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Review

A Critical Perspective and Inclusive Analysis of Sustainable Road Infrastructure Literature

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Abstract: In response to the important environmental impacts produced by the road transport network during all its life cycle stages, a set of measurements to include sustainable principles have been identified between 1997–2021, analysed and mapped by applying SciMAT and VOSviewer. The results have shown the predominance of issues which analyse the life cycle assessment of road infrastructures in its both environmental and economic dimension as a way to mitigate their effects on climate change, including the reduction of resources and energy consumption, or of energy consumption and greenhouse gases emissions during the construction and operation stages, respectively. However, the incorporation of the social life cycle assessment dimension, their adaptation to climate change, and the use of smart roads are still in an early stage. Therefore, efforts to include these issues are necessary to address their design according to the resilience concept and ensuring a cleaner and more competitive and climate-neutral Europe.

Keywords: sustainable road; sustainable highway; green road; green highway; rating systems; sustainability

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1. Introduction

Road transport shows important advantages in comparison to other modes of transport, for example accessibility, adaptability to individual needs [1], the promotion of robust and sustainable regions [2]. Road transport also delivers economic benefits [3]. In consequence, a huge global road infrastructure network is operating nowadays, and it is expected to increase by 2050 [4], resulting in the main used transport mode in European countries [5] which includes strategic infrastructures in the economic [6,7] and social [6] development of countries.

Road infrastructure integrates all road categories as the main element [8], as well as a set of facilities, structures, signage and markings, and electrical systems, to guarantee safe and efficient traffic [9]. This infrastructure has significant environmental impacts during all its life cycle stages, i.e., construction, operation, and maintenance, including: consumption of natural resources (raw materials and energy), airborne emissions, acoustic pollution, ground and surface water contamination, habitat disturbance, land use or negative effects on plants [10], lighting disturbances [11], wildlife or animal movement [12], soil acidification produced by nitrogen oxide emissions, or chemical effects of road dust [11], among others. Besides, worldwide, the transport sector produces 32% of greenhouse gas (GHG) emissions, of which 75% are related to road transport [13], of which the largest portion is produced during the road operation phase due to vehicle exhaust fumes [14]. Besides, large quantities of natural resources are consumed during road construction and maintenance; in fact, roads consume about 60% of natural resources [15]. On the other hand, large amounts of waste are produced in road construction, leading to a significant negative environmental impacts and climate change effects [16]. In consequence, the construction, operation, and maintenance of roads have clear effects on climate change [16]; besides, road transport has also negative effects from a social point of view, for example because of the high mortality rate associated with traffic accidents worldwide [17].

To solve the problems described above, and according to the sustainability concept reported by Bruntland in 1987, environmental impact, social equity, and economic efficiency are dimensions that have to be prioritised by governments [18] for sustainable road development throughout all the stages of its life (planning, construction, maintenance, and disposal) [19], as a way to ensure economic growth and social development, as well as environmental safety [20]. As a result, the implementation of sustainability in road infrastructure has become dependent on providing measurements and guidance for including sustainable principles in road projects [21], resulting in a dozen voluntary certification and rating systems to evaluate the level of sustainability of road design, construction, and maintenance. These systems give a set of guidelines to achieve more sustainable road transportation to road transport infrastructure designers and managers [22]. Despite all of this, and taking into account the need both to implement measures to mitigate climate change and also to adapt to it, nowadays, it is necessary to implement new key milestones included in different agreements or planning in the concept of sustainable road infrastructure in Europe. This is the case of the 2030 Agenda for Sustainable Development, the European Circular Economy plan, and the European Green Deal.

The 17 Sustainable Development Goals (SDGs), which are part of the 2030 Agenda for Sustainable Development, include a total of 169 targets aimed at people, planet, prosperity, peace, and partnership [23]. In this framework, road transport can help deliver on some of the targets of the SDGs, including: SDG2 (zero hunger), on the basis of the key role of road transport in making sure that workers, equipment, products, and food get efficiently and quickly to people; SDG9 (industry, innovation and infrastructure), because of the importance of infrastructure in the connectivity between economies for trade in goods and services, and between the people who trade; SDG11 (sustainable cities and communities), in relation to the prominence of road infrastructure in mobility and logistics networks in cities; SDG13 (climate action) because of the importance of road transport in the decarbonization of the sector, from the energy source to the energy use, including the uses of resources in the construction and maintenance stages; and finally, SDG17 (partnerships and collaboration), in relation to the crucial and necessary public–private collaboration. On the other hand, the first European Circular Economy Action Plan, Closing the loop, in 2015, as well as the New Circular Economy Action Plan, For a cleaner and more competitive Europe, adopted by the European Commission in 2020, aim at the implementation of the 3 Rs principles (Reduce, Reuse, Recycling). These principles also influence infrastructure design [24], providing the idea of sustainability and green construction, and reducing environmental damage through the recycling and reuse of waste and reduced use of resources, materials, and energy [8], as well as finding ways to reduce the emission of greenhouse gases and other emissions released from fossil fuels [25]. Finally, the European Green Deal adopted a set of proposals for reducing net greenhouse gas emissions by at least 55% (compared to 1990 levels) by 2030. The European Green Deal emphasised important targets that are necessary in the transport sector in order to achieve a 90% reduction of greenhouse gas emission by 2050 [26].

As a result, the need to fulfil the cited new key milestones in terms of sustainability, as well as the severe effects of the increasing temperature, precipitation and storm events, and rising sea levels on road infrastructure, as a consequence of climate change [27–31], make it necessary to evolve towards the concept of resilience, which is defined as "the ability to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner" [32]; in fact, the ability of roads to be adapted to climate change is understood not only as part of mitigation, but also resilience. On the other hand, nowadays the concept of smart roads, referred to those that improve user, vehicle, and infrastructure connections, is achieving an important role for more efficient, safe, and sustainable roads; definitely when on the subject on resilient roads [33].

According to the above, it is possible to assert that road infrastructure sustainability is a broad research field involving a huge diversity of approaches and disciplines. In addition, the pace of research in the field of sustainability is rapid, outstripping the capacity to cover all the aspects related with it in a single review [34]. Therefore, a critical perspective and inclusive analysis of the literature is needed to facilitate global knowledge acquisition in this research field. To do that, bibliometrics, a concept presented by Alan Pitchard in 1969 and boosted by the advent of the Internet during the last decades, could provide both with objective criteria for evaluating the research in this field [35]. Some bibliometric analyses related with sustainable roads have been published; these include a study on self-healing asphalt as a way to improve road sustainability [18], or another to determine the extent of the previous research that has been carried out on the consumption of energy in all stages of road construction projects to improve sustainable and green roads [36]. However, bibliometric analysis studies defining the state-of-the-art of the concept of sustainability applied to road infrastructure in its global dimensions have not been reported. Such an analysis could be considered a good way to identify not only the evolution of the research field of sustainable roads, but also how new subjects that which are clearly related with sustainability concepts, such as resilience, adaptation to climate change and smart roads, will be incorporated in the future.

In consequence, the main objective of this study has been to perform a bibliography analysis and systematic literature review (SLR) of sustainable road infrastructure using a science mapping approach to gain a one-stop overview and to identify knowledge gaps [37]. This work aims to identify the evolution of current and future trends in road infrastructure sustainability research field. Results can be used as a guideline for the development of future planning strategies, as well as research in low carbon climate-responsive road infrastructure adapted to climate change and supported by new technological advances.

2. Materials and Methods

This paper collects and synthesises the available research on sustainable road transport infrastructure to produce a quantitative evaluation and literature review. To develop this study, the applied methodology includes three different phases and sub-phases summarised in Figure 1 and described below.

