

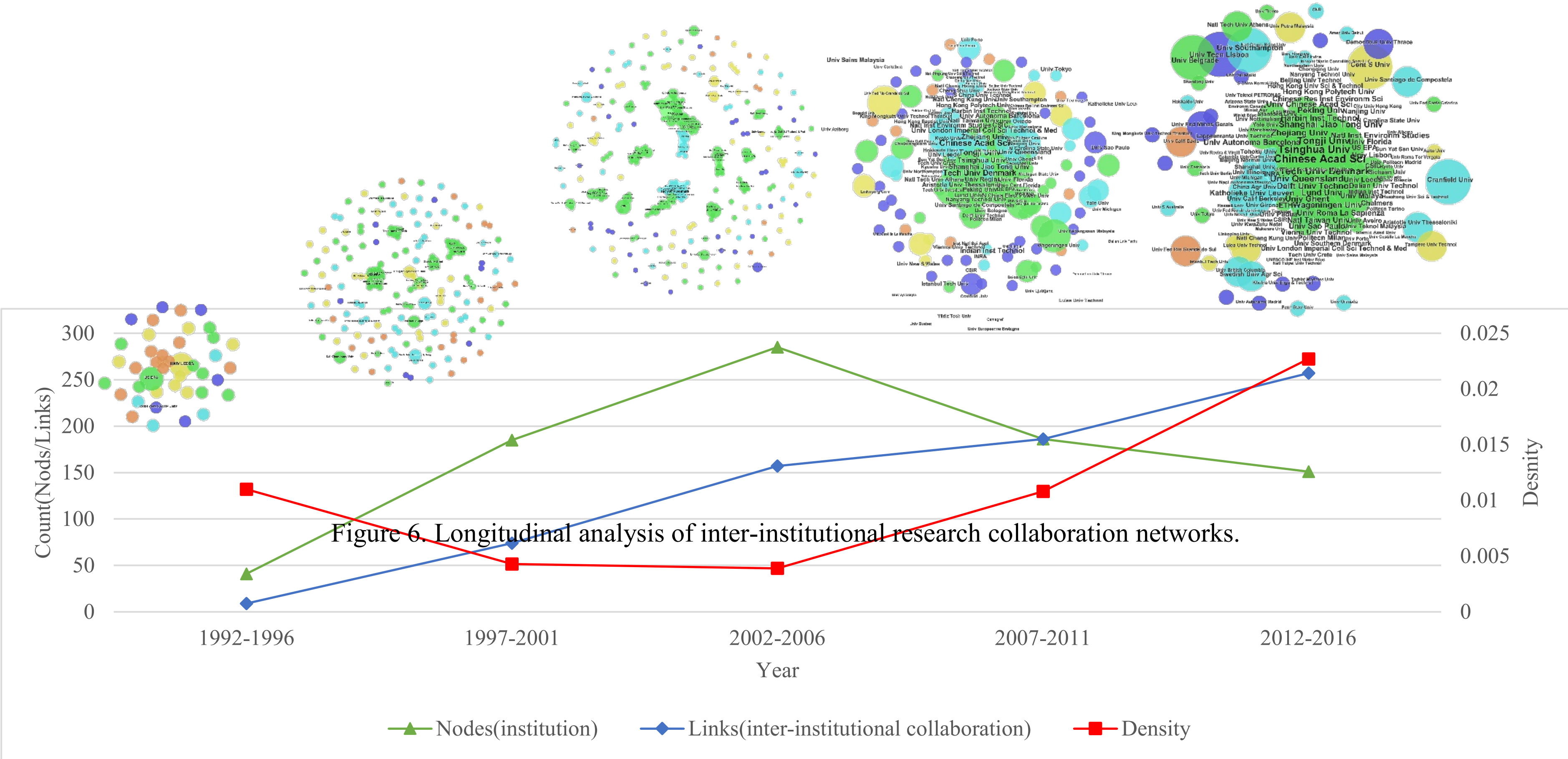

Figure 6. Longitudinal analysis of inter-institutional research collaboration networks.

