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Life cycle assessment in the Visegrad Group: a bibliometric analysis

Keywords: life cycle assessment, LCA, bibliometric analysis, Visegrad Group

Introduction

Life cycle assessment (LCA) is one of the frequently used tools for environmental impact assessment. It provides an analytical tool for evaluating a wide range of environmental aspects of the life cycle of a product or service (Hauschild et al., 2018). Although the idea of LCA dates back to the 1970s and was termed resource and environmental profile analysis (Klöpffer & Grahl, 2014), the LCA methodology saw great methodological development in the 1980s and 1990s, when many methodological procedures were developed and are still being developed today (Bjørn et al., 2018a). Like many other methodologies for environmental impact assessment, LCA has its shortcomings and limitations (Bjørn et al., 2018b). The complexity of environmental assessment using LCA is made possible by a number of simplifications and uncertainties (Hellweg et al., 2014). There is also a need to develop LCA based on current knowledge and technological progress (Karuppiah et al., 2023). The task of the LCA scientific community

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is to find ways to solve the outstanding problems of LCA (Reap et al., 2008). The Society of Environmental Toxicology and Chemistry (SETAC) has played a key role in the development and advancement of LCA through workshops, publications, and support for standardization (Fava et al., 2014). The three most active countries in LCA research are the USA, China, and Italy (Gaurav et al., 2021, 2023).

Four post-communist countries in Central Europe: Poland, Czechia, Hungary, and Slovakia, created an informal association called the Visegrad Group (Visegrad Four, V4) in 1991 with the aim of deepening mutual cooperation and harmonizing the development of these countries. The state of research and mutual cooperation of scientific teams dealing with LCA in the V4 has not yet been investigated. The purpose of this review is to map LCA research in the V4 using bibliometric methods. Bibliometrics is a research methodology that uses statistical methods to extract, aggregate, and analyze quantitative aspects of bibliographic information (Moed, 2005). Bibliometric analysis uses methods such as statistical analysis, citation analysis, and bibliometric mapping for a description of the intellectual structure in individual fields of study by analyzing the social and structural relationships between authors, countries, institutions, topics, etc. (Donthu et al., 2021). Therefore, this methodology was selected for mapping of LCA research in the V4.

For the purpose of mapping LCA research in the V4, the study seeks to answer the following research questions:

– RQ1 – What literature is relevant to LCA research in the V4 countries in terms of major publications and key authors?
– RQ2 – What specific areas of research are related to LCA in the V4 countries?
– RQ3 – How do the V4 countries cooperate in LCA research with each other and with other countries?
– RQ4 – What is the development of the production of scientific literature on LCA in the V4 countries?

Material and methods

Data collection

The Scopus database was used for bibliometric data collection, which is a source--neutral abstract and citation database indexing peer-reviewed scientific works such as articles, contributions at conferences, or books. Scopus was chosen because it covers more journals published in Europe than the Web of Science database (Asubiaro et al., 2024) and ensures high accuracy of metadata records

(Baas et al., 2020). Moutik et al. (2023) showed that Scopus indexes more articles focusing on LCA than Web of Science. Also, unlike new databases such as Dimension.AI, Crossref, or Lens.org, which rely primarily on Crossref data, i.e., on articles with an assigned DOI, Scopus is not limited to scientific articles with a DOI, but indexes all articles in selected journals.

Previous bibliometric analyses focused on LCA were analyzed to determine suitable search terms. Especially in the last few years, a large number of such studies focusing on individual countries have been published such as Brazil (Bodunrin et al., 2018), China (Nie, 2013), South Korea (Odey et al., 2021), Mexico (Güereca et al., 2015), New Zealand (Engelbrecht et al., 2018), Portugal (Burman et al., 2018), Sweden (Croft et al., 2019), groups of countries (Maepa et al., 2017) or parts of/entire continents such as Africa (Brent et al., 2002; Harding et al., 2021; Isah et al., 2024) or globally (Hou et al., 2015; He & Yu, 2020; Gaurav et al., 2021, 2023). On the other hand, other studies focus on particular areas such as construction (Yılmaz & Seyis, 2021; Aparna & Baskar, 2024), agriculture, and the food industry (Koblianska et al., 2024; Matos et al., 2024; Villagrán et al., 2024). Another area is the application of LCA to natural resources, such as bibliometric analysis of LCA studies evaluating groundwater (Carrión-Mero et al., 2022; Herrera-Franco et al., 2022). Dunmade (2019) analyzed a review of LCA teaching in Nigeria using bibliometric approaches. Other studies are focused on subfields of LCA, such as life cycle cost analysis (Martinho, 2023) or social life cycle assessment (Ghosh, 2023).