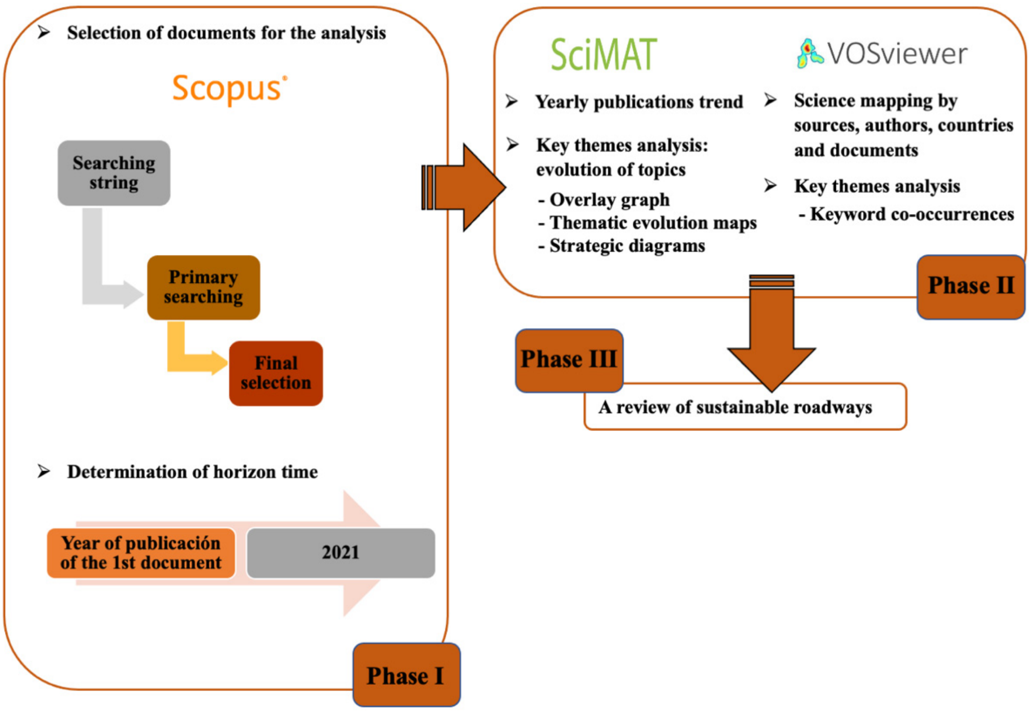


Figure 1. Applied methodology description.

2.1. Phase I. Selection of Documents for the Analysis and Determination of Time Horizon

The combination of words identified as key in the field of sustainable roads has been applied to define the search strings in the scientific bibliography database, using the Scopus database because of its broader bibliometric scope and most current data [38,39]. Following PRISMA flowchart guidelines, the primary resulting search has been filtered for title and abstract to remove unwanted papers in order to result in the final set of relevant documents included in this study for analysis. Finally, the time horizon of this research has been determined according to the year of publication of the first paper in the field, and it will extend until 2021, since the document search was carried out in March 2022.

2.2. Phase II. Scientometric Analysis

The final set of relevant documents selected for this study were exported from the Scopus database both as Comma Separated Values (CSV) and Research Information System (RIS) files to be dealt with using the open software tools VOSviewer (version 1.6.18) and SciMAT (version 1.1.04), respectively, with the objective of performing their bibliometric analysis. The most relevant publication sources, authors, countries, documents and keywords in the research field were assessed during the analysis and networks and illustrated by creating maps and graphs, and displaying their statistical values according to the following sequence for scientometric analysis:

- Yearly publication trend. The analysis of the number of publications is important to know the developments and patterns in the research. In consequence, the time horizon has been analysed in terms of the total and cumulative number of papers published, but it has also been categorised into different sub-periods for a more detailed knowledge of the publication trend.
- Science mapping. VOSviewer has been applied to determine qualitatively and quantitatively measures such as the number of published documents and number of citations to produce scientific maps which represent the most relevant publication sources, countries, authors, and documents.
- Key themes analysis. Keywords of a document identify the most relevant concepts considered and discussed; they are the core content of the document, so their analysis is essential. VOSviewer has been applied for keywords co-occurrence analysis which relates and connects papers keywords, whereas SciMAT has been used to study the evolution of research themes with an overlay graph, evolution maps, and strategy diagrams.

2.3. Phase III. A Review of Sustainable Roadways

Finally, the most relevant themes and challenges of sustainability in road infrastructure identified in the bibliometric analysis have been briefly analysed to give experts in the field a comprehensive view of the current situation and guide about the prospect of future research in the field.

3. Results

The results of the bibliometric analysis, as well as their discussion and the literature review, have been developed according to the defined sequence. The most relevant results are summarised below.

3.1. Selection of Documents for the Analysis and Determination of Horizon Time

With the objective of refining the search, this review has defined the following search string in the title, abstract and keywords, in the Scopus database: "sustainable road" OR "sustainable highway" OR "sustainability of road" OR "sustainability of the road" OR "sustainable roadway" OR "green road" OR "green highway" OR "green roadway" OR "sustainable pavement" OR "green pavement". The primary search resulted in 936 documents which were filtered according to the PRISMA flowchart (Figure 2) to include only articles and conference proceedings written in the English language, and to exclude documents published in 2022, as well as documents which did not fall within the scope of the review. This screening resulted in a final set of 683 documents which were exported as both CSV and RIS files. As the first articles were found in the year 1997 (Figure 3a), the time horizon of this study was established from that year to 2021.

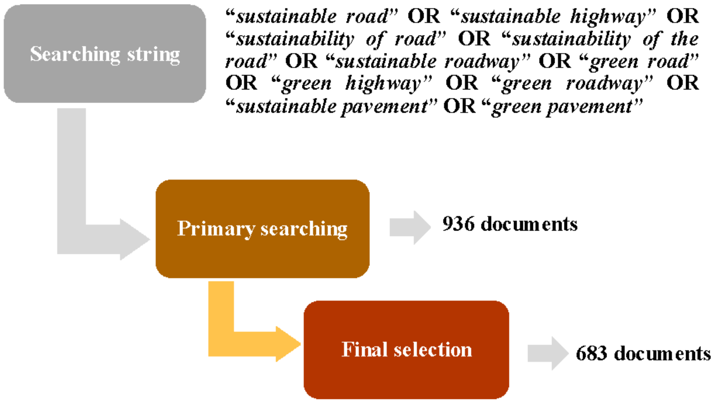
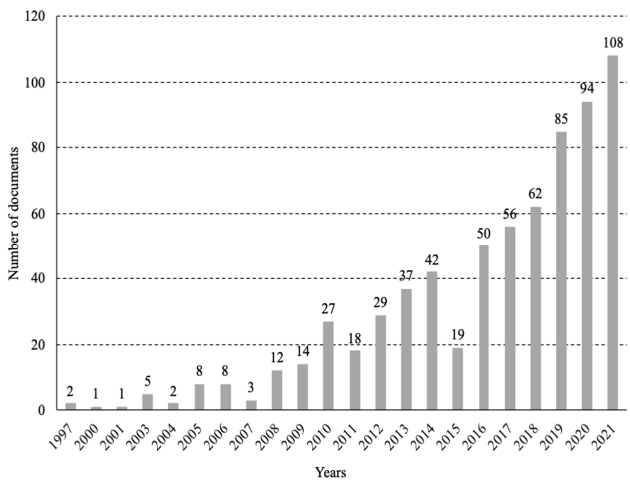
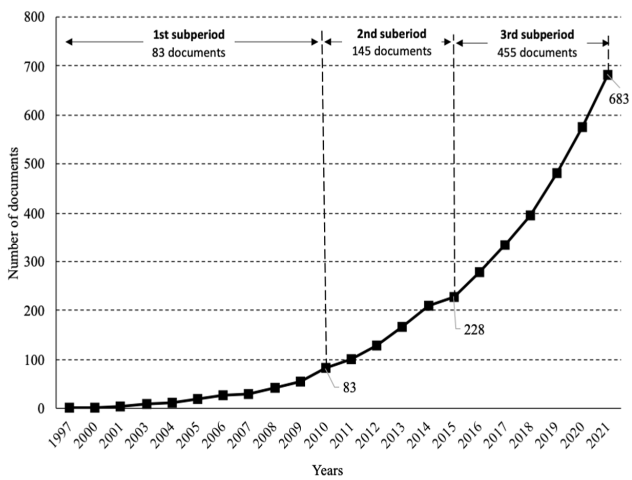


Figure 2. Results of the application of PRISMA flowchart.



(**a**)



(**b**)

Figure 3. Number of documents published in the time horizon (1997–2021) and subperiod: (**a**) document per year and (**b**) accumulated number of documents.

3.2. Scientometric Analysis

The scientometric analysis was developed according to the defined sequence, including yearly publication trends, science mapping, and key themes analysis. The results in terms of the qualitative and quantitative contribution to the research field are analysed and discussed below.