4.3 Inter-national research collaboration network

The CBRC in waste management research is further examined by focusing on national level. Figure 7 scrutinizes the networks of collaborations between nations and regions, along with the geographical dispersal of WM research. This research collaboration network comprises 86 nodes and 477 links, with a density of 0.1305, indicating that cross-boundary research collaboration, if examined at the national level, is more intensive than co-author or institutional networks. All countries and regions are labeled with the same size of texts but differs in the size of nodes which indicates the number of publications. Countries with more than 200 publications consist of the US, China, Spain, UK, Italy, Japan, Germany, India, France, Canada, Australia, Taiwan, Sweden, Brazil, Netherlands, South Korea, Turkey, Denmark, Greece, Belgium, Switzerland, Portugal, Austria, and Malaysia. American scholars published 2,187 articles in total, followed by Chinese with 2,106, while the UK, Spain, Italy, Japan, Germany, India, France, Canada, and Australia each published between 500 to 1000 papers. The principal cluster of collaboration, however, transpired between researchers from the UK, India, Turkey, Greece, Malaysia, Iran, Egypt, Ireland, Israel, Pakistan, Nigeria, Saudi Arabia, Hungary, Jordan, United Arab Emirates, Iraq, Cyprus, Lebanon, and North Ireland. While the other very productive countries, such as the US, China, Spain, Italy, Japan, and Germany, fell outside this cluster. The UK has the largest centrality (0.24), followed by Belgium (0.14), the US (0.13), Japan (0.13), Netherlands (0.12), and France (0.11), and as such have central (i.e., influential, with higher centrality in the network than others) positions within the network. It is worth noticing that US has the strongest citation burst among all the countries, evidenced by the purple ring circled the node. Other countries with very strong citation bursts are the UK, France, Belgium, and the Netherlands. The citation bursts indicate the sharp increases of interest in the published articles (Chen, 2006). However, countries with very high publication counts such as China, Spain, Italy, and India, experienced relatively lower influence, likely owing to factors of languages, research capacities, quality, previous impact in WM, and their respective state's level of international influence. A greater number and depth of efforts are necessary to further internationalize research collaboration across different country boundaries.