Based on the keywords used in previously published bibliometric studies of LCA, a list of keywords and their variants describing the field of LCA was created and used in this study. The following query was used to search for publications by authors from the V4 countries:

> TITLE-ABS-KEY (“life cycle assessment” OR “life-cycle assessment” OR “lifecycle assessment” OR “environmental LCA” OR “social LCA” OR “life cycle sustainability assessment” OR “lifecycle sustainability assessment” OR “life-cycle sustainability assessment” OR “economic LCA” OR “conceptual LCA” OR “life cycle management” OR “life-cycle management” OR “lifecycle management” OR “life cycle cost*” OR “life-cycle cost*” OR “lifecycle cost*” OR “life cycle impact” OR “life-cycle impact” OR “lifecycle impact”) AND (AFFILCOUNTRY (Czech OR Slovakia OR Hungary OR Poland)) AND PUBYEAR < 2024

Data collection was performed on 2 July 2024, and data was exported in CSV format. Due to the date of data collection and the limitation to the year 2023 and older (including information on the number of citations), it is unlikely that there will

be a significant expansion of the indexed works or the number of citations during this period. Of course, this can happen due to additional inclusion of conference proceedings or corrections to import mechanisms, when some works are omitted. Diacritics were removed as part of pre-processing, as names with diacritics are not always listed correctly in the Scopus database.

Method selection

Every scientific article includes some kind of literature review, which demonstrates that the author has placed their study in the context of current knowledge. However, the usual descriptive (narrative) literature reviews can be biased by the researcher's criteria, which threatens scientific objectivity (Tranfield et al., 2003). Therefore, several robust methods have been developed in recent years to eliminate possible biases in literature reviews. To obtain the latest picture of the development of the scientific field and the current state of knowledge, bibliometrics, systematic reviews, and meta-analyses were used. All three methods use statistical analysis of large amounts of data. Bibliometrics focuses on the analysis of descriptive information of scientific publications (keywords, data on authors, etc.) and is therefore suitable for analyses of large sets of publications ranging from hundreds to thousands of publications (Donthu et al., 2021). Bibliometric methods introduce objectivity into the evaluation of scientific literature and have the potential to increase rigor and mitigate researcher bias in scientific literature searches (Zupic & Čater, 2015). Similarly, systematic reviews and meta-analyses make it possible to bring new knowledge about the development in a specific scientific field in a methodologically robust and verifiable way. However, these methods are based on examining the content of published studies (Hodgkinson & Ford, 2014). Meta-analyses are more narrowly focused than systematic reviews. Meta-analysis aims to analyze the variability of the value of some quantity in the examined set of documents. These three methods are often combined depending on the goals of the analysis. Based on the size of the obtained data set and the set of research questions, bibliometrics was chosen as the main research method.

Data analysis

In order to find answers to the research questions, several types of bibliometric data analysis were performed using different tools. Using the Scopus web interface, basic analyses of the number and types of publications, number of citations, number

of authors, and cooperation between countries were performed. These analyses were performed by enlarging or narrowing the basic query, and the data was transferred to a spreadsheet to generate graphs and tables. Bibliometric network analysis was used to express links between publications. Links between countries and between keywords were analyzed to answer the research questions. The bibliometric software VOSviewer (van Eck & Waltman, 2010) version 1.6.20, which uses a mapping technique called similarity visualization (van Eck & Waltman, 2007), was used to analyze the bibliometric networks. In the case of countries, a co-authorship analysis was used. Researchers, research institutions, or countries are linked in co-authorship networks based on the number of publications they have co-authored. In the case of keywords, co-occurrence analysis was used. Keyword co-occurrence networks were limited to keywords that achieved at least 10 co-occurrences. The number of co-occurrences of two keywords is the number of publications in which both appear together in the title, abstract, or keywords (van Eck & Waltman, 2014). Weights by number were not considered either for countries or for keywords.