3.2.1. Yearly Publications Trend

Figure 3 summarises the documents published per year (Figure 3a) and the accumulated number of documents (Figure 3b), showing the increase in the number of documents along the time horizon, related to the growing interest by researchers in exploring the sustainability of roads. For better compression of the yearly publication trend, the time horizon has been subdivided into the following three sub-periods, depending on the inflection points in the evolution of roadway sustainability and the number of documents (Figure 3b):

- First sub-period (1997–2010). Latent period. This is the longest period but includes only 83 documents, so it could be considered that work was being conducted in the research field in the first steps of the sustainability concept, but was not yet developed or manifested.
- Second sub-period (2011–2015). Initial development period. With a significant increase in the number of articles compared with the previous sub-period, specifically 145 documents published in 5 years, this is considered an initial development period. This increase can be explained by the increased concern for the environment, as revealed in the long traction of sustainable rating systems for roadways gained in 2010 after the application of Leadership in Energy and Environmental Design (LEED) in the case of building. This resulted in tools such as Environmentally and Economically Sustainable Transportation Infrastructure–Highways (BE2ST-in-Highways) or Green Leadership in Transportation and Environmental Sustainability (GreenLITES) [22]. The end of this period was established as 2015, corresponding to the approval of the 2030 Agenda, as well as the first European Circular Economy Action Plan.
- Third sub-period (2016–2021). Consolidation period. With 455 published documents, this is the one with the highest number of documents and it corresponds to the consolidation of the development step in the research field after the approval of the circular economy plan in Europe, as well as the 2030 Agenda for sustainable development, and, in consequence, an increase of measures to stimulate its growth. This consolidation of the development in the research field is reflected in the increase of the number of sustainable rating systems developed for roadways, for example GreenPave and GreenRoads, in 2017, Invest and Envision in 2018, and The Civil Engineering Environmental Quality Assessment & Award (CEEQUAL) in 2019 [22].

3.2.2. Science Mapping

The final set of relevant documents selected for this study were analysed with the software tool VOSviewer to identify the most relevant publication sources, authors, countries, and documents in the research field to be assessed. The results are summarised in Tables 1–5 and Figures 4 and 5, and analysed and discussed below.

In the case of sources of publication, journal rankings with the highest number of documents published, citations, average normalised citation scores, average publication year and impact factor in the last 5 years were identified. Of these, a total of 11 sources among the three rankings (Table 1), which could be considered the most influential in the research field, especially those which are included in more than one ranking: *Construction and Building Materials* and *Journal of Cleaner Production* in the publication count and total citations ranking, and *European Journal of Operational Research* and *International Journal of Coal Geology* in the total citations and average normalised citations ranking, all of them with high values of impact factor in the last 5 years. The wide spectrum of source categories observed in Table 2, with a total of 11 and the predominance of MATERIALS

SCIENCE MULTIDISCIPLINARY, emphasises the different aspects of sustainability in roads [40], including those related with construction and maintenance (CONSTRUCTION AND BUILDING TECHNOLOGY, ENGINEERING CIVIL, MATERIAL SCIENCE MULTIDISCIPLINARY), operation (OPERATION AND MANAGEMENT SCIENCE, TRANSPORTATION SCIENCE AND TECHNOLOGY) as well as the environmental dimension (BIODIVERSITY, ECOLOGY, ENGINEERING ENVIRONMENTAL, ENVIRONMENTAL SCIENCE, GREEN AND SUSTAINABLE SCIENCE AND TECHNOLOGY) or their relation with cities (URBAN STUDIES).

Table 1. Main sources of publication in terms of publication count, total citations and average normalised citations, and source quality.

Source	N° Documents	Total Citations	Average Normalised Citations	Average Publication Year	Impact Factor Last 5 Years	Ranking Position		
						Publication Counts	Total Citations	Average Normalised Citations
Advanced Functional Materials	1	323	15.109	2013	11.21	-	-	3
Cities	1	136	10.390	2017	6.788	-	-	4
Construction and Building Materials	29	708	3.095	2020	8.194	2	1	-
European Journal of Operational Research	1	448	28.295	2014	6.598	-	3	1
International Journal of Coal Geology	1	480	16.186	2012	7.387	-	2	2
International Journal of Pavement Engineering	11	169	2.218	2018	4.088	4	-	-
Journal of Cleaner Production	16	395	3.618	2020	11.016	3	5	-
Journal of Materials in Civil Engineering	11	151	1.250	2018	4.077	5	-	-
Landscape and Ecological Engineering	1	175	10.096	2011	2.106	-	-	5
Research in Transportation Economics	2	422	9.739	2010	3.172	-	4	-
Sustainability	31	187	0.916	2020	4.089	1	-	-

Table 2. Categories of the sources leading the ranking.

Source	Categories [1]										
	1	2	3	4	5	6	7	8	9	10	11
Advances Functional Materials								X			
Cities											X
Construction and Building Materials		X			X			X			
European Journal of Operational Research									X		
International Journal of Coal Geology										X	
International Journal of Pavement Engineering				X						X	
Journal of Cleaner Production					X	X	X				
Journal of Materials in Civil Engineering		X		X				X			
Landscape and Ecological Engineering	X		X								
Research in Transportation Economics									X		
Sustainability						X	X				
Total journals per category	1	2	1	2	2	2	2	3	2	2	1

[1] Categories: 1. BIODIVERSITY; 2. CONSTRUCTION AND BUILDING TECHNOLOGY; 3. ECOLOGY; 4. ENGINEERING, CIVIL; 5. ENGINEERING, ENVIRONMENTAL; 6. ENVIRONMENTAL SCIENCE; 7. GREEN AND SUSTAINABLE SCIENCE AND TECHNOLOGY; 8. MATERIALS SCIENCE, MULTIDISCIPLINARY; 9. OPERATION RESEARCH AND MANAGEMENT SCIENCE; 10. TRANSPORTATION SCIENCE AND TECHNOLOGY; 11. URBAN STUDIES.

Figure 4 shows a low number of connections between the journals in terms of citations, revealing both the cited wide spectrum of source categories and the fragmentation and multidisciplinary of the research field which links, for example, themes related with categories ENGINEERING-ENVIRONMENTAL, ENVIRONMENTAL SCIENCE, GREEN AND SUSTAINABLE SCIENCE AND TECHNOLOGY, OPERATION RESEARCH AND MANAGEMENT SCIENCE, ENGINEERING CIVIL and TRANSPORTATION SCIENCE AND TECHNOLOGY (Cluster integrated by *Journal of Cleaner Production*, *International Journal of Pavement Engineering* and *European Journal of Operational Research*),CONSTRUCTION AND BUILDING TECHNOLOGY, MATERIAL SCIENCE and ENGINEERING CIVIL (Cluster integrated by *Construction and Building Materials* and *Journal of Materials in Civil Engineering)* or ENVIRONMENTAL SCIENCE, GREEN AND SUSTAINABLE SCIENCE AND TECHNOLOGY and OPERATION RESEARCH AND MANAGEMENT SCIENCE (Cluster integrated by *Research in Transportation Economics* and *Sustainability*).

Figure 4. Network relationship of sources in terms of total citations.

Table 3. Main authors in terms of publication count, total citations, and average normalised citations.

Author	N° Documents	Total Citations	Average Normalised Citations	Average Publication Year	Ranking Position		
					Publication Counts	Total Citations	Average Normalised Citations
Arulrajah A.	8	264	2.870	2019	5	-	-
Bektaş T.	1	448	28.295	2014	-	3	1
Berthelot C.	9	50	0.449	2013	3	-	-
Dai S.	2	681	12.794	2012	-	1	-
Demir E.	1	448	28.295	2014	-	4	2
Hainin M.R.	11	106	0.656	2015	2	-	-
Huang X.-L.	1	323	15.109	2013	-	-	4
Laporte G.	1	448	28.295	2014	-	5	3
Liu Q.-C.	1	323	15.109	2013	-	-	5
Santos J.	9	228	2.050	2018	4	-	-
Seredin V.V.	2	681	12.794	2012	-	2	-
Wang D.	12	50	0.543	2019	1	-	-

Table 3 shows the main authors in terms of the publication count, total citations, and average normalised citations and then, the most influential in the research field, particularly Demir E. and Laporte G., who are included in two of the rankings—total citations and average normalised citations. Wang D. has the highest number of published documents (12), followed by Hainin M.R. (11). In terms of total citations, Dai S. and Seredin V. lead the ranking with 681 citations, and Bektaş T., Demir E. and Laporte G. show the highest average normalised citation scores (28.2947). With the objective of analysing the collaboration between authors, the mapping of co-authorship by authors with a minimum of 1 document and 35 citations has been analysed, resulting in 172, as summarised in Figure 5a. A total of 36 sets of collaboration groups of authors were identified, with the highest number being 14 authors in cluster 1 (in red). Finally, the mapping of co-authorship by countries with a minimum of 10 documents (Figure 5b) revealed 3 scientific communities in the clusters in red, green, and blue, which include 7, 6, and 4 countries, respectively. The USA, United Kingdom, Canada, Australia, and China are the countries with the highest number of relationships with other countries. These countries have been among the three rankings

(Table 4), so they could be considered the most influential in the research field, especially Canada, which is included in all of them, followed by the USA and China, present in both the publication count and the total citations ranking, and the Netherlands, which is in both the total citations and average normalised citations ranking. Finally, Table 3 shows that the USA, Canada, and the United Kingdom have been publishing in the research field for the longest time (2013 and 2014); in fact, these countries promoted most of the road rating systems in use [22]. However, China, India, Malaysia, and Spain have more recently been incorporated in this field (2018), although they have not yet defined their own systems.

