Life Cycle Sustainability Assessment of Alternative Green Roofs – A Systematic Literature Review

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Abstract

There is general agreement on the importance of green roofs as ways of reducing GHG emissions, reducing overall costs and improving sustainability in urban areas. This systematic literature review highlights life cycle sustainability assessment as an essential criterion to evaluate green roofs. A bibliometric analysis was used to quantitatively review relevant literature. The Scopus database was chosen as a bibliographic database of academic publications. Thes period of search started from 2003 and final search was conducted on February 15, 2023. Based on further in-depth reading, 88 publication records which met the selection criteria, including 74 papers and 14 conference papers. Researchers from the United States contributed almost 31 % of the documents. We evaluated leading studies in this field and discussed assessment method, system boundaries and research gaps through a critical literature review and a systematic search review. Finally, we propose a framework and identify a gap and future research. The environmental aspect of green roofs have received more attention than economic issues. We found that most economic evaluations of green roofs are limited to their construction stage. As yet there is no comprehensive social study on green roofs. We considered a unified study of the economic, environmental impact and social evaluation of green roofs to be warranted. Additionally, various measurement methods should be used to assess the economic profitability of green roofs over the long term. In summary, this study provides a deeper understanding of the environmental, social, and economic performance of green roofs and identifies research gaps as well as future research directions.

Keywords: Life Cycle Sustainability Assessment; Green roofs; Life Cycle Assessment; Circular Economy; Social Life Cycle Assessment;

1. Introduction

1.1 Life Cycle Sustainability Assessment

An increasing population worldwide has expanded the rate of construction of new buildings in recent decades. For example, the value of construction was around 7.3 trillion in 2021, and it is expected to increase by about 14.41 trillion by 2030 [1]. The construction building industry is responsible for consuming about 40% of all global resources, producing 33% of all emissions and 40% of all waste worldwide [2, 3]. Consequently, the construction industry generates almost 40% of annual CO_2 emissions. Sustainable development adheres to the principles of respect for nature, environmental protection, and responsible management of social and economic standards. The statistics above highlight the need for sustainability to be considered in the construction sector to control resource consumption and eliminate waste. Urban sustainability and global climate change issues can be addressed by designing cities that are climate-conscious and energy-efficient [4]. In recent years, green roof construction has become an increasingly popular design tool because of the numerous environmental benefits it provides [5]. Using a green roof can support the sustainability objectives of an organization because it conserves energy by insulating a building and reducing thermal heat gain [6]. Reducing the energy consumption of buildings can also result in a significant reduction of CO_2 emissions from fossil fuel-fired power plants [7], reducing pollution [8] as well as energy consumption [9]. Green roofs also decrease the heat island effect, leading to a natural change of water [10]. This study focuses on the Sustainability Life Cycle Assessment (SLCA) of green roofs. Furthermore, it identifies the gaps in previous studies. This will help researchers explore additional challenges of the sustainability of green roofs in future studies.

Life Cycle Sustainability Assessment (LCSA) is one of the most valuable methods of evaluating sustainability in the building sector. LCSA refers to the assessment of three sustainability pillars [11,12]. These pillars are life cycle assessment (LCA), life cycle cost (LCC) and social life cycle assessment (SLCA). LCA is a methodology for assessing the environmental impacts associated with all the stages of the life cycle of a building. LCC includes all costs associated with the life cycle of a building. SLCA is a method that can be used to assess the social and sociological aspects of buildings, their actual and potential positive as well as negative impacts during their life cycle [107]. In 1987, the Brundtland report [109] referred to the terms of LCSA for the first time. Accordingly, Agenda 21 built on the Brundtland Report, which stressed the importance of linking social and economic development with environmental protection [110]. Each of these assessments has its own distinctive methodology [14]. SLCA generally uses a questionnaire to identify the most appropriate product from a social perspective. Some questions that have been asked in this context relate to freedom of association, economical, social, and environmental impacts, and fewer occupational accidents [15]. It is important to note that LCSA is similar to the circular economy. According to a previous study [16], LCSA can be used to evaluate circular economy strategies as it incorporates a comprehensive framework and is also capable of preventing barriers between value chains and stockholders. Previous studies [16,17] indicate that circularity indicators cannot be used in isolation. They argue that LCSA needs to be used to evaluate the entire process of a product.

1.2 Types of Green Roofs

As mentioned above, one of the ways of constructing sustainable buildings is to build green roofs [19]. Numerous studies over the past decade have identified the environmental benefits of green roofs in cities. Green roof systems have many components, including roofing membranes, a protection layer, a drainage layer, a filter layer, an irrigation system for the dry climates, and different types of vegetation, all resting on an insulated structure [10]. Generally, these roofs fall into three categories [20]: extensive, intensive and semi-intensive. Figure 1 shows the main features of green roofs. First, the extensive green roof is of modest depth, has plants with shallow roots, and requires low maintenance. Second is the intensive green roof, with a deeper layer of soil, and planted with various trees and plants and require considerable maintenance. Currently and in widespread use, ‘extensive’ green roofs are planted with homogeneous species and display shorter-term characteristics than intended [21].

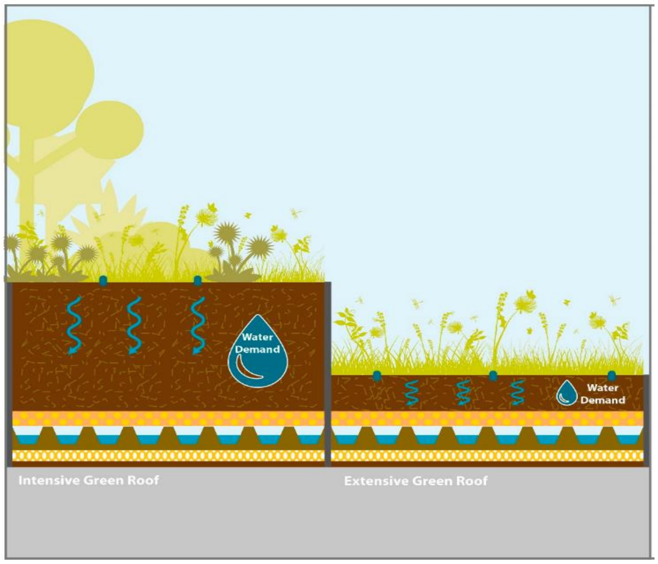

Figure 1, Roofs with greenery of two types: extensive (right) and intensive (left) [22]

The third type of green roof is called semi-intensive [23]. Figure 2 shows different configurations of this type. Green roofs with semi-intensive features are an intermediate type between extensive and intensive roofs. They support a wide variety of shrubs and herbs, and provide ample possibilities for landscaping [24]. Semi-intensive green roofs differ from extensive green roofs, in which vegetation grows naturally. Clients and landscape architects and can choose plant types based on their interests and needs. As a way to address the listed urban circularity challenges, green roofs can be integrated into newly constructed and existing buildings (intensive, extensive and semi-intensive) [22] thereby offering solutions to service “circular cities” [25].

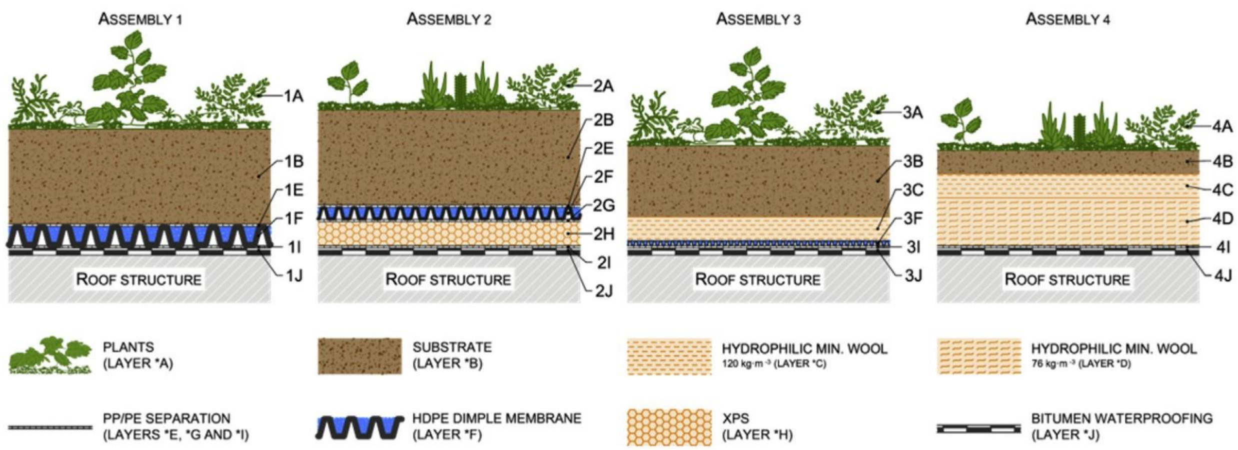

Figure 2, Semi-intensive green roofs [24]

The maximum depth of roofs is 180mm, 250mm and 760mm for extensive, semi-intensive [24] and intensive green roofs, respectively. The vegetation planted in intensive roofs include trees, shrubs and lawns, while extensive roofs are limited to grasses, herbs and moss. However, semi-intensive roofs are of average soil depth compared to the two previous roof planting systems. They support shrubs, grass and herbs but not trees [26]. The weights for these roofs vary between 200 kg/m², 300 kg/m² and 800 kg/m² for extensive, semi-intensive and intensive green roofs respectively. The weight of an extensive green roof system is understandably the lowest among the alternatives and there is therefore no need to strengthen the roof structure [27]. However, the weight intensive green roof gardens needs to be considered when designing the roof structure system. Extensive green roofs are not trafficable by people and are considered inaccessible. In contrast, their intensive counterparts are suitable for social interactions and can be used by the public [28].

