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Review

# Sustainable infrastructure: A review and a research agenda

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A B S T R A C T

This paper proposes a taxonomy of themes and a research agenda on sustainable infrastructure, with a focus on sustainable buildings (SB) and green infrastructure (GI). The citation databases of Web of Science formed the basis for a novel strategic thematic analysis of co-citation and co-occurrence of keywords with a longitudinal identification of themes during the last two decades (from 1995 to 2015) of an emerging and ever growing research area. SI is a multidisciplinary endeavour, including a diversified array of disciplines as general engineering, environmental ecology, construction, architecture, urban planning, and geography. This paper traces that the number of publications in SI is growing exponentially since 2003. Over 80% of total citations are concentrated in less than 10% of papers spread over a large number of journals. Most publications originate from the United States, Europe, Australia, and Asia. The main research streams in SI are green infrastructure, sustainable buildings, and assessment methods. Emerging and prevailing research themes include methodological issues of cost-effectiveness, project management and assessment tools. Substantive issues complement the research agenda of emerging themes in the areas of integration of human, economic and corporate social responsibility values in environmental sustainability, urban landscape and sustainable drainage systems, interdisciplinary research in green material, integrated policy research in urbanization, agriculture and nature conservation, and extensions of Green Building (GB) and GI to cities of developing countries.


**Contents**



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## 1. Introduction

Since the first attempts to assess infrastructure's environmental impact in the late 1980's, the sustainable infrastructure (SI) field has gradually been broadening its scope from green building (GB) to green infrastructure (GI) and from environmental sustainability (ES) to the triple bottom line (TBL) of economic, social, and environmental sustainability (Ferrer et al., 2016). The term environment means in this paper "surroundings in which an organization operates, including air, water, land, natural resources, flora, fauna, humans, and their interrelationships" (ISO, 2015). GI is "a patchwork of natural areas that provides habitat, flood protection, cleaner air, and cleaner water;" it relates mainly to the "storm water management systems that mimic nature soak up and store water" (Fiksel et al., 2012). Sustainable development as stated in the Brundtland report is "… development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987).

Although green building (GB) and green infrastructure (GI) are often interchangeably related to SI topics (e.g. Kevern, 2011; Naumann et al., 2011), they carry different meanings. Kibert (2016) defined green buildings as "… healthy facilities designed and built in a resource-efficient manner, using ecologically based principles." GI is defined "… as planned and managed natural and semi natural systems that provide products and services with environmental, social, economic, and/or health benefits" (Dimuro et al., 2014). Sustainable infrastructure (SI) supports the buildings, engineering works, and infrastructure that are essential for the society survival (Boyle et al., 2010). Consequently, SI topics are of the upmost relevance for the wellbeing of people, the economy and the earth, which includes considerations about natural hazards (Padgett et al., 2009).

SI research can currently be ascertained by the large number of literature reviews in the subject, appearing in citation databases. A query in the titles, abstract, and keywords of Web of Science (WoS) database with the search keywords "sustainab* infrastructure" OR "sustainab* construction" OR "sustainab* building" OR "green construction" OR "green building" OR "green infrastructure, " after restricting to English language titles and setting type of documents to review only, resulted in the retrieval of 122 reviews. This result attests the vigor and relevance of the field. Narrowing the analysis to contemporary reviews appearing after 2013, the most prominent themes outlined in broad categories include energy (e.g., Pombo et al., 2016; Yu and Su, 2015; Hong et al., 2015; Fumo, 2014; Pietrosemoli and Rodríguez Monroy, 2013), built materials (e.g., Oyelami and Van Rooy, 2016,; Govindan et al., 2015; Achal and Mukherjee, 2015; Bories et al., 2014; Memon, 2014; Madurwar et al., 2013), evaluation and assessment tools (e.g., Wu et al., 2016; Suzer, 2015; Pushkar and Shaviv, 2014, 2014; Alyami et al., 2013; Pushkar and Shaviv, 2014; Alyami et al., 2013), emissions (e.g., Wang et al., 2014a), water system (e.g., Ma et al., 2015; Rashidi et al., 2015), and ecosystems services (e.g., Salmond et al., 2016; Ziter, 2015). In a literature review focusing predominantly on environmental issues related to water and sustainability, Zhou et al. (2013) proposed a similar taxonomy in broad categories of SI topics published in 2012 in peer reviewed journals and conferences. The categories were sustainable water, wastewater utilities and treatment, sustainable water resources management, industrial and corporate approaches to sustainability, storm water and green infrastructure, energy in wastewater industry, climate change and water reuse, life cycle assessment applications, and sustainability rating systems.

Although several recent reviews have covered specific topics related to SI, none provides a general overview of main themes and a longitudinal analysis of how they have evolved in the recent past, as intended in the present review. This longitudinal approach differs from previous literature reviews in two important ways. The scope is broader and intended to depict the landscape of research in SI, rather than to focus on a specific topic or subtheme. It retraces the evolution of themes in time, in a dynamic analysis showing the progression of main SI research streams.

The purpose of this paper is to provide a general overview of the research themes in the area of SI and to portray its evolution in time, with the objective of answering three specific research questions (RQs). First, which are the main themes in the area of sustainable infrastructure? Second, are the themes stable in time, and if not, how have they evolved? Third, what are the emerging themes and the future research directions in sustainable infrastructure?

The structure of the paper is as follows. After this introduction, there is a description of the materials and methods of the systematic literature review and bibliometric analysis. The presentation of results of the co-citation and co-word analysis ensues and describes a longitudinal taxonomy of themes. The discussion of main findings and the research agenda conclude the paper.

## 2. Research methods

Basic bibliometric analysis are combined with co-citation and co-word analysis in an objective and transparent manner following the procedures outlined in Thomé et al. (2015, 2016). The next subsections describe the methods of the systematic literature review, citation, co-citation, and co-word analysis.

### 2.1. Systematic literature review

A seven-step approach based on Cooper (2010) is adapted to conduct the systematic literature review, following the guidelines contained in Thomé et al. (2016). The first step is the planning and formulation of the problem. A research team was instituted from the onset and the team comprises the co-authors of this paper. The co-authors discussed the conceptualization of sustainable infrastructure, they formulated the research questions, and they defined the research expected outcomes: the taxonomy of themes, the description of their evolution in the past 20 years, and the future research directions. The second step is the search strategy definition, which includes selection of computerized databases, search keywords, criteria to include or to exclude papers in the review, coders' training, and assessment and discussion of disagreements among reviewers.

The approach to search and to select studies was based on von Brocke et al. (2009) and Thomé et al. (2012, 2014). The Thomson Reuters' Web of Science™ (WoS) database was selected. The Scopus citation database could be selected as well and should provide similar results in the scientific field of natural sciences and engineering (NES) (Mongeon and Paul-Hus, 2016). WoS was preferred over the Scopus citation database due to the following reasons. First, despite a larger coverage of journals in Scopus citation database overall, WoS has a larger number of unique journal titles in NES (Mongeon and Paul-Hus, 2016). Second, it offers a more thorough coverage of older literature (Hlwik, 2016). Finally, the Histcite™ software interact directly with WoS and eases the analysis of citation networks, as applied in this paper.

The third and fourth steps are data gathering and quality evaluation. The WoS database was exported to Histcite™ for basic statistics and bibliometric analysis. The fifth and sixth steps of the protocol adopted for this systematic literature review are data analysis and interpretation. The seventh is the result presentation (Thomé et al., 2016). Data analysis followed an inductive approach (Seuring and Müller, 2008). Basic statistics on publication years, disciplinary fields, journals, research institutions, and impact factors were analysed with Histcite™. They were complemented with the use of Pajek (De Nooy et al., 2004) for co-citation network visualizations and SciMAT software (Cobo et al., 2012a) for the identification and longitudinal analysis of themes based on user's and WoS keywords. SciMAT was selected among several bibliometric programs available for quantitative content analysis (Cobo et al., 2011a) because it is particularly suitable to dynamic co-word longitudinal analysis of themes (Cobo et al., 2012a, 2012b).