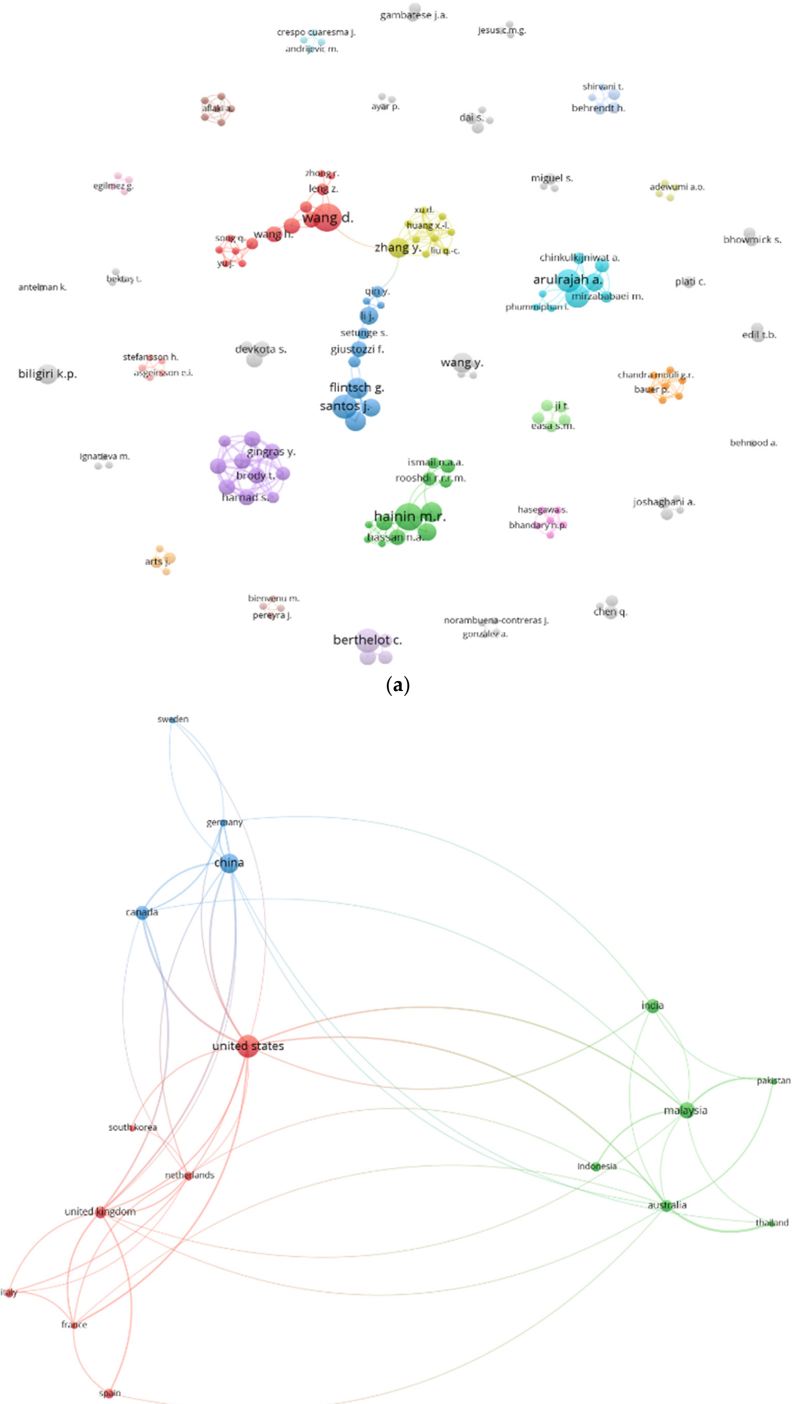


Figure 5. Network visualisation co-authorship with minimum 35 citations (**a**) and by countries with minimum 10 citations (**b**).

Table 4. Main countries in terms of publication count, total citations, and average normalised citations.

Country	N° Documents	Total Citations	Average Normalised Citations	Average Publication Year	Ranking Position		
					Publication Counts	Total Citations	Average Normalised Citations
Australia	36	408	1.5002	2017	-	-	4
Canada	53	1235	1.502	2013	4	4	3
China	101	1639	1.377	2018	2	1	-
India	50	491	1.385	2018	5	-	-
Malaysia	66	470	0.705	2018	3	-	-
Netherlands	22	781	2.6695	2016	-	5	1
Spain	24	335	1.4025	2017	-	-	5
United Kingdom	40	1573	2.5849	2014	-	3	2
USA	129	1638	1.135	2014	1	2	-

To conclude the science mapping analysis, Table 5 summarises the list of the top 10 main documents published in this research field in terms of total citations and average normalised citations, corresponding to the documents with the highest impact in the research field [41], which have been published predominantly in the second period (2011–2015). The five shaded documents are included in both lists, so they are the most relevant documents in the research field. The titles show that the sustainability of roads has been approached from different perspectives such as energy conservation, construction materials, and also policy instruments to promote and support sustainable roads.

Table 5. Main documents in terms of total citations and average normalised citation.

Document	Authors	Total Citations	Average Normalised Citations	Publication Year	Journal	Ranking Position	
						Total Citations	Average Normalised Citations
A review of recent research on green road freight transportation.	Demir E., Bektaş T., Laporte G.	448	28.295	2014	European Journal of Operational Research	1	1
Part II: policy instruments for sustainable road transport.	Santos G., Behrendt H., Teytelboym A.	229	10.569	2010	Research in Transportation Economics	2	4
The access/impact problem and the green and gold roads to open access.	Harnad S., Brody T., Vallières F., Carr L., Hitchcock S., Gingras Y., Oppenheim C., Stamerjohanns H., Hilf E.R.	217	1.793	2004	Serial Reviews	3	-
Part I: externalities and economic policies in road transport.	Santos G., Behrendt H., Maconi L., Shirvani T., Teytelboym A.	193	8.908	2010	Research in Transportation Economics	4	7
Planning and design of ecological networks in urban areas	Ignatieva M., Stewart G.H., Meurk C.	175	10.096	2011	Landscape and Ecological Engineering	5	6
Pervious concrete as a sustainable pavement material-research findings and future prospects: a state-of-the-art review	Chandrappa A.K., Biligiri K.P.	166	11.790	2016	Construction and Building Materials	6	3
Are totally recycled hot mix asphalts a sustainable alternative for road paving?	Silva H.M.R.D., Oliveira J.R.M., Jesus C.M.G.	138	4.654	2012	Resources, Conservation and Recycling	7	-

Table 5. *Cont.*

Document	Authors	Total Citations	Average Normalised Citations	Publication Year	Journal	Ranking Position	
						Total Citations	Average Normalised Citations
The healing capability of asphalt pavements: a state-of-the-art review	Ayar P., Moreno-Navarro F., Rubio-Gámez M.C	119	8.452	2016	Journal of Cleaner Production	8	-
Energy for sustainable road transportation in China: challenges, initiatives, and policy implications	Hu X., Chang S., Li J., Qin Y.	104	4.800	2010	Energy	9	-
Optimizing pervious concrete pavement mixture design by using the taguchi method	Joshaghani A., Ramezanianpour A.A., Ataei O., Golroo A.	100	6.109	2015	Construction and Building Materials	10	-
Application of rejuvenators to improve the rheological and mechanical properties of asphalt binders and mixtures: a review.	Behnood A.	98	14.512	2019	Journal of Cleaner Production	-	2
Urban heat island mitigation strategies: a state-of-the-art review on Kuala Lumpur, Singapore, and Hong Kong.	Aflaki A., Mirnezhad M., Ghaffarianhoseini A., Omrany H., Wang Z.-H., Akbari H.	136	10.390	2017	Cities	-	5
Life-cycle sustainability assessment of pavement maintenance alternatives: methodology and case study	Zheng X., Easa S.M., Yang Z., Ji T., Jiang Z.	54	7.997	2019	Journal of cleaner production	-	8
Sustainability factors in pavement materials, design, and preservation strategies: a literature review	Plati C.	51	7.552	2019	Construction and Building Materials	-	9
Dynamic traffic assignment: a review of the methodological advances for environmentally sustainable road transportation applications	Wang Y., Szeto W.Y., Han K., Friesz T.L.	79	6.967	2018	Transportation Research Part B: Methodological	-	10

3.2.3. Key Themes Analysis

The keywords of articles are considered to be major content of the research [42], so keyword analysis is very important to recognise and determine the scope of the research field [42]. In this research, VOSviewer was used to develop the keywords analysis in terms of keywords co-occurrence (Figure 6). On the other hand, SciMAT was used to develop the analysis in terms of overlay graphs (Figure 7), thematic evolution maps (Figure 8), and strategic diagrams (Figure 9).