1.3 Theoretical Background

Vegetation such as vertical gardens, green façades and green roofs contribute to sustainability in cities as they absorb carbon from alternative urban sources [10]. Green roofs provide important benefits including reducing the heat island effect, extending roof life and reducing carbon emissions [29]. Additionally, Kosareo and Ries [30] found that extensive and intensive green roofs could reduce stormwater run-off and mitigate urban heat island impact by 90% and 60%, respectively. Another study [31] found that 19.8 ha of green roofs in Chicago improved air quality by removing about 1700 kg of air pollutants in one year. An investigation by Mirnezhad, Bin Aminudin and Yeap [32] measured and evaluated the heat transfer between conventional and green roofs. They found that green roofs could decrease temperature by 1-2 ºC in hot and humid climates. Other researchers [33] investigated the energy performance of three different green roofs in a Mediterranean climate. They found that intensive green roofs required less cooling energy than extensive green roofs. Energy use was 20%, 70%, and 60% lower for extensive, semi-intensive and intensive green roofs compared to a traditional roof. These results confirm the advantages of green roofs. Another study [34] found that 50%–75% of roofs could improve air quality when covered with plants. Green roofs also have other advantages such as providing noise barriers in urbanized regions [35].

Green roofs produce fewer environmental emission in both the production and use phases [36]. Some studies have focused on the LCA of green technologies, such as green roofs. For example, one of the first LCA studies of extensive green roof systems investigated reducing the energy consumption of residential buildings [37]. Other study [38] compared the LCA of four existing roofs, namely: intensive green roofs, extensive green roofs, semi-intensive green roofs and conventional roofs. This showed that extensive green roofs generated the least biodiversity loss and was considered the best option. Yet another study evaluated the LCA of roofs and established that the manufacturing phase of intensive green roofs resulted in higher GWP (global warming potential) compared with extensive green systems and gravel roofing systems [39]. In contrast to research advocating green roofs as a sustainable building method [39, 40], other research offers a contrary perspective. For example, one study compared the LCA of conventional and green roofs [42]. This showed that conventional roofs have less environmental impact than extensive green roofs. This is not surprising because extensive green roofs require considerably more materials and components than conventional ones. Different studies have compared the LCA of green roofs with different insulation materials, heat resistances, and waterproof layers [43]. The investigators argue that green roofs contribute the highest emissions and most damage to human health and the ecosystem. This relates to the construction of green roof as more materials are needed compared to roofs designed only for heat resistance or waterproofing. A LCA study conducted by Rincón, [44] evaluated the reduction in cooling and heating of alternative layers of recycled rubber, pozzolana when insulated and not insulated with polyurethane for extensive green roofs and conventional roofs. They showed that recycled rubber could decrease the environmental impact of extensive green roofs compared to a non-insulated conventional roof. Another LCA study [24] analyzed four different semi-intensive green roofs, including hydrophilic mineral wool and extruded polystyrene. Yet another LCA study [45] evaluated ten alternative flat roofs with and without plantings. They found that green roofs with plants had a higher environmental impact benefit and lower cost. These studies clearly highlight the need for a comprehensive life cycle boundary analysis for evaluating alternative case studies. Some reviews of green roof literature have been conducted in the past few years. For example, a LCA study [50] of green roofs revealed that they could have less environmental impact than traditional roofs. Additionally, this study recommended that industry byproducts be studied more thoroughly.

Some studies have estimated the cost of green roofs versus conventional roofs. For example, a cost analysis of traditional roofs versus extensive green roof systems was conducted by Talbot [46]. They found that green roofs cost around 25% less than traditional roofs at the end of their lifetime [47]. They showed that green roofs (extensive and intensive) are more economical than other non-greened roofs. Another LCC study conducted by Chan and Chow [48] compared conventional roofs with green roofs. Their findings were that for the replacement cost of a conventional roof, the cost payback period is about ten years. Additionally, a limited number of articles have combined LCA and LCC as a single study [41, 47]. The study reported in this paper has been conducted to evaluate the LCSA of all sustainability approaches: LCA, LCC, and SLCA. We also propose a framework that highlights gaps in current knowledge to inform further research.

2. Method

2.1 Principles and Procedures

The results of this study are presented in two sections. The first presents the result as a bibliometric analysis which is shown as a co-occurrence map of keywords, geographical distribution, organization and counties. The second section analyses different details of LCA, LCC, and SLCA based on various characteristics used in their assessment. Recently, academic researchers have become increasingly interested in bibliometric analyses [51]. Bibliometric evaluation includes statistical strategies and mathematical methods to evaluate the bibliometric data from a previously selected publication, such as articles and conference papers [52]. The bibliometric method could be described as a quantitative review technique such as analyzing citations on bibliometric data such as units of publication and citation. The bibliometric technique considers a review method to discover the relationship among emerging research topics, journal citations, and the current state of the existing research area.

Figure 3 shows the systematic procedures of selecting appropriate literature for this study. In the first stage, appropriate keywords were chosen to target SLCA and green roofs. The evolution of the search terms used is presented in Table 1. Searches were conducted using the keywords and their combinations. The final search was conducted on February 15, 2023. In the second stage, the Scopus database was chosen as a bibliographic database of academic publications. Scopus is one of the most commonly used databases for bibliometric analyses due to its unique features [53]. Our searches were limited to articles and conference papers as well as book chapters to identify high-quality research. We searched for English documents published between 2003 and 2022. As part of stage 3, 164 publications were found related to the definition of the search (title, abstract, and keywords). All duplicate papers were excluded (exclusion) based on the titles of articles and grey literature, and 154 records were retained for further processing. A review of abstracts identified 42 papers outside the scope of the study and these were discarded. The remaining 112 articles were checked for their title, abstract and keywords, and 13 records that did not focus on environmental or economic aspects of sustainability assessment were excluded. Based on a further in-depth reading, ten papers were removed, leaving 88 records which met the selection criteria, including 74 papers and 14 conference papers. The last analysis stage (4) is explained in the bibliometric analysis section (2.2). It is worth mentioning that papers related to surveys of air conditioner resizing and storm-water related to green roofs were considered outside the scope of this research.

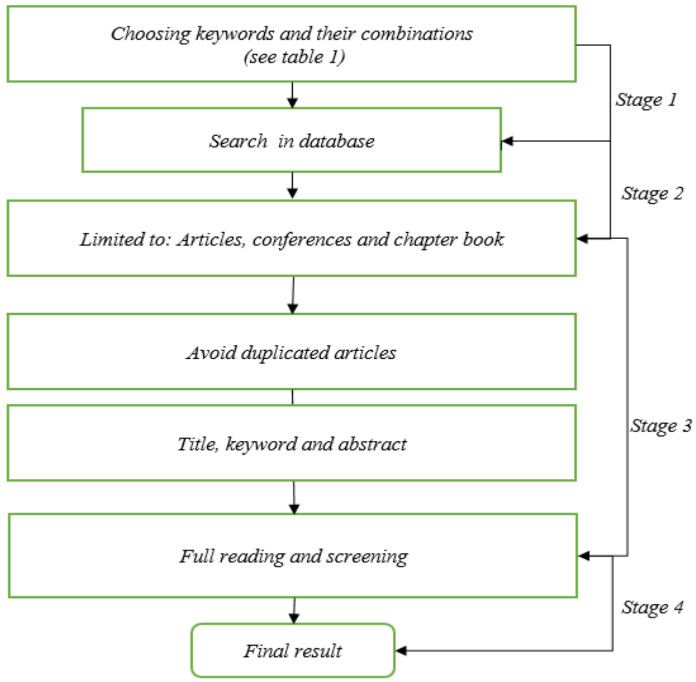

Figure 3. Procedures of selections of article

2.2 Bibliometric Analysis

Visualizing similarities (VOS) viewer software has become increasingly popular in bibliometric research. This software was developed [54] to present bibliometric maps in a visually appealing manner. It allows literature to be efficiently collated, similarities between selected publications identified within parameters, and significant themes identified among publications [55]. In addition, it was possible to map the sciences encountered and analyze networks using VOSviewer (ver.1.6.19). Moreover, in terms of bibliometric mapping, clustering and the visualization of networks, this study was limited in its analyses of keywords and co-authorships. We retrieved data from the Scopus database and exported them in a .csv (Microsoft Excel) file [55]. The selected keywords for the database are illustrated as shown in Table 1.

Table 1. *Results of keyword search terms*

Query	**Number of articles**	**After refine**
"green roof " AND "Sustainability" AND "Life Cycle"	44	32
"green roof " AND "Sustainability" AND "Life Cycle assessment" AND “LCA”	21	18
"green roof " AND "Sustainability" AND "Life Cycle cost"	13	13
"green roof " AND "Life Cycle cost"	35	34
"green roof " AND "Life Cycle assessment" AND “LCA”	62	59
"green roof " AND "Social Life Cycle assessment"	0	0
"green roof " AND "Life Cycle cost" AND "Life Cycle assessment" AND “LCA” AND “LCC”	9	8
"green roof " AND "Life Cycle assessment" OR "Life Cycle cost" AND "Social Life Cycle assessment"	0	0
Initial Title Screening Total		164
Total after removing duplication		**88**

To conduct a bibliometric analysis, three primary steps are required. They include an evaluation of performance, network analysis and science mapping. An evaluation of performance involves evaluating the number of publications and citations (the h-index) as well as related metrics (e.g., the number of citations). This reflects the influence and strength of relationships between different title attributes of articles using their co-occurrence weights and total link strengths. An analysis of citations may include citation analyses, co-citation analyses, bibliographic coupling analyses, co-word (keyword) analyses, and co-authorship analyses. Through network analysis, bibliometric mapping results can be enhanced. A common method is to evaluate and visualize network metrics and cluster data. The methodology adopted for this study followed previous research [56]. Data obtained from Scopus were used for a performance analysis that included the number of publications, citations, and impact factor.

