Journal of Cleaner Production 183 (2018) 231–250

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Review

A scientometric review of global research on sustainability and sustainable development

Timothy O. Olawumi*, Daniel W.M. Chan

Department of Building and Real Estate, Faculty of Construction and Environment, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

A R T I C L E I N F O

Article history:
Received 22 November 2017
Received in revised form
29 January 2018
Accepted 15 February 2018
Available online 16 February 2018

Keywords:
Sustainable development
Sustainability
Research trends
Scientometric
Built environment

A B S T R A C T

The concept of sustainable development has gained worldwide attention in recent years which had enhanced its implementation. However, few studies have attempted to map the global research of sustainability. This study utilizes scientometric review of global trend and structure of sustainability research in 1991–2016 using techniques such as co-author, co-word, co-citation, clusters, and geospatial analyses. A total of 2094 bibliographic records from the Web of Science database were analyzed to generate the study's research power networks and geospatial map. The findings reveal an evolution of the research field from the definition of its concepts in the Brundtland Commission report to the recent development of models and sustainability indicators. The most significant contributions in sustainability research have originated primarily from the United States, China, United Kingdom and Canada. Also, existing studies in sustainability research focus mainly on subject categories of environmental sciences, green & sustainable science technology, civil engineering, and construction & building technology. Emerging trends in sustainability research were sustainable urban development, sustainability indicators, water management, environmental assessment, public policy, etc.; while the study generated 21 co-citation clusters. This study provides its readers with an extensive understanding of the salient research themes, trends and pattern of sustainability research worldwide.

Contents

* Corresponding author.
E-mail addresses: timothy.o.olawumi@connect.polyu.hk (T.O. Olawumi), daniel.w.m.chan@polyu.edu.hk (D.W.M. Chan).

https://doi.org/10.1016/j.jclepro.2018.02.162
0959-6526/

1. Introduction

The fulcrum for the worldwide attention being paid to the concept of sustainable development (SD) was the Brundtland Commission report of 1987 which help defined SD as seeking “to meet the needs and aspirations of the present without compromising the ability to meet those of the future” (WCED, 1987). However, there have been challenges in meeting some of the thresholds of SD due to the limitation imposed by the social issues, technological advancement and the ability of the ecosystem to accommodate human carbon footprints. Therefore, it is unrealistic to have a single SD blueprint for every country or region. Hence, each country would need to develop its SD policies and standards but with a global objective in mind.

As noted by Axelsson et al. (2011), sustainability and SD are two concepts that have gained reception at national and global levels due to challenges and risks faced in areas such as rural development, environmental conservation, energy, climate change, human wellbeing etc. Hence, in recent years there have been a shift in focus and action plans to address these problems. SD is currently adopted as a growth strategy in the built environment. According to Sartori et al. (2014), sustainability is described as a process and mechanism to achieve the intended sustainable development; while according to Dovers and Handmer (1992), it is a process of “intentional change and improvement,”.

As noted by Norton (2005), the two terms of sustainability and SD are often used interchangeably, however, Axelsson et al. (2011) argued that the two concepts are quite different. Axelsson et al. (2011) described sustainability as a policy vision of the society with primary purpose of preventing the depletion of natural resources. Clark (2002) however, observed that the issue of what sustainability means is more complex and per Parrotta et al. (2006) and Ramakrishnan (2001), it currently involves issues such as biodiversity conservation, ecological integrity etc.

In contrast, as stated by Axelsson et al. (2011), SD is more of a collective societal process that involves multiple stakeholders with differing salience level and powers. Nevertheless, Lee (1993) described both concepts as a “social learning and steering process” which involved both management and governance mechanism. The concept of sustainability is conceptual (Ekins et al., 2003) and hence easily misunderstood, although still hugely popular (Slimane, 2012). SD is however multidimensional in scope (Slimane, 2012), an integrated concept (Sartori et al., 2014) and based on the principles of sustainability (Dovers and Handmer, 1992). SD also helps to find a balance between preserving the ecosystem and meeting human needs. The three pillars of SD are environmental, social and economic sustainability; and these constructs must be harmonized to achieve a holistic SD.

Environmental sustainability is concerned with confining human activity within the carrying capacity of the ecosystem (such as materials, energy, land, and water, etc.) prevailing in the locality and places emphasis on the quality of human life (air quality, human health). Moreover, the economic sustainability considers the efficient use of resources to enhance operational profit and maximize market value. It also deals with substituting natural for manmade resources, reuse, and recycling. However, the social sustainability focuses on the social well-being of the populace, balancing the need of an individual with the need for the group (equity), public awareness and cohesion, and participation and utilization of local labors and firms. Sartori et al. (2014) acknowledged that the approach to sustainability defers based on the field of application, such as engineering, management, ecology, etc. Sala et al. (2015) considered sustainability assessment as an appraisal method to evaluate the level of the implementation of these sustainability measures. The sustainability assessment results will be used for decision-making and policy formulation for real-world SD applications (Hacking and Guthrie, 2008).

Several studies have been published to addressed salient challenges facing sustainability in the built environment. Ahmad and Thaheem (2017) developed a social sustainability assessment framework for residential buildings using a weighted aggregation approach to improve its performance value. Also, Ahmadian et al. (2017) and Akanmu et al. (2015) utilized a Building Information Modelling (BIM)-based approach to address sustainability issues regarding material selection and supply decisions. Moreover, Damtoft et al. (2008) discussed issues relating to climate change initiatives and SD. Meanwhile, studies (see Akinade et al., 2015; Althobaiti, 2009; Forsberg and von Malmborg, 2004; Gao et al., 2015; Huang et al., 2010; Wang et al., 2015); attempted to integrate technological and innovative tools to advance the concept of sustainability and SD.

1.1. Knowledge gap, research objectives, and value

Sustainability is a wide and complex research field which several applications in different disciplines and industries. However, previous review papers on sustainability in the built environment have focused mainly on environmental sustainability, a gap which the current study tends to bridge. For instance, Wong and Zhou (2015) examined the concept of green BIM and sustainability across the various stages of building development. The authors examined the research frontiers of green BIM and proposed a ‘one-stop-shop’ BIM for environmental sustainability. Also, Darko et al. (2017) classified the drivers of green building and categorize them into five (5) sub-levels such as external drivers, property-level drivers, corporate-level drivers, project-level drivers, and individual-level drivers. Both Wong and Zhou (2015) and Darko et al. (2017) used the Scopus database.

Similarly, Falkenbach et al. (2010) reviewed the drivers for sustainable building by examining the perspective of various stakeholders in the real estate market. Aarseth et al. (2016) carried out a systematic literature review (SLR) and highlighted several project sustainability strategies that could be employed in project organizations to enhance project performance. Lele (1991) carried out a critical review of the concept of SD and discusses the idea in relation to issues such as economic growth, environmental degradation, community participation, and international grade. However, the review didn't include discussions of extant literature as sustainability was still a relatively new concept as of the time.

Also, the previous studies such as Wong and Zhou (2015), Aarseth et al. (2016) and Darko et al. (2017) analyzed 84, 68 and 42 journal papers respectively as compared to a relatively higher corpus of papers in this study (2094 articles). Moreover, no previous review of the sustainability research corpus mapped out the linkage or working relationships among the clusters of sustainability researchers and their institutions. Also, no previous studies have analyzed its research corpus to such depth to include aspects such as co-citation clusters, keywords, or research clusters.

Given the above, this study aims to bridge these gaps in extant literature by undertaking an in-depth scientometric review of the global on the sustainability and SD; with a view to providing researchers and practitioners with a comprehensive understanding of the status quo and research trend in its research, with a focus on the three pillars of sustainable development. Therefore, to achieve the study aim, five scientometric techniques will be employed as discussed under Section 2 which will be used to (i) track the evolution of the sustainability research field, (ii) identify the key researchers and institutions. Also, part of the objectives of this study is to (iii) identify the key subject categories, (iv) research keywords and co-citation clusters as well as (v) deduce the salient and emerging research themes.

Meanwhile, a large corpus of journal articles (2094 bibliographic records) would be analyzed, which is a significantly high volume of articles than previous reviews on sustainability or elsewhere. Section 2 discusses the research approach utilized and the literature search and indexing strategy. Subsequent sections such as Section 3 outlines the findings and results of the scientometric reviews; Section 4 discusses the salient research clusters; and Section 5 outlines the conclusion and future directions. The findings of the study are expected to contribute to the existing body of knowledge by highlighting the trend and pattern of sustainability research field, establishing its research themes and clusters, mapping the network of key sustainability researchers and institutions and recommending areas for future studies. It will also serve as a consultation toolkit for policy making for government agencies.

2. Research methodology

The study carried out a scientometric review, analyses, and visualization to achieve the predefined research objectives of providing the academics and industry practitioners an in-depth understanding of the structure (clusters), research areas and trending topics in sustainability's studies in the built environment aided with illustrative diagrams and maps. The scientometric analysis is described as one of the most used methods to evaluate and examine the research development and performance of academics, faculties, colleges, countries and even journals in an identified research field (Konur, 2012).

The scientometric analysis is a technique that allows for a broader yet concise capturing and mapping of a scientific knowledge area by identifying structural patterns and tracing salient research frontiers using mathematical formulae and visualization. Moreover, other scientific methods such as bibliometric technique (Albort-Morant et al., 2017; Olawumi et al., 2017; Santos et al., 2017); content analysis (Park and Cai, 2017); literature reviews (Wong and Zhou, 2015); latent semantic analysis (LSA) (Yalcinkaya and Singh, 2015); and scientometric analysis (Montoya et al., 2014; Zhao, 2017); have been used by several authors across research areas such as green building and innovation, building information modelling (BIM), public-private partnerships (PPPs), energy, and sustainability.

Five scientometric techniques would be adopted in this study. (1) Co-Author analysis: This includes co-occurrences of authors, countries/regions and faculties/institutions in the indexed corpus of journal articles. (2) Co-Word analysis: This identifies co-occurring keywords or terms and co-occurring Web of Science (WoS) subject. (3) Co-Citation analysis: This analysis includes co-cited authors, co-cited articles/documents, and co-cited journals. (4) Clusters analysis: This includes burst detection analysis and silhouette metric analysis. (5) Geospatial analysis: Geospatial network visualization (animated maps) of journal articles and authors' origin and generation of Keyhole Markup Language (KML) files for use in using Google Earths.

The above five (5) scientometric analysis and its visualization could be performed using a software package "CiteSpace" developed by Chaomei Chen. CiteSpace version 5.0.R7 (32bit) was used to analyze the indexed corpus articles because per Chen (2016), CiteSpace is very useful in mapping knowledge domains and aiding its illustration with graphical maps. More information on how to utilize the software "CiteSpace" for scientometric reviews of a research field are available in the literature (*see* Chen, 2016, 2014, 2005a; Chen and Morris, 2003). Fig. 1 depicts the study's research design.

2.1. Literature search strategy and research data

One of the decision to make in undertaking an analysis of a knowledge domain such as in this study is for the researcher(s) to identify scientific databases to use. The three primary scientific databases are Scopus, ISI Web of Science and Google Scholar, Olawumi et al. (2017) provided a comparative assessment of strength and weakness of these three databases. Similarly, several core journals publishing houses have their databases such as those of Elsevier- Science Direct, ASCE Library, Emerald, Wiley Online Library, ProQuest, EBSCO, Taylor & Francis, Springer Link, IEEE Explore among several others available for journal search and retrieval (JSR). Nevertheless, based on the submission of previous authors (Marsilio et al., 2011; Neto et al., 2016; Olawumi et al., 2017; Zhao, 2017); Web of Science core collection database was adopted for this study's JSR. It is because WoS is regarded as the most comprehensive and it also contains the most relevant and influential journals in its record combined with WoS scientific robustness.