Results and discussion

Structure and number of publications on life cycle assessment in V4 countries

A total of 1,665 records meeting the criteria listed in the data collection were searched. The dominant type of output is the research article (n = 961), followed by contributions in proceedings (n = 549) and review articles (n = 82). The chapters in a book also reach a significant number (n = 53). A total of nine books on LCA were published by authors from V4 countries. Minority outputs were letters to editors (n = 4), editorials (n = 4), notes (n = 2), and errata (n = 1). Figure 1 shows the share of individual types of publications. Figure 2 shows the development in the number of publications and citations. Before 2005, publications on LCA written by authors from V4 countries were rather rare. After 2005, there is a clear trend of an increasing number of these publications. It can be assumed that the increase in the number of articles is associated with the standardization of the entire methodology in the ISO 14000 series of standards (International Organization for Standardization [ISO], 2015), and the resolution of a number of methodological shortcomings, which culminated in 2006 with the adoption of a number of revised ISO standards (Pryshlakivsky & Searcy, 2013). The increasing impact of LCA

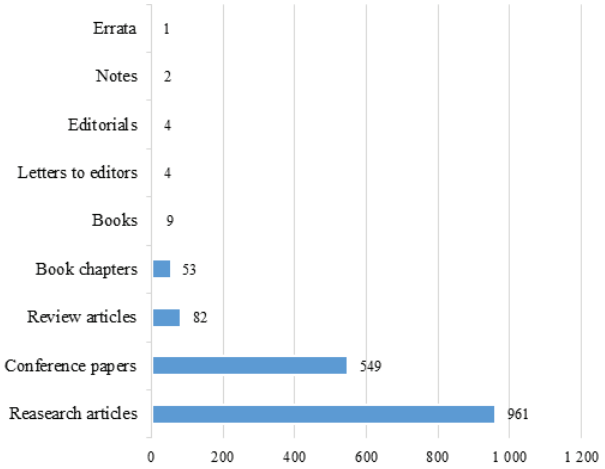

FIGURE 1. Structure of publications on LCA written by authors from V4 countries
Source: own work based on Scopus data.

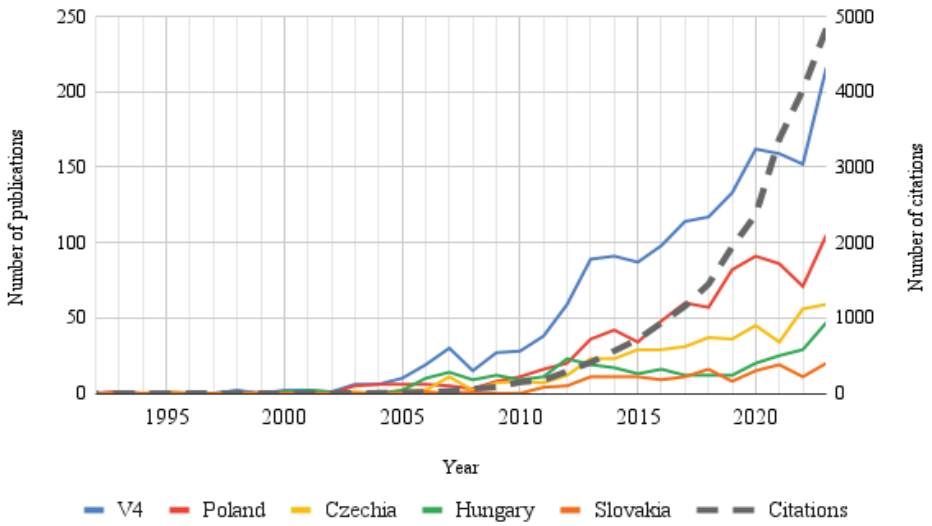

FIGURE 2. Number of publications on LCA written by authors from V4 countries over time
Source: own work based on Scopus data.

research in the V4 countries is evidenced not only by the number of publications but also by the number of citations, which is growing every year (Fig. 2 – grey dashed line), even though recent publications have not yet had enough time to gain many citations.