Three types of visualisation are available in VOSviewer: overlays, networks, and densities. Data clustering was effected solely using network visualisation. Keywords and topics are displayed as well as their co-occurrences, co-authorship, and country of origin regardless of co-occurrence of words or co-authorship. Additionally, colors indicate the popularity and similarity of studies. As these are frequently used in multiple studies, line colors used for the interconnection of words change. Smaller connections are indicated by lighter colors, while larger connections are indicated by darker colors.

3 Results

3.1 Bibliometric Data

This section expands on the descriptive analysis of bibliometric evaluation. Different criteria have been considered such as years of publication, geographical distribution, number of citations and the journals in which the papers were published. Preliminary results based on document type distribution showed that around 79.5% of papers are published in journals versus 26% as conference papers. Only 4.5% are book chapters. Most of the publications related to the green roof are articles (70), which represent 79.55% of all the documents. The second source of publications, conference papers, provided 14 papers and represents 15.9% of all the selected documents. The last source, book chapters, provided four papers accounting for only 4.5%. Most publications were published in international journals.

Growth in the number of publications related to this topic is shown in figure 4. The first study related to the life cycle of green roofs was about LCC in 2003 [57], while the first green roof study of LCA was not until 2006 [37]. The number of publications rose during 2007 and then decreased in the next year (2008). No relevant research was published during 2009, showing that research about green roofs was sporadic. However, since 2012 the number of publications stabilized to more than four papers every year. Still, many picks and some bottom observed probably showed the uncertainty about LCSA research about a green roof. Only one paper relevant related was published in 2011, but output rose to eight in 2012 and decreased to four papers in 2021. Prior to that, only nine papers were published until 2011, and from 2012 to 2022, this number rose to 79, showing an 88% increase rate. The annual publication rate increased in 2022 to 13 papers, being the highest number of publications to date. The growth trend publications in life cycle studies of the green roof thus has many ups and downs. In contrast, similar studies about building or construction show an increase each year [58]. This shows that the importance of life cycle studies of green roofs have not been prioritised. Figure 4 also shows the number of citations these papers attracted. The first citations appeared only two years after the first published article in 2005. Unlike the number of publications that have not increased steadily during the last twenty years, the number of citations has had a more stable growth trajectory. The total number of citations increased from 23 in 2009 to 458 in 2021 only decreasing to 423 in 2022.

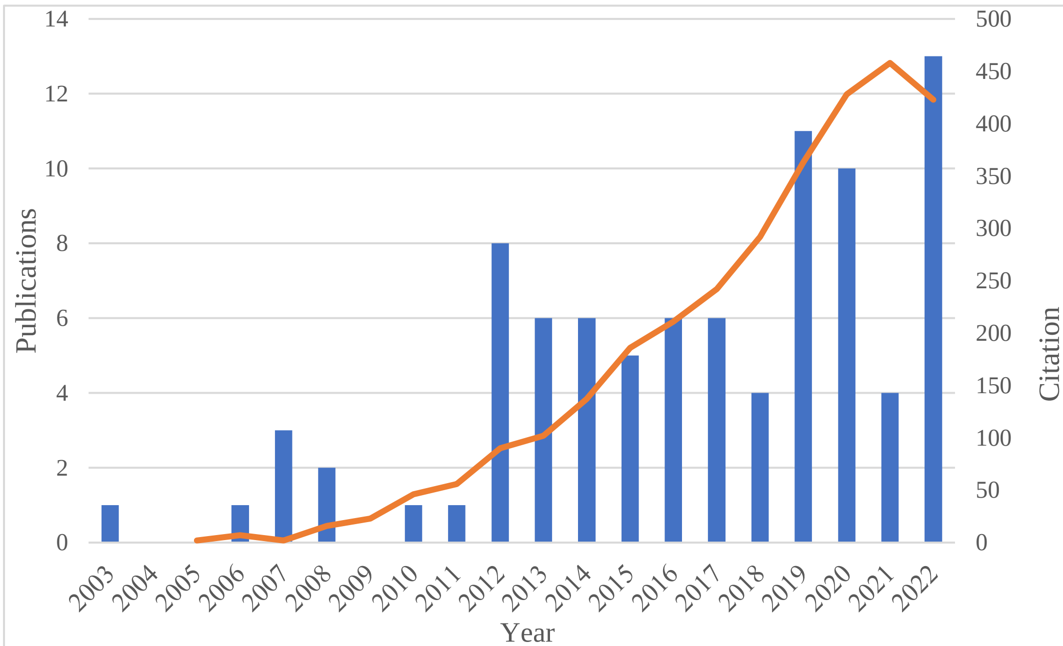

Figure 4. Annual growth of publications from 2003 to 2022

Table 2 shows the primary outlets that publish life cycle studies of green roofs. The "Journal of cleaner production" and "Building and environment" published the most articles. However, "Building and Environment" attracted the highest citations. Table 2 also lists the journals' highest total link strength in green roofs for LCSA. Journals such as the Journal of Cleaner Production, Building and Environment, International journal of life cycle assessment, Environmental and climate technologies, Environmental science and technology, Energy and buildings, and Science of the total environment received the highest co-citation link strengths. These journals are the preeminent research outlets for green roofs and LCSA.

Table 2, Main sources of research from 2003 to 2022

Source	**Documents**	**Citations**	**Total link strength**
Building and environment	7	746	55
Web of conferences	2	0	3
Energy and buildings	2	207	7
Environmental and climate technologies	2	1	8
Environmental monitoring and assessment	2	73	4
Environmental science and technology	3	405	23
International journal of life cycle assessment	2	31	2
International journal of sustainable building technology and urban development	2	21	10
Journal of cleaner production	7	281	55
Journal of environmental management	3	289	3
Science of the total environment	2	37	9
Journal of Water (Switzerland)- MDPI	2	28	5

3.1.1 Geographical Distribution

Figure 5 shows the geographical distribution of the documents analysed. This shows that researchers in the United States are actively in green roof and life cycle research. In addition, authors in many European countries such as Italy, Spain, Germany, Portugal, and the Netherlands are publishing a high number of publications in this field. However, researchers in China are the only ones in Asia that are active in this field. The United States and Italy have been listed as the top countries for publications since 2003, and these countries have made a significant contribution to life cycle and green roof topics. Table 3 provides details of regions/ countries for these papers. To compare citations, the United States and Italy have the highest number relative to their number of publications. The citation is 1108 (31%), 465 (13%), 304 (9%), 296 (8%), and 220 (6%) for the United States, Italy, Singapore, Canada, and Germany, respectively.

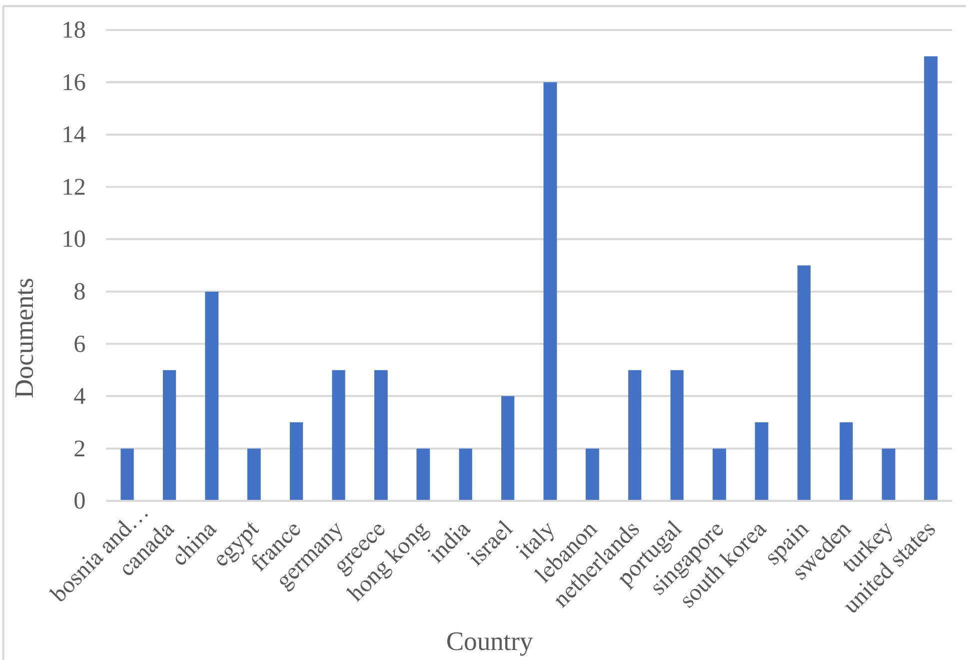

Figure 5. Total link strength of active key regions from 2003 to 2022

Italy has the highest link strength among other countries. This represents the country's core role in cooperating with others on this topic. Thus, Italy has made a solid contribution to developing green roof life cycle studies. Researcher in Italy have co-authored papers on green roofs and their life cycle applications with researchers in several countries. Other countries with high total link strengths include Germany, Portugal, and Greece, respectively. Surprisingly, the total link strength of the United States is among the lowest in the ranking of nine out of twenty countries. This might relate to the fact that researchers from the United States rarely collaborate and publish papers with researchers from other countries.