A comprehensive literature search, retrieval, and indexing were carried out on WoS core collection using the search string- "*sustainability* and sustainable development**" as seen in Fig. 2. A fuzzy search is denoted with a "*" and the selected time-span ranges from 1991 to 2016 (26 years).The search results were refined to include only journal articles and articles written in the English language because published journal articles would have undergone a thorough peer review process and most authors do republish their conference papers and thesis in scholarly journals afterward (Olawumi et al., 2017). Journal articles are regarded as more reputable sources and also classified as "certified knowledge" (Ramos-Rodríguez and Ruíz-Navarro, 2004) and are more comprehensive than other sources (Ke et al., 2009; Yi and Chan, 2013; Zheng et al., 2016). CiteSpace meanwhile uses several databases as its source of data such as WoS, Scopus, PubMed among others but do convert such data from other sources to WoS format before processing the data. Hence, Chen (2016) advise the use of WoS database for use in JSR to prevent loss of data during the conversion process and reduce the processing time.

Moreover, sustainability research areas which are not relevant to the built environment were excluded from the search results. Mainly research areas such as "Environmental Science Ecology" "Engineering," and "Construction Building Technology" were retained. A total of 2094 bibliographic records were collected in September 2017, and the articles were then downloaded and

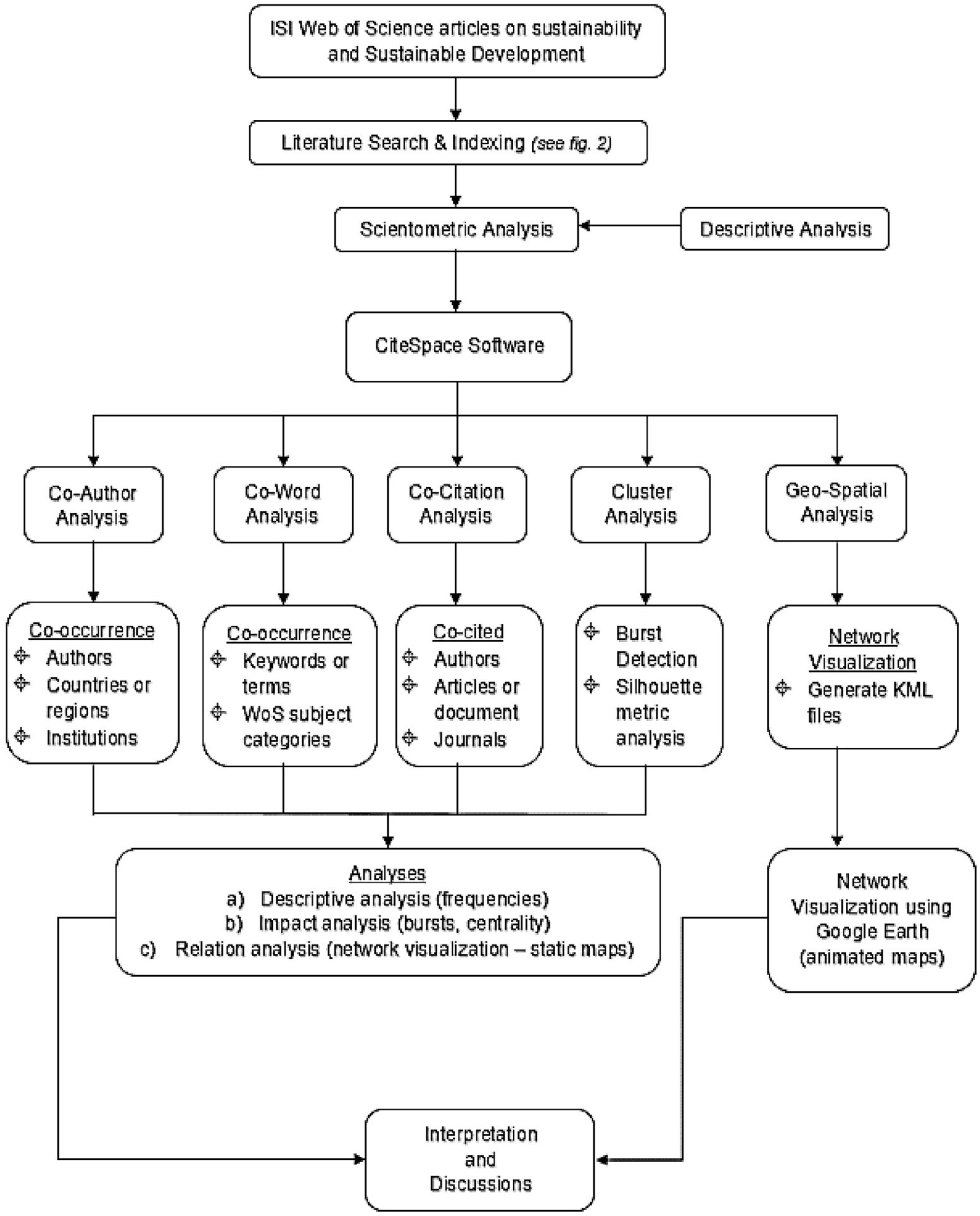

Fig. 1. Outline of research design.

indexed into Mendeley reference manager. Also, the CiteSpace software was installed, and the WoS records captured, saved in WoS "Marked List" and downloaded and inputted as research data for use as explained in the CiteSpace manual (Chen, 2014). The first paper on sustainability was in 1991 which focused on developing legislation and standards to control wood processing in Australia (Gifford and McFarlane, 1991) which has two citations so far and focused on the environmental aspect of sustainability. Fig. 3 shows the distribution of the 2094 bibliographic records from the year 1991–2016.

The number of articles on sustainability increased significantly between 2011 and 2016 and it crossed the 100 articles per year threshold in the year 2011 and subsequently crossed the 200 articles and 300 articles per year thresholds in 2013 and 2015 (2-year intervals).

3. Scientometric analysis, results and discussion

This section discusses the facets and results of this study's scientometric analysis as described in the research design (Fig. 1). The following sections entail the co-author analysis, co-word analysis, co-citation analysis, clusters analysis and geospatial analysis. Since the study is examining a lengthy period of research (1991–2016), time slicing was employed. According to Chen (2005b), time slicing is a "divide-and-conquer strategy that divides a period into a series of smaller windows." A 2-year per slice was used for co-author analysis, co-word analysis, co-citation analysis and clusters analysis while a 1-year per slice was used for the geospatial analysis.

The Pathfinder utility in CiteSpace was used to prune the network to remove redundant links through the process otherwise known as 'network pruning.' Moreover, among the pruning utilities

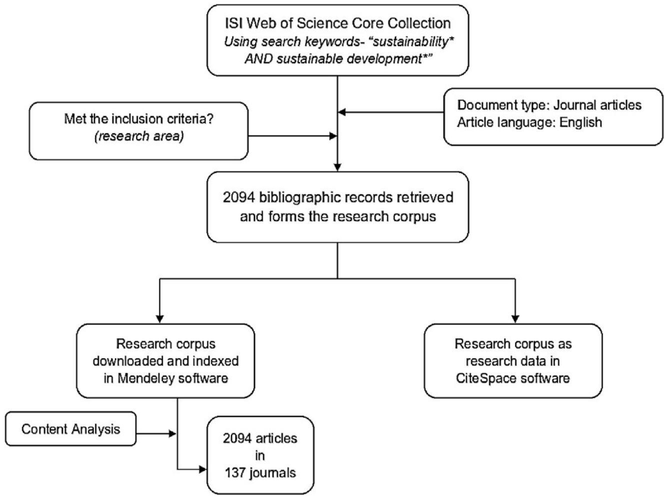

Fig. 2. Literature search and indexing strategy.

in CiteSpace, Pathfinder is regarded as the better choice (Chen, 2014) and details of its pros and cons are explained in Chen and Morris (2003).

3.1. Co-author analysis

Information available from the WoS records in this research field contains relevant details about the authors which are useful in establishing prolific authors, institutions or faculties and countries. Hence, such data can be extended to evaluate networks of co-authors, a network of countries or regions and those of institutions.

3.1.1. Co-authorship network

An analysis of the most productive authors (see Table 1) reveals Donald Huisingh (University of Tennessee, Knoxville), Rodrigo Lozano (University of Gävle) and Yong Geng (Shanghai Jiao Tong University) as the three researchers with most publications in the field.

A co-authorship network was generated as shown in Fig. 4 identify the network of authors represented by nodes and links. Each representative node represents each author while each link represents the pattern of collaboration established in the publications (Zhao, 2017). The network was pruned as before described resulting in 144 nodes and 99 links in the co-authorship network. The node size corresponds to the number of publication by each author while the thickness of the links represents the strengths of 'cooperative relationships' among the author. The co-authorship network has a Modularity, $Q = 0.942$ and a mean Silhouette, $S = 0.470$. The modularity (Q) and the mean silhouette values (S) reveals the "overall structural properties" of the network, that is a very high Q value (say $Q > 0.70$) denotes loosely assembled clusters while the S-metric measures the homogeneity of the clusters (Chen, 2014). Hence, the dispersed nature of the clusters of authors within the network as seen in Fig. 4.

Meanwhile, the color of the links (e.g., blue, green, yellow and red) corresponds to the color encoding of the different time span in a 2-year slice as seen above the co-authorship networks. Moreover, regarding collaborative relationships and workings in the field, the network established several research communities constituted by central authors of the research community and other authors in the community. Three main research communities with robust collaboration among the authors include the highly productive research circuit of Donald Huisingh and Rodrigo Lozano as the central authors and other researchers such as Maik Adomssent, Liyin Shen, Jana Dlouha, Gyula Zilahy, and Kunhui Ye. Another research community with Yong Geng and Tsuyoshi Fujita as the central authors of the circuit including Huijuan Dong, Zhe Liu, Jingzheng Ren, and Liang Dong. Lastly, Robert Axelsson and Per Angelstam as the central authors of a research community which includes Kjell Andersson and Marine Elbakidze as authors within the circuit.

3.1.1.1. Citation bursts and centrality scores. The impact of the authors and collaboration was analyzed using the citation burst and betweenness centrality. The citation burst is based on Kleinberg's algorithm (Kleinberg, 2002) and it measures the increase in citations within a short time span. Two authors have citation bursts, which are Donald Huisingh (burst strength = 3.43, 2013–2016) and John Cairns (burst strength = 3.42, 1991–2000). Also, the betweenness centrality which is based on Freeman's work (Freeman, 1977) is defined as the degree to which "a point [or node] falls on the shortest path between others and therefore has a

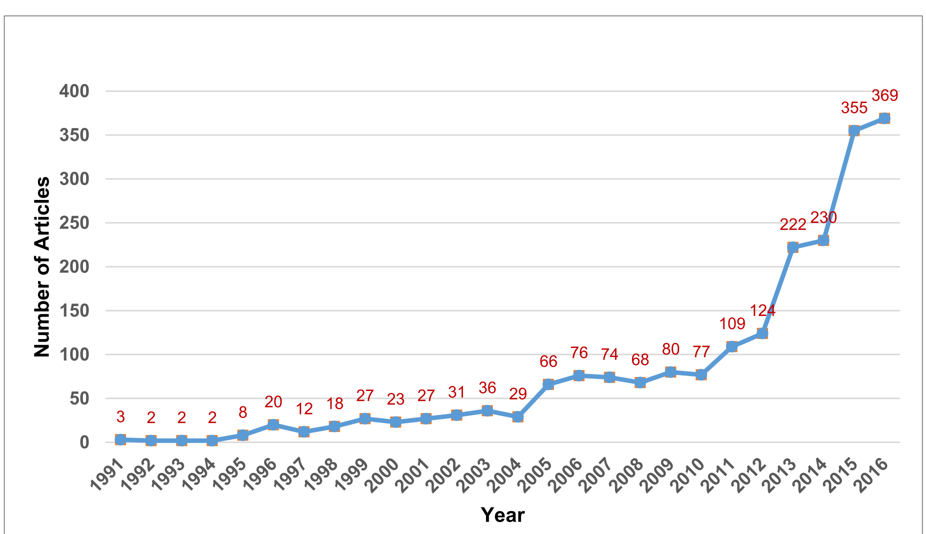

Fig. 3. Distribution of the indexed research corpus from 1991 to 2016.