In total, publications written by authors from V4 countries received 22,613 citations. Authors from Poland participated in the most publications; they authored a total of 801 publications, and these publications received 11,573 citations. Czech authors participated in 455 publications that received 5,317 citations, Hungarian authors participated in 317 publications that received 5,401, and Slovak authors participated in 153 publications that received 1,187 citations.

TABLE 1. Number of publications by language used

Language	Number of publications	Share of the total number of publications [%]
English	1,626	97.66
Polish	37	2.22
Czech	7	0.42
German	2	0.12
Serbian	1	0.06
Lithuanian	1	0.06
Hungarian	1	0.06
Chinese	1	0.06

Source: own work.

Even in the case of authors from V4 countries, it is evident that the dominant language of contemporary science is English, of which 97.7% of all publications were published (Table 1). The reason why the sum of publications in individual languages is higher than the searched 1,665 publications is that Scopus registers 11 publications in two languages.

The most productive authors

Based on the number of publications, the 10 most active authors in each V4 country were selected. Based on the number of citations, the higher the number of citations, the better the ranking will be given to authors with the same number of publications. The list of the 10 most productive authors is shown in Table 2. A specific situation occurs with Jiří J. Klemeš, who has 35 publications with 2,115 citations and is thus the most cited author. However, he spent his career both at universities in Hungary and at the Brno University of Technology in Czechia. Therefore, the affiliations of his publications were individually analyzed in order to correctly assign them to individual countries.

TABLE 2. A list of the 10 most active authors from each V4 country

Poland	Number of publications	Number of citations	Czechia	Number of publications	Number of citations
D. Burchart-Korol	38	929	V. Kočí	35	419
J. Kulczycka	28	110	J.J. Klemeš	21	528
A. Lewandowska	25	646	A. Lupíšek	18	125
K. Grzesik,	21	55	J. Furch	17	66
J. Adamczyk	19	401	P. Hájek	16	239
B. Bieda	18	157	K. Struhala	16	127
A. Tomporowski	17	261	D. Vališ	12	134
A. Żelazna	16	50	R. Černý	10	328
R. Dylewski	15	232	J. Fořt	10	282
K. Pikoń	15	167	B. Teplý	9	91
Hungary	Number of publications	Number of citations	Slovakia	Number of publications	Number of citations
L. Horváth	77	465	S. Vilčeková	20	90
I.J. Rudas	71	352	A. Eštoková	16	85
Z. Szalay	15	146	E.K. Burdová	12	31
J.J. Klemeš	14	1,587	J. Štefko	11	51
V. Mannheim	13	112	J. Mitterpach	10	86
A.J. Toth	13	212	M. Ondová	10	52
B. Kiss	12	198	M. Potkány	8	83
P. Mizsey	12	275	A. Sedláková	7	44
G.L. Kovács	10	54	R. Vaňová	7	30
D. Fozer	9	247	M. Debnár	5	76

Source: own work.

Cooperation

LCA researchers in the V4 countries collaborate with scientists from around the world, as illustrated in Figure 3. However, cooperation within the V4 countries represents only a small part of international cooperation.

Table 3 shows that the share of cooperation within the V4 is the highest in the case of Slovak authors and the lowest in the case of Polish authors. There is no publication that is authored by authors from all four V4 countries, and only one publication (Ključnikov et al. 2023) was authored by authors from three V4 countries.

Table 4 shows the five countries for each V4 country with which they most often publish LCA research. Authors from the V4 cooperate with authors from 75 other countries. Excluding other V4 countries, Polish authors cooperate with authors from 68 countries, Czech authors cooperate with authors from 52 countries, Hungarian authors cooperate with authors from 49 countries, and Slovak authors cooperate with authors from 30 countries.