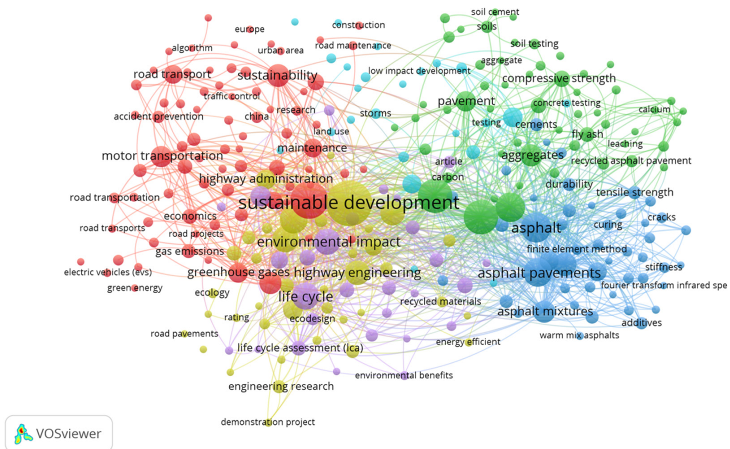


Figure 6. The network mapping of keyword co-occurrences.

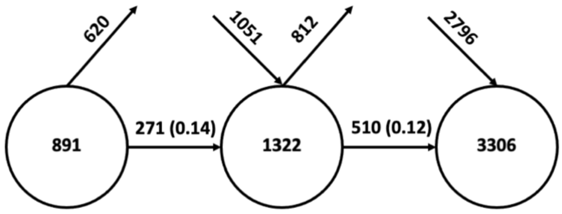


Figure 7. Overlay graph of the research field.

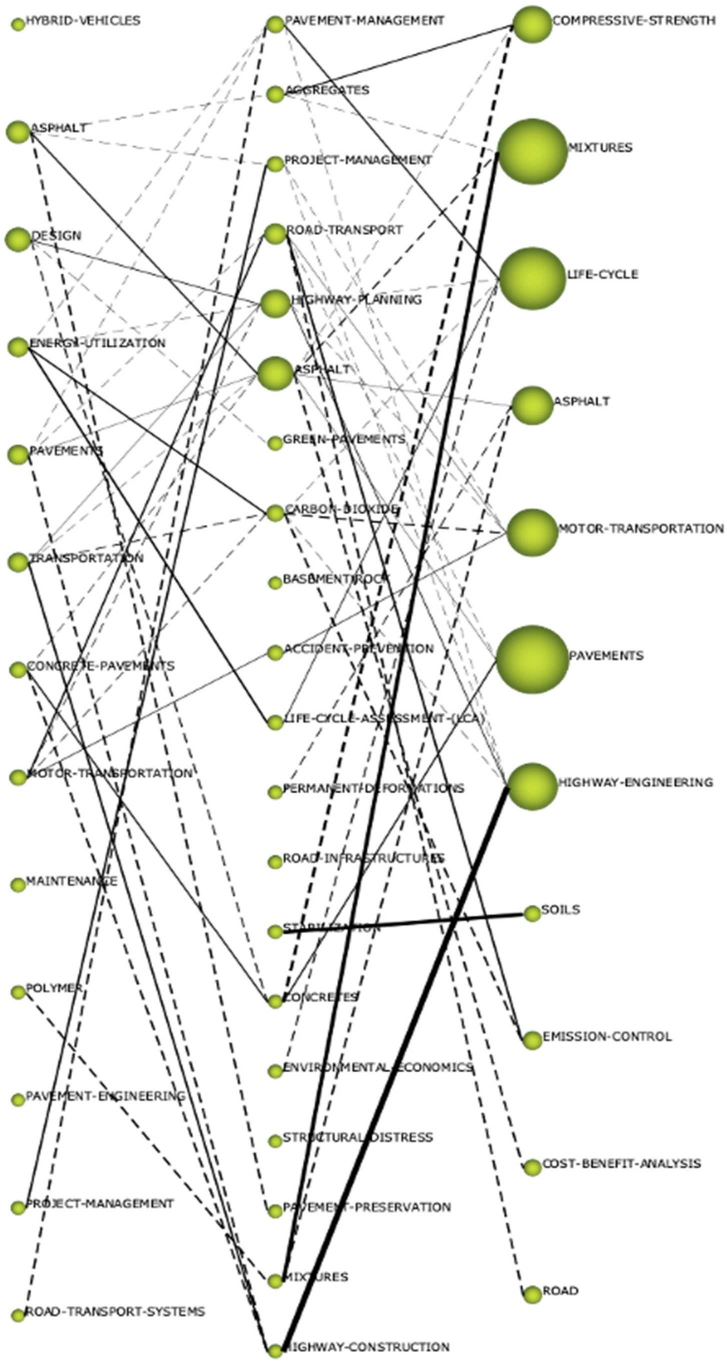


Figure 8. Thematic evolution map of the research field in terms of number of documents.

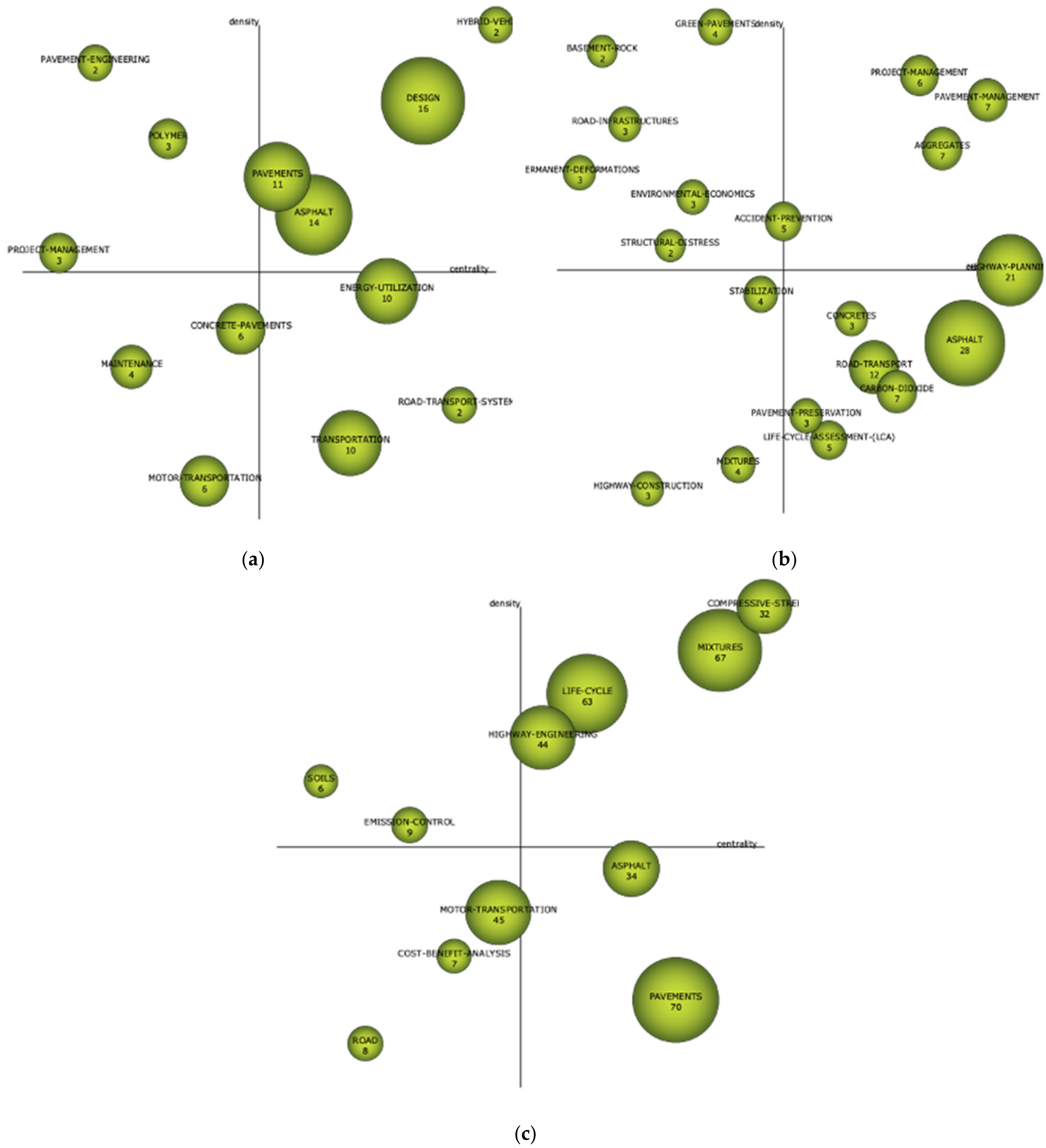


Figure 9. Strategic diagrams by number of documents for 1st, 2nd, and 3rd periods (**a**–**c**), respectively).