Table 1
Top 13 most productive authors with their h-index.

Authors	Institution	Country	Counts	h-index
Donald Huisingh	University of Tennessee, Knoxville	USA	25	29*
Rodrigo Lozano	University of Gävle	Sweden	16	29
Yong Geng	Shanghai Jiao Tong University	China	10	49
Per Angelstam	Swedish University of Agricultural Sciences	Sweden	7	54
Roland Scholz	Swiss Federal Institute of Technology, Zurich	Switzerland	7	53
Adisa Azapagic	University of Manchester	UK	7	42
James Mihelcic	University of South Florida	USA	7	37
Sekar Vinodh	National Institute Technology Tiruchirappalli	India	7	26
Xiaoling Zhang	City University of Hong Kong	Hong Kong SAR	7	22
Tomas Ramos	Universidade Nova de Lisboa, Lisbon	Portugal	7	21
Marine Elbakidze	Swedish University of Agricultural Sciences	Sweden	7	20
Robert Axelsson	Swedish University of Agricultural Sciences	Sweden	7	19*
Rebeka Lukman	University of Maribor	Slovenia	7	10*

Note: * - the h-index of the authors are based on ResearchGate.net calculation while the other authors h-index are based on Google Scholar.

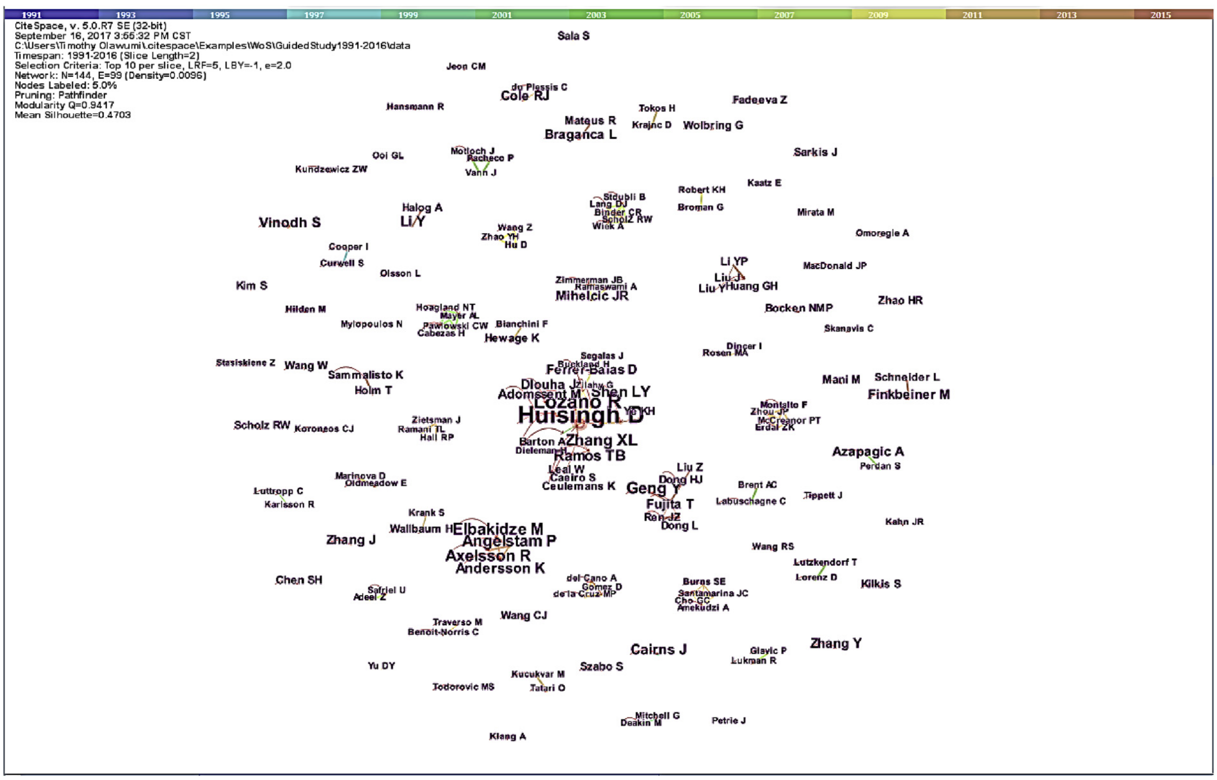

Fig. 4. Co-authorship network.

potential for control of communication."

Centrality scores in CiteSpace are normalized in the unit interval between 0 and 1 (Chen, 2014), and a node of high centrality score is one that connects two or more large groups of nodes in the network with the node itself in-between and it is denoted by purple trims in the network. Such nodes with high betweenness centrality form the basis of separating clusters (Girvan and Newman, 2002) and helps to identify pivotal and salient scientific publications over time. In Fig. 4, Donald Huisingh (centrality = 0.02), Rodrigo Lozano (centrality = 0.01), Xiaoling Zhang (centrality = 0.01), Kim Ceulemans (centrality = 0.01), Andrew Barton (centrality = 0.01) and Heloise Buckland (centrality = 0.01) are the nodes with purple trims and they serve as links between different authors and research communities. It is noteworthy that Donald Huisingh is also the most productive author in the field, with the strongest citation burst and more connections and collaborative relationships with several researchers in the field.

3.1.2. Network of institutions/faculties and countries/regions

This section explores the contribution of institutions and countries to the body of knowledge in the field. The network generated 49 nodes and 99 links with modularity, Q = 0.466 and a mean Silhouette, S = 0.589. Since the Q-value of the network is below average, the nodes within the network are densely packed (see Fig. 5). Eight (8) countries were identified in the network (Fig. 5) with a greater contribution (*more than 100 articles*) to the research area of sustainability and SD. These include the USA (428 articles, 20.44%); China (275 articles, 13.13%); United Kingdom (258 articles, 12.32%); Canada (157 articles, 7.50%); Germany (132 articles, 6.30%); Netherlands (131 articles, 6.26%); Australia (128 articles, 6.11%), and Sweden (124 articles, 5.92%). These results revealed the advanced level of research and development in sustainability

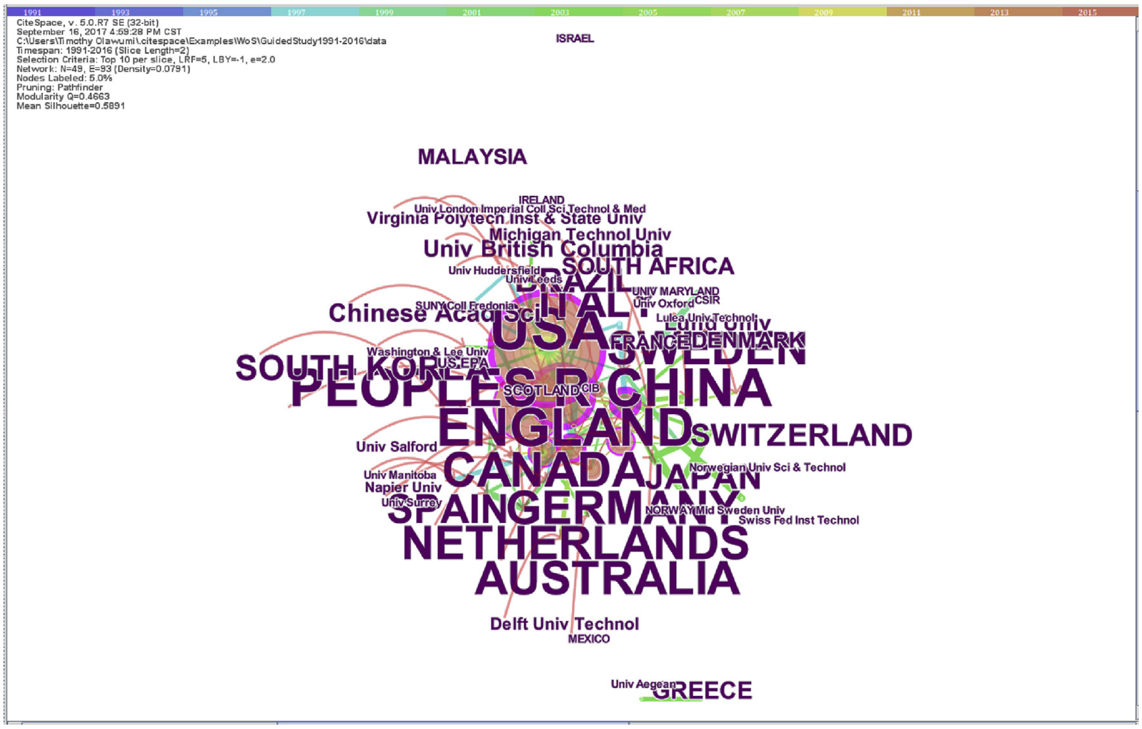

Fig. 5. Network of countries and institutions.

studies in these countries and with most of the counties being European countries. It is noteworthy that countries such as the USA, the origin of the world-renowned building rating system (LEED-Leadership in Energy and Environmental Design) have the most articles on sustainability field and several building energy simulation software and devices originated from the US. In the United Kingdom, we have another building rating system (BREEAM-Building Research Establishment Environmental Assessment Method) while in Australia, we have the Green STAR building rating system. In respect to collaborative research, authors from countries such as the USA, China, the UK, Canada, Sweden, South Korea, Netherlands, Australia, Switzerland have strong international collaborations.

Furthermore, in terms of institutions and faculties research outputs. The research on sustainability has progressed significantly in several universities among which are Chinese Academy of Sciences, China PR (67 articles), Delft University of Technology, Netherlands (37 articles), University of British Columbia, Canada (30 articles) Wageningen University Research, Netherlands (28 articles). The University of Tennessee Knoxville and the University of Tennessee System, both in the USA (25 articles each); ETH Zurich, Switzerland and Lund University, Sweden (24 articles); the United States Environmental Protection Agency, USA and the University of Leeds, United Kingdom (23 articles). Also, we have the Hong Kong Polytechnic University, Hong Kong SAR and the State University System of Florida, USA (22 articles) and the University of California, USA (20 articles). These institutions are unique in their outputs of research in the field of sustainability.

3.1.2.1. Citation bursts and centrality scores. Moreover, significant citation bursts were identified in some countries as shown in Table 2. While for institutions, we have Chinese Academy of Science (burst strength = 5.40, 2009–2010), University of British Columbia (burst strength = 4.66, 1999–2006) and Lund University (burst strength = 4.37, 2005–2006). It is evidently clear from the citation burst analysis that there was no citation burst between 2015 and 2016 for both countries and institutions; which is consistent to the fact that sustainability studies have garnered worldwide attention and consideration in recent years; one of which culminated in the signing of the Paris climate change which was signed by 166 countries. Hence, it would be difficult for a country or institutions to receive high citations in that period.

Table 2
Countries' citation burst.