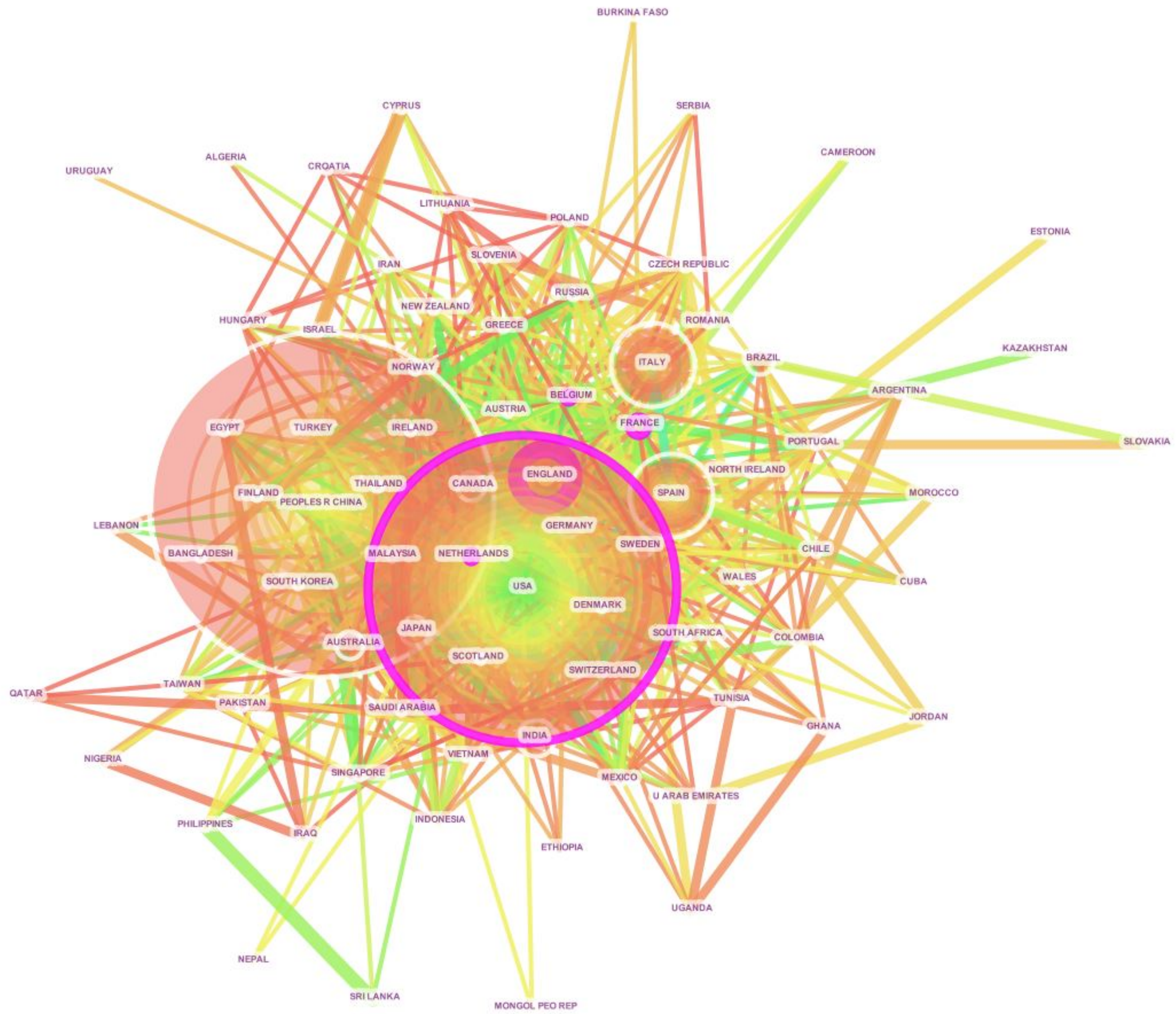

Figure 7. Cluster view of inter-national research collaboration network.

This section further analyzes the longitudinal change of the inter-national research collaboration networks calculated every five years from 1992 to 2016 as shown in Figure 8. The meanings of the x- and y-axis are the same as in Figure 4 and 6, while the nodes represent countries and regions; the links, the collaborations between countries and regions; and the density, the intensity of the inter-national collaboration network. Figure 8 reveals that the number of countries present in the networks stopped increasing in 2012, while density kept rising throughout the entire period. From 1992 to 2011, the US and UK enjoyed the highest numbers of papers published and the highest centralities. The UK kept its leader's position until 2016. However, after 2006, China edged into the group with the highest number of published papers despite an overall low centrality score. Nevertheless, its extraordinary number of publications made make China conspicuous. France came third from 2002 to 2016. Germany consistently made one of the top four most influential countries from 1992 to 2011, while several other developed European countries, particularly Belgium and Sweden, along with Canada and Japan rounded out the leader's board.