The link between two countries or circles shows that authors in these countries cooperate with author from other countries. The thicker the connection, the stronger the cooperation between the two countries in terms of the number of contributions. The lines and circles in yellow represent new researchers conducting research on the topic. Bosnia and Herzegovina and Sweden are countries where researchers have recently published papers about green roofs and life cycles. It is also interesting to note links between countries. For example, a strong relationship is found between the United States, Germany, Canada and the Netherlands. Researchers from these countries have been contributing to this topic for the longest time.

Table 3, Details of regions/ countries in selected papers

Country	Documents	Citations	Total link strength
Bosnia and Herzegovina	2	14	1113
Canada	5	296	167
China	8	140	351
Egypt	2	13	66
France	3	52	231
Germany	5	220	1386
Greece	5	56	1332
Hong Kong	2	192	9
India	2	8	4
Italy	16	465	1582
Lebanon	2	43	204
Netherlands	5	86	187
Portugal	5	72	1361
Singapore	2	304	59
South Korea	3	186	46
Spain	9	209	1161
Sweden	3	1	7
Turkey	2	19	1136
United states	17	1108	385

Figure 6 shows the network of countries in which LCSA studies were conducted from 2003 to 2022. Each circle represents countries with publications about green roofs and LCSA, and the size of each circle represents the number of publications. The large circles for Italy and the United States thus mean that researchers in these countries have published most papers in this field. The link between two countries or circles shows that authors in these countries cooperate with those from other countries. The thicker the connection, the stronger the cooperation between the two countries in terms of the number of contributions. The lines and circles in yellow represent new researchers conducting research on the topic. Bosnia and Herzegovina and Sweden are countries where researchers have recently published papers about green roofs and life cycle studies. It is also interesting to note links between countries. For example, a strong relationship is found between the United States, Germany, Canada and the Netherlands. Researchers from these countries have been contributing to this topic for the longest time.

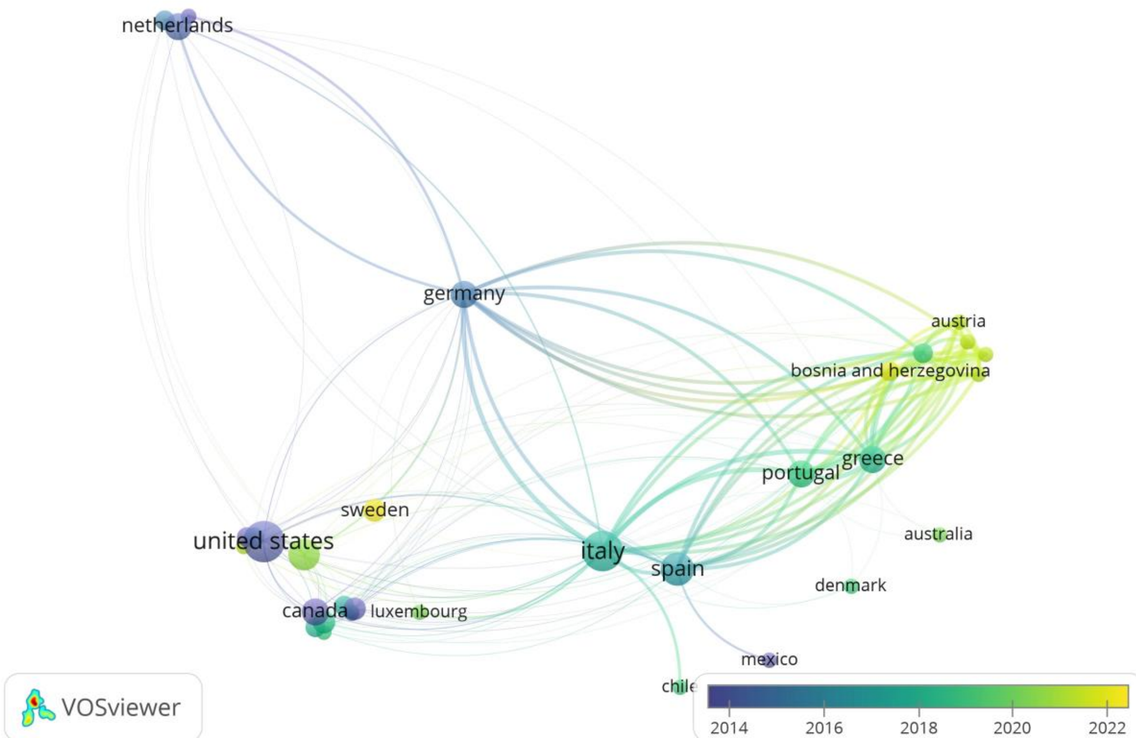

Figure 6. A network of regions/ countries in which LCSA studies were conducted in 2003 to 2022.

3.1.2 Co-occurrence of Keywords

One of the main components of any research paper is the keywords that represent their content. The co-occurrence of the keywords ‘green roof’ and ‘life cycle studies’ was effected by setting the minimum frequency to two keywords in VOSviewer software. Next, the process of filtering was conducted to merge synonyms such as “green roof” and “green roofs” and to convert abbreviations into full terms (“life cycle assessment” and “LCA”). Some general terms such as (“method”, “conclusion”, etc.) were ignored. Analysis of the keywords revealed 298 results for the green roof and life cycle topic with one co-occurrence threshold. When the minimum number of co-occurrences was changed to at least two, the threshold number decreased to 50. Consequently, sixteen keywords with the highest number of co-occurrences were selected as shown in Table 4. The most cited keyword was “Life cycle assessment, LCA, Life cycle analysis, etc.” with an occurrence of 33, which covered 25% of all shares and with total link strength of 71 (26%). The second highest keyword was “green roof, green roofs”, with a frequency of 30 (23%) and total link strength of 54 (20%). The third highest cited keyword was life cycle cost, with a frequency of 13 (10%) and total link strength of 24 (9%). The remaining highest cited keywords are environmental impact (8%), sustainability (5%), extensive green roof (5%), energy efficiency (5%), energy saving (4%), low impact development (3%), and green infrastructure (3%), respectively.

Table 4, Details of Co-occurrence of keywords of the selected publications

	Keyword	Occurrences	Total link strength
1	Life cycle analysis	2	7
2	Life cycle approach	2	4
3	Life cycle assessment	33	71
4	Life cycle cost	13	24
5	Green roof	30	54
6	CO_2 emission reduction	2	6
7	Sustainability	7	20
8	Sustainable development	3	6
9	Low impact development	4	2
10	Green infrastructure	4	6
11	Environmental impact	10	22
12	Extensive green roof	6	16
13	Energy efficiency	6	14
14	Energy saving	5	10
15	Urban heat island	2	5
16	Vegetative roofs	2	4

The current network map shows five highly interconnected clusters. Among the top five knowledge areas of life cycle and green roof, the most popular topics were life cycle assessment, green roof, life cycle cost, and environmental impact. Furthermore, these keywords were strongly associated with different clusters. The other cluster in concern is mainly related to green construction and infrastructure, and their corresponding issues can be seen as “ecology”, “green architecture”, “green infrastructure”, “retention”, and “sustainable development”. The purple cluster relates to “life cycle cost”, “low impact development”, “energy saving”, and “cradle to grave”. The green cluster refers to “environment impact”, “recycle”, “building”, “extensive green roof”, “life cycle approach”, “urban area”, “vegetable roof”, while the light blue cluster relates to “life cycle assessment”, “rooftop agriculture”, and “sustainability”, and “storm water”. The blue cluster relates to “energy consumption”, “maintenance”, “flat roof”, “environment performance”, and “eco-design”. The yellow cluster refers to “green roof” “green wall”, “white roof”, “urban heat island” “energy efficiency”.

The red cluster in figure 7 is mainly related to green construction and infrastructure. Corresponding issues can be seen as “ecology”, “green architecture”, “green infrastructure”, “retention”, and “sustainable development”. The purple cluster relates to “life cycle cost”, “low impact development”, “energy saving”, and “cradle to grave”. The green cluster refers to “environment impact”, “recycle”, “building”, “extensive green roof”, “life cycle approach”, “urban area”, “vegetable roof”, while the light blue cluster relates to “life cycle assessment”, “rooftop agriculture”, and “sustainability”, and “storm water”. The blue cluster relates to “energy consumption”, “maintenance”, “flat roof”, “environment performance”, and “eco-design”. The yellow cluster refers to “green roof” “green wall”, “white roof”, “urban heat island” “energy efficiency”.