Countries	Burst strength	Span
Japan	9.66	2011–2014
Brazil	8.16	2009–2014
Switzerland	5.71	1999–2012
Greece	5.15	2003–2008
United Kingdom	5.03	1991–2002
South Africa	4.66	1999–2006
Spain	4.30	2009–2010
Malaysia	4.13	2011–2012
Sweden	4.03	2005–2006
Denmark	3.44	1997–2008

More so, in terms of high between centrality as identified by purple trims in the network (Fig. 5). The network revealed countries such as United Kingdom (centrality = 0.54), Sweden (0.49), the USA (0.47), Netherlands (0.40), Canada (0.18), China (0.12), Germany (0.12) and France (0.10). For institutions, we have the Imperial College London (centrality = 0.08), University of Oxford (0.03), University of Salford (0.02) and Lund University (0.01) with strong connections and acting as key exchange platforms between the countries and institutions.

3.2. Co-word analysis

Several research topics and themes have merged and evolved in sustainability research over the decades which represents the trends and frontiers in the field. Data from the WoS bibliographic records are evaluated to develop the network of co-occurring keywords and subject categories in the sustainability field.

3.2.1. Network of co-occurring keywords

Keywords are descriptive and significant words and serve as a reference point in finding and understanding the concepts and contents of research articles. It also reveals the development of the research field over time (Zhao, 2017). Two kinds of keywords are obtainable from the WoS bibliographic records which are the (i) author keywords and the (ii) keywords plus. The former is provided by the authors in their articles while the other is based on the journal's classification of the research output. The two kinds are utilized in developing the network of co-occurring keywords in CiteSpace, and the software has a utility to merge similar keywords. A research network of co-occurring keywords as shown in Fig. 6 with 71 nodes and 136 links. Also, the network has a modularity (Q = 0.523) and mean silhouette, S = 0.769. The node size for each keyword is a representative of the frequency of the keyword in the record.

Meanwhile, the co-word analysis reveals high-frequency keywords (Fig. 6) in the dataset which are “sustainability” (frequency = 778), “sustainable development” (frequency = 472), “management” (frequency = 212), “system” (frequency = 193), “indicator” (frequency = 141), “framework” (frequency = 112). Other high-frequency keywords include “China” (frequency = 89), “model” (frequency = 89), “energy” (frequency = 88), “performance” (frequency = 84), “impact” (frequency = 82), “climate change” (frequency = 53), “environment” (frequency = 44) and “design” (frequency = 43).

3.2.1.1. Citation bursts and centrality scores.

Fourteen (14) keywords were identified from the network with citation bursts as shown in Table 3.

Table 3
Keywords' citation bursts.

Keywords	Burst strength	Span
Environment	14.15	2004–2012
Climate change	13.82	2009–2014
Design	13.01	2013–2014
City	11.82	2013–2014
Policy	10.34	2013–2014
Sustainable development	8.88	1999–2006
Impact	7.40	2013–2016
Construction	6.95	2005–2008
Sustainability indicator	5.40	2003–2006
Industrial ecology	5.34	1998–2008
Innovation	5.10	2007–2008
Energy	4.42	2009–2012
LCA	4.26	2003–2010
Sustainable building	3.81	2005–2006

All these keywords with citation bursts represent the salient topics and themes in sustainability studies and research. It is noteworthy that keywords such as “climate change,” “design,” “energy,” “sustainable development,” “sustainability indicator,” “environment” and “policy/framework” have both high frequencies and citation bursts. It is consistent with the fact that more efforts are devoted to these critical research themes which are pivotal in achieving a sustainable urban development.

Several keywords also have high betweenness centrality scores and these include: “sustainability” (centrality = 0.80), “sustainable development” (0.64), “indicator” (0.25), “system” (0.21), “China” (0.20), “management” (0.19), and “environment” (0.17). Other keyword with high betweenness centrality are “public policy” (0.16), “framework” (0.12), “research policy” (0.11), “natural capital” (0.08), “decision making” (0.08), “energy” (0.07), “city” (0.06) and “ecological footprint” (0.06). These keywords and themes have greatly influenced the development of the sustainability research field and help connect several research topics.

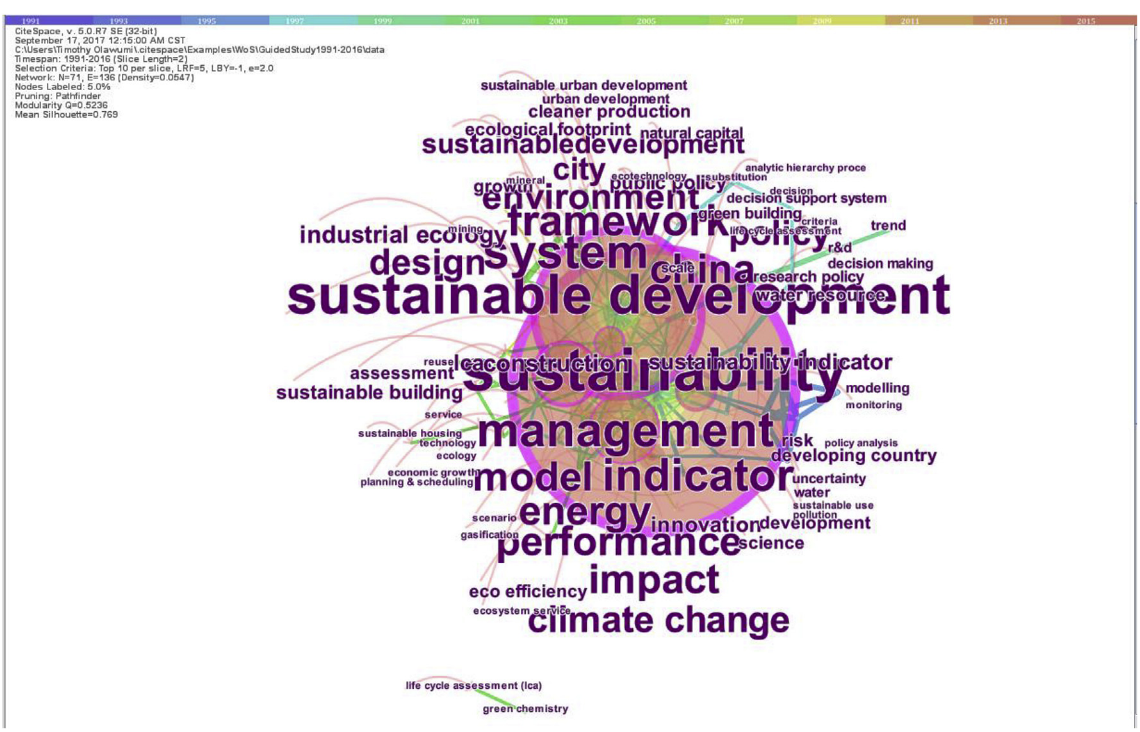

Fig. 6. Network of co-occurring keywords.

3.2.2. Network of co-occurring subject categories

The bibliographic records in WoS database are classified into subject categories depending on the scope of the corresponding journal, and an article could be assigned one or more subject categories. A network of co-occurring subject categories was developed as shown in Fig. 7 with 22 nodes and 61 links. The modularity, Q = 0.467 and with a mean silhouette value, S = 0.534. The node size for each subject category is a representative of the number of articles classified within each category in the dataset. Eight (8) subject categories with 100 articles or more were identified: Environmental sciences (1327 articles); green & sustainable science technology (1294 articles), environmental engineering (925 articles); civil engineering (410 articles), environmental studies (376 articles); construction & building technology (254 articles), ecology (203 articles), and water resources (161 articles). A significant sustainability research articles have been published under these subject categories.

Meanwhile, a look at the generated network and the color of the links reveals increasing publications in the area such as urban studies, computer science and interdisciplinary applications, architecture, ergonomics, and transportation. A study by Kerebih and Keshari (2017) which employed GIS to develop a numerical model for groundwater flow is a good example of the application of computer-based technology in technology research. Other studies (Khan et al., 2017; Stuermer et al., 2017; Wang et al., 2017; Xia et al., 2017) integrated technology-based application for sustainability research. For urban studies, Kamal and Proma (2017) modeled a quantitative ranking system for sub-urban Texas using GIS while Boren et al. (2017) proposed a sustainable transport system and roadmap for southeast Sweden. Meanwhile, Zamani et al. (2012) advocated for green architecture to reduce environmental pollution and Ruiz-Larrea et al. (2008) recommended that sustainable concepts (e.g., energy efficiency) be integrated into the design of structures as it would key to sustainable industrialization.

3.2.2.1. Citation bursts and centrality scores.

Moreover, some subject categories received citation bursts: environmental studies (burst strength = 23.98, 2014–2016), water resources (burst strength = 20.80, 1993–2009), construction & building technology (burst strength = 11.93, 1998–2002), chemical engineering (burst strength = 9.61, 2000–2007) and civil engineering (burst strength = 5.16, 2000–2002). Other subject categories with citation bursts are transportation (burst strength = 4.80, 2001–2010), ecology (burst strength = 4.44, 2009–2010) and industrial engineering (burst strength = 3.41, 2005–2010). These categories represent the most active areas in the evolution of sustainability research. Areas such environmental sustainability have received significant citations in recent years (2014–2016), and this aligns with the findings of Olawumi et al. (2017).

Also, some subject categories nodes received high betweenness centrality score as indicated by purple trims in the network (Fig. 7) and these include engineering (centrality = 0.77), civil engineering (0.63), environmental science & ecology (0.46), environmental sciences (0.26), environmental engineering (0.23), computer science (0.22), and construction & building technology (0.18). They connect the distinct aspects and concepts in the research field and are pivotal in the development of the field.

3.3. Co-citation analysis

Co-citation is the number of instances in which two items, say in this case, authors, documents, or journals are cited by a journal article (Chen, 2005a; Small, 1973) and described by Zhao (2017) as a "proximity measure" for the items. Indexed bibliographic records from WoS database are analyzed to produce the journal co-citation network, author co-citation network, and the document co-citation network.

3.3.1. Journal co-citation network

The 2094 WoS bibliographic records used for this study are

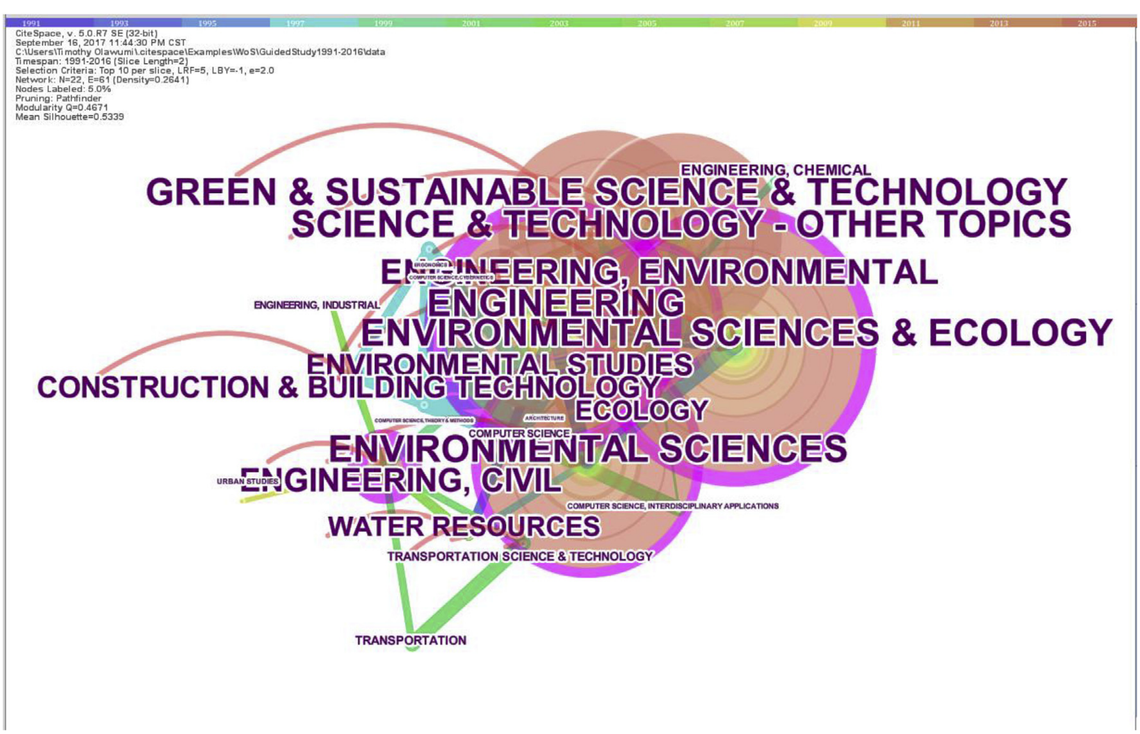

Fig. 7. Network of co-occurring subject categories.

sourced from a hundred and thirty-eight (138) journals; with thirty-seven (37) journals having at least ten (10) records in the research corpus. The structure of the published research corpus on sustainability studies is consistent with the Pareto principle in that 1764 articles (84 percent) are published in 28 journals (20 percent) which relate to an 84/20 rule for this study's research corpus. Table 4 shows the top 20 source journals for sustainability research along with their impact factors (IF). Meanwhile, the publishers in the USA and Netherlands account for six (6) and (5) journals of the top 20 source journals.