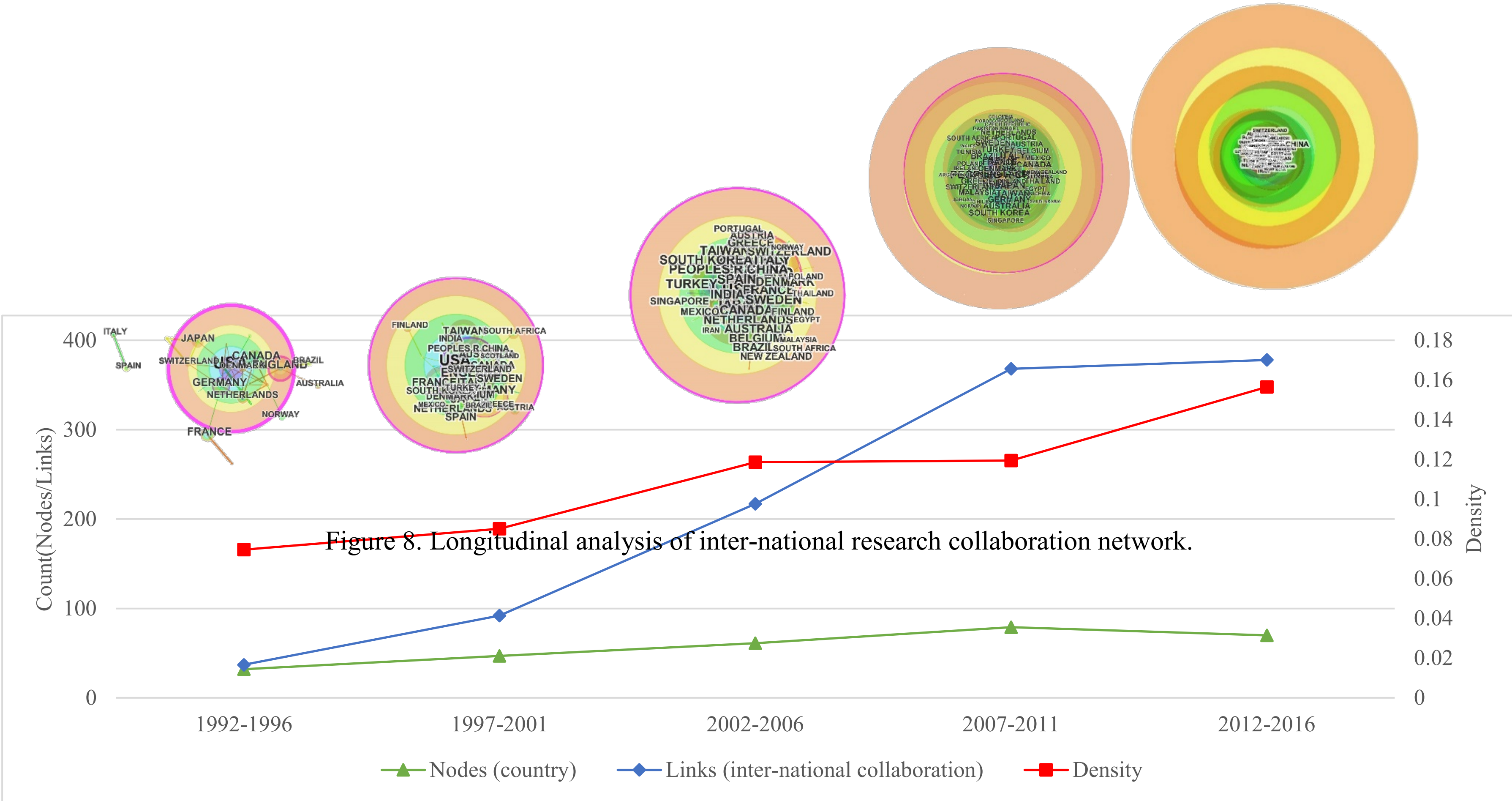

Figure 8. Longitudinal analysis of inter-national research collaboration network.

4.4 Inter-disciplinary research collaboration network

Given that hardly anyone will have all the disciplinary knowledge necessary to manage every aspect of WM, inter-disciplinary research collaboration would be extremely advantageous for the development of the field. This section investigates inter-disciplinary research collaboration in WM. Since the papers extracted from *WoS* cannot be appropriately categorized into disciplines based on their data structure, the authors of this paper adopt an alternative method. By combining keywords from *WoS* and disciplines from the university ranking agency, *QS*, keywords and subjects were manually mapped one by one. There are forty-seven subjects in *QS*, among which only a few closely relate to WM research. The first step, to confirm the most relevant subjects with the adoption of *Delphi*, was accomplished by inviting ten experts in WM research and practice to conduct three rounds of *Delphi* until they reached an agreement. The six subjects/disciplines deemed closely relating to WM were Chemical Engineering, Civil and Structural Engineering, Biological Sciences, Environmental Sciences, Materials Science, and Business and Management. Meanwhile, the authors shepherded a pilot study using all the keywords of the 15,396 papers from *CiteSpace* and found out 1,252 keywords appearing more than ten times in the dataset. The total occurrence of these keywords, 75,924, characterizes 88% of all the keywords. The authors then studied the 1,252 representative keywords thoroughly and sorted them into different disciplines as identified in the first step. Depending on its nature, a keyword may fit several disciplines. Finally, the authors replaced all the keywords with the disciplines and employed *CiteSpace* to analyze the network of the disciplines in order to understand their inter-disciplinary collaboration. If one paper contains keywords from different disciplines, then there is a very high chance that the paper is collaborated in an inter-disciplinary way. Otherwise, if keywords of a paper belong to a single discipline, then likely that the paper has no inter-disciplinary collaboration.

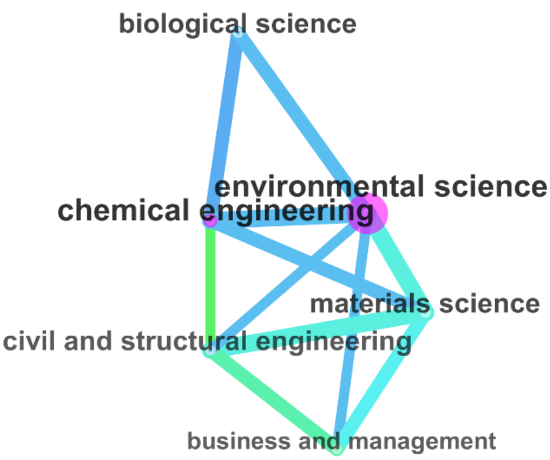

Figure 9. Inter-disciplinary research collaboration network.

Figure 9 exhibits the network of inter-disciplinary collaboration and the inter-disciplinary characteristics of WM research. In the figure, chemical engineering and environmental science are the apparent pillars of WM research. The nodes of environmental science and chemical engineering are highlighted by purple circles because they have high centrality and thus significance within the network. The thicker the circle, the bigger the centrality. However, though more research studies relate to chemical engineering, it is environmental science that boasts a higher centrality. Material science, civil and structural engineering, and biological science have similar counts, while the former two are more significant than the latter. Business and management proves comparatively less present in WM research, although basically these papers explore the management of waste. The strength of the links between disciplines offers a brief insight into the closeness of their combinations. Material science and civil and structural engineering, chemical engineering and environmental science, together with environmental science and material science are the most closely collaborated. Chemical engineering and material science, biological science and environmental science, biological science and chemical engineering, material science and business and management also closely collaborate. Interestingly, chemical engineering and biological engineering do not collaborate at all with business and management. Overall, the share of "soft" approaches (i.e., business and management, half of environment science) is just 15.5%, and the rest goes to hard approaches. This phenomenon implies that WM research has paid more attention to the "hard" approaches characteristic of fields like chemical engineering and biological engineering than the "soft" methods of fields like business and management.