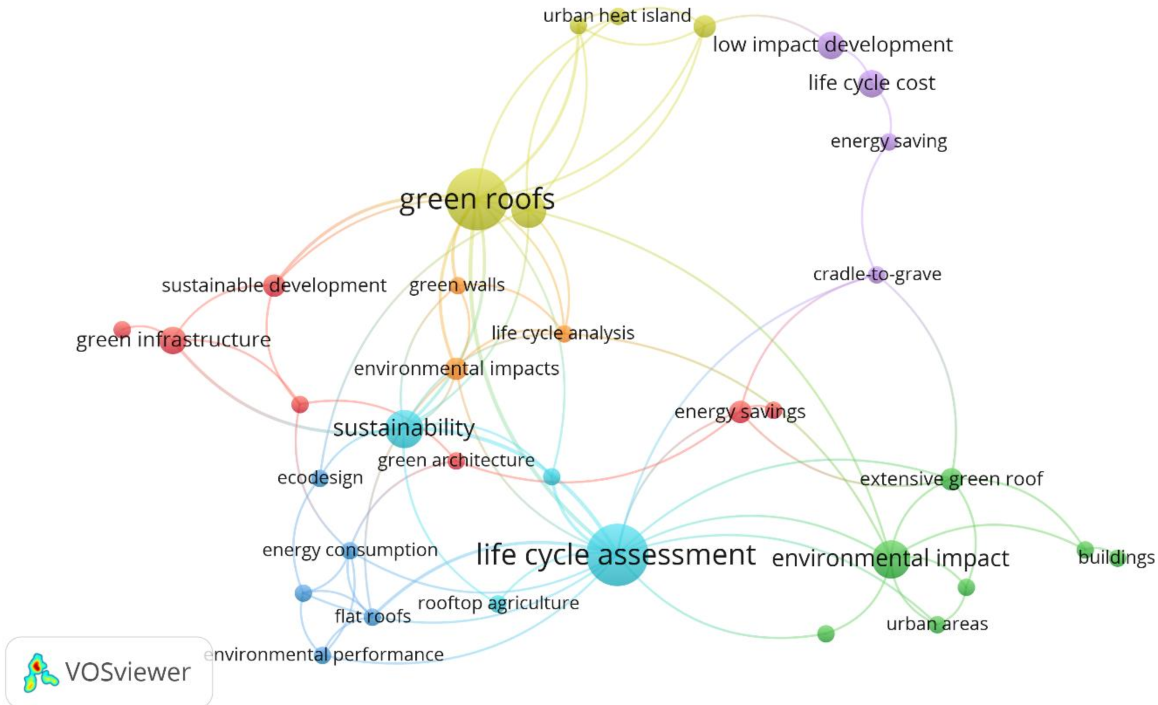

Figure 7. Co-occurrence map of the keywords from 2003 to 2022

3.2 Life Cycle Sustainability Analysis

3.2.1 LCA Evaluation

The meta-analysis can be used to inform recommendations or provide guidance for future designs. Table 5 presents the top 12 most cited research papers in Scopus. The most cited research article is “Comparative environmental life cycle assessment of green roofs” [30] from Building and Environment, with 250 citations. This is one of the first studies to use the Simapro software to evaluate the LCA of green roofs. This study considered the Impact 2002+ life cycle impact assessment (LCIA) method for four environment categories: ozone layer depletion; acidification; eutrophication; and global warming. They claimed that intensive green roofs are ideal in all five impact categories. The second highest cited article “Comparative life cycle assessment of standard and green roofs” from the journal of environmental science & technology has 223 citations. It is the first investigation to use Simapro Software to analyse the LCA of green roofs [37]. However, it only evaluated extensive green roofs for a range of environmental categories, including abiotic depletion, ozone layer depletion, freshwater aquatic ecotoxicity, terrestrial ecotoxicity, global warming, photochemical oxidation, human toxicity, eutrophication, acidification, ecotoxicity, and marine aquatic. However, the authors did not mention the LCIA method by name. Another highly cited article [59] used the CML-2 and Eco-indc-99 LCIA methods for analysis.

Table 5, Most cited articles on life cycle assessment of green roofs

	Source	Year	Location	Types of roof	Functional unit	Lifetime (Years)	Method /Software	Total citations
1	[30]	2007	USA	Extensive/ Intensive	-	50	Simapro	250
2	[37]	2016	Canada	Extensive	-	50	Simapro	223
3	[60]	2010	United States	Green roof	-	-	-	67
4	[59]	2007	UK	Innovative system	treated greywater	15	Simapro	65
5	[61]	2015	Finland	Extensive	$1m^2$	40	Simapro	64
6	[44]	2014	Spain	Extensive	$9\ m^2$	50	LCAmanager	59
7	[24]	2017	Czech Republic	Intensive	$1\ m^2$	20	GaBi	54
8	[62]	2013	Spain	Extensive	$50\ m^2$	-	European database	51
9	[27]	2012	Italy	Extensive	$1\ m^2$	50	Simapro	48
10	[63]	2012	Netherlands	Extensive	kWh of electricity	30	Simapro	42
11	[64]	2014	Spain	Extensive/ Intensive	$300\ m^2$	30	Ecoinvent 99 (EI99), IMPACT 2002+ and Cumulative Energy Demand	37
12	[65]	2018	Portugal	semi-intensive	$1\ m^2$	50	GaBi	34

The fourth and fifth most cited papers also evaluated extensive green roofs, as well as most of the other studies. This may be because this kind of green roof does not require changing the last ceiling thickness of building with needing the lowest thickness of soil; consequently, it is particularly suitable for existing building structures [66]. Most studies evaluated one type of green roof, either the extensive green roof [27], intensive green roof [24], or semi-intensive green roof [65]. Some researchers compared the LCA of different types of green roofs. For example, one study [30] compared two types of green roof (extensive and intensive green roofs), finding that ozone layer depletion, acidification, eutrophication, and global warming impact categories of intensive green roofs were better than those of extensive roofs. Another study found that intensive green roofs have the highest impact on all damage categories, including human health and climate change, compared to extensive green roofs [64]. A further study [67] compared the LCA of alternative roofs: traditional gravel ballasted roofs, and white reflective roofs with extensive and intensive green roofs. They found that many life cycle stages need to be evaluated in future research, such as water retention, pollutant extraction from the atmosphere by a green roof, and thermal insulation effects. Their results indicated that both green roofs perform better than other alternatives [67].

There are many different LCIA methods that have been used in alternative LCA studies. Despite most studies using the IMPACT2002 +, ReCiPe v1.06, and CML2 baseline, other LCIA methods were used in a few studies. For example, one study [68] applied the UM-LCA method. The UM-LCA approach has limitations and these should be considered when evaluating results. A study by Goldstein et al. (2013) discussed how UM-LCA can be useful only with appropriate geographic boundaries and functional units. The differences between the UM-LCA method and other LCIA methods such as IMPACT2002 +, ReCiPe v1.06, and CML2 need further investigation to identify their differences. The LCIA methods used included Impact 2002+ (six times, 24%), followed by CML 2001, ReCiPe v1.06, and CML2 baseline (four times, 16%). The eco-Indicator 99 method was used twice (8%). Other LCIA such as TRACI v2.1 [69], LCA/EPD [70], IPCC [71], European database [62], and Cumulative Energy Demand [64] were only used once in different studies. The majority of LCA studies used Simapro software to analyze green roofs (19 times, 70%), followed by GaBi software (three times, 11%). Other software was used once in different LCA studies, eBalance 4.7 [72], CYPE Engineers [73], Athena [69], EPA-W [43], and LCA-calculator [66].

3.2.2 LCC Evaluation

Table 6 shows the most cited articles on the LCC of green roofs. Different LCC methods may be used including the net present value (NPV), present value (PV), internal rate of return (IRR), and pay back period (PBP). The most cited study [20] is from the Journal of Environmental Management, entitled “Life-cycle cost-benefit analysis of extensive vegetated roof systems” with 254 citations. Most studies used NPV to compare different scenarios. Some studies [74] used other methods, such as PBP and IRR. Some studies compared extensive and intensive green roofs. For example, one study [57] compared two intensives (80% shrub & 50% tree) with an extensive green roof. They found that the initial cost of extensive, intensive with 80% shrubs and intensive with 50% trees was 89 $ M^2, 178 $ M^2, 197 $ M^2, respectively. The extensive green roof was therefore considered a lower-cost option. Only a few studies compared the LCC between intensive and extensive green roofs. Mohapatra et al., (2020) believed that semi-intensive roofs deliver higher energy efficiency than extensive green roofs. However, the LCC of the semi-intensive roof was not evaluated in any of the selected publications. Other costing methods such as total rate of return (TRR), discounted payback period (DPP), and external rate of return (ERR), could be used in future studies to evaluate green roof costs and energy consumption.

Table 6, Most cited articles on life cycle cost of green roof

	Source	Location	Types of roofs	Method/Software	Total citation
1	[20]	USA	Extensive	NPV	254
2	[74]	Italy	Extensive	NPV, IRR, PBP	215
3	[75]	USA	Extensive	cost-effectiveness	190
4	[57]	Singapore	Extensive/Intensive	Discounting method	184
5	[76]	Hong kong	Green roof	PV	163
6	[77]	United states	Extensive	NPV	119
7	[78]	Italy	Extensive	NPV	56
8	[79]	China	Green roof	NPV	31
9	[80]	Hong Kong	Extensive	PV	28
10	[81]	USA	Green Roof	-	17
11	[99]	Italy	Extensive/ Intensive	NPV, Life Cycle Revenue, and Discounted Cashflow	12

3.2.3 LCA & LCA Evaluation

Table 7 shows the most cited articles on LCA and LCC of green roofs. One of these is “LCC and $LCCO_2$ analysis of green roofs in elementary schools with energy saving measures” by Hong et al., (2012) published in the Journal of Energy and Buildings, with 88 citations. The authors evaluated 16 case studies with green roofs, incorporating external insulation, exterior blinds, double glazing, and a light-emitting diode. The impact of alternate green roofs could not be distinguished in this study since its focus was on a different element of existing buildings. The first study about LCA that claimed to have a consequential life cycle analysis was by Wang, Eckelman and Zimmerman [82]. A consequential LCA provides an estimate of how global environmental burdens are affected by the production and use of a product and how to make changes to improve choices [83]. This study focuses on the LCA of alternative rainfall scenarios of green infrastructures such as green roofs. Another study [49] analyzed the life cycle CO2 and LCC of sixteen different types of vegetation for green roofs. This revealed that green roofs, sedum, and grass generate low total costs. In another study, two green roof types, roof farm and extensive roof garden, were compared. This found the roof farm to be more expensive than the roof garden [84]. Another study [66] assessed the energy environment and cost of a building and applied some strategies such as retrofitting of extensive green roofs, windows, and thermal insulation. LCA and LCC were compared in another [42], finding that traditional roofs have less environmental impact compared to extensive green roofs. It is probably because extensive green roofs require more materials than a traditional one. In conclusion, none of the reviewed studies identified the most effective green roofs with respect to LCA and LCC. Furthermore, none of these studies considered semi-intensive green roofs and how these differ from the other two types of green roof. Therefore, it is currently not possible to identify the optimum green roof structure.