The references cited by each of the 2094 indexed research corpora were analyzed and was used to generate a network of co-cited journals with 69 nodes and 133 links to identify the most significant cited journal as shown in Fig. 8. The network has a modularity (Q = 0.53) and mean silhouette, S = 0.80. The node size is a representative of the co-citation frequency of each journal within the dataset. Moreover, the co-citation frequency of the top five most co-cited journals as revealed within the network are Journal of Cleaner Production (frequency = 722); Ecological Economics (frequency = 482), Journal of Environmental Management (frequency = 312); Science (frequency = 300), and Energy Policy (frequency = 278). These journals have made significant contributions to sustainability studies, and hence they are more cited by researchers in the field.

3.3.1.1. Citation bursts and centrality scores. Twenty-four (24) cited journals received citation bursts, out of which 11 journals received citation bursts of 10.0 and above as shown in Table 5.

The highlighted journals with citation bursts imply articles in these journals have received strong citations within the specified 'short' time span. Hence they are recommended together with the top 20 source journals for researchers in the field to follow.

Some nodes received high betweenness centrality scores as identified by purple trims in the network (Fig. 8). The network revealed source journals such as Ecological Economics (centrality = 0.80), Our Common Future (0.49), International Journal of Sustainable Development and World Ecology (0.32), Environmental Management (0.30), Water Science & Technology (0.26), Nature (0.24), Science(0.23), Energy Policy (0.20), Journal of Cleaner Production (0.13), Ambio (0.13) and Environmental Impact Assessment Review (0.12). These journals serve as links between distinct journals and acts as key intellectual hubs for academics, practitioners and government bodies.

3.3.2. Author co-citation network

The author co-citation analysis draws a pattern of relationships among distinct authors whose work appeared as cited references in the same publication. The dataset from the WoS records was used in generating the author co-citation network as shown in Fig. 9 with 98 nodes and 271 links. Also, the network has a modularity (Q = 0.529) and mean silhouette, S = 0.781. The node size is a representative of the co-citation frequency of each author within the dataset, and the links indicate an indirect cooperative alliance of the authors based on their co-citation frequency.

The ten (10) most cited authors were identified from the network, and it is noteworthy that five (5) of the ten most cited authors are international and regional governmental organizations, this finding is a great plus to the global drive for sustainable urban development. These authors include (*note: * headquarter of organization*): United Nations (frequency = 230, USA*), World Commission on Environment and Development [WCED] (frequency = 209, USA*), World Bank (frequency = 129, USA*), Rodrigo Lozano (frequency = 126, Sweden), Organization for Economic Co-operation and Development [OECD] (frequency = 110, France*), European Commission (frequency = 87, Belgium*), John Elkington (frequency = 54, Australia), Thomas Saaty (frequency = 50, USA), Donella Meadows (frequency = 44, USA) and Robert Yin (frequency = 41, USA). Also, there is affiliation-based diversity among the authors, which lends further credence to the evolution of sustainability research field. One of the authors in the person of Rodrigo Lozano also appeared among the top productive author in the field (Table 1) and based on WoS records his article on "*Envisioning sustainability three-dimensionally*" (Lozano, 2008) has received 117 citations as at the end of 2016.

3.3.2.1. Citation bursts and centrality scores. Authors with citation bursts with an increase in their articles' citations within a brief period were identified from the networks. These authors include: WCED (burst strength = 29.67, 1996–2012), European Commission (burst strength = 13.24, 2004–2018), IPCC (burst strength = 12.85,

Table 4
Top 20 source journals in the research corpus.

Source Journal	Host Country	Impact Factor (IF)	Publisher	Count	Percentage
Journal of Cleaner Production	USA	5.715	Elsevier Sci Ltd	496	23.69
Sustainability	Switzerland	1.789	MDPI AG	371	17.72
International Journal of Sustainable Development and World Ecology	USA	1.864	Taylor & Francis Inc	176	8.40
Sustainability Science	Japan	3.429	Springer Japan KK	56	2.67
Ambio	Sweden	3.687	Springer	52	2.48
Water Science and Technology	United Kingdom	1.197	IWA Publishing	46	2.20
International Journal of Life Cycle Assessment	Germany	3.173	Springer Heidelberg	46	2.20
Resources Conservation and Recycling	Netherlands	3.313	Elsevier Science BV	41	1.96
Proceedings of The Institution of Civil Engineers Engineering Sustainability	United Kingdom	0.341	ICE Publishing	40	1.91
Clean Technologies and Environmental Policy	USA	3.331	Springer	32	1.53
Building and Environment	United Kingdom	4.053	Pergamon-Elsevier Science Ltd	29	1.38
Water Resources Management	Netherlands	2.848	Springer	27	1.29
Ecological Engineering	Netherlands	2.914	Elsevier Science BV	27	1.29
Journal of Industrial Ecology	USA	4.123	Wiley-Blackwell	25	1.19
Sustainable Cities and Society	Netherlands	1.777	Elsevier Science BV	24	1.15
Environment Development and Sustainability	Netherlands	1.080	Springer	24	1.15
Energy and Buildings	Switzerland	4.067	Elsevier Science SA	24	1.15
Transportation Research Record	USA	0.598	Natl Acad Sciences	21	1.00
Current Opinion in Environmental Sustainability	United Kingdom	3.954	Elsevier Sci LTD	21	1.00
Water International	USA	1.538	Routledge Journals, Taylor & Francis LTD	20	0.96

Note: Impact Factor (IF) as at the year 2016.

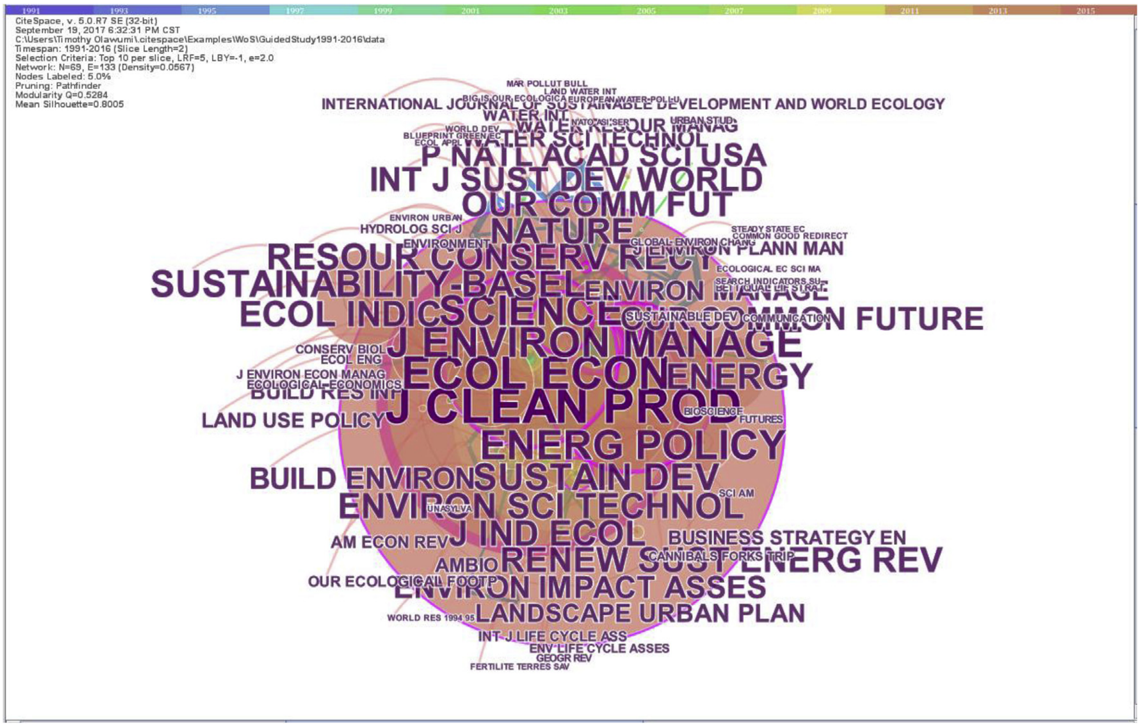

Fig. 8. Journal co-citation network.

Table 5
Journals' citation bursts.

Journals	Burst strength	Span
World Commission on Environment and Development [WCED]	47.71	1996–2009
International Journal of Sustainable Development & World Ecology	37.63	1997–2010
Building and Environment	24.59	2007–2012
Environmental Science & Technology	23.50	2011–2014
Proceedings of the National Academy of Sciences	23.19	2013–2014
Environmental Impact Assessment Review	21.34	2009–2012
Journal of Industrial Ecology	19.08	2013–2014
Nature	18.23	2011–2014
Journal of Environmental Management	17.55	1993–2008
Landscape and Urban Planning	14.34	2011–2012
Sustainable Development	11.11	2013–2016

2011–2014), UNESCO (burst strength = 12.26, 2013–2014), and Mathis Wackernagel (burst strength = 11.49, 1996–2010), Johan Rockstrom (burst strength = 11.30, 2013–2014). Other authors with citation bursts are Karl-Henrik Robert (burst strength = 11.24, 1998–2008), World Bank (burst strength = 9.77, 2004–2012), David Pearce (burst strength = 9.53, 1993–2000) and Donella Meadows (burst strength = 8.85, 2013–2014). Articles, documents, and communique issued by these authors are worth following, and their works have influenced the development of sustainability research and the idea of the sustainable urban city.

Moreover, some nodes with high betweenness centrality were identified from the network (Fig. 9) as indicated by purple trims. Authors with high betweenness centrality scores are Mathis Wackernagel (centrality = 0.46), WCED (0.22), OECD (0.19), Rodrigo Lozano (0.17), Donella Meadows (0.15), and World Bank (0.15). Other authors with high centrality scores are Gordon Mitchell (centrality = 0.13), Robert Costanza (0.12), Joel Heinen (0.12), European Commission (0.12) and Karl-Henrik Robert (0.11). These authors are the influential and pivotal contributions to sustainability research and help connect the different research communities. Zhao (2017) noted that it is an unlikely occurrence for an author to receive a high betweenness centrality score and have high citation count and that in cases of such rare instances then such author(s) have made significant impacts in such field.