Longitudinal changes of the inter-disciplinary research collaborations were also studied and shown in Figure 10. In this analysis, nodes, links, and densities of the networks were calculated every five years from 1992 to 2016. The meanings of the x- and y-axis are the same as those in Figures 4, 6, and 8, while the nodes represent disciplines; the links, the collaborations between disciplines; and the density of the network, the closeness of the inter-disciplinary collaborations. The analysis intriguingly revealed that the overall links and density of the networks declined slightly from 1992 to 2016. The count and closeness of the inter-disciplinary collaborations also changed together with the centrality of the disciplines in WM research. In 1992-1996, the biological science closely collaborated with chemical engineering and material science. Material science (centrality=1.2) was the most influential discipline. From 1997 to 2002, the era when most inter-disciplinary collaboration materialized, chemical engineering (centrality=1.2) became the leading discipline and collaborated mostly with biological engineering and environmental science. During 2002 through 2006, the collaborations between different disciplines declined. Chemical engineering ceased collaboration with civil and structural engineering (Park & Tucker, 2017), as did material science and environmental science. In 2007 to 2011, the linkage between disciplines remained the same as 2002 to 2006, while the leading discipline was environmental science (centrality=1.1). The collaboration patterns fluctuated from 2012 to 2016, during which there were only six connections between the six disciplines in total. Chemical engineering and material science (both centrality=1.2) became the most significant disciplines of WM research.

With a deeper investigation of the keywords citation bursts as shown in Figure 11, the topics and approaches that received the most and the least attention over the past few years were identified. Food waste was the most researched topic and life-cycle assessment (LCA) proved the most adopted method in WM. Besides, “China”, waste impact, waste-to energy, and sustainability received a great deal of attention with very strong citation bursts in recent years. While topics like nitrification, landfill, as well as methods including mathematical modelling and simulation were losing concentration from WM academics recently. Other keywords, such as “risk assessment”, “biological treatment”, “waste water” and “hazardous waste” became old-fashioned in the twenty-first century. These changes reflect the evolution of research hotspots in WM, i.e. from biological or chemical waste treatment to the utilization of waste as energy and resource for sustainability, from hazardous waste and waste water to food waste, from developed countries to developing countries. It is safe to assume that next research frontier of WM is how to convert daily produced waste to energy and other resources in a sustainable way.