- Keyword Co-Occurrences

Keyword co-occurrence analysis has been used to recognise the relationships between documents. The co-occurrences of the index keywords, full counting, and a minimum of 5 occurrences were used for keywords analysis, resulting in 272 keywords included in 6 clusters (Figure 6) as described in Table 6 in terms of the number of keywords, influential keywords, themes assigned and average normalised citations of the cluster. To do that, first the terms with the highest average normalised citation in each cluster were identified; then, each cluster was related to the principal theme according to their keywords; finally, the average normalised citation the clusters was determined as an average number of the average normalised citation of the keywords included in each one. The themes identified from these clusters were: road transport systems (Cluster 1), sustainable pavements (Cluster 2), construction materials for roads (Cluster 3), sustainable development (Cluster 4), sustainability assessment (Cluster 5) and roads design (Cluster 6).

Table 6. Description of keywords clusters in terms of number and influential keyword, theme assigned and average normal citation of the cluster.

Cluster		Number of Keywords	Influential Keywords	Theme Assigned	Cluster Average Normal Citations
1	Red	79	Roads and streets, Sustainability	Road transport systems	1.144
2	Green	54	Sustainable pavements	Sustainable pavements	1.561
3	Blue	47	Asphalt pavements, Mixtures	Construction materials for roads	1.529
4	Yellow	39	Sustainable development	Sustainable development	0.863
5	Purple	29	Environmental impact, Life cycle	Sustainability assessment	1.299
6	Sky blue	24	Concretes, Design	Road design	1.072

Although road transport systems and sustainable pavements are the clusters with the highest number of keywords (79 and 54, respectively), themes with the highest average normalised citation values corresponded to both of them, related with the construction of roads, specifically sustainable pavements (Cluster 2) and road construction materials (Cluster 3) (1.561 and 1.529, respectively). In relation to road transport systems, the highest number of keywords is related with the interest in topics of this theme such as electric vehicles, fossil fuels, energy efficiency or transportation safety, among others, connected directly with the fact that the very high contribution of road transportation to carbon dioxide emissions and a way to reduce them needs an understanding of vehicle emissions models to achieve green road transportation [43], using, for example, long cycle life and power density rechargeable batteries to increase electric energy storage for a sustainable road transport system [44]. On the other hand, in relation to the sustainable pavements and road construction materials themes, highlighting the important research developing to increase the use of waste to replace some road construction materials, as well as the recycling of asphalt pavement in road rehabilitation, helps to reduce energy, preserve natural resources, and limit consumption and waste production [45–47].

- Evolution of Themes in the Time Horizon

The evolution of topics over time in the research field has been studied using an overlay graph (Figure 7), thematic evolution maps (Figure 8), and strategic diagrams (Figure 9), all of them produced with SciMAT.

The overlay graph represents the stability of keywords during the horizon time thanks to the measure of the number of keywords in common between consecutive sub-periods [48]. Analysis of the overlay graph shows that the number of associated keywords for each sub-period, which are included in each circle, increases along the time horizon; besides, the low similarity index value shows the incorporation of new themes. These results reveal that the research field is still in development, in accordance with the measures that need to be implemented to achieve the Sustainable Development Goals of the 2030 Agenda.

Figure 8 shows the thematic evolution map of the research field in terms of the number of documents, analysis of which should point out the following:

- Although some themes are not connected with others in other periods, or only one connection is identified, in general terms, the research field shows that the sustainable roads research field presents great cohesion, given that the most frequently identified themes are connected with a line in the previous year; besides, the thickness of most of the edges is high, meaning an important thematic nexus [48], for example in the case of HIGHWAY CONSTRUCTION and HIGHWAY ENGINEERING, and MIXTURES, and between the second and third sub-periods. In the case of solid lines, these link

themes that share the same name; this means that both themes are labelled with the same keywords, or the label of one theme is part of the other theme; this is the case, for example, of themes such as ENERGY UTILISATION and CARBON DIOXIDE and LIFE CYCLE ASSESSMENT, in the first and second periods, or CONCRETE PAVEMENT and CONCRETES and PAVEMENT in the first, second, and third periods, respectively. On the other hand, the dotted lines link themes that share elements that are not the name of the themes; this is the case, for example, of MIXTURES and COMPRESSIVE STRENGTH in the second and third periods, respectively, or ASPHALT, AGGREGATES and MIXTURES in the first, second, and third periods, respectively.
- With a higher number of connected elements, a greater cohesion stands out in the case of issues related to pavements with themes such as PAVEMENTS, CONCRETE PAVEMENT, ASPHALT, PAVEMENT MANAGEMENT, some of them present in more than one period. Themes related with transport, for example, ROAD TRANSPORT or MOTOR TRANSPORTATION, are the other group that shows a greater cohesion. These results show that both themes are the most considered in the concept of sustainable roads.
- DESIGN has the highest number of core documents in 1997–2010, and it evolved into HIGHWAY PLANNING, GREEN PAVEMENT, and CONCRETE themes. In 2011–2015, the ASPHALT theme appeared with the highest number of documents, and it evolved with MIXTURES, PAVEMENTS and ROAD themes. Finally, in the last period 2016–2021, the PAVEMENTS theme appeared with the largest number of documents. Again, these results show the importance of pavements in the concept of sustainable roads; in fact, the production of asphalt pavement requires of the consumption of resources such as aggregate and bituminous binder, among others; so, the introduction of eco-friendly materials is an essential pillar in order to reduce the use of them, as well as the environmental negative effects associated [49]. Besides, the ASPHALT thematic cluster appeared with the same label in all sub-periods, and the number of published documents increased with time.
- The ENERGY UTILISATION thematic cluster appeared in 1997–2010 and evolved with the LIFE CYCLE ASSESSMENT, PAVEMENT MANAGEMENT, HIGHWAY PLANNING and CARBON DIOXIDE themes; all of them, in addition to the ENVIRONMENTAL ECONOMICS theme, evolved in the last period with the LIFE CYCLE theme, which appeared in a large number of publications in this period.
- Finally, Figure 8b shows that all the themes have close values of average citations over the time horizon. Taking into consideration the high number of published documents with time, the last period has the greatest number of documents compared to the first and second periods, which have documents published from 10 to 20 years ago. This result means that the research field has developed at a progressive pace.