3.3.3. *Document co-citation network*

Document co-citation analysis evaluates the references cited by the 2094 bibliographic records towards understanding the intellectual structures of sustainability knowledge domain. Citation records from the WoS records reveal that 35 cited documents received a hundred or more citations as at the end of 2016 as shown in Table 6. Also, 13 articles (37 percent) of the top 35 top cited articles were published in the *Journal of Cleaner Production* which was also the source journal with most publication on sustainability topics. Mohanty et al. (2002) who received the highest citations count of 770 citations examined the challenges and opportunities in using natural fibers or its polymers which are based on renewable materials to resolve environmental issues in the industry. The article also advocated production of materials and products from a mix of both renewable and nonrenewable sources and continuous

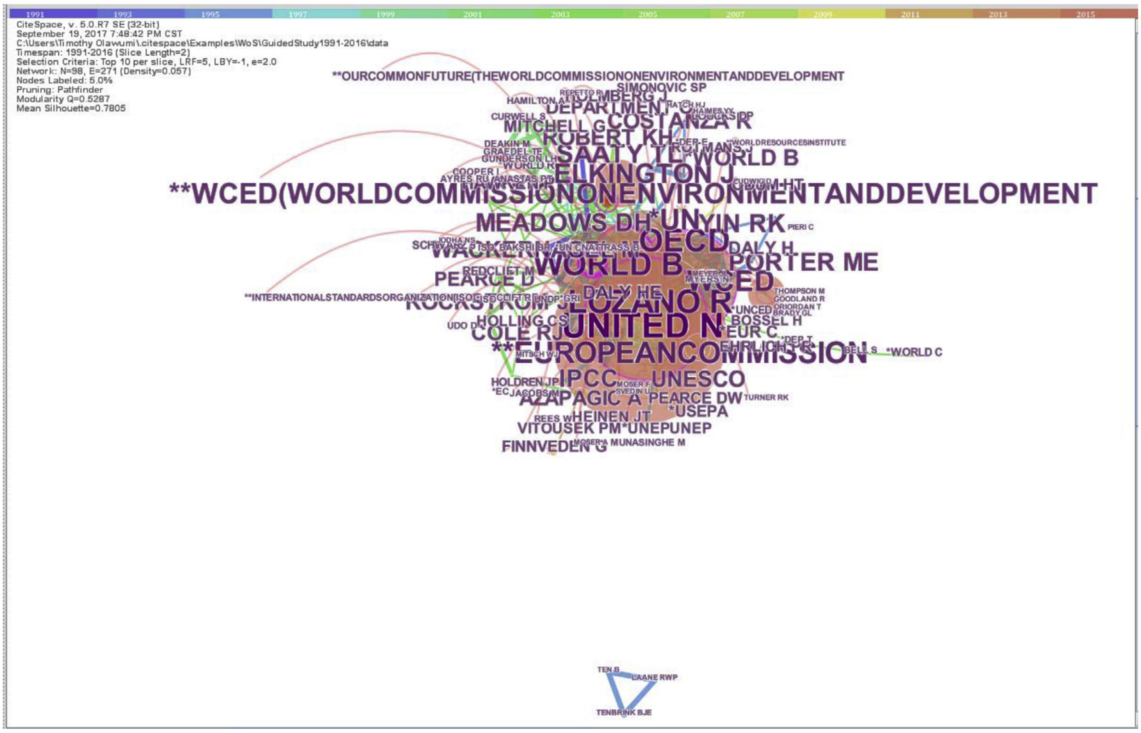

Fig. 9. Author co-citation network.

Table 6
Top 35 cited articles based on WoS citation metric.

S/N	Article	Total citations	S/N	Article	Total citations	S/N	Article	Total citations
1	Mohanty et al. (2002)	770	13	Luttropp and Lagerstedt (2006)	168	25	Liu et al. (2008)	116
2	Nicol and Humphreys (2002)	358	14	Sophocleous (2000)	167	26	Troschinetz and Mihelcic (2009)	110
3	Kennedy et al. (2007)	311	15	Glavic and Lukman (2007)	163	27	Baddoo (2008)	109
4	Ortiz et al. (2009)	271	16	Fiksel (2003)	162	28	Krotscheck and Narodoslawsky (1996)	107
5	Azapagic (2004)	233	17	Lozano (2006)	140	29	Jeon and Amekudzi (2005)	106
6	Robert et al. (2002)	226	18	Schneider et al. (2010)	135	30	Cole (1999)	106
7	Folke et al. (1997)	215	19	Krajnc and Glavic (2005)	131	31	Kloepffer (2008)	104
8	Tukker and Tischner (2006)	212	20	Mitchell et al. (1995)	125	32	Corinaldesi and Moriconi (2009)	103
9	Damtoft et al. (2008)	208	21	Brown et al. (2009)	122	33	Makropoulos et al. (2008)	102
10	Labuschagne et al. (2005)	196	22	Adger et al. (2002)	120	34	Lozano and Huisingh (2011)	100
11	Cucek et al. (2012)	174	23	Dovi et al. (2009)	118	35	Shrestha et al. (1996)	100
12	Maxwell and van der Vorst (2003)	173	24	Lozano (2008)	117			

research in that direction.

Moreover, Nicol and Humphreys (2002) investigated the theoretical concept of thermal comfort in buildings and recommended several parameters such as the best comfort temperature, indoor temperature and the advocated the need for the development of sustainability criteria for adaptive thermal comfort in facilities. Meanwhile, Kennedy et al. (2007) carried out a comparative analysis of the urban metabolism of eight cities across five continents and discovered an increased metabolism with respect to water, solid waste, energy and air pollutants flow which threatens the sustainability of these cities. They advocated for the development of strategies to reduce its impact on the ecosystem.

A document co-citation network (see Fig. 10) was generated from the WoS dataset which resulted in 176 nodes, and 549 links and each node represented a cited document and labeled with the name of the first author and the year of publication, while the link signifies the co-citation relationship between two articles. Also, the network has a modularity ($Q = 0.741$) and mean silhouette, $S = 0.538$. The node size for each document is a representative of the co-citation frequency of the node article. The node documents in this network (Fig. 10) are in the distinct set of 74,998 articles cited by the 2094 bibliographic records in this study and may not constitute part of the indexed corpus. The top six (6) co-cited documents with more 30 or more co-citation counts are: WCED (1987) (frequency = 178), Rockström et al. (2009) (frequency = 45), Lozano (2006) (frequency = 39), Gardiner (1995) (frequency = 38), Lozano (2010) (frequency = 30), and Seuring and Müller (2008) (frequency = 30).

3.3.3.1. Citation bursts and centrality scores. Several documents (19 articles) received citation bursts, of which the top 10 articles with citation bursts were identified and include: Gardiner (1995) (burst strength = 11.12, 2013–2016), Rockström et al. (2009) (burst strength = 10.65, 2011–2012), Robert et al. (2002) (burst strength = 10.07, 2005–2012), Lozano (2010) (burst strength = 9.56, 2013–2016) and Seuring and Müller (2008) (burst

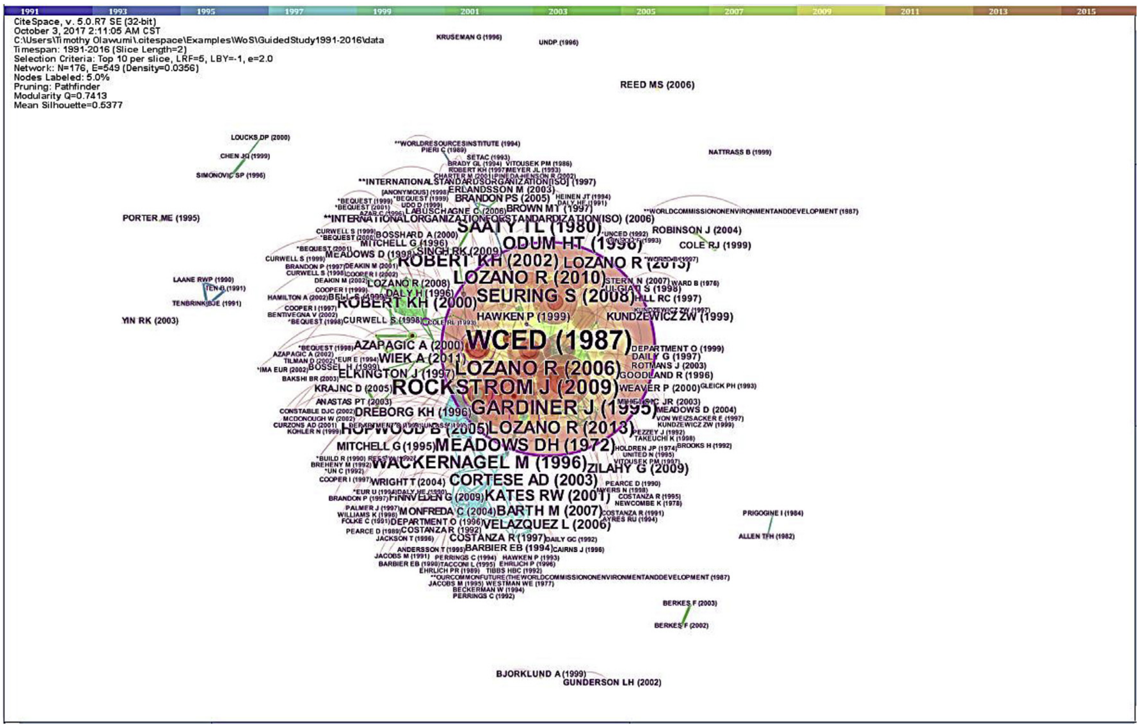

Fig. 10. Document co-citation network.

strength = 9.56, 2013–2016). Articles such as Lozano (2006) (burst strength = 9.34, 2013–2016), WCED (1987) (burst strength = 9.34, 2005–2012), Robèrt (2000) (burst strength = 6.22, 2005–2011), Barth et al. (2007) (burst strength = 5.70, 2013–2014), and Cortese (2003) (burst strength = 5.49, 2009–2014) received increased citations over a short period. Lozano (2010) research focused on integrating SD studies in curricula of universities and schools and used Cardiff University as a case study, and the findings revealed a more balanced and holistic course delivery. Also, Lozano (2006) presents challenges that could be faced by institutions who decide on integrating SD concepts in their curriculum and highlight ways of resolving such issues.

Meanwhile, some documents also have high betweenness centrality scores as denoted by purple trims in the network (Fig. 10) and these include: WCED (1987) (centrality = 0.70), Elkington (1997) (0.45), Wackernagel et al. (1999) (0.35), Mitchell (1996) (0.28), Meadows et al. (1972) (0.19) and Mitchell et al. (1995) (0.17). These documents are the fundamental bedrock of sustainability research and form the base of most sustainability themes.

3.4. Clusters analysis

Cluster analysis is an exploratory data mining technique used in this study to identify and analyze the salient terms and context, its trends and their interconnection within the sustainability research field. CiteSpace was used as the tool to get insight into the distribution and structures of the research themes over the years. These terms, themes or context are of distinct classification, and the Log-Likelihood ratio (LLR) was used as the clustering technique due to its ability to generate high-quality clusters with high intra-class similarity and low inter-class similarity. Hence, keywords or terms grouped within a group must be related to one another and different from keywords in other categories. Therefore, cluster analysis facilitates the classification of a large corpus of research data into manageable units and helps to deduce information about each group or cluster objectively.

Clusters defined in this study are in two parts: (i) keyword clusters-which are based on the classification of the author keywords and the keywords plus (journal's indexed terms); and (ii) document co-citation clusters – which are based on keywords in cited references or documents.