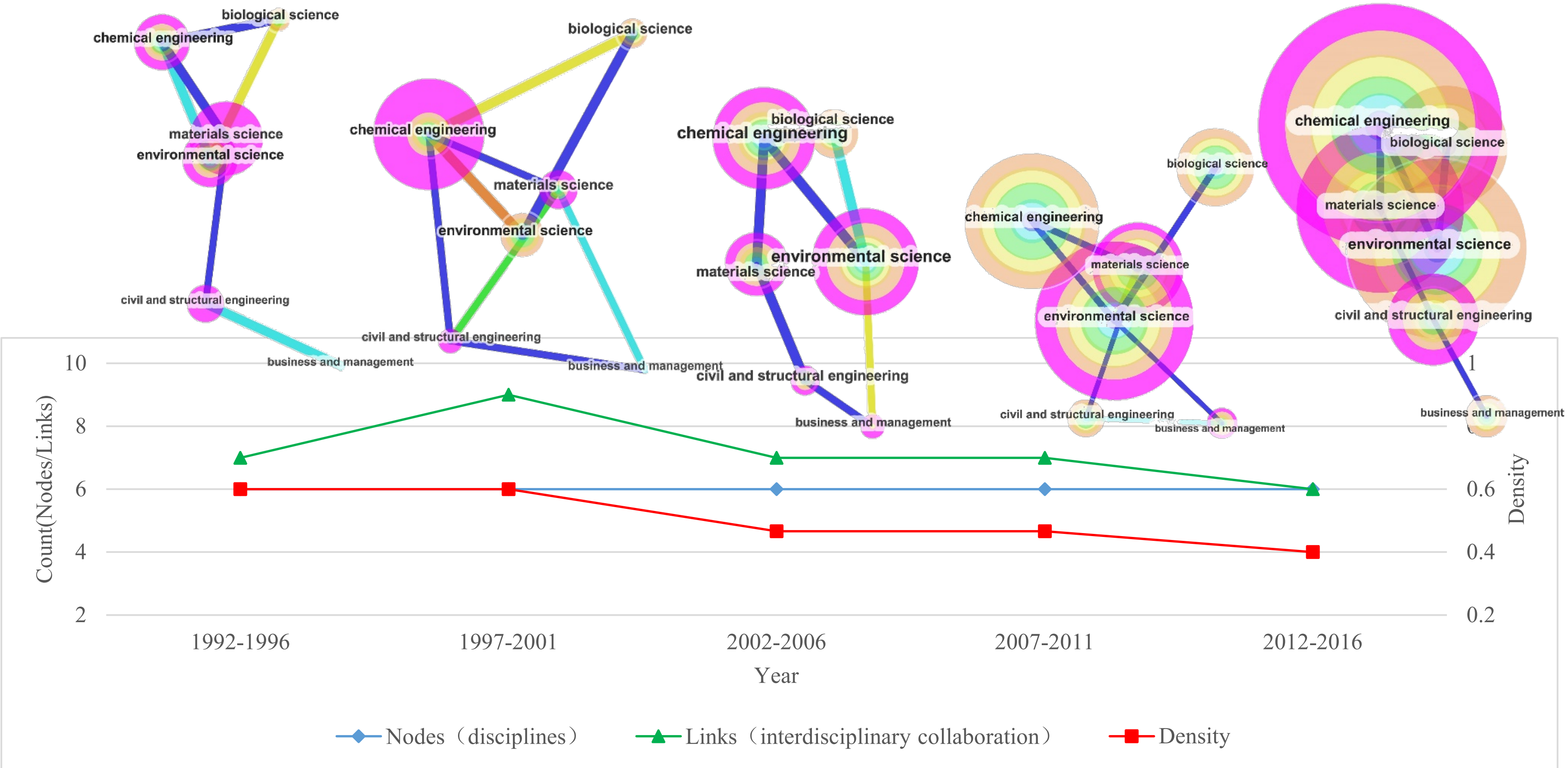

Figure 10. Longitudinal analysis of inter-disciplinary research collaboration network.