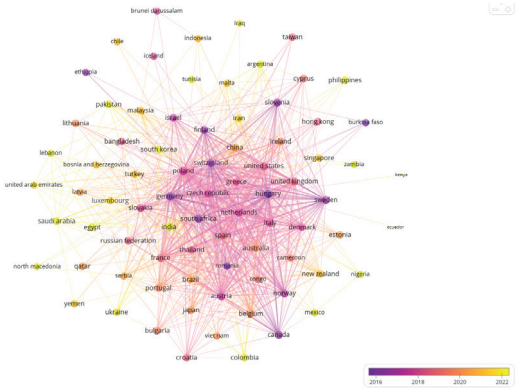

FIGURE 3. Cooperation networks between V4 countries based on co-authorship of published articles
Source: own work based on Scopus data.

TABLE 3. Share of co-authorship within V4 countries

Country	Total number of publications	Number of publications with co-authors from					Share of co-authors from the V4 [%]
		Poland	Czechia	Hungary	Slovakia	V4	
Poland	801	–	22	9	10	40	5.0
Czechia	455	22	–	6	13	40	8.8
Hungary	317	9	6	–	2	17	5.4
Slovakia	153	10	13	2	–	24	15.7

Source: own work.

TABLE 4. Top five partner countries for publishing research on LCA

Poland	Czechia	Hungary	Slovakia
Germany (40)	USA (23)	Austria (22)	Czechia (13)
Italy (39)	Poland (22)	Italy (16)	Poland (10)
Spain (26)	Germany (22)	Spain (14)	Spain (6)
USA (25)	China (18)	USA (14)	Germany (5)
UK (25)	Italy (16)	Germany (13)	the Netherlands (4)

Source: own work.

Conversely, the number of articles that were not created in collaboration with partners from other countries is shown in Table 5, which proves that the involvement of scientists from V4 countries in international research groups is still very limited. If authors from the V4 cooperate internationally, then they cooperate with authors mainly from other European countries, as well as the USA or China. Cooperation with researchers from Australia or South America is very rare.

TABLE 5. Publications written only by authors from a particular V4 country

Country	Total number of publications	Number of publications written by authors only from the given country	Share of publications written by authors only from the given country [%]
Poland	801	565	70.5
Czechia	455	289	63.5
Hungary	317	193	60.9
Slovakia	153	111	72.5

Source: own work.

Another perspective provides cooperation on the author level. Figure 4 shows cooperation between authors with 10 or more papers. The figure shows that the cooperation between the most active authors is very limited.

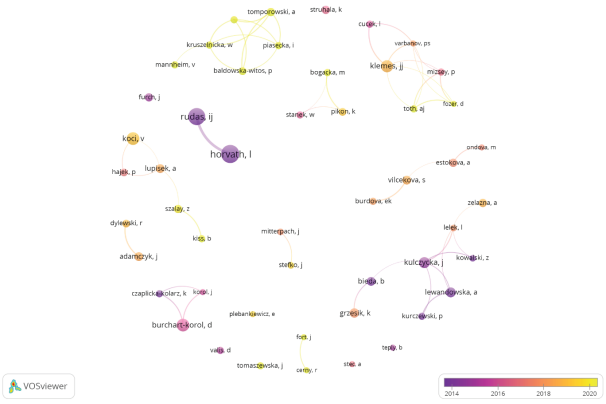

FIGURE 4. Cooperation networks between authors with 10 or more published articles from V4 countries based on co-authorship

Source: own work based on Scopus data.

Authors create clearly defined author collectives that are not interconnected through joint articles. In particular, there is practically no international cooperation within the V4 among the most active authors.

Most frequently used journals

Journals in which authors from the V4 countries most often publish research in the field of LCA were analyzed. Table 6 lists the journals in which ten or more articles were published. These journals published one-third of the total number of publications on LCA research in the V4 countries. The most often used

is the journal Energies from the publishing house MDPI, which is mainly used by authors from Poland. Even in the field of LCA, the fact that the publishing house MDPI is very popular among Central European scientists (despite certain controversies) has been confirmed (Sasvari & Urbanovics, 2023). This is evidenced by the placement of several journals of the MDPI publishing house (Energies, Sustainability, Materials, Applied Science, Buildings) in Table 6. In second place is the Journal of Cleaner Production, which is the second most frequently used journal, even among authors from around the world (Gaurav et al., 2021).