3.4.1. Keywords clusters

Nine salient keyword clusters were identified in the clustering of the indexed corpus keywords as defined by the LLR algorithm. The keyword clusters as shown in Table 7 are labeled and sorted by size; the cluster size is the number of member in each cluster. Hence, cluster #0 "sustainable development" and #1 "sustainable indicator" with 12 members each are the cluster IDs with the largest group size and cluster #8 "green chemistry" been the smallest sized cluster with two (2) members. Majority of the relationships (as depicted by green links) in clusters #0, #1, #2 and #4 are formed between 2003 and 2006 while some links in clusters #1 and #2 are formed between 2015 and 2016. The relationships between clusters #3 and #5 (depicted by blue links) are mostly developed in the early days of sustainability research (1993–1996). It is evident from the keyword cluster network (Fig. 11) that recent development in sustainability research has centered around clusters #1 and #2, as shown by the orange and red links.

The silhouette scores for the clusters ranges from 0.558 to 1.000 which shows the members of the cluster falls well within their group. The silhouette metric according to Rousseeuw (1987) measures and compares the average homogeneity (tightness and separation) of a cluster and could be used to validate a cluster. Meanwhile, the mean year depicts whether the cluster is formed by recent articles or old ones. Clusters #3, #5 and #7 are formed by relatively old articles than other clusters.

3.4.2. Documents co-citation clusters

Twenty-one (21) document co-citation clusters were generated

Table 7
Keyword clustering of Sustainability research (1991–2016).

Cluster ID	Size	Silhouette	Cluster label (LLR)	Alternative label	Mean year
#0	12	0.588	Sustainable development	LCA; economic growth	2000
#1	12	0.749	Sustainability indicator	Framework; analytic hierarchy process	2003
#2	11	0.569	Public policy	Research policy; R & D	2002
#3	10	0.617	Impact	Performance; pollution	1998
#4	9	0.860	China	Water resource; ecological footprint	2002
#5	6	0.933	Indicator	Monitoring; sustainable use	1995
#6	5	0.832	Management	Perspective; strategy	2005
#7	4	0.774	Natural capital	Decision; cost benefit	1995
#8	2	1.000	Green chemistry	Metrics; hydrocarbon	2003

Fig. 11. Keyword clusters network.

from the research power network using the LLR algorithm as shown in Fig. 12. Meanwhile, only 12 clusters (see Table 8) are significant while the other nine (9) clusters have zero silhouette scores and just one (1) cluster member, hence are not counted as salient clusters in sustainability research. The 12 salient and significant clusters are sorted by size as shown in Table 8. Cluster #0 "water management" with 38 members is the largest cluster of proportion and while clusters #12 to #20 with just one member are the smallest clusters by size. Most of the relationships in the clusters as depicted by light blue and green links revealed that most of the relationships within the clusters are formed between 1994 and 2001; and this timespan forms the period in which the bedrock of the sustainability research field was laid.

The silhouette metric scores for the 12 salient document co-citation clusters ranges from 0.758 to 1.000 which shows relatively higher scores than the keyword clusters and shows that there is consistency within the cluster members. Meanwhile, as regards the clusters' mean year, most of the clusters are formed by relatively old documents, and this is consistent with the fact that the foundation of sustainability research was formed from the mid-1990 to early 2000s. As shown in Table 5, each salient cluster has representative documents which are the journal articles or documents with the most co-citation frequency within each cluster. The representative document influences the labeling of each cluster and are also well cited in the field, hence worth following.

3.5. Geospatial analysis

A geospatial analysis of sustainability research corpus was carried out with the generation of Keyhole Markup Language (KML) files using CiteSpace. These KML files are then converted into animated maps using Google Earth® application which ease its visualization functionality for the location (or origins) of the authors of the study's indexed sustainability research corpus and highlighting the authors' published documents from 1991 to 2016 at a specific location.

Fig. 13 shows the geospatial visualization of published sustainability research documents across Europe spanning the period from 1991 to 2016. The red nodes on the map (see Fig. 13) are the origins of the published works while the lines (of differing colors such as green, yellow, orange, red, pink and purple, etc.) connects the location of documents of the same year. Some of the nodes are a

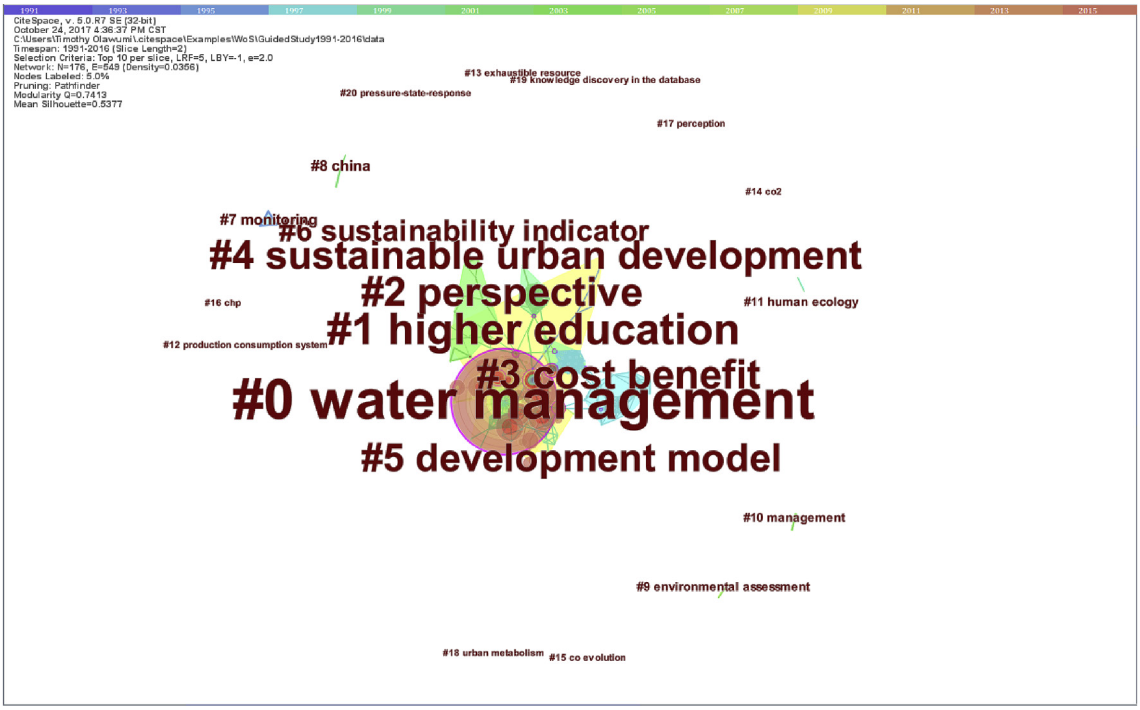

Fig. 12. Document co-citation clusters.

Table 8
Documents co-citation clusters of Sustainability research (1991–2016).

Cluster ID	Size	Silhouette	Cluster label (LLR)	Alternative label	Mean year	Representative documents
#0	39	0.827	Water management	Flood protection; hydrological data	1994	WCED (1987)
#1	24	0.852	Higher education	University; campus sustainability	1999	Lozano (2006)
#2	21	0.758	Perspective	Sustainable consumption and production; systemic perspective	2001	Rockström et al. (2009)
#3	21	0.951	Cost-benefit	Substitution; conservation	1992	Costanza et al. (1998)
#4	20	0.992	Sustainable urban development	Evaluation; classification of assessment method	1999	Mitchell (1996)
#5	19	0.945	Development model	Environmental protection; public participation	1995	Wackernagel and Rees (1998)
#6	11	0.967	Sustainability indicator	Guideline; service	1999	Azapagic and Perdan (2000)
#7	3	1.000	Monitoring	Modelling; policy analysis	1990	Ten Brink et al. (1991)
#8	3	1.000	China	Water resources management; urban water supply	1998	Loucks (2000); Simonovic (1996)
#9	2	1.000	Environmental assessment	Building assessment; stakeholder participation	2001	Robinson (2004)
#10	2	1.000	Management	Himalaya; India	2002	Berkes et al. (2003)
#11	2	1.000	Human ecology	Hierarchy theory; diversity	1983	Prigogine and Stengers (1984)

combination of several linked nodes within the same location; this is revealed when such nodes are clicked on the animated map.

Also, when any of the nodes is clicked, the pop-up dialog is revealed (see Fig. 14) detailing the documents linked to the specified node. Such information detailed as a link, the name of the first author, year of publication and the journal of the published document. When a specific document link is clicked, the Google Earth® app will redirect the user to the source (web link) of the published document or article. The animated map is handy for academics and practitioners, as a more dynamic alternative to scientific databases such as Scopus or ISI Web of Science in the quest to ease the identification of sustainability research publications within a city or region. Hence, using this study animated map would be useful in tracking the trend of articles published over the years in the various countries. The dataset for the geospatial map (*including the dynamic geospatial map and the KML files*) is accessible as published via Mendeley data, https://doi.org/10.17632/sv23pvr252.1 (Olawumi and Chan, 2017) and also as an e-component with this paper.

4. Identification of the salient research clusters

The salient clusters in sustainability research field as shown in Table 8 are cluster #0 to cluster #11, however, to conserve space, the review centered on seven (7) clusters (clusters #0 to cluster #6) with a minimum of 11 cluster members. Cluster #0 "water management" has 39 members and the representative document is a communique published by the United Nations (WCED, 1987) which detail the opinions, reflections of the Brundtland conference on environment and SD. The report gave the first definition of sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987). It further for an actualization of SD, there must be the identification of needs and the limitations that might hinder the capacity to meet such needs. The report by

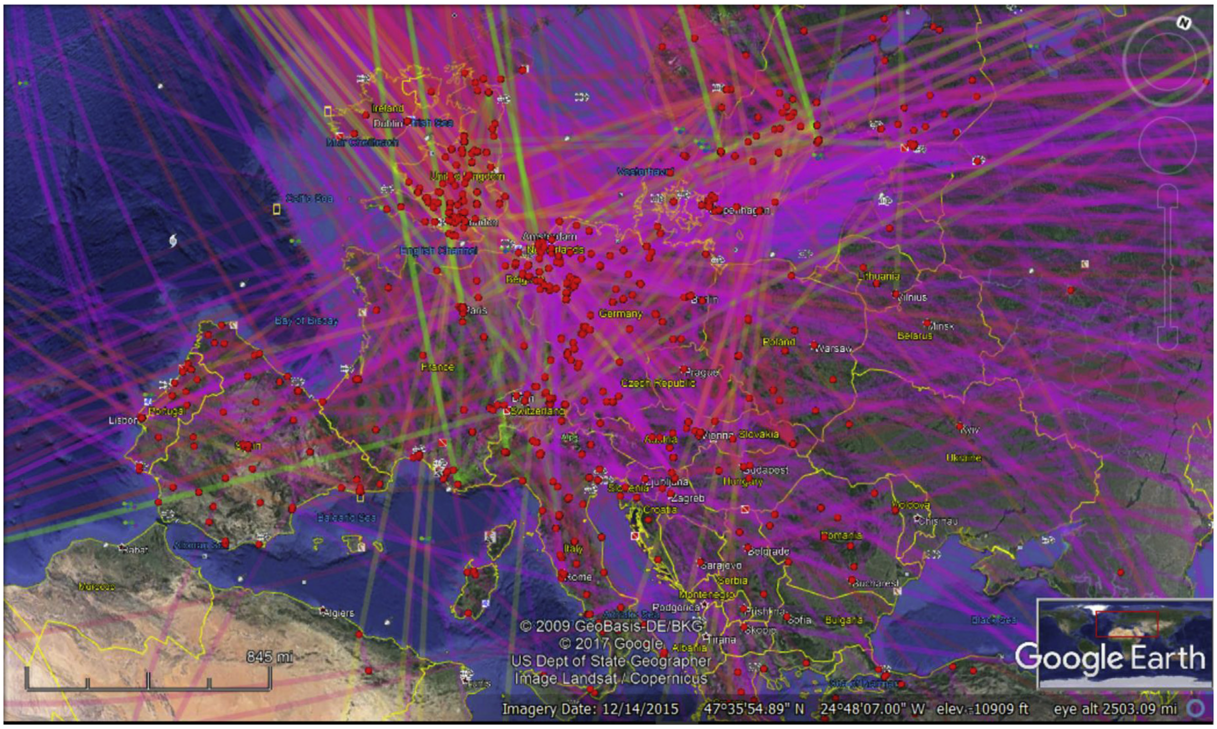

Fig. 13. Geospatial visualization of published research documents (Europe).