### 2.2. Citation, co-citation, and co-word analysis

Citation analysis identifies the most influential authors and their fields of research. Co-citation analysis describes the research field structure, the "backbone, " or the research fronts. Two papers are considered co-cited if both appear in another paper's citations. The fundamental assumption of co-citation analysis is that documents cited together are more likely to belong to the same or close subject areas (Fahimnia et al., 2015a, 2015b).

Co-word analysis is indicative of the prevailing thematic areas in a research field or the research streams (Cobo et al., 2011a; Zhao and Strotmann, 2015). Co-citation and co-word analyses to identify prevalent themes and their evolution are exploratory network analyses that use network graphical representation.

Thematic clusters were built in SciMAT software into three sequential periods: 1995–2010, 2011–2013, and 2014–2015. Therefore, older and seminal works with a large number of citations and more recent research in sustainable infrastructure were included in the analysis. The co-word analysis generated the thematic clusters based on the WoS-indexed keywords. A document was further classified as "core document" and "secondary document" if it had respectively at least two keywords and one keyword presented in the thematic network. For each period and thematic cluster, the core documents responding to up to 80% of total citations for that cluster and period were selected to characterize the thematic cluster.

Themes were analysed based on the co-occurrence of keywords identified with the normalized similarity index: $e_{ij} = c_{ij}^2/c_i c_j$. $C_{ij}$ is the number of documents in which two keywords i and j co-occur; $c_i$ and $c_j$ are the numbers of documents in which each one occurs (Callon et al., 1991). This index equals to zero if two words never appear together in a document and equals to one if two words always appear together. The simple centre algorithm (Cobo et al., 2012a, 2012b) is implemented in SciMAT to generate auto-labelled thematic clusters. It is a simple algorithm traditionally used in co-word analysis (e.g., Cobo et al., 2011b, 2012b; Thomé et al., 2015).

Interlinked themes emerge from the clustering process. Each cluster is classified according to Callon's density and centrality indexes. Centrality measures the interaction among thematic clusters and it is a gauge of the thematic relevance of a discipline or a research field. It is given by $c = 10\sum e_{kh}$, where k is a keyword belonging to the theme and h is a keyword belonging to other themes. Density expresses the weight of an association of keywords within a given cluster. It is equal to $d = 100(\sum e_{ij}/w)$, where i and j are keywords belonging to the theme and w is the total number of keywords in the theme. Strategic thematic diagrams are formed by displaying thematic clusters along the two axes of centrality and density ranks. Both ranks vary from zero to one. Fig. 1, adapted from Cobo et al. (2011a; 2012b), summarizes the meaning of each quadrant of the strategic thematic diagrams.

The diagram of Fig. 1 is commented clockwise from top down. When co-occurrence of keywords and centrality are high (above the median), it means that the themes underlying the keywords are commonplace in the research area (high centrality) and appear frequently in the on-going research (high density). That is why it is said that they are core themes. However, when density is low but centrality is above the median, themes are said to be transversal (as denoted by high centrality) and they have a high potential for new research as denoted by a low density (i.e., themes not yet sufficiently developed in the research stream despite its high centrality or relevance to the area). Emerging or disappearing themes would be both of a low density (appearing not often in the research stream as denoted by a density below the median and not well related to other thematic clusters as denoted by a low centrality). Finally, the association of a high density with a low centrality denotes isolated and well researched themes, treated apart from core or central themes. In summary, while centrality depicts the scale of relevance of the themes to the research area, density denotes how often the theme appears in a research stream. Promising new research is usually although not exclusively situated in the low density area of the Callon's chart, where the themes are not extensively researched and thus deserve further scrutiny (Callon et al., 1991; Cobo et al., 2011b, 2012b).

The inclusion index measures the strength of the links between themes in two successive periods and equals $\frac{\#(U \cap V)}{min(\#U, \#V)}$. U and V are

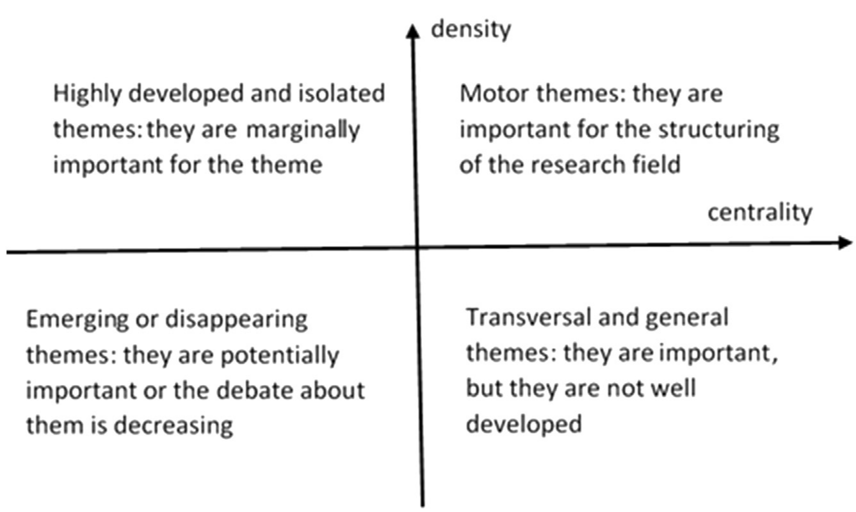


**Fig. 1.** Callon's (Callon et al., 1991) thematic strategic diagrams.

disjoint sets in a bipartite graph, in which the edges can only connect elements from the subset U to the subset V. The inclusion index equals to one if the elements of V are fully contained in U and it is not sensitive to the number of items in the subsets, as other indexes are, like the Jaccard and cosine indexes (Cobo et al., 2011b).

## 3. Results from citation, co-citation, and co-word analyses

This section summarizes the results from basic bibliometric statistics, citation, co-citation and co-word analysis.

### 3.1. Basic statistics

Results from the search keywords applied to WoS appear in Table 1.

An initial search with the keywords "sustainab*" (which regroups sustainable, sustainability, and their plural) associated with "infrastructure" or "construction" resulted in 816 papers. The inclusion of "building" enlarged the initial search, resulting in 1507 documents. The addition of "green infrastructure", "green construction" or "green building" resulted in 3333 documents. Several of these documents were conference proceedings and book chapters published in different languages. Then the search was restricted to peer-reviewed papers and reviews published in English, narrowing the database to 1769 documents (1674 papers and 95 reviews), with no restrictions on publication dates. The restriction of the selected papers to peer-reviewed journals intends to reduce the risk of including low quality studies in the database. However, this selection tends to the limitation of excluding practitioners and publications from industry.

Table 2 depicts the top disciplinary fields from which these papers were retrieved, as classified by the WoS categories. WoS can classify papers in one or more categories or disciplinary field.

The fields of general engineering and environmental sciences ecology are predominant in the database followed by construction and architecture. There is a non-negligible number of papers classified in general geography, physical geography, and urban study. Energy fuel and material science are well represented as well, while business economy occupies a modest and isolated tenth position in the sustainable infrastructure ranking.

Initial basic statistics show the number of papers published by year with an exponential growth of publications on sustainable infrastructure starting after 2003 as depicted in Fig. 2. Seven papers appearing in the WoS collection before 1995 are not in Fig. 2 because of readability. The first paper dates from 1967 and one isolated paper appears for each year between 1967 and 1994.