TABLE 6. Journals in which authors from V4 publish research on LCA

Journal	Number of		Number of articles from			
	articles	citations	Poland	Czechia	Hungary	Slovakia
Energies	91	811	77	9	9	4
Journal of Cleaner Production	83	4,357	49	25	13	2
Sustainability	77	956	34	26	10	9
International Journal of Life Cycle Assessment	45	975	35	7	5	0
International Multidisciplinary Scientific Geoconference Surveying Geology and Mining Ecology Management SGEM	33	64	17	6	0	11
IOP Conference Series Materials Science and Engineering	23	100	12	10	0	2
Science of the Total Environment	22	701	15	8	1	0
IOP Conference Series Earth and Environmental Science	18	43	4	11	0	1
E3S Web of Conferences	18	91	17	0	0	1
Procedia Engineering	17	318	5	10	0	1
Chemical Engineering Transactions	17	107	9	5	0	1
Energy	16	914	10	3	3	0
Przemysł Chemiczny	14	32	14	0	0	0
Materials	14	245	12	1	0	1
Applied Sciences	14	152	8	3	1	3
CESB 2016 – Central Europe Towards Sustainable Building 2016: Innovations for Sustainable Future	13	19	0	12	0	1
Renewable and Sustainable Energy Reviews	12	401	5	7	0	0
Transport Means Proceedings of the International Conference	11	20	1	9	0	1
Buildings	11	85	5	6	0	0
Advanced Materials Research	11	40	2	4	2	3
MATEC Web of Conferences	10	44	6	3	0	1
Journal of Environmental Management	10	180	6	2	2	0

Source: own work.

It is worth mentioning that of the ten most frequently used journals, five are conference proceedings journals (International Multidisciplinary Scientific Geoconference Surveying Geology and Mining Ecology Management SGEM, IOP Conference Series Materials Science and Engineering, IOP Conference Series Earth and Environmental Science, E3S Web of Conferences, Procedia Engineering). The other five journals in the top 10 are highly visible journals that are in the first or second quartiles, according to SJR. On the one hand, this is an example of the fact that authors from the V4 prefer high-quality journals. On the other hand, it should also be noted that with the exception of the International Journal of Life Cycle Assessment, the other four journals (Energies, Journal of Cleaner Production, Sustainability, Science of the Total Environment) are examples of mega-journals that publish tens of thousands of articles per year.

Publications with high citations

Table 7 shows the 20 articles with the highest number of citations. The most cited articles are in the fields of energy, engineering, and environmental science.

The most cited publication (Čuček et al., 2012) is the study of authors from Hungary and Slovenia. This publication is an overview or narrative review of footprints, which are defined footprint-based indicators that can be used to measure sustainability. The publication also assesses composite footprints, which combine two or more individual footprints, and create multi-objective optimization problems. Currently, the researchers combine individual footprints into the environmental footprint family.

Polish authors co-authored the second and the third most-cited publications. The second most cited article (Kacprzak et al., 2017) is again a narrative review that compares existing sewage sludge management solutions for environmental sustainability, focusing on treatment and disposal strategies within current European and national legislation. It discusses using decision-making tools like end-of-waste criteria and LCA to evaluate environmental, economic, and technical aspects of different systems. The third most cited publication (Kargarzadeh et al., 2018) is also a narrative review that presents the recent advances made in the production of cellulose nanofibrils and cellulose nanocrystals, including conventional mechanical and chemical treatments, as well as other promising techniques and pretreatment processes aimed at designing an economically efficient and eco-friendly production route for nanocellulose. These most cited articles thus confirm the conclusions of some studies (e.g., Montori et al., 2003; Cronin et al., 2008), showing that review articles have a greater social impact than original research articles.