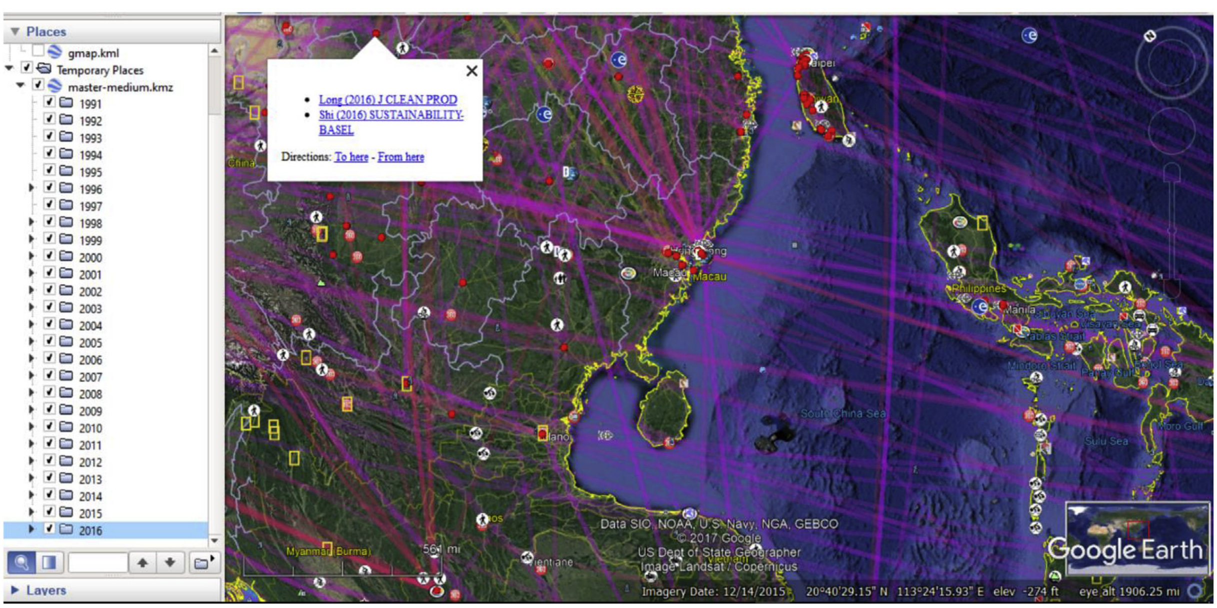

Fig. 14. Geospatial visualization of published research documents (showing part of China).

WCED (1987) also highlighted challenges faced in the realization of sustainable urban development which includes issues related to energy, industrial growth, the ecosystem, urban problem in developing countries and resource base (such as water management, land use, human resources, technological support) among others.

Meanwhile, a study by Holden et al. (2014) shows no country has achieved the four thresholds of sustainable development as identified in the Brundtland report, with many nations far off the minimum target. Accordingly, they argued for the integration of technology and behavioral changes of stakeholders for the actualization of sustainable urban development by 2030. Cluster #1 “higher education” had 24 members with Lozano (2006) has the representative document for the cluster. Lozano (2006) work focused on how the SD concepts proposed in the Brundtland report can be integrated into universities and colleges. Accordingly, Lozano (2006) highlighted the possible resistance the idea of institutionalizing SD could face from the stakeholders and presented strategies to overcome these challenges to integrate the SD ideas and concepts in universities' policies, system, and activities and ensure campus sustainability.

Cluster #2 "perspective" had 21 members with Rockström et al. (2009) has the representative document for the cluster. Rockström et al. (2009) proposed a novel approach to serve as guideline or preconditions for current and future urban development. They argued that defining boundaries for human development which help to prevent catastrophic environmental changes and ensure the stability of the built environment. Cluster #3 "cost-benefit" also had 21 members with the representative document published by Costanza et al. (1998, 1998) attempted to make an analogy between the ecosystem functions and ecosystem services and argued that they contribute the social well-being of humans as well as represent a significant part of the economic value of the planet earth. The article also highlighted various valuation method to estimate the ecosystem services and recommended the need to safeguard the scarce ecosystem services to prevent its misuse.

Cluster #4 "sustainable urban development" had 20 members with the representative document published by Mitchell (1996, 1996) outlined the challenges and limitations faced in the application of SD index and the various sustainability principles which have been hindering the implementation and promotion of SD at the local level. Also, Mitchell (1996) noted that there is no specific measurement tool for assessing SD. Although some building rating systems such as LEED, BREEAM, BEAM Plus and others have been developed since then; yet these tools focused mainly on some aspect environmental sustainability with gaps to be filled in areas such as social and economic sustainability constructs of SD.

Cluster #5 "development model" had 19 members with the representative document published by Wackernagel and Rees (1998, 1998) relayed the need for humans to reduce its ecological impacts on the environment and categorized the challenge being faced in achieving it, as that has more to do with human's social behavior than a technical or environmental crisis. A planning model was proposed by Wackernagel and Rees (1998) to serve as a tool for the measuring humans' ecological footprints. Cluster #6 "sustainability indicator" had 11 members with the representative document published. Azapagic and Perdan (2000, 2000) proposed a framework featuring sustainability indicators that cover the three pillars of SD-social, economic and environmental sustainability. Although the sustainability indicators (SI) were designed for its application for the whole industry, it would be more useful and functional when refined to specific sectors of the built environment. The SI can only be implementable when its users or stakeholders adopt appropriate strategies by evaluating alternative options. One of such multi-criteria decision-making technique is the Analytic Hierarchy Process (AHP) or the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS).

5. Conclusions and future directions

The concept of sustainability and sustainability development have received increasing global attention and consideration from government agencies, academics, practitioners and international organizations. It has evolved from its concept statements stated in the 1987 Brundtland commission report to the integration of technological tools to enhance its implementation. This study provides a scientific visualization method to analyze 2094 WoS bibliographic records using scientometric techniques such as co-author analysis, co-word analysis, co-citation analysis, clusters analysis, and geospatial analysis. These methods were used to an in-depth understanding of the status quo and trend in sustainability research field.

An analysis of the research publication trend revealed a steady increase in the number of the bibliographic records of the years which shows more efforts and resources are devoted to sustainable urban development. Also, as regards general productivity and contribution among authors, findings revealed Donald Huisingh, Rodrigo Lozano, and Yong Geng as the top three lead authors in the field. These authors along with Tsuyoshi Fujita, Robert Axelsson, and Per Angelstam are the central authors within their research circuits. However, only Donald Huisingh and John Cairns received high citation bursts over a short period, although John Cairns does not have many publications.

Meanwhile, in terms of distribution of the publications on sustainability, the majority of the journal articles originated from the United States, China, United Kingdom, and Canada. The Chinese Academy of Sciences, China PR, Delft University of Technology, Netherlands, and the University of British Columbia, Canada are the most productive institutions in sustainability research projects. Also, the diversity of the highly cited authors from various regions and organizations reveals the evolution of sustainability research and demonstrates its widely flourishing acceptance. Also, there are some active and connected exchange platforms between the countries and institutions.

Furthermore, key subject categories such as "environmental sciences," "green & sustainable science technology," "environmental engineering," and "civil engineering" have had considerable influence on the structure and development of sustainability research and help to connect the distinct aspects and concepts in the research field. In terms of keywords, "sustainability", "sustainable development", "management", "system", "indicator", and "framework" had the most frequency; while "impact", "environment", "climate change", "design", "policy", "city" and "energy" received the citation bursts in recent years (2012 to date). It is consistent with the fact that more efforts are devoted to these critical research themes in the past years which are pivotal in achieving a sustainable urban development.

The core and high impact journals such as Journal of Cleaner Production, Sustainability, International Journal of Sustainable Development & World Ecology, Sustainability Science, Ambio, and Water Science & Technology have published significant findings in sustainability research. Some of these journals also received co-citation frequency and high citation bursts in the past years and a considerable number of the 35 highly cited articles are published in these journals. Also, the top 20 source journals have a minimum of 1.00 impact factor. The document co-citation analysis reveals Mohanty et al. (2002), and Nicol and Humphreys (2002) have the most cited documents while publications by the Brundtland Commission, WCED (1987) received the highest co-citation frequency along with documents such as Rockström et al. (2009) and Lozano (2006). Meanwhile, documents such as Gardiner (1995), Seuring and Müller (2008), Lozano (2006), Barth et al. (2007) and Cortese (2003) received high citation bursts in recent years (2014–2016).

Cluster analysis was used in this study to analyze and conceptualize the salient terms and context of sustainability research using two approaches of keyword and document co-citation clusters. Nine (9) keyword clusters and twenty-one (21) document co-citation clusters were identified based on the indexed research corpus. These emerging trends and hot-topics related to sustainability research can be summarized as sustainable urban development, sustainable indicators and impact, water management, environmental assessment, strategy, public policy and monitoring, cost-benefit analysis, stakeholders' participation, campus sustainability and human ecology.

The discussion section on the salient research clusters reveals the evolution of sustainability research field from the definition of its concepts in the Brundtland Commission report to the recent development of models and sustainability indicators to enhance the actualization of sustainable urban development. Moreover, a geospatial analysis and visualizations of the research corpus produced a useful and dynamic animated map to improve the ease of identifying the sustainability researchers' origin and highlighting the authors' published documents for a specified year and region.

The study provided valuable information to researchers, practitioners and governmental bodies in the field of sustainability research. The power research networks offered valuable insight and in-depth understanding of the key scholars, institutions, state of the research field, emerging trends, salient topics and an animated map for researchers. Also, the study helped to crystallize out information and key findings to enhance the implementation of a holistic sustainability to achieve SD. It also identified the key authors and institutions who they can consult to assist in developing sustainability policies or templates for their applications.

The scientometric analysis and visualization had helped to reflect the global picture of sustainability research accurately, and these tools could be useful to visualize the emerging trends in other research fields. Meanwhile, it is recommended for researchers to focus more attention on the emerging sustainability research themes such as ecological footprint, LCA, sustainability assessment model, policy analysis and monitoring, evaluation metrics, stakeholder participation. The findings will be applicable to (1) government agencies and corporate organizations in their policy formulation and consultation as well as partnering with the key institutions identified in the study, (2) graduate students in identifying gaps and progresses made in the sustainability research area (3) academics in networking with other researchers in their areas of specializations (4) industries or sectors such as the construction industry in identifying and enhancing their level of implementation of sustainability to achieve a sustainable smart city initiative.

Future studies on sustainability research themes may focus on the application or integration of innovative technologies such as BIM, augmented reality, radio-frequency identification (RFID), geographical information system (GIS) among others to enhance the sustainability of the built environment towards the achievement of sustainable smart cities. Other aspects for future research may center on the application of sustainability knowledge in waste management, reduction of carbon footprint, campus sustainability, green neighborhoods as well as developing country-specific sustainability evaluation index.

Acknowledgement

This research study is supported through funding by the Sustainable City Laboratory under the auspice of the Department of Building and Real Estate, The Hong Kong Polytechnic University, Hong Kong. The team of reviewers and the editor are appreciated for their comments and suggestions to improve the paper.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jclepro.2018.02.162.

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