Table 3 depicts publications by the 15 leading journals in number of papers. Publications in sustainable infrastructure come from a large variety of journals partly due to the interdisciplinary nature of the research field. The five top journals are from the construction and built environment followed by urban planning and sustainability-oriented journals. Analysis of the number of citations generated by journals as an impact indicator, based on total local citations scores (TLCS) and total global citations scores (TGCS), finds this ranking almost unchanged, except that the top five now include Landscape and Urban Planning Journal. TLCS report the number of citations from the 1769 papers selected for the review. TGCS report the number of citations in the whole WoS collection.

**Table 2**
Top disciplinary fields of sustainable infrastructure.

| Web of science categories | No. of papers |
|---|---|
| Engineering | 680 |
| Environmental sciences ecology | 511 |
| Construction building technology | 448 |
| Architecture | 218 |
| Energy fuels | 194 |
| Urban studies | 171 |
| Materials science | 130 |
| Geography | 81 |
| Water resources | 71 |
| Business economics | 71 |
| Physical geography | 60 |

Table 4 regroups the top 20 research institutions on sustainable infrastructure. There is a concentration of research in polytechnic institutes, civil engineering, architecture, and construction departments of universities, as well as in two US governmental agencies (environmental protection agency and forestry services).

### 3.2. Citation analysis

The top ten most published authors and their subject area are in Table 5. They appear ranked by the average yearly number of local citations instead of the total number of local citations, in an attempt to circumvent the fact that recent papers have not had the time to receive large numbers of citations. This is particularly relevant in fields as management, for which the journals' aggregate cited half-life is above ten years. The dissemination of citations is slower than in other fields, like Applied Physics, for which the half-life is 5.8 years (Larsen and von Ins, 2010).

The field is heavily concentrated in few leading authors and subject areas, with a prevailing view towards green and sustainable building, urban GI and ecosystems, and environmental assessment methods, with a particular reference to green project management and the GBC project, which is relevant to the national environmental assessment systems and the ISO certification for environmental management. Tzoulas, Niemela, Yli-Pelkonen, Korpela, Venn, James, and Kazmierczak are co-authors of an influential literature review in ecosystems, human health, and GI (Tzoulas et al., 2007).

### 3.3. Co-citation analysis

Fig. 3 depicts the co-citation graph generated by Histcite graph maker and visualized with Pajek for the top 30 papers with the largest local citation scores. Papers are identified by the name of the

**Table 1**
Papers selected for review.

| First selection of papers | No. of papers included |
|---|---|
| "sustainab* infrastructure" OR "sustainab* construction" | 816 |
| "sustainab* infrastructure" OR "sustainab* construction" OR "sustainab* building" | 1507 |
| "sustainab* infrastructure" OR "sustainab* construction" OR "sustainab* building" OR "green construction" OR "green building" OR "green infrastructure" | 3333 |
| Exclusion criteria: | |
| Restricted to peer-reviewed papers and reviews | 1837 |
| English language only | 1769 |

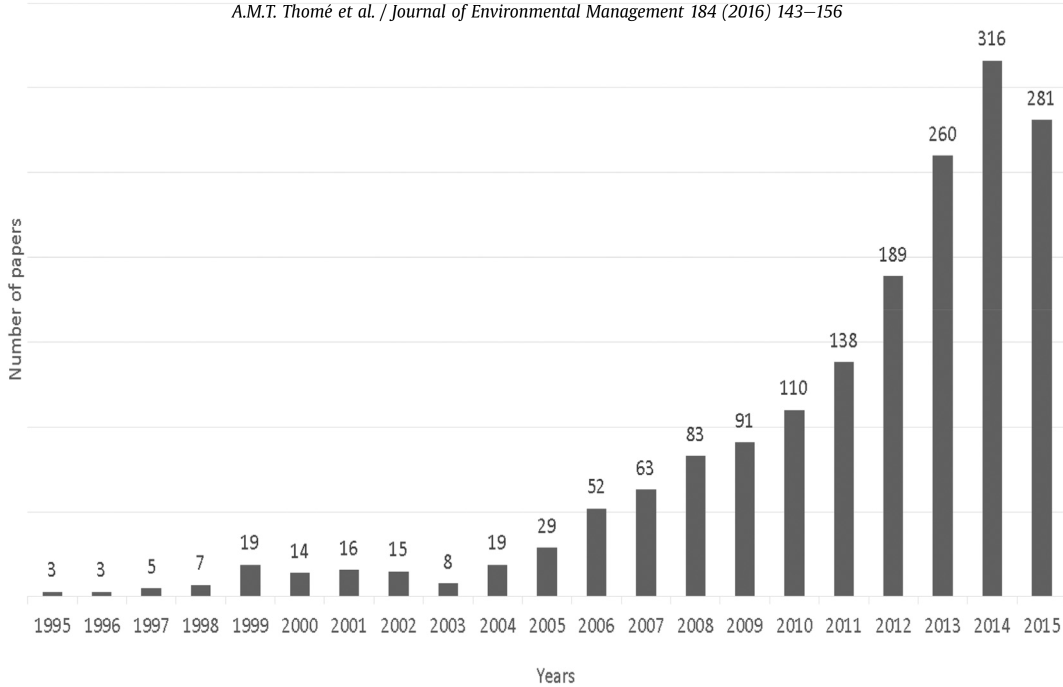


**Fig. 2.** Number of papers on sustainable infrastructure per year.

**Table 3**
Top fifteen journals on sustainable infrastructure.

| Journal | No. of papers | TLCS | TGCS |
|---|---|---|---|
| Journal of green building | 154 | 93 | 215 |
| Building and environment | 89 | 232 | 1220 |
| Building research and information | 77 | 294 | 954 |
| Energy and buildings | 72 | 139 | 994 |
| Construction and building materials | 50 | 43 | 607 |
| Landscape and urban planning | 49 | 183 | 757 |
| Sustainability | 29 | 9 | 67 |
| Renewable & sustainable energy reviews | 27 | 40 | 323 |
| Journal of cleaner production | 25 | 32 | 163 |
| Urban forestry & urban greening | 25 | 38 | 126 |
| Journal of construction engineering and management-ASCE | 19 | 56 | 167 |
| Proceedings of the institution of civil engineers-engineering sustainability | 18 | 16 | 70 |
| Renewable energy | 18 | 17 | 224 |
| Journal of environmental management | 17 | 56 | 302 |
| Habitat international | 16 | 31 | 81 |

TLCS: local citation score, within this WoS collection of 1769 papers; TGCS: global citation score, within the entire WoS citation database.

**Table 4**
Top twenty research institutions on sustainable infrastructure.

| Institutions with subdivisions | No. of papers |
|---|---|
| Hong Kong Polytech Univ. | 30 |
| US EPA | 25 |
| Drexel Univ, Dept Civil Architectural & Environm Engn | 9 |
| Kyung Hee Univ, Dept Architectural Engn | 9 |
| Natl Univ Singapore, Dept Bldg | 9 |
| Univ British Columbia, Sch Architecture | 9 |
| Univ Reading, Sch Construct Management & Engn | 9 |
| Chongqing Univ, Fac Construct Management & Real Estate | 8 |
| Stanford Univ, Dept Civil & Environm Engn | 8 |
| Univ Cent Florida, Dept Civil Environm & Construct Engn | 8 |
| Univ Hong Kong, Dept Geog | 8 |
| Univ Illinois, Dept Civil & Environm Engn | 8 |
| Univ S Australia, Sch Nat & Built Environm | 8 |
| Virginia Tech, Myers Lawson Sch Construct | 8 |
| Natl Cheng Kung Univ, Dept Architecture | 7 |
| Oregon State Univ, Dept Wood Sci & Engn | 7 |
| Univ Hong Kong, Dept Architecture | 7 |
| US Forest Serv, USDA | 7 |
| Ajou Univ, Dept Architecture | 6 |
| Michigan State Univ, Sch Planning Design & Construct | 6 |

first author and the year.