To finish the analysis of the evolution of the themes of the research field, strategic diagrams in terms of the number of documents have been included in Figure 9 for the three periods considered (1997–2010, 2011–2015, 2016–2021). These diagrams are divided into four quadrants related to the four types of research topic: transversal, motor, highly developed and isolated, and emerging [48]. Because of the contribution to GHG emissions, the importance of themes related to materials production and road maintenance and rehabilitation [50] is revealed in this figure throughout the whole of the time horizon; in the case of pavement theme, which is one of the elements of road infrastructure with the highest environmental impact, especially in the construction and maintenance stages, the majority of the current research on the life cycle assessment of roads has focused on the material type or only the pavement overlay, disregarding the structure as a whole [51]. In this sense, in the first period, the PAVEMENT term appears as a motor theme, evolving to a transversal one in the third period; in the second one, PAVEMENT MANAGEMENT and PAVEMENT PRESERVATION are motor and transversal themes, respectively, and the concept of GREEN PAVEMENT appears as highly developed and isolated. In fact, in 2010 the rating systems GreenPave and Green Roads were established in Canada and the USA, respectively [22]. In relation to the material type, asphalt vs. concrete pavements is observed across the whole-time horizon, including ASPHALT in the first period as a motor term, and CONCRETE PAVEMENT as an emerging one. Both materials (ASPHALT and CONCRETE) appear in the second period in transversal quadrants, while MIXTURES appears as an emerging theme. Finally, MIXTURES and ASPHALT are observed in the third period, in the motor and, again, transversal quadrants, respectively. With increasing awareness of the environmental impact of road and highway construction and development there was growing interest among industry practitioners in coming up with sustainable initiatives [52]. In fact, in the second period, terms related to these concepts such as CARBON DIOXIDE and LIFE CYCLE ASSESSMENT are included in the transversal quadrant, or LIFE CYCLE as motor theme in the third period. Finally, terms related to the environmental impact and safety of the use of vehicles are highlighted, as another important pillar on which it is necessary to work to reduce emissions during the operation stage of road infrastructure, which could be identified as motor themes, as in the case of HYBRID VEHICLE in the first period, and ACCIDENT PREVENTION on the border between the highly developed and isolated and motor quadrants. Finally, terms identified in studies suggesting that the design quality and lifetime of roads depend closely on the comprehensive understanding of the infrastructure can be highlighted along the time horizon, specifically DESIGN, PROJECT MANAGEMENT, and HIGHWAY ENGINEERING, all of them in the motor quadrant. However, terms to identify how the climatic conditions of different territories can dislocate the constructed transportation facilities [53] have not been identified along the time period, showing that the implementation of this topic in the concept of roads sustainability is still emerging.

Finally, a higher centrality value (X axis in Figure 9) shows a higher contribution of a theme to the development of the research field [54]. This is the case of themes related with transport in the first sub-period, including HYBRID VEHICLES and ROAD TRANSPORTATION SYSTEMS in the top positions with centrality values of 241.11 and 210.93, respectively, HIGHWAY PLANNING and PAVEMENT MANAGEMENT with 163.98 and 136.45 in the second sub-period, or COMPRESSIVE STRENGTH and MIXTURES with 86.04 and 75.98 centrality values in last sub-period. On the other hand, and according to the concept of density (Y axis in Figure 9), HYBRID VEHICLES, GREEN PAVEMENTS, and COMPRESSIVE STRENGTH are the themes with the greatest strength of internal relationships among all the keywords of the research theme, meaning that they are undergoing the highest development [54].

3.3. A Review of Sustainable Roadways

The scientometric evaluation has stated that road infrastructure sustainability is a broad topic and is linked to several topics that are very important in developing the concept of sustainable roads. These topics combine to form a broader definition of the concept of road infrastructure sustainability. According to the papers included in this research, the most relevant topics that give the sustainable roads theme a broader and more extensive concept are the use of materials for more sustainable pavements during the construction and maintenance stages, sustainable road transport and the use of tools to identify the level of sustainability, which will be analysed below. Besides, more recent research reveals that, nowadays, it is necessary to address the sustainability of road infrastructure also from the perspective of adaptation to climate change and smart intelligence concepts. In consequence, this study has recognised the following crucial issues in the current field of research, which have also been briefly reviewed in subsequent subsections: (i) sustainable road transport systems; (ii) materials for more sustainable pavements; (iii) tools for roads sustainability assessment; (iv) adaptation of road infrastructure to climate change; and (v) smart road infrastructure.

3.3.1. Sustainable Road Transport Systems

During the operational stage, traffic operation takes places in a complex system including road infrastructure, vehicles, vehicle operation, and weather conditions. In consequence, the improvement of traffic management and road safety are important roles in the sustainable road concept [55]. In fact, the sustainable road transport theme has been included in the keywords co-occurrence analysis in Cluster 1 (red), with the highest number of keywords. It includes a high number of keywords related with energy sources, fuels, electric vehicles, and also road systems, traffic, and transportation safety.

In consequence, even though road transport plays an important role in economic development and social integration, it also affects negatively to the environment and society [56]. Thus, road transportation activities and facilities have impacts on the economy (traffic congestion, mobility barriers, accident damage and costs), society (human health impacts and community interaction) and the environment (air and water pollution, non-renewable resources depletion) [57]. Besides, the classic approach to traffic design aims to increase the level of mobility, so it is important to plan transport infrastructure and cities without reducing the necessary traffic [58]. This is why the reduction of the emissions and energy use associated with the transport services is considered a strategic issue of energy policy [59].

As road transport, utilising a huge amount of fossil fuel is considered worldwide as a significant source of pollutant emissions [60], causing global warming and fossil fuel depletion. The total energy consumption, total number of fatalities, and greenhouse gases emissions are approaches to evaluate the development of sustainable road transport systems [61]. Therefore, countries must take more serious actions on CO_2 emission reduction and energy saving initiatives in this field [62]. In this sense, sustainable transport should contain a set of components to increase its efficiency with respect to environmental, social, and economic aspects [5]. Hence, the implementation of alternative transport fuels and vehicles is important in order to achieve energy saving and preserve air quality; thus, electric vehicles or eco-driving contribute significantly to sustainable road transport through cost reduction and environmental protection [63]. On the other hand, improvements to the rechargeable batteries of electric vehicles in their cycle life, in terms of their energy and power density, are important to increase electric energy storage to achieve a green road transportation system [44]. As a result, the vehicle electrification could provide GHG reduction potentials of 2–6% [50] of air pollution, and reduce noise, enabling pleasant and safer driving, and providing community welfare [64].

3.3.2. Materials for More Sustainable Pavements

The relevance of materials used in pavement have been highlighted in the analysis of themes and this topic is clearly identified in Cluster 2 (green) of the keywords co-occurrence analysis, including 54 keywords. It contains a huge number of keywords related to pavement, recycling, waste management and aggregates, identifying road sustainability through pavement design, the materials used, and waste recycling.

Other stages, such as materials production and road maintenance and rehabilitation, contribute substantially to GHG emissions as well, highlighting the importance of optimizing the management of these stages.

The construction, operation, and maintenance of pavements consume a huge amount of natural energy and material resources, inducing environmental impacts. In fact, asphalt, with an annual worldwide production of over 1 billion tons for paving operations, is one of the most extensively used materials in the road construction industry [45]. The scarcity and rising cost of aggregates have forced highway agencies to develop new engineering strategies in the pavement sector to reduce the costs of road pavements construction and maintenance and improve their environmental performance, by using solutions moving toward sustainable pavement practices [65]. The strategies developed include: the use of reclaimed asphalt pavement as an alternative pavement design for new construction, maintenance, and rehabilitation projects [66], as well as more recycled and environmentally friendly materials [67].

The use of reclaimed asphalt pavement as a recycled material in road construction is a valuable strategy to preserve natural energy and resources and to construct sustainable pavements [45,46]. In fact, in Europe, 47% of the available reclaimed asphalt pavement was utilised in warm or hot mix asphalt applications, and 22 million tons were utilised in other road construction applications stockpiles [68]. In USA, 71.8 million tons were accepted in 2011, 84% of which were utilised in road construction [69]. Because the recycled asphalt is not sustainable when degraded, whereas 100% hot mix asphalt performs the materials cycle by fully using the valuable materials in reclaimed asphalt in high quality road constructions [58], the reuse of hot recycling and construction waste results in good quality materials that can be used to construct sustainable and durable pavement structures [70].

On the other hand, reducing the virgin aggregate and binder content in warm and hot mix asphalt, reducing the emissions generated in mixture production and the energy consumed, and implementing preventive treatment are approaches to improving the sustainability of pavements [71]. To do that, some of the solutions mentioned in the literature are: long-lasting pavements [72]; industrial by-products and waste [73]; reclaimed asphalt pavement materials [74]; pavement preservation strategies [75]; and asphalt mixes requiring a lower manufacturing temperature [76].

Finally, alternative materials have been used for sustainable pavement, for example: stabilised quarry fines [77]; construction and demolition waste, fly ash, and jet grouting, as fillers [78]; fly ash as a stabiliser, which at 30% of total content improves the pavement resilience, although more than 30% reduces the pavement performance [66]; high pozzolanic mineral admixtures like silica fume could be used to make high quality pavement that is more economic, durable and environmentally friendly [79]; and rubber-modified asphalt improves the pavement performance in both low and high temperature conditions [80], providing a sustainable solution for the urban solid waste which is generated by waste tyres [81,82].

3.3.3. Tools for Roads Sustainability Assessment

With the increased concern about sustainability, several efforts have been made to develop assessment methods, indicators, assessment tools, and rating systems [34]. In fact, the sustainability assessment theme of Cluster 5 (purple) in the keywords co-occurrence analysis contains a large number of keywords related to life cycle assessment, environmental impact and costs.