Table 7, Most cited articles on life cycle assessment and life cycle cost of green roof

	Source	Location	Types of roof	Functional unit	Lifetime (Years)	LCA method/Software	Citation
1	[85]	Republic of Korea	Extensive / Intensive/ Mix system	Not spacified	15	-	88
2	[82]	United States	Green roof	1298 m2	40	SimaPro	101
3	[49]	Korea	Extensive	-	40	-	71
4	[66]	Italy	Extensive	-	100	Design Builder	42
5	[84]	Republic of Korea	Extensive	140m2	40	ecoinvent database (v3.3)	10
6	[42]	Greece	Extensive	-	45	SimaPro	2

3.3 Life Cycle System Boundary Monitoring

3.3.1 System Boundary of LCA

Table 8 shows research about the LCA of green roofs and the various phases of the life span of green roofs. Since an evaluation of cradle-to-gate (A1-A3) is compulsory in LCA studies, we have excluded studies that consider only these stages. The literature includes cradle-to-gate (A1–A3) [70], cradle-to-site (A1–A5) [67], and cradle-to-grave (A1–C4) [44,85]. All these studies focused on the production and manufacturing stage (A1–A3) more than others. This might be related to EPD (Environmental Product Declaration) EN15804 and EN15978, as any LCA must assess A1–A3. No studies focused on the entire life cycle of a green roof. In other words, even studies that presented their system boundaries as a complete life cycle do not include all the subcategories of these phases. Figure 8 shows that there is no mention of repair (B3), refurbishment (B5), and reuse (D1) in any LCA studies. These stages need further evaluation.

Although almost half of the LCA studies considered maintenance (B2), the assumptions made differed from one study to another. There thus appears to be a need for a robust framework and clear understanding. The maintenance of the wall of a building is quite different from a green roof. For example, one study considered the maintenance for a green roof to be that the plants needed cleaning [38]. The maintenance of semi-intensive green roofs was seen as intermediate maintenance, and was limited to occasional irrigation, weeding, and fertilization [72]. However, in this study, the maintenance of the main structure of the green roof and its alternative layers has not been considered. Another study [69] claimed that their study had considered maintenance. However, this was limited to weed control. Another study [87] considered only fertilization for the 40 year life span of the roof. A further study [24] considered fertilization of the substrate, visual checks and weeding for the maintenance stage. Maintenance includes regular visual inspection and actions necessary to retain the desirable functionality level [88]. Unlike the study of Manso, Castro-Gomes, Paulo, Bentes and Teixeira [65] waterproofing and irrigation require maintenance every ten years of the 50 year life span of the roof. This is different to the work of other researchers. Thus, a detailed framework for maintaining different green roofs is needed as the depth of soil in the various roofs is different and may affect the process.

Table 8 Description of Life cycle stages of selected articles related to the life cycle assessment

		Raw Material Extraction	Transport	Manufacturing in Factory	Transport to Site	Installation and Erected Process	Use	Maintenance	Repair	Replacement	Refurbishment	Operation Energy Use	Operation Water Use	Demolition	Transport	Waste Processing	Disposal	Reuse	Recovery	Recycling	Landfill
Source	Year	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D1	D2	D3	D4
[45]	**2022**	■	■	■	■	■									■	■					
[70]	**2022**	■	■	■																	
[89]	**2020**	■	■	■	■	■															
[72]	**2020**	■	■	■	■	■	■	■							■						■
[86]	**2020**	■	■	■	■	■	■					■								■	■
[69]	**2020**	■	■	■	■	■		■						■	■	■	■				
[66]	**2020**	■	■	■	■	■								■	■	■	■				
[87]	**2020**	■	■	■	■	■		■													
[65]	**2018**	■	■	■	■	■	■	■													
[73]	**2018**	■	■	■	■	■		■													
[59]	**2007**	■	■	■	■	■	■														
[24]	**2017**	■	■	■	■			■		■					■		■				
[90]	**2017**	■	■	■	■	■															
[91]	**2016**	■	■	■	■	■	■														
[67]	**2016**	■	■	■	■	■															
[43]	**2015**	■	■	■																	
[61]	**2015**	■	■	■	■	■															
[44]	**2014**	■	■	■	■	■															
[88]	**2013**	■	■	■	■	■		■												■	■
[27]	**2012**	■	■	■	■	■	■	■						■	■	■	■		■		■
[92]	**2008**	■	■	■			■	■													
[30]	**2007**	■	■	■	■	■															
[84]	**2018**	■	■	■	■	■	■	■													
[49]	**2012**	■	■	■	■	■		■		■		■	■				■				
[37]	**2016**	■	■	■	■	■	■	■													
[93]	**2014**	■	■	■	■	■	■	■						■	■	■	■				
[94]	**2019**	■	■	■	■	■									■		■				■
[38]	**2019**	■	■	■	■			■		■			■		■	■	■				
[71]	**2022**	■	■	■																	
[42]	**2021**	■	■	■	■	■															
[60]		■	■	■	■	■						■	■								

The replacement (B4) stage for green roofs also needs further evaluation. For example, one study [24] considered replacement of the substrate but it was not clear what materials were used, what was replaced and how many times this was done during the life span of the roof. Another study considered replacing irrigation, plants, and sealing [38]. Yet another study [30] claimed that the average life span of a conventional roofing system is usually 10 to 15 years before replacement. The same study stated that is was necessary to assess a green roof and disclose the life span of the green roof before replacement was considered. The different layer of a green roof, including thermal insulation, root barriers, vapour barriers and waterproof layers, have different life spans. These need to be considered separately for replacement and / or maintenance. On the other hand, since green roofs are exposed to the elements, the life span of green roof layers and components can be affected compared to the materials used inside. These scenarios need to be considered in future studies.

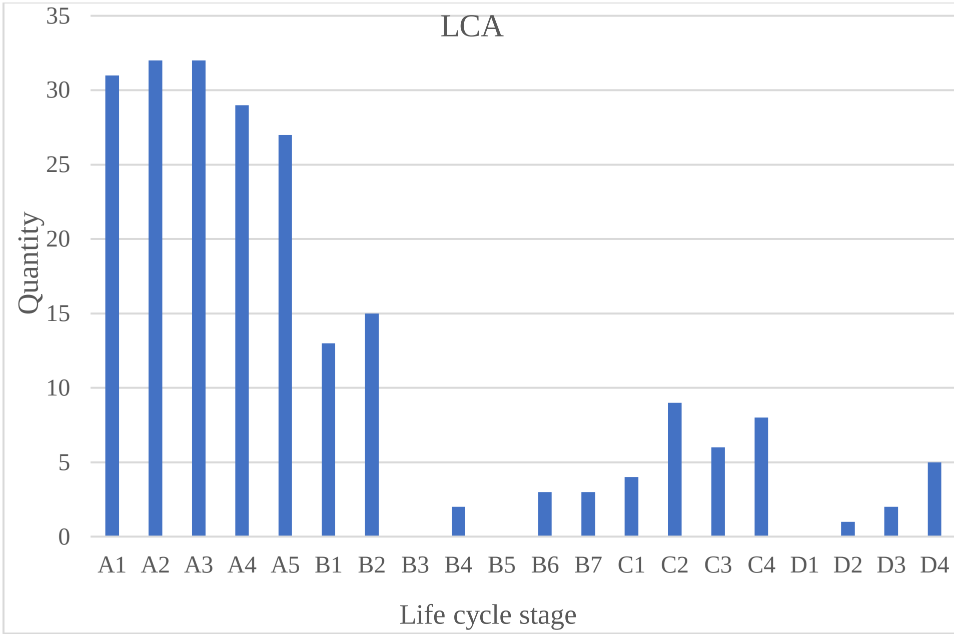

Figure 8, Life cycle assessment stage of system boundaries

The operational energy use stage (B6) was considered in few green roof studies. One study [86] analyzed the LCA and energy consumption of extensive green roofs. Other researchers included B6 and considered annual energy consumption for extensive green roofs [48,59]. Future studies could investigate operation energy use of alternative green roofs. Another study [86] considered recycling, but was limited to the energy consumption of extensive green roofs. Environmental performance was not calculated. Extensive green roofs can be retrofitted to existing buildings without structural changes. The environmental performance of intensive green roofs on existing buildings may present larger benefits during the use phase as larger reductions in heating and cooling energy use are expected [91]. However, additional structural requirements would likely increase upstream environmental impacts. This needs to be considered with bigger system boundaries and include reuse and recycling.