Two clusters of related research emerge from Fig. 3. The work led by Cole (1999), Cooper (1999), Crawley and Aho (1999) and Kohler (1999), focused on GB assessment tools. Walmsley (2006) led a second cluster more concerned with GI and ecosystems. Newsham et al. (2009) and Wang et al. (2006, 2005) appeared as isolated clusters treating GB optimization techniques and GB sustainable energy consumption respectively.

Cole (1999), Cooper (1999), Crawley and Aho (1999) and Kohler (1999) led the debate on GBC project and environmental assessment of buildings. A distinction was made early on between agendas for 'green' (relative comparisons among similar buildings in a given region) and 'sustainable' buildings (absolute energy and mass flows and their impacts on the environmental sustainability of the planet) (Cole, 1999; Cooper, 1999). The movement towards the "greening of buildings" in the 1990's led to a variety of assessment tools ranging from the operational impact of building materials to the broader impact of buildings on the environment (Crawley and Aho, 1999). Kohler (1999) discussed the scenarios for

**Table 5**
Top ten authors in sustainable infrastructure.

| Authors | No. of papers | TLCS/year | Subject area |
|---|---|---|---|
| Zuo J | 7 | 10.00 | Sustainable construction/GB |
| Niemela J | 3 | 8.39 | Urban GI and ecosystems |
| Yli-Pelkonen V | 2 | 8.39 | Urban GI and ecosystems |
| Tzoulas K, Korpela K, Venn S, James P, Kazmierczak A | 1 | 7.89 | Urban GI and ecosystems |
| Cole RJ | 13 | 7.77 | Environmental assessment methods/GB Challenge (GBC) |
| Hwang BG | 5 | 5.58 | GB project management |

TLCS: local citation score within this WoS collection of 1769 papers.

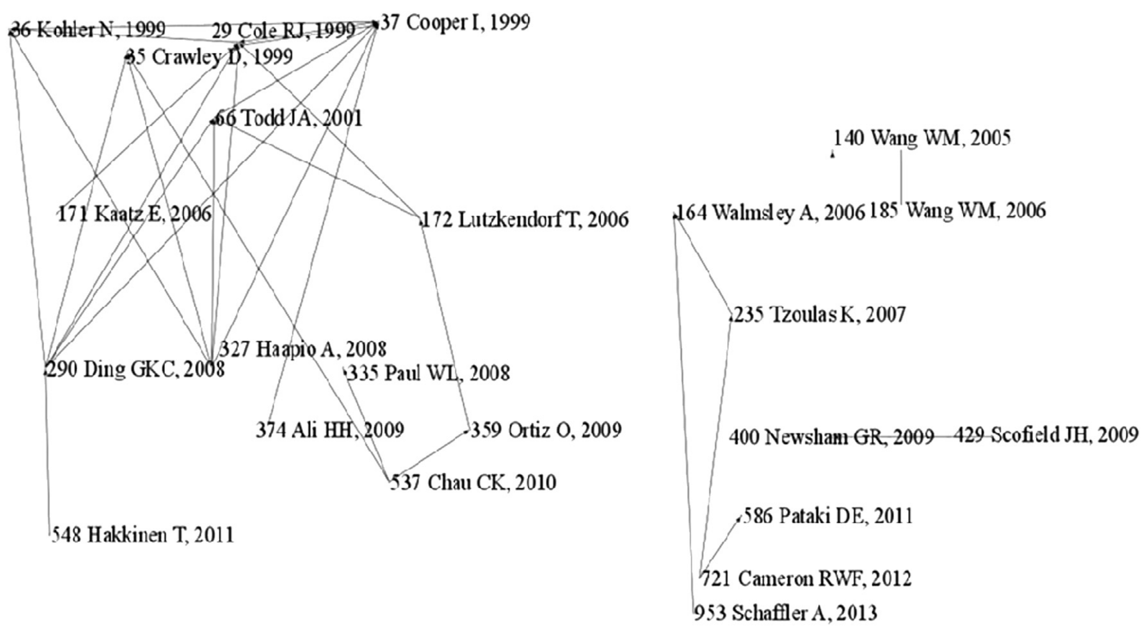


**Fig. 3.** Co-citation network for sustainable infrastructure.

extending GBC into Life Cycle Assessment methodology and other life cycle phases as well as the replacement of GB by a larger concept of sustainable development. The "Green Building Challenge" conference held in Vancouver in September 1998 challenged developed countries to reduce the environmental impact of the built environment tenfold by 2040 and to stop new constructions entirely. Cooper (1999) called for a shift from a "narrow view" of resource-efficiency to a "broader view" of sustainability of the built environment. This movement contributed to the development of national environmental assessment tools.

Todd et al. (2001) reviewed the GBC assessment tool in light of the national built environment assessment tools developed in the turn of the last century. Kaatz et al. (2006) introduced social and technical concerns into the assessment methods of building sustainability. Lützkendorf and Lorenz (2006) built upon the new generation of assessment tools integrating sustainability concerns into GB. Ding (2008) embraced a global perspective in discussing the development, role, and limitations of environmental building assessment methods in ascertaining building sustainability used in different countries. Haapio and Viitaniemi (2008) classified and compared different environmental assessment tools for buildings. Paul and Taylor (2008) focused on indoor environmental quality of GB compared with conventional constructions in Australia, and they found no evidence that GB was more comfortable than conventional buildings, as perceived by users. Ortiz et al. (2009) reviewed life cycle assessment applied to the building sector to improve the economic, social, and environmental indicators of sustainability. Ali and Al Nsairat (2009) emphasized that GB's characteristics differ from country to country in factors like culture, climate, and humidity. They adapted parameters for GB assessment tools to Jordan, applying the AHP method among construction managers. Chau et al. (2010) investigated the preferences and willingness-to-pay for enhancements on various aspects of GB environmental performance. Häkkinen and Belloni (2014) analysed barriers and drivers for SB, which they found were beset by organizational and procedural difficulties, as well as by the perception of risks and unforeseen costs preventing the adoption of new GB technologies.

Wang et al. (2005) proposed an optimization model for GB design taking into account the environmental and economic performance of buildings in a life-cycle approach and Wang et al. (2006) suggested using genetic algorithms to optimize GB shapes.

Newsham et al. (2009) compared energy consumption for LEED certified and conventional buildings. LEED certification is one of the most widely used GB rating systems developed by the US Green Building Council. Newsham et al. (2009) found that although LEED certified buildings consumed 28–35% less energy than conventional buildings, there was little or no correlation between LEED certification levels or energy credits from LEED's certification acquired at design time with energy performance after construction. However, Scofield (2009) argued that Newsham et al. (2009) "offer no evidence that LEED-certification has collectively lowered either site or source energy for office buildings".

Walmsley (2006) turned to GI planning in the United States. GI was defined as inter-connected systems of green spaces in urban settings predominantly for ecological functions. There was a growing focus in the mid of the first decade of this century on cities with transportation systems accommodating “pedestrian cities” within the confines of metropolitan and regional areas (Walmsley, 2006). Tzoulas et al. (2007) suggested a conceptual framework of associations among urban green space, ecosystem, and human health. Pataki et al. (2011) proposed a framework to integrate biogeochemical processes into designing, implementing, and evaluating GI net effectiveness, with examples for greenhouse gas (GHG), storm water runoff mitigation, and improvements in air quality and health. Cameron et al. (2012) discussed GI development of domestic gardens. Schäffler and Swilling (2013) applied insights of social-ecological resilience to the urban infrastructure transition in Johannesburg, concluding that ecosystems valuations should take into account the specificities of developing world cities.

The co-citation analysis has shown a growing concern with the environment in the construction industry literature. The prevailing themes moved from “greening” to “sustainable, ” from the original concerns with the value of green compared to conventional building techniques to the absolute value of the environmental impact of GHG, and the energy consumption resulting from the construction industry. GI stream of research has enlarged its views to include human health and ecosystems in the urban setting.