One of the most commonly applied techniques to measure the impacts of roadway design along its service life [83] is a life cycle assessment (LCA). The estimator in this approach divides the service life of the pavement into the following stages: material production, construction, maintenance, rehabilitation, and end of life. As LCA is related with measuring only the environmental impacts, life cycle sustainability assessment (LCSA) is considered an appropriate approach to evaluate the pavement sustainability, embracing environmental life cycle assessment (E-LCA), social life cycle assessment (S-LCA) and life cycle cost analysis (C-LCA) [84]. The pavement C-LCA, published by the American Association of State Highway and Transportation Officials (AASHTO) in 1960, and the pavement E-LCA framework have been widely developed [85]; however, pavement S-LCA is still in an underdeveloped state, but its integration into pavement management is highly recommended [86].

On the other hand, given that the implementation of sustainability in road infrastructure has become focused on providing measurements and guidance for including sustainable principles in road projects [21], the use of a rating system to meet certain mandatory and minimum prerequisites could be a useful tool [87]. In this sense, a dozen voluntary certification and rating systems have been developed to evaluate the level of sustainability of road or roadway design, construction, and maintenance, including: CEEQUAL, Envision, BE2ST in-Highways, GreenRoads, GreenLITES, Invest, GreenPave, I_LAST, STARS, IS, and

LEED ND [22]. Despite these systems being based on a set of best practices and showing a potential for supporting road projects managers in achieving environmentally sustainable, resilient, and smart transportation road infrastructures [21], new research is required to better develop these systems [34].

3.3.4. Adaptation of Road Infrastructure to Climate Change

Climate change may present both opportunities and risks for the management of the road infrastructure network [29,88]. Thus, changes in climate can lead to a decrease of the stress imposed on roads, however the effects on roads as a consequence of climate change have been reported in terms of the effects of high temperatures, daily temperature variation, heat waves increase, thawing and thawing permafrost and freezing, precipitation increase, low precipitation and drought conditions, changes in yearly precipitations, rising sea levels, river flow patterns, more frequent storm cyclones, and increasing forest fires [28]. Some of the effects reported include: reduction of pavement life [28,89], thermal expansion at bridge joints [90], rutting of flexible pavements [31,91], longitudinal and fatigue pavement cracking [92], effects on pavement roughness [93], changes in landscape/biodiversity [28], landfill instability caused by thawing [94], roads sinking and pipelines, pavement layers and bridge collapse [95], occurrence of differential freezing [96], avalanches and rockslides [97], ground stability impacts [98], loss of soil cover [99], increased susceptibility to wildfires, risk of runoff flooding, landslides, slope failure [28], erosion of road platforms and adjacent land [99], submergence of roads [100], saturation of unbonded layers (Knott et al., 2019), erosion of the road base and its structures [28], and higher salinity which affects asphalt and blockage of drainage systems [99], among others.

In consequence, preventive actions are necessary to protect and adapt road infrastructure against future impacts of climate effects and reduce maintenance costs [88]. Although Clusters 4 (yellow) and 6 (sky blue) in the keywords co-occurrence analysis include some keywords that could be related with effects of climate change, for example storms or drainage, the keyword adaptation has not been specifically identified among the most relevant themes. This means that the incorporation of the adaptation of road infrastructure to climate change is still an early stage in terms of sustainability.

3.3.5. Smart Road Infrastructure

The term "smart" is the acronym for Self-Monitoring Analysis and Reporting Technology and it is used to describe the availability of innovative technologies in different scopes. The smart road concept refers to road infrastructure that improves its operational capability to meet the major challenge of connecting users, vehicles, and infrastructure in an intelligent, efficient, safe, and sustainable manner, as well as improve the maintenance of roads [33]. This concept means the use of Information and Communications Technologies (ICT) in road infrastructure operation and maintenance, which can transfer data in real time to avoid accidents and delays, and allow damage detection of pavements, etc., but also the use of so-called intelligent materials [33].

The key functions of the smart road, in terms of the use of ICT, are [33]: self-awareness, information connection, self-adaptability, and energy harvesting. Thus, sources such as drones, sensors, cameras, satellite systems, among others, installed in different components of a road infrastructure are Big Data resources [101] and allow the sharing of information, connection, and cooperation. For example, they can be installed in pavement for temperature, moisture or structure damage detection and sub-grade/soil settlement and slope monitoring [102]; but they can also be used for traffic flow monitoring and management [33] to provide feedback to traffic managers, but also to users of vehicles to support their decision-making, as well as being connected to autonomous vehicles in the future to allow automatic adaptation to the circumstances of the traffic, weather, etc. On the other hand, road infrastructure can be seen as a suitable scenario for the use of clean energy, with the promotion of the use of electric vehicles [103,104], but also for its production thanks to the collection of solar, thermal, and mechanical energy from pavements, sub-grade, and other infrastructures [105]. Finally, intelligent materials are considered to be materials that are aware of their state and properties, monitored automatically and maintained proactively, with the objective of reducing carbon emissions and the consumption of resources or energy, namely, to be environmentally responsible. For example, materials sensitive to light and temperature have been developed to paint road pavements [33]; on the other hand, materials with the self-healing or self-restoring abilities have been developed for pavements thanks to the use of nano-particles, induction heating, and rejuvenation [106,107]. Induction heating also represents an active research field in safety design for the electric melting of ice and snow [108].

In short, smart roads can achieve greater resilience of the infrastructure. In consequence, this concept should be included in researching the sustainability of road infrastructure, both for the development and application of technologies to support it, and for the development of a framework of indicators to evaluate the implementation level as a tool to define strategies for planning. However, the contribution of the smart road infrastructure concept to sustainability is still in the early stages of development; in fact, the co-occurrence analysis of this research has only identified a few keywords clearly related with it, for example, intelligent artificial in Cluster 5 (purple), which has been identified with the theme of sustainability assessment and intelligent systems, intelligent vehicles, electric vehicles, or traffic control in Cluster 1 (red), related to sustainable transport.

4. Conclusions

This study summarised the state-of-the-art in sustainable roads by using a scientific metric evaluation of the literature and discussion of the results. As a result, the researchers were able to obtain the following set of relevant conclusions from the most reliable sources by using the scientific metric computational tool, which can be used as the starting point for the future research, plans and strategies to improve the sustainability and resilience of these infrastructures.

The bibliometric review of 25 years of research on sustainable roads (1997–2021) has shown that this concept has been approached from different perspectives, such as energy conservation and construction materials, but also policy instruments to promote and support sustainable practices during all the stages of road infrastructure projects. The research field is led by countries integrated in still small and scattered scientific collaboration clusters, such as the one including the USA, United Kingdom, Canada, and Australia, which have promoted road rating systems in their territories, and which some other countries such as China have recently joined.

The analysis of the themes of the research field has shown that the environmental and economic dimension of the LCA (E-LCA and C-LCA) is clearly developed along the different stages: construction, material production, maintenance, and end of life. Both of them are clearly developed themes related to innovation in construction materials to reduce the consumption of natural resources for roads, as well as the energy consumption and emissions production during the construction and maintenance stages, and with the objective of mitigating their effects on climate change. In this sense, a special mention is needed for the use of waste to replace some road construction materials, which contributes to circular economy principles. On the other hand, the reduction of energy consumption during the operation stage, as a result of fossil fuels use, is clearly displayed through means such as electric vehicles or energy efficiency, which are directly connected with the development of solutions to reduce the great contribution of road transportation to carbon dioxide emissions. However, the social life cycle assessment (S-LCA), which is only identified in themes related to traffic and road safety, is still in an early stage and its integration into road infrastructure management is highly recommended.

The same gaps have been identified in the case of the integration of the concept of adaptation of road infrastructures to climate change. It is necessary to take into account that road infrastructures have long operational lifetimes that make them sensitive to climate variations over their time of use. However, they are still designed and managed on the basis of the existing climate at the time of their construction and historical climate data which does not take into account changes of climate in the short, medium, and long term, so this could be translated into an increase in social and economic maintenance costs in the future as a consequence of the damage that will occur to them. In this sense, smart roads will achieve greater resilience, not only because of the integration of new technologies as a fundamental element of these infrastructures, but also due to the development of smart materials with, for example, self-healing or self-restoring abilities, contributing to a more environmentally friendly infrastructure. In consequence, it is possible to conclude that the concept of sustainability of both new and existing road infrastructures, as well as the guidelines and rating systems in use, should be revised to address the resilience concept and rethink their design for the future in order to fulfil the important SDGs targets, as well as creating a cleaner and more competitive Europe, and reducing net greenhouse gas emissions during the next decades.

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