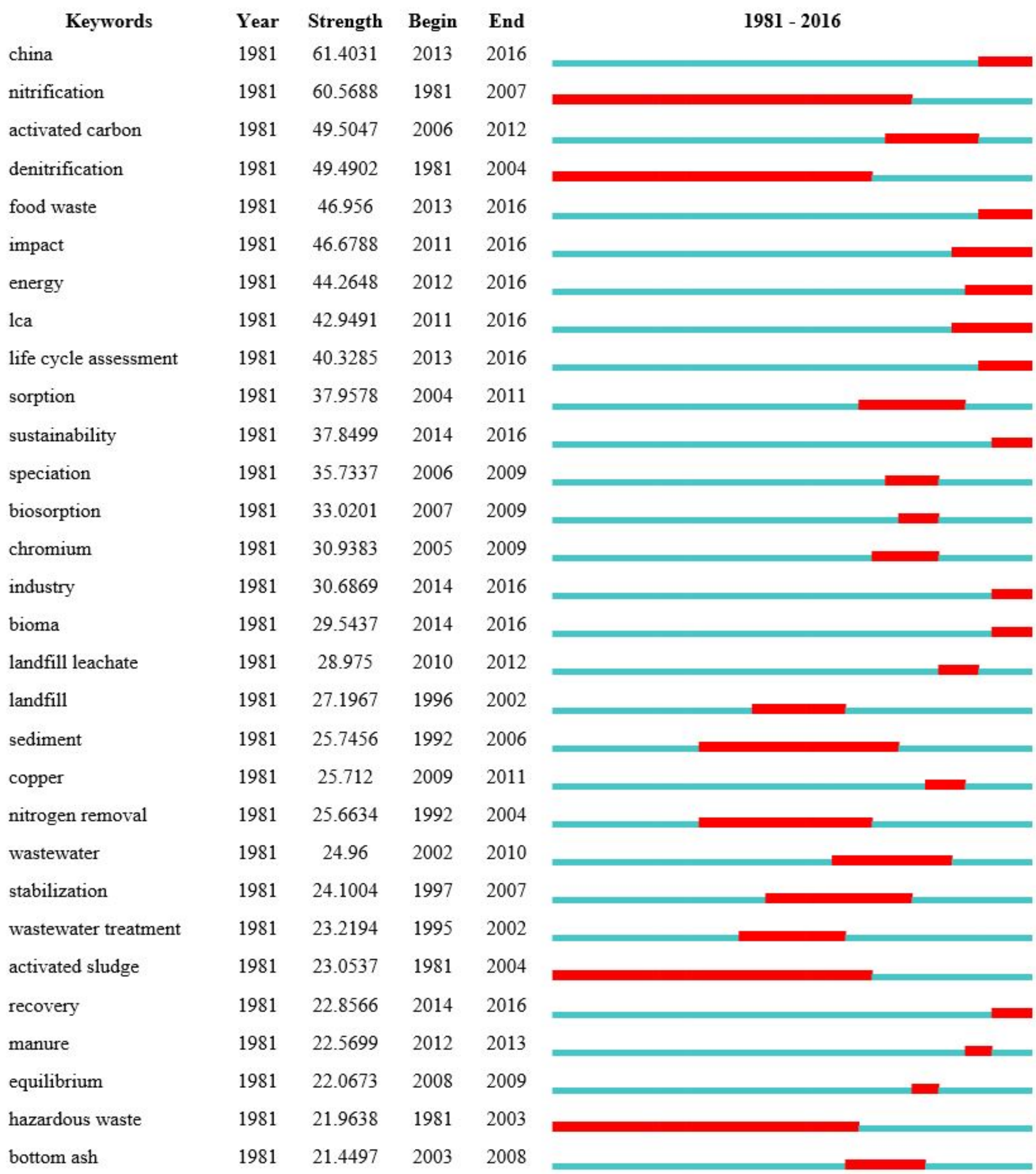

Figure 11. Top 30 keywords with the strongest citation bursts

5. Discussion

Based on a series of network analyses covering 15,396 relevant papers sourced from the eight most relevant journals, a clear and vivid picture of cross-boundary research collaborations in WM research emerged. Overall, the cross-boundary research collaboration between WM researchers lacks intensity. Several scholars, such as Christensen TH from the Technical University of Denmark, published a substantial amount of WM research, but no core scholars stood out in the framework of cross-boundary research collaboration (CBRC) networks. Examining the CBRC from an institution level, no institution occupied a critical position as evidenced by their low centralities in the collaboration networks. Interestingly, many governments and non-government institutions, such as APHA, the European Commission, and the US EPA, played positive roles in fostering CBRC in the WM field. Countries known for their high research capability like the US and the UK enjoyed greater significance in the field than their developing counterparts, even though few influential scholars dominated the networks. Emerging countries like China made rapid progress in research publication numbers, but need to endeavor more into the aspects of CBRC and pioneering achievements in order to enhance their connectivity with international peers and gain greater influence. Surprisingly, the extension around inter-disciplinary research collaboration in WM has yet to be seen. It is found that “hard” approaches (e.g., WM-related technologies from chemical engineering, biological science, material science, and civil and structural engineering), are widely researched, while “soft” economic, managerial, or policy measures are relatively sparse in CBRC. It appears that the “soft” and “hard” researchers are working on different spheres. The authors of this paper encourage them to step out from their comfort zones and collaborate with other disciplinary researchers in order to stimulate more innovative methods for handling waste.

Longitudinal evaluations of WM CBRC are exceptionally informative. Although CBRC from the individual, institutional, and national perspectives remains quite limited, evidence suggests a steady if modest increase in collaborations over time. As the need for sensible and sustainable methods for handling waste becomes more urgent, in both developing and developed countries alike, CBRC will likely rise. A *de facto* world waste market subsists, trafficking solid wastes like paper, plastics, waste electrical and electronic equipment (WEEE) to developing economies as cheap material resources (Manomaivibool, 2009). Conflicting involvement on the part of multi-national companies with local initiative groups, cities and national governments, etc. will both directly and indirectly affect the waste sector (Saarikoski, 2000). Indeed disposal is not the only outcome for waste. Rejected items can enjoy second lives as cheap resource material (Bergeron, 2017), energy via combustion (Brunner and Rechberger, 2015), fertilizer (Sower, 2002), scrounged food (Goula and Lazarides, 2015) and wealth (Mumtaz et al., 2010) when reprocessed using appropriate technologies and creative ideas. In addition to the ethical issues around international waste trading (Lu, 2013), lack of knowledge in managing exported waste has exasperated ecological problems in developing countries (Marshall and Farahbakhsh, 2013). A crucial need exists for collaboration in the management of waste from a global perspective. Diverse and cutting-edge methods, borrowed from computer science, engineering, management and data science, should be developed and applied to WM research. Calling for free, transparent and accessible data, the "Open Data" movement (Auer et al., 2007) may solve the CBRC in WM shortage of data hurdle, and by crossing traditional institutional and national boundaries to achieve big data levels, CBRC can accelerate to deal with the grand challenges of waste management.