### 3.4. Co-word analysis

Table 6 depicts the total number of papers selected for co-word analysis and the number of papers analysed for each thematic cluster. In total, 76 papers out of 257 core documents were full-text reviewed.

Fig. 4 depicts the number of keywords per period.

The field evolved from 182 keywords in 1995–2010 to 245 in 2011–2013 and to 262 in 2014–2015. The constantly increasing number of keywords attests the growing thematic diversity discussed under the umbrella of SI. Out of the original 182 keywords from 1995 to 2010, 27 did not reappear in 2011–2013, but 155 did reappear in 2014–2015. In 2011–2013, there were 90 new keywords added and 31 out of the 245 keywords did not reappear in 2014–2015. The fact that keywords strongly reappeared in the following periods can be an indication that this relatively new research field is gradually consolidating.

Fig. 5 shows the thematic evolution. The thickness of the lines represents the strength of the association measured by the inclusion index (see Section 2.2). A continuous line in Fig. 5 means that the thematic cluster appears with the same name in the following period, or it is part of another cluster with another name. A dotted line means that the theme shares elements that are not the names of the themes. The spheres are proportional to the number of documents. Environmental assessment methods appeared with the larger number of core documents in 1995–2010. It evolved to the themes of construction and buildings in 2011–2013. GI reappeared in 2011–2013 merged with the themes of cities and ecosystems. The construction thematic cluster from 1995 to 2010 remained with the same label in 2011–2013, but with a larger number of core documents published in the theme and it merged with buildings. The fly-ash thematic area appeared with few documents in the first period and evolved to the thematic clusters of cement in 2011–2013, which evolved itself into strength in 2014–2015.

Among the clusters formed in 2011–2013, cities merged with GI in 2014–2015; construction split in building and design; ecosystem integrated the themes of cities, GI, and landscape; emissions integrated with design; and buildings split in buildings and design.

The analysis of the leading papers in each thematic cluster and period allows a better understanding of the evolution of the SI themes. The Appendix presents the main themes of the papers included in each cluster; they are summarized next.

During 1995–2010, the GBC project led the debate on environmental assessment methods (Cole, 1999; Cole and Larsson, 1999; Kohler, 1999). Papers in this cluster began with the identification of the elements of GB, with the measurement and comparison with conventional buildings (Lützkendorf and Lorenz, 2006; Retzlaff, 2008), with discussions on how to make GB assessment global under different cultures and climates (Ali and Al Nsairat, 2009). It evolved to incorporate the built environment in the GB assessment and the international standards for environmental management (e.g., ISO 14001). Concerns with urban ecology were at the heart of the GI cluster literature since the beginning. Several papers dealt with declining vacant urban spaces (Weber et al., 2006; Gill et al., 2008; Schilling and Logan, 2008) and the mitigation of the effects of lost natural environment in cities (Haase, 2008; Jorgensen and Gobster, 2010). The cluster on construction

**Table 6**
Number of papers retrieved for co-word analysis by period, thematic cluster, and type of document.

| Period | Thematic cluster | No. of documents | | | |
|---|---|---|---|---|---|
| | | Core | Secondary | Total | With up to 80% citations |
| 1995–2010 | Environmental-assessment-methods | 18 | 92 | 110 | 7 |
| | Green-infrastructure | 13 | 35 | 48 | 5 |
| | Construction | 8 | 33 | 41 | 3 |
| | Fly-ash | 3 | 11 | 14 | 1 |
| | **Subtotal** | **42** | **171** | **213** | **16** |
| 2011–2013 | Cities | 32 | 74 | 106 | 14 |
| | Construction | 31 | 116 | 147 | 12 |
| | Cement | 6 | 10 | 16 | 2 |
| | Ecosystem | 6 | 26 | 32 | 4 |
| | Emissions | 4 | 37 | 41 | 1 |
| | Buildings | 6 | 50 | 56 | 2 |
| | **Subtotal** | **85** | **313** | **398** | **35** |
| 2014–2015 | Cities | 34 | 56 | 90 | 5 |
| | Green-infrastructure | 23 | 88 | 111 | 6 |
| | Buildings | 16 | 83 | 99 | 4 |
| | Design | 36 | 145 | 181 | 5 |
| | Strength | 15 | 37 | 52 | 4 |
| | Landscape | 6 | 44 | 50 | 1 |
| | **Subtotal** | **130** | **453** | **583** | **25** |
| **Total** | | **257** | **937** | **1194** | **76** |

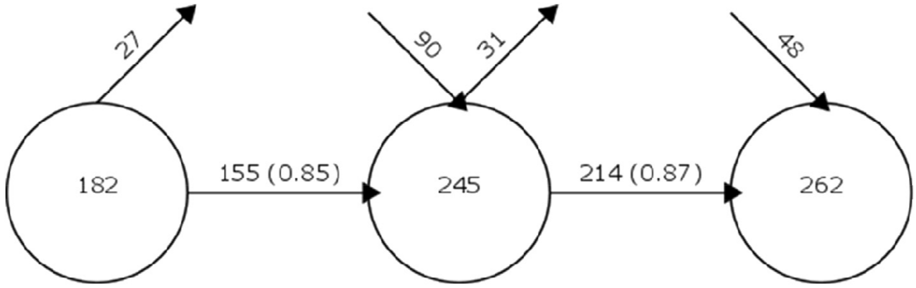


**Fig. 4.** Overlap of keywords during the three periods.

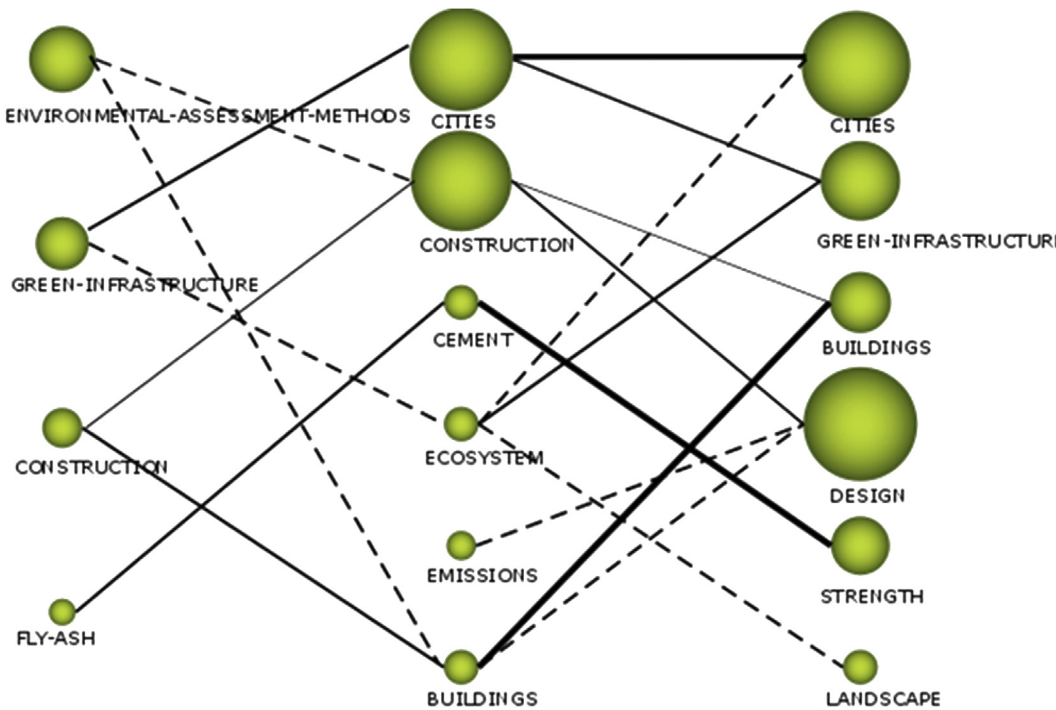


**Fig. 5.** The evolution of thematic networks in sustainable infrastructure: 1995–2015.

regrouped more practice-oriented papers dealing with barriers and enhancers of sustainable built environment (Williams and Dair, 2007; Qi et al., 2010). The fly-ash cluster was the precursor of a constant research stream on the use of by-products and waste materials to lower the environmental impact of the construction industry (e.g. Corinaldesi and Moriconi, 2009). It continued consistently in the following periods under the different labels of cement and strength.