3.3.2 The System Boundary of LCC

The system boundaries of cost or economic performance need to be analyzed in a similar manner to environmental performance in terms of their objectives and scope. According to ISO 15686-5 (2017), economic performance can be evaluated in different phases of the life cycle of a green roof. Table 9 presents various studies which concentrate on the economic assessment of these roofs at different stages of their life cycle. It is imperative to consider the inclusion of green roofs at the design stage. This is so that structural integrity is taken into account [10], Thus the A0 stage is added as a design phase. Surprisingly, no studies considering the costs of the design stage. However, most studies included the manufacturing cost (A1-A3), as this shows stakeholders what needs to be spent to construct a green roof. LCC for extensive green roofs have been analysed considering only manufacturing and construction stages [42]. One of the first studies that included disposal costs for green roofs used the benefit-cost analysis (BCA) method [78]. However, this study only considered an extensive roof. Currently, no other studies were located that evaluate the cost of waste and disposal of other green roofs, namely, intensive and semi intensive green roofs. Therefore, it is suggested that the end of life costs of alternative green roofs is evaluated.

Table 9, Description of Life cycle stages of selected articles related to the life cycle cost

	Design	Raw Material Extraction	Transport	Manufacturing in Factory	Transport to Site	Installation and Erected Process	Use	Maintenance	Repair	Replacement	Refurbishment	Operation Energy Use	Operation Water Use	Demolition	Transport	Waste Processing	Disposal	Reuse	Recovery	Recycling	Landfill
Source	A0	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D1	D2	D3	D4
[42]		■	■	■	■	■															
[66]		■	■	■	■	■		■													
[78]		■	■	■	■	■		■							■	■	■				
[60]		■	■	■	■	■						■	■								
[92]		■	■	■	■	■				■		■									
[84]		■	■	■	■	■	■	■									■				
[49]		■	■	■	■	■			■	■											
[95]		■	■	■				■				■	■	■		■					
[20]		■	■	■																	
[77]		■	■	■	■	■		■		■		■	■								
[96]				■	■			■		■				■							
[97]		■	■	■			■	■		■		■									
[80]		■	■	■	■	■															
[76]		■	■	■	■	■		■				■									
[85]		■	■	■	■	■			■	■											
[98]		■	■	■	■	■															
[57]		■	■	■				■		■											
[99]		■	■	■	■	■		■		■				■			■				

One study [92] compared the LCC of an extensive green roof with that of a built-up roof. Another study compared green roof construction cost on different buildings, such as for a single-family, multi-family and commercial buildings [60]. Roof farms with roof gardens have also been compared for extensive roofs [84]. A limited number of studies compared the LCC of intensive and extensive green roofs. However, no study compared all three types. Figure 9 shows that most studies do not account for all LCA phases (from raw material extraction to disposal). No study examined all green roof layers or the potential use of recycled materials. The refurbishment (B5) stage should be considered in future studies.

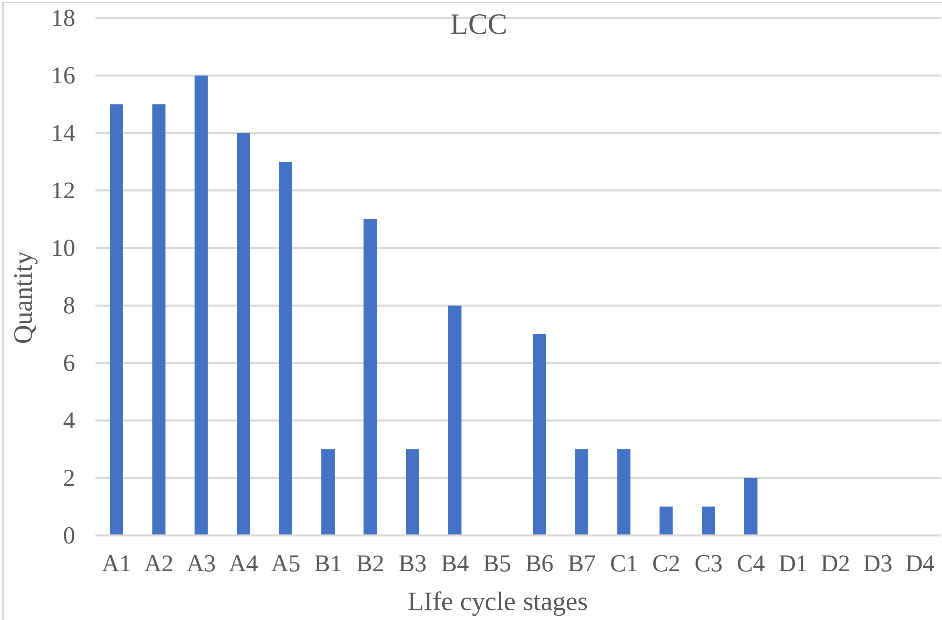

Figure 9, Life cycle cost stage of system boundaries

4. Optimal Type of Green Roof

Table 10 presents studies that evaluated alternative types of green roofs. Surprisingly, there is little agreement on the best choice. For example, studies that evaluated the LCA of green roofs indicated that intensive green roofs are ideal and more environmentally friendly [29, 87,29]. On the other hand, some studies claim that extensive green roofs are more sustainable compared to intensive green roofs [63,86]. Some studies compared all three green roof types, finding that extensive green roofs as an ideal sustainable choice [37, 100]. Furthermore. SLCA is a neglected area of green roof research. Some investigations on the SLCA of green roofs have been conducted recently. For example, a survey of the importance of cost of garden and farm roofs found that people did not consider economic cost to be an essential aspect of green roofs [84]. A recent review [103] of urban green infrastructure showed that most published research investigated how green structures affect the thermal performance of buildings, but none evaluated human well-being and health. Other research [93] has evaluated green roofs in terms of selected criteria, such as Structural design force, fire safety and durability. There is as yet no comprehensive published research on SLCA.

Another study [30] conducted a LCA study of three types of green roofs in the USA. The system boundaries considered were for manufacturing and transporting raw materials, maintenance and disposing of the materials at the end of their life. The Impact 2002+ LCIA method was used, and identified the intensive green roof as the best choice. Extensive and extensive green roofs were compared in another study using CML2 baseline 2000 v2.1 LCIA method. This was conducted for Sydney, a coastal area, and for a life cycle of 25 years [100]. The system boundaries for this study included the manufacturing process, installation of green roofs and separate assessment of air pollutants. Transportation and demolition were not considered. The findings were that intensive green roofs reduce global warming emissions more than extensive green and non-green roofs. This study demonstrated that intensive green roofs have lower total environmental impacts in several categories, such as abiotic depletion, terrestrial ecotoxicity, photochemical oxidation, acidification and eutrophication. This study concluded that intensive green roofs were the type to be recommended.

Table 10, different studies combining of green roofs

Source	**Intensive**	**Semi-intensive**	**Extensive**	**Best choices**
Life cycle assessmnet				
[30]				Intensive
[64]				Extensive
[100]				Intensive
[38]				Extensive
[93]				Extensive
[67]				Extensive
Life Cycle Cost				
[57]				Extensive

Some other studies arrived at contrasting results. A study using two LCIA methods IMPACT 2002+ and Ecoinvent 99 (EI99) to evaluate different roofing systems, including extensive and intensive green roofs [64]. The result of the LCIA studies showed that extensive roofs have a lower impact in the material manufacturing, transportation, maintenance phase and disposal stage. Another study [67] compared the LCA of alternative roofs using the Impact 2002 LCIA method using 15 impact categories. System boundaries were limited to the manufacturing and transportation stages. The findings were that extensive green roofs had a lower environmental impact for all categories than intensive green roofs. A further study [38] compared all three types of green roof using two LCIA methods: IMPACT 2002+ and ReCiPe 2016. This study's system boundary comprised manufacturing, transportation, maintenance, replacement, water use, and disposal. However, both maintenance and replacement were limited to cleaning, sealing and plants, and not defined separately for the green roof structure and materials which need to be replaced every 10 or 15 years based on other studies. A different investigation indicated that an extensive green roof is an ideal choice [93]. Table 10 shows that only one study evaluated the semi-intensive green roof. There are thus opportunities for more studies to evaluate this green roof and compare it with other alternatives, such as intensive and extensive coverings for all life cycle stages, including the load and benefit stages. Only one study was found to have investigated the LCC of all different green roofs [57]. Another study [102] pointed out that extensive and inaccessible public green roofs costs at least $108, while an intensive and publicly accessible green roof costs at least $355. Some other studies have combined LCA and LCC as one unified research. However, a study [85] considered both extensive and intensive green roofs, but it is unclear which one is more effective or environmentally friendly. This is because the study simultaneously combined green roofs with other strategies, such as internal and external insulations, venetian blinds, single and double glazing, fluorescent lamps and LED. This made it impossible to identify the contribution of alternative green roofs on energy saving and cost-efficient options.

Table 10 highlights the lack of an LCA study that compares all green roof types simultaneously, both environmentally and economically, in a holistic manner. None of the investigations explored above considered the load and benefits stage, which include reuse, recycling, and recovery. Recycling might have a reverse impact on both LCA and LCC as it has a net positive impact. This could affect decision-making about the choice of types of green roofs.

5. Discussion and Research Gaps

Based on the literature, the following research gaps are proposed for further investigations. Figure 10 shows the framework of knowledge gaps to be surveyed in future.