The findings supplement previous research, which taken as a whole principally addressed statistical analyses of WM research. For example, Chen et al. (2015) examined WM research also extracted from *WoS*, but between 1997 and 2014, covering 9401 papers including proceeding papers, reviews and others. Although Chen et al.'s findings, e.g., publication output trend, predominant countries, institutes and journals, are very similar with ours, they focused solely on the top keywords, while our paper included citation burst detection, which illustrates more specific keywords trends. For example, this paper's most cited emerging keyword, "China", indicates the recent and growing popularity of WM research in the region. The second major difference between Chen et al. and this paper concerns this paper's emphasis on the collaboration networks. Through a deeper investigation into the CBCR networks at individual, institutional, national and disciplinary perspectives, this paper identified level of closeness in WM research collaboration. This reveals the demand for further and enhanced collaboration to meet the ever-increasing need to address sustainability in WM, especially in developing countries.

However, a number of limitations remain. From the research perspective, this research investigated cross-boundary research collaboration based on published articles, a major form of research collaboration, but not the only one. Also, the research started with a default supporting of research collaboration, which sometimes is not needed. Theoretically, research collaboration has ill-defined borders, and the "boundary" may vary across institutions, fields, countries, as well as over time (Katz and Martin, 1997), this research only examined some of it. From the aspect of research methods, one limitation of this research is that only data in .txt format can be inputted into *CiteSpace* for analysis and only *WoS* provides dataset download in .txt. Thus, only data retrieved from *WoS* can be used in *CiteSpace* network analysis, preventing analysis of articles available only in other databases like *Scopus* and *GoogleScholar*. Fortunately, both the data source and analysis software are representable and reliable. Another limitation concerns *CiteSpace's* inability to differentiate authors with the same name and its abbreviation, such work must be done manually which is time-consuming and arduous. A third limitation concerns how disciplinary information is poorly sorted and tagged in big databases. *WoS* and *Scopus* only provide a paper's category information based on the sorting of the journals. Analyzing such information requires an indirect approach, which can be imperfect and hard to accomplish. Future research can explore other databases or other software to analyze CBRC in both WM and of course other research fields. Though there might be inadequacies due to the availability of data and functions of the analytical tool, ultimately this investigation can help seasoned researchers and newcomers in the WM sector find and connect with other researchers, institutions, regions, and disciplines to build collaborations.

6. Conclusion

With data from *WoS* between 1981 and 2016 and scientific citation network analysis software *CiteSpace*, this paper investigated cross-boundary research collaboration (CBRC) in the field of waste management (WM) from four perspectives, namely, inter-individual, inter-institutional, inter-national, and inter-disciplinary. Surprisingly, CBRC in the WM field proved rather limited. Real boundaries, be they physical or ideological, prevent CBRC from fully realizing universally. However, according to the longitudinal analyses, the research collaborations at the four cross-boundary perspectives became more and more concentrated in a self-organized way. Researchers are encouraged to abandon silo mentalities and collaborate more inter-disciplinarily.

Specifically, the CBRC in WM between individuals, institutions, and nations have been respectively increasing gradually if slowly over the examined time period, 1996 to 2016. Modern information and communication technologies (ICTs) afforded the infrastructure necessary to catalyze CBRC, although it has never been easy. Evidenced by the inter-individual and inter-institutional networks, the CBRC in WM research is relatively decentralized. No researcher or institution enjoys an obvious leading role. Developed countries like the US, the UK, and others in Western European comprise the epicenter of WM research, likely owing to their research capabilities, quality standards, and respective countries' international influence, while developing countries, China especially, are catching up in both the amount of research published and its value and importance. Two discipline "islands" in particular, one mainly formed by science and technology, and the other by business and management, exemplify the disconnections between boundaries. Finally, the keywords burst detection analysis revealed frontiers for future research.

This research filled the gap of a missing quantitative investigation into CBRC in WM, which is significant for new researcher, further research and education of WM. It also confirmed the feasibility of co-authorship as a method to study research collaboration (Melin and Persson, 1996). It contributed to the measurement of research collaboration by promoting a convenient and effective method, i.e. social network analysis (SNA), to measure research collaboration from four cross-boundary perspectives. Other researchers who want to investigate the CBRC in other fields can also conduct SNA. The findings provide some implications to the WM research group by: highlighting the CBRC gaps between the developed and developing poles, and among different disciplines, shedding light on the increasing popularity of energy and resource regeneration from daily waste. This research can also provide guidance to WM practice by pointing out directions, i.e., calling for collaboration among academia, industry and government from different economic entities to boost sustainable WM, such as applying advanced technologies from developed countries to handle the growing waste from developing countries.

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