Clusters of cities and construction led the research in 2011–2013 with a majority of papers. Cities focused on the integration of GI in urban settings, predominantly from a planner's perspective (Mitsova et al., 2011; Gómez-Baggethun and Barton, 2013; Kremer et al., 2013; Schäffler and Swilling, 2013) and on GI integration in projects for urban reforestation (Young, 2011; McLain et al., 2012; Kirkpatrick et al., 2013; Young and McPherson, 2013). Other prevailing themes were the use of gardens within cities (Hunter and Brown, 2012), water governance (Larson et al., 2013), and case studies on the expansion of GI in cities in the developing countries (Yu et al., 2011; Kitha and Lyth, 2011; Schäffler and Swilling, 2013). McLain et al. (2012) criticized the US "narrow focus" on storm water management programs to greening the cities.

Construction focus was on the re-evaluation of assessment tools to integrate GI (Kajikawa et al., 2011), the use of building information modelling (Bynum et al., 2013), and the introduction of new "green" technologies in GI (Cheng et al., 2011; Saadatian et al., 2012). The review of barriers and enhancers of sustainable buildings (Häkkinen and Belloni, 2014; Li et al., 2011), sustainable energy, and cost efficiency of GB projects (Robichaud and Anantatmula, 2011; Tatari and Kucukvar, 2011; Ghaffarianhoseini et al., 2013) were equally represented under the label of construction. Extensions to the developing world appeared on Chua and Oh (2011), Li et al. (2011), Alyami et al. (2013). The TBL values on construction appeared on the paper from Reza et al. (2011).

Cement was an extension of the fly-ash cluster and consistently treated alternate construction materials for GB (Iucolano et al., 2013; Madurwar et al., 2013). Ecosystem discussed urban futures resilience (Hale and Sadler, 2012) and extensions of GI in urban settings (Madureira et al., 2011; Lu et al., 2012; Qureshi et al., 2013). The impact of ozone emissions (Cros et al., 2012) was an isolated paper under emissions; cool roofs (Boixo et al., 2012) and barriers and enhancers of green construction (Shi et al., 2013) comprised the buildings cluster.

The scope of research themes broadened during 2014–2015 encompassing themes debated since the 1970's under the label of urban ecology. Cities encompassed research on vacant and abandoned properties in urban settings as in the preceding period (Nassauer and Raskin, 2014) and integrated ecological footprint (Cowell and Lennon, 2014), larger view of ecological dimensions of reforestation (Baró et al., 2014), and users' preferences on green urban planning (Faehnle et al., 2014; Kabisch and Haase, 2014). The GI cluster reappeared with the same label than in 1995–2010. It called for interdisciplinary research on green façades (Hunter et al., 2014), conceptual frameworks integrating socio-ecological perspectives in GI with ecosystems services (Hansen and Pauleit, 2014), and sustainable drainage systems (Sjöman and Gill, 2014). The papers in the GI cluster from this period reinforced the TBL approach to sustainability. Supply and demand for ecosystem services should match environmental quality and human well-being perspectives (Baró et al., 2015), and financial analysis should integrate life cycle assessment of wastewater treatment system (Dimuro et al., 2014). Policy concerns came to the forefront of the debate with a call for the alignment between the European Common Agricultural Policy and nature conservation (Hodge et al., 2015).

Building covered the selection of building materials (Pajchrowski et al., 2014) as in precedent periods, and policies to mitigate GHG emissions (Onat et al., 2014; Wang et al., 2014a). Design appeared regrouping previous themes in a literature review in GB, covering definitions and scope of GB, comparisons with conventional buildings, approaches to build GB, and lack of economic and social sustainability concerns in GB (Zuo and Zhao, 2014). Energy savings, energy cost-efficiency (Ahn et al., 2014; Y. Liu et al., 2014a, 2014b), and integration of corporate social responsibility into GB (Wang et al., 2014b) compounded the design cluster. Strength was remarkably consistent with fly-ash and cement clusters of previous periods and it was completely devoted to construction materials (Bernardi et al., 2014; Ferreira et al., 2014; Liu et al., 2014a, 2014b; Millogo et al., 2014). Finally, landscape appeared as with the analysis of social-ecological systems over more than 15-year experience in urban Stockholm (Andersson et al., 2014).