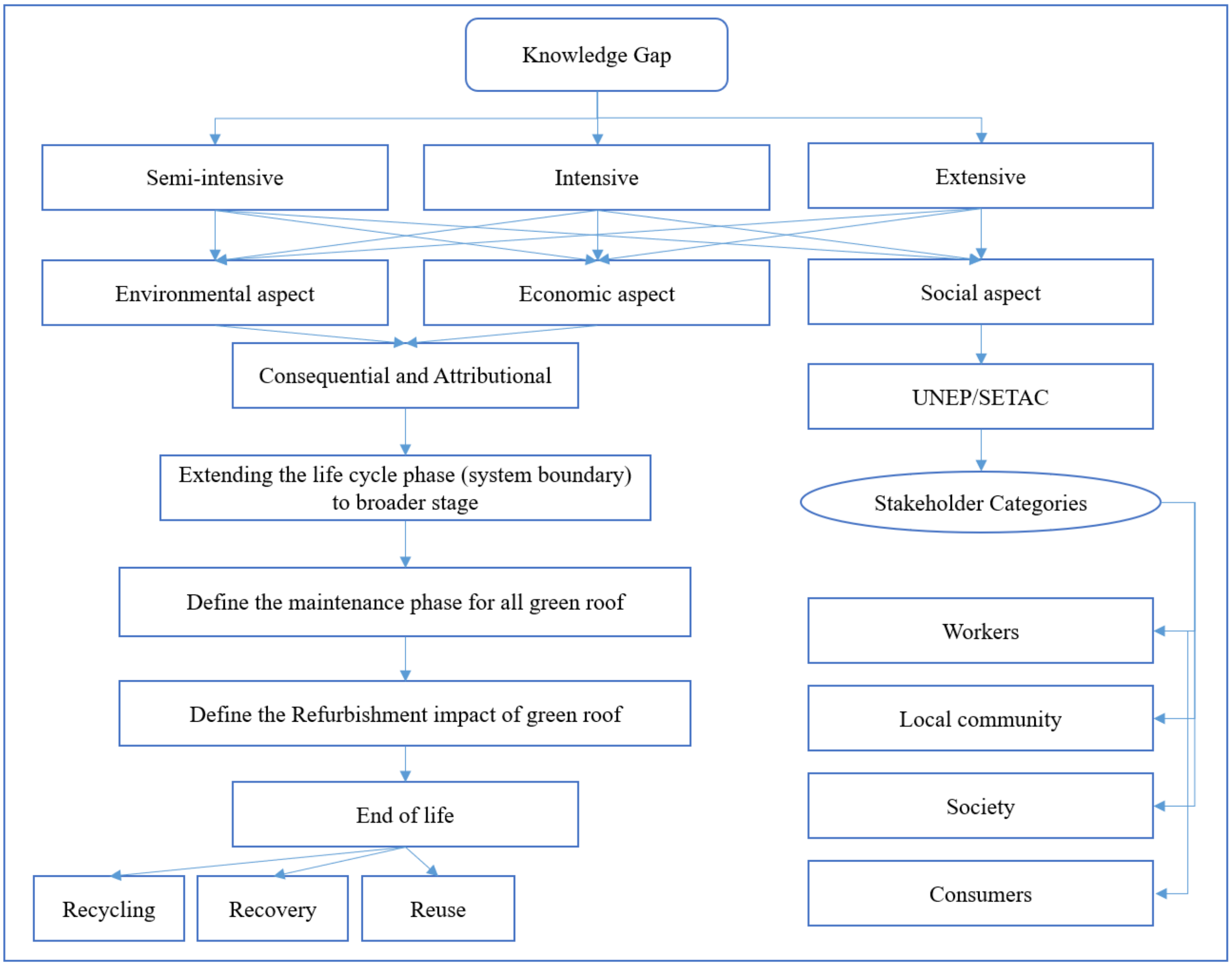

Figure 10, the framework of knowledge gaps and future research

- Firstly, semi-intensive green roofs needs further investigation for both LCC and LCA compared to other green roofs. This is mainly because a semi-intensive green roofs have been omitted in many studies, especially for cost comparisons.
- Comparing attributional and consequential modelling is also a topic for future studies of green roof LCA. A limited number of LCA studies consider the attributional method [68, 65]. No studies about the consequential LCA study on a green roof were located. The LCC for both consequential and attributional modelling needs to be considered for alternative green roofs. Consequential LCA has come to the fore in LCA research to respond to a different key question that is not addressed by

attributional LCA. The consequential approach is useful when large-scale decisions need to be made, like for urban planning policies that could relate to green roofs. In the consequential approach, system boundaries are expanded to include avoided processes due to reuse and recycling at the end of life [83].

- There is no agreement on the best LCA alternative green roof in literature. We recommend that this topic is investigated, considering all the life cycle stages of green roofs.
- The system boundary of SLCA is based on the Society of Environmental Toxicology and Chemistry [104]. Social- UNEP/SETAC allows for comparisons of different products or materials [103, 104]. The principal stakeholder categories are divided into workers, local community, society, and consumers. Each category is for different purposes such as freedom of association, health and safety, fair salary for workers, or consumer satisfaction.
- Future research into LCA, LCC and SLCA of alternative green roofs is warranted. Such comparisons might use multi-criteria analysis using the multi-criteria decision-making (MCDM) method. Since each LCA, LCC and SLCA has a different unit of measurement (Balasbaneh, 2020; Balasbaneh & Sher, 2021), it requires a technique that can compare alternatives. The MCDM method presents a foundation for prioritizing, sorting, and selecting materials and helps in overall assessment.
- There is no evidence of recycling, reuse and recovery (D1-D3) having been considered in previous LCA and LCC studies. Some work has been recently conducted on the end-of-life of green roofs. For example, one study reported the use of recycled polystyrene foam slabs (as thermal insulation) in a green roof [42]. Green roofs may comprise concrete, steel, mastic asphalt, waterproof membrane, root barrier, thermal insulation, drainage, filtration, and substrate. Future studies are encouraged to consider the recycling of all these materials at the end of their life cycle.
- There are currently no studies on the repair and refurbishment stages (B3, B5) for the LCA of green roof materials at the end of the life span of a roof or building. Equally, there are no studies on the refurbishment stage (B5) for LCC. LCC and LCA studies of renovation and refurbishment of existing roofs to extensive green roofs would be informative and encourage the provision of sustainable solutions.
- It is currently not clear what the difference is between maintenance (B2) of alternative green roof cost and environmental impact following EN15804 and EN15978. Although some research has claimed there is no need for any maintenance of extensive green roofs (Williams et al., 2010), other studies have claimed that maintenance had been considered for this stage including irrigation, fertilizing the substrate, and sealing. It is also necessary to appreciate that intensive and semi-intensive green roofs have different maintenance requirements. In fact, the lack of maintenance guidelines and insufficient data on green roof performance may be a significant obstacle to the adoption of green roof technology.
- Waste processing (C3) modules (Koroxenidis & Theodosiou, 2021) are also neglected in most green roof studies. The differences and magnitude of waste among three different alternative roof are thus not clear.
- A lack of rigour in current decision-making has been observed in the choice of green roofs. This is a critical issue and related to the importance of constructing green roofs for human health and sustainable cities. This area should be addressed in future research (Table 10).
- One of the latest studies [108] argues that installing a green roof in a tropical climate is significant and can improve the LCC of the existing building as a retrofit option to save energy. However, the

LCA and LCC of retrofitting conventional roofs to green roofs or alternative green roofs require further exploration.

- Studies mainly examined the environmental performance of specific climates in specific contexts regarding location and climate without comparing the effects of different contexts. Providing additional insight into location and climate impacts will be useful in future studies.
- Finally, an integrated and coherent approach is needed to address the complexity of decision-making to evaluate green roofs and reveal the best options. This requirement can be fulfilled by integrating LCA, LCC, and S-LCA into a framework for LCSA to promote a sustainable circular economy.

6. Conclusion

This paper has reported on a literature review of green roofs. It has focused on life cycle sustainability assessment in the context of the environment, economic and social impact. This study has evaluated current research to determine the future directions and research gaps. The bibliometric analysis has identified current trends and progress in the field of life cycle sustainability assessment (LCSA) of green roofs. A search pattern query was used to find relevant article sources, including green roof, life cycle assessment, life cycle cost, social life cycle assessment, and sustainability. We found that the number of publications between 2003 and 2022 has increased by 88% from 2012 until 2022. However, there are many gaps in the current literature that need to be filled to enable selection of the best green roof. The US and Italy are countries whose researchers publish most in this field, followed by Spain and China.

Secondly, the results of a meta-analysis and systematic search review showed that most of the studies compare green roofs with traditional roofs. A limited number of studies compare different types of green roofs. Very few studies considered the LCA of semi-intensive green roofs. No study compared the costs of all three green roof from cradle to the grave for all stages. Simapro software and IMPACT2002 + as a life cycle impact assessment (LCIA) method were the most applied approaches used in LCA studies. Most of these studies focus on the production and construction of green roofs. The repair stage, refurbishment stage and reuse of materials at the end-of-life span have not been considered in any LCA studies.

The cost of the design stage for green roofs needs to be evaluated in future research since different green roof types require various structures due to the weight and thickness of these roofs. The refurbishment stage and scenario after the lifespan of the building have not been considered in any LCC studies. The most critical outcome from this study relates to the social life cycle assessment of alternative green roof that has not been evaluated in any studies. We have conducted a thorough review of literature of green roofs, revealing areas that have been thoroughly investigated as well as those that have not. This is the major contribution of this paper – to identify areas of future research

Declarations
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
Ethics approval and consent to participate Not applicable

Authors' contributions: All authors contributed to the study conception and design. All authors read and approved the final manuscript.
Competing interests: The authors declare that they have no competing interests.
Consent to Participate: Not applicable.
Consent for publication: Not applicable.
Funding information is not applicable
Data availability: The datasets used and analysed during the current study are available from the corresponding author on reasonable request

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