Fig. 6 synthesizes the evolution of strategic thematic diagrams

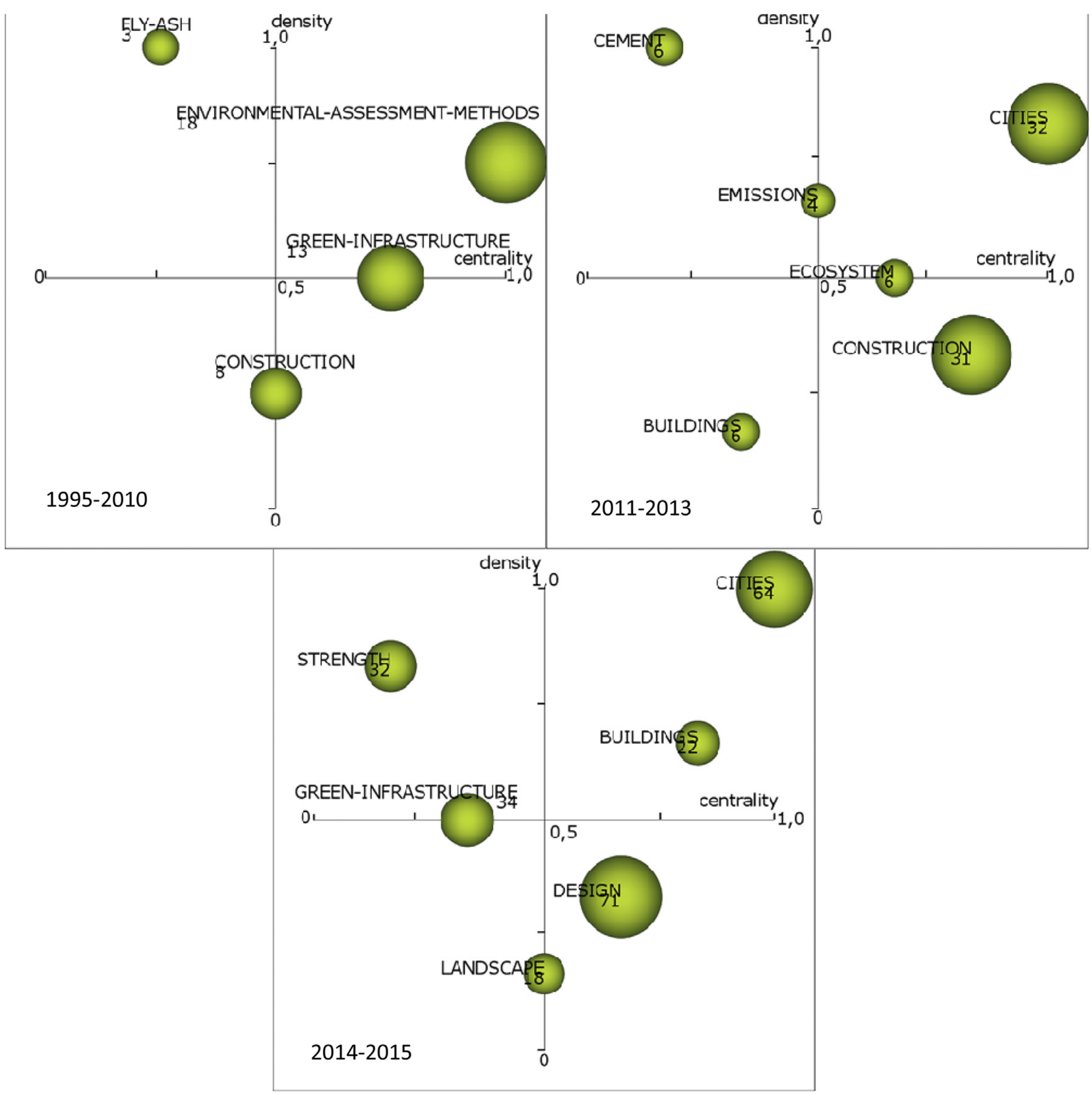


**Fig. 6.** Strategic thematic diagrams: 1995–2015.

for the three periods. The size of the spheres is proportional to the number of documents in each cluster, indicated in Fig. 6 on the label of the clusters. Environmental assessment methods appeared with a high density and high centrality, as a motor theme during 1995–2010, which is consistent with results from the co-citation analysis. GI appeared with high centrality and average density, as a motor theme, but not yet a dominant theme. Construction appeared as a potentially new theme, with low density and average centrality. Fly-ash treated replacement material for GB. It was a consolidated area of marginal importance to sustainable infrastructure in the early period, and it remained so under the labels of cement and strength respectively in 2011–2013 and 2014–2015, left in the same upper left quadrant of Fig. 6.

Cities became the dominant theme after 2010. Buildings appeared as a new theme in 2011–2013 and moved to a motor theme in 2014–2015, with high centrality and density. Ecosystem was an influential theme in 2011–2013 while construction appeared with a core centrality, but still not very dense position, which indicated the potential for future developments of this cluster. In 2014–2015, buildings and cities were dominant themes; GI reappeared in a less central position while landscape appeared as a promising new area. Design seemed to gain importance as a potential research stream, central to the research field, but still not high on density.

## 4. Discussions and conclusions

This paper offers a systematic review of the extant literature in sustainable infrastructure from 1995 to 2015. It applies a rigorous, transparent, and reproducible research protocol to a collection of 1769 papers published in peer-reviewed journals indexed in the WoS citation database.

The descriptive analysis of basic bibliometric data drives to some initial conclusions. Sustainable infrastructure is a multidisciplinary research domain with contributions originated mainly from engineering, environmental sciences, construction, and architecture. Additional disciplinary fields related to urban development and use of resources, like energy, urban studies, and geography, compose the research domain. The field of green and sustainable infrastructure is relatively new, lively, and ever growing. An exponential growth in the number of yearly publications appears after 2003. A comparison made between three publication periods (1995–2010, 2011–2013, and 2014–2015) attests the vitality and consolidation of the field. This segmentation of the bibliographic database allowed the analyses of old, as well as recent and actual themes. A more and more diversified number of keywords describes the research streams and it shows an expanding thematic area. However, over 80% of the keywords remain the same in the successive periods, attesting of gradual consolidation. The multidisciplinarity also brings a large diversity of publishing journals in different areas. These thematic and disciplinary diversifications contrast with a concentration of the most influential research institutions in North America, Europe, and Asia. For global concern, this finding is particularly relevant, engaging all countries in the search of TBL sustainability for the people, the economy, and the Planet. Equally, the citation analysis shows that few authors concentrate the larger impact measured by the number of citations.

The descriptors of sustainable infrastructure literature are the background against which to discuss the research questions. In answering the first question, the co-citation network shows two large research fronts: “assessment tools and international standards for sustainable buildings” and “GI in cities. ” The two streams (‘tools and standards for SB’ and ‘GI’) tend to converge to the sustainable development of the infrastructure in recent papers, but they keep their specificity. The first evolved to international standards and certification like the environmental ISO series and the European Charter for the Environment. GI links more with the greening of urban spaces and ecological concerns, primarily related to storm water and wastewater treatment systems, reforestation, and gardening, but gradually evolving to integrate TBL sustainability values. Those are the two streams of research characterising the main themes in the area of sustainable infrastructure.

Regarding the second question, the analysis of the thematic clusters shows a growing concern with TBL sustainability, evolving from early preoccupations with materials for the greening of buildings, resource efficiency, and the narrow view confining GI to storm water runoff. The thematic clusters for 2014–2015 clearly focus on broad ecological concerns in urban settings, integration of users in GI assessments, and expansion to integrate economic and social aspects of environmental sustainability. There are stability and a consolidation of some themes like replacement construction materials, successive refinements of assessment tools, and adapting assessment tools to cities in the developing world.

In addressing the third question, a research agenda is proposed. The analysis of thematic clusters and some methodological limitations of the present study form the basis of the agenda. The first group of research areas appears from the analysis of emerging trends after 2011, those that have low to average density and centrality (buildings in 2011–2013 and GI and landscape in 2014–2015). Themes showing low density do not appear often in current research and are therefore likely candidates for further research. It is complemented by themes with high centrality and low to average density (construction and ecosystems in 2011–2013 and design in 2014–2015), as depicted in the strategic thematic diagrams of Fig. 6. Their low density attests a need for additional research on the consolidation of the research areas.

A diversified array of ecosystems research falls under ecosystems and landscape themes like the urban resilience of green infrastructure, low-carbon industrial parks, and integration of users' preferences in designing urban green spaces. Under construction and design, emerging research areas are barriers and drivers for SB, integration of corporate social responsibility and TBL values into SB, alternative sources of energy and energy savings, sustainable architectural design for heat and ventilation, effective green project management practices, strategies to meet national green labels in the built environment, build information modelling approaches, and critical appraisals of assessment frameworks.

Finally, four research opportunities derive from the methodological limitations inherent to the nature of the bibliometric analysis presented in this paper. Different search keywords could lead to different results, and further experimentation with other combinations of keywords is justified. The combination of WoS database, Scopus, and Google Scholar, despite the large intersections among them, could lead to a more exhaustive review. In-depth analysis of specific thematic clusters would lead to a better understanding of their evolution. More stable themes, like assessment tools, alternative construction materials for GB, and sustainable infrastructure research in developing countries are some examples. The inclusion of non-peer-reviewed material or grey literature under the form of thesis, dissertation, and papers from industry magazines could open venues to new themes.

## Appendix

**Table A1**
Thematic clusters – Talking-bullets from papers regrouping 80% of total number of citations per cluster and period.

| Period | Thematic cluster | Description of themes within cluster |
|---|---|---|
| 1995–2010 | Environmental-assessment-methods | Led by the green building challenge (GBC) assessment framework (Cole, 1999). There are early calls to replace "green building" with sustainable development (Kohler, 1999). GBC evolves to global operations (Cole and Larsson, 1999). Different assessment tools are compared (Lützkendorf and Lorenz, 2006), guidelines to choose among different assessment tools are provided (Retzlaff, 2008), and extensions to developing countries are proposed (Ali and Al Nsairat, 2009). |
| | Green-infrastructure | Weber et al. (2006) apply a green infrastructure evaluation tool to Maryland, USA. Schilling and Logan (2008) describe the challenges vacant and abandoned properties create in America's older industrial cities. Gill et al. (2008) discuss landscape-planning challenges in Great Manchester, UK posed by urban heat island and an enhanced surface runoff, altered surface cover, more built and fewer vegetated surfaces. Spatial consequences of urban decline (Haase, 2008) and a literature review of studies measuring the biodiversity and other green space concepts in urban ecology (Jorgensen and Gobster, 2010) integrate equally this cluster. |
| | Construction | The cluster regroups barriers to achieve sustainability in the built environment in the UK (Williams and Dair, 2007), factors influencing contractors to adopt green construction practices (Qi et al., 2010), and building life-cycle impact on the environment, its financial and social conditions (Medineckiene et al., 2010) |
| | Fly-ash | The use of resources from by-products and waste materials to lower the environmental impact of cement and concrete (Corinaldesi and Moriconi, 2009) |
| 2011–2013 | Cities | Gómez-Baggethun and Barton (2013) synthesize the knowledge and methods to classify and value ecosystem services for urban planning. Mitsova et al. (2011) describe a model to incorporate green infrastructure knowledge in urban planning. The importance of robust planning for green infrastructure in fast changing South African cities is in Schäffler and Swilling (2013). Other themes under cities follow. The economic valuation of green infrastructure in urban settings (Vandermeulen et al., 2011), and the development of the green infrastructure (e.g., urban forests) projects in large scale in the US metropolitan areas (Young, 2011). The use of ArcGIS and Google Earth to locate vacant lots in New York, USA, and to suggest the use for urban planning is in Kremer et al. (2013). Kirkpatrick et al. (2013) describe the role of trees in sustainable cities. The sustainability appraisal for water governance for the Phoenix region, USA (Larson et al., 2013), and the metropolitan tree planting initiatives (Young and McPherson, 2013). The identification of factors that spread the use of gardens within cities (Hunter and Brown, 2012). The integrated urban land uses planning in the city of Panyu in Southern China (Yu et al., 2011). The Lafarge ecosystems programme in Mombasa, Kenya (Kitha and Lyth, 2011). The research on urban greening programs in seven US cities, concluding that they are narrowly oriented toward storm water management (Newell et al., 2013). The urban reforestation in Seattle, USA (McLain et al., 2012). |
| | Construction | The barriers and drivers for sustainable buildings (Häkkinen and Belloni, 2014). A solar-driven thermoelectric cooling module with a waste heat regeneration unit designed for the green building applications (Cheng et al., 2011). The TBL sustainability criteria for the selection of a sustainable flooring system in Tehran, Iran (Reza et al., 2011). The sustainable energy performance of green buildings (Ghaffarianhoseini et al., 2013). The specific modifications to the conventional building practices to optimize the delivery of cost-efficient green building projects (Robichaud and Anantatmula, 2011). The sustainable architectural technology for heating and ventilation (Saadatian et al., 2012). Malaysia's green developments focusing on the Malaysian National Green Technology Policy and Green Building Index (Chua and Oh, 2011). The artificial neural network model built to predict cost premium of the LEED certified green buildings based on LEED categories (Tatari and Kucukvar, 2011). The identification of the controllable critical project management factors for delivering the green mark certified projects in Singapore (Li et al., 2011). The assessment frameworks for the building environment revisited (Kajikawa et al., 2011). The application of ecological principles to develop an integrated urban land-use planning for Panyu, Southern China (Alyami et al., 2013). The use of the building information modelling (BIM) (Bynum et al., 2013). |
| | Cement | The application of agro-waste as ingredient for the alternate sustainable construction materials (Madurwar et al., 2013). The use of the artificial aggregates based on the recycled plastic materials; mostly the polyolefin and the polyethylene terephthalate wastes are used as partial replacement of natural aggregates for the manufacturing hydraulic mortars (Iucolano et al., 2013) |
| | Ecosystem | Resilience analysis applied to a case study on urban future, illustrating efforts to protect and enhance the quality, quantity, and accessibility of green infrastructure within cities (Hale and Sadler, 2012). The research on low-carbon industrial park in the Beijing development area (BDA) – the international business park in Beijing, China (Lu et al., 2012). The implementation of green structures at the Municipality of Porto, Portugal (Madureira et al., 2011). How the socio-economic conditions of the differentiated and multicultural community influence the community's preferences for the urban green spaces in Karachi, Pakistan (Qureshi et al., 2013). |
| | Emissions | The long-term exposure of three green building material and an activated carbon (AC) mat that remove ozone from indoor air to real environments on the ozone removal capability and the pre- and post-ozonation emissions (Cros et al., 2012). |
| | Buildings | The estimation of savings with the use of cool roofs in Andalusia, South of Spain (Boixo et al., 2012). The barriers for the adoption of green construction in Shanghai, China (Shi et al., 2013). |
| 2014–2015 | Cities | The vacant and abandoned properties in urban areas: highly vacant districts as socio-ecological systems. Design, and planning may have unintended consequences for human health, water quality, adaptation to climate change, and a panoply of other ecosystem services (Nassauer and Raskin, 2014). The user preferences for urban green spaces in Berlin, Germany (Kabisch and Haase, 2014). Case studies in environmental capital, ecological foot printing, and green infrastructure (Cowell and Lennon, 2014). The contribution of ecosystem services provided by urban forests to evaluate their contribution to comply with policy targets of air quality and climate change mitigation in the municipality of Barcelona, Spain (Baró et al., 2014). How the input from residents' participation can be integrated into planning and decision-making in the planning of the urban green infrastructure in the Helsinki metropolitan region, Finland (Faehnle et al., 2014). |

(*continued on next page*)

**Table A1** (*continued*)

| Period | Thematic cluster | Description of themes within cluster |
|---|---|---|
| | Green-infrastructure | A call for interdisciplinary research on green façades (Hunter et al., 2014). A conceptual framework for the assessment of multi-functionality from a social–ecological perspective that can inform the design of planning processes and support stronger exchange between green infrastructure and ecosystem services research (Hansen and Pauleit, 2014). The assessment of mismatches between ecosystem service (ES) supply and demand with the use of the environmental quality standards (EQS) indicating the relationship between environmental quality and human well-being (Baró et al., 2015). The residential areas make varying contributions to surface runoff throughout the different rainfall events. The analyses of these contributions and the associated effect of different surface covers and sustainable drainage systems on runoff generation (Sjöman and Gill, 2014). The need to align the European common agricultural policy with the nature conservation policies (Hodge et al., 2015). The use of the replacement cost methodology (RCM) for financial analysis and life cycle assessment (LCA) for the environmental assessment applied to suspended solids requirements for a wastewater treatment system (Dimuro et al., 2014). |
| | Buildings | The influence of the building material selection on the environmental and economic parameters of a building in a Finnish context (Pajchrowski et al., 2014). The assessment of the greenhouse gas (GHG) mitigation policies in China (Wang et al., 2014a). |
| | Design | The systematic review concludes that the common themes in green building are the definition and scope of green building; the quantification of benefits of green buildings compared to conventional buildings; and various approaches to achieve green buildings. There is a lack of economic and social sustainability concerns (Zuo and Zhao, 2014). The assessment of the impact of LEED lighting on energy savings (Ahn et al., 2014). There is potential for integrating the GB and corporate social responsibility in construction sector, adding affordable housing as an additional element in the economic dimensions in the UK (Wang et al., 2014b). The system dynamics (SD) utilized to study the mid and long term impacts of the green building related policies on the GHG emissions stock in the US (Onat et al., 2014). The cost–benefit evaluation of the energy-efficiency technology application (EETA) on green buildings in China (Liu et al., 2014a, 2014b). |
| | Strength | The use of alternative material in construction, like the Hibiscus Cannabinus Fibers (Millogo et al., 2014), the lightweight aggregate foamed geo polymer (Liu et al., 2014b), the biologically cemented sandstone bricks (Bernardi et al., 2014) and the alkali activate concrete (Ferreira et al., 2014). |
| | Landscape | The analysis of cities as social–ecological systems, synthesis of the literature, and examples from more than 15 years of research in the Stockholm urban region, Sweden (Andersson et al., 2014). |

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