TABLE 7. The most cited publications – top 20 (only citations before 2024 are included)

Authors	Title	Year	Source	DOI	Number of citations
Čuček et al.	A review of footprint analysis tools for monitoring impacts on sustainability	2012	Journal of Cleaner Production	10.1016/j.jclepro.2012.02.036	692
Kacprzak et al.	Sewage sludge disposal strategies for sustainable development	2017	Environmental Research	10.1016/j.envres.2017.03.010	516
Kargarzadeh et al.	Advances in cellulose nanomaterials	2018	Cellulose	10.1007/s10570-018-1723-5	329
De Benedetto & Klemeš	The Environmental Performance Strategy Map: an integrated LCA approach to support the strategic decision-making process	2009	Journal of Cleaner Production	10.1016/j.jclepro.2009.02.012	299
Mikulčić et al.	Reducing greenhouse gasses emissions by fostering the deployment of alternative raw materials and energy sources in the cleaner cement manufacturing process	2016	Journal of Cleaner Production	10.1016/j.jclepro.2016.04.145	241
Boyano et al.	Exergoenvironmental analysis of a steam methane reforming process for hydrogen production	2011	Energy	10.1016/j.energy.2010.05.020	236
Ürge-Vorsatz et al.	Mitigating CO_2 emissions from energy use in the world's buildings	2007	Building Research and Information	10.1080/09613210701325883	203
Burchart-Korol	Life cycle assessment of steel production in Poland: A case study	2013	Journal of Cleaner Production	10.1016/j.jclepro.2013.04.031	202
Den et al.	Lignocellulosic biomass transformations via greener oxidative pretreatment processes: access to energy and value-added chemicals	2018	Frontiers in Chemistry	10.3389/fchem.2018.00141	198
Mayer et al.	Environmental and economic multi-objective optimization of a household level hybrid renewable energy system by genetic algorithm	2020	Applied Energy	10.1016/j.apenergy.2020.115058	194

Čuček et al.	Total footprints-based multi-criteria optimisation of regional biomass energy supply chains	2012	Energy	10.1016/j.energy.2012.01.040	191
Weinzettel et al.	Life cycle assessment of a floating offshore wind turbine	2009	Renewable Energy	10.1016/j.renene.2008.04.004	180
Frenger et al.	Reducing energy consumption in LTE with cell DTX	2011	IEEE Vehicular Technology Conference	10.1109/VETECS.2011.5956235	179
Weißbach et al.	Energy intensities, EROIs (energy returned on invested), and energy payback times of electricity generating power plants	2013	Energy	10.1016/j.energy.2013.01.029	173
Jędrzejczak et al.	The role of lignin and lignin-based materials in sustainable construction – A comprehensive review	2021	International Journal of Biological Macromolecules	10.1016/j.ijbiomac.2021.07.125	172
Mia et al.	Multi-objective optimization and life cycle assessment of eco-friendly cryogenic N_2 assisted turning of Ti-6Al-4V	2019	Journal of Cleaner Production	10.1016/j.jclepro.2018.10.334	165
Pfister et al.	Understanding the LCA and ISO water footprint: A response to Hoekstra (2016) "A critique on the water-scarcity weighted water footprint in LCA"	2017	Ecological Indicators	10.1016/j.ecolind.2016.07.051	155
Puppán	Environmental evaluation of biofuels	2002	Periodica Polytechnica Social and Management Sciences	–	124
Sun et al.	Uncovering energy use, carbon emissions and environmental burdens of pulp and paper industry: A systematic review and meta-analysis	2018	Renewable and Sustainable Energy Reviews	10.1016/j.rser.2018.04.036	121
Bong et al.	A review on the global warming potential of cleaner composting and mitigation strategies	2017	Journal of Cleaner Production	10.1016/j.jclepro.2016.07.066	119

Source: own work.

Czech authors contributed up to the ninth most cited publication. Slovak authors did not participate in the most cited publications.

Subject areas

The Scopus database ranks individual indexed contributions into subject areas. LCA is an interdisciplinary research field; therefore, the division into subject areas makes it easier to identify the area on which LCA research focuses. The dominant subject areas are technical fields, and the most widespread in all V4 countries is engineering. This makes the V4 countries slightly different from the rest of the world, where environmental sciences are the most widespread and engineering the second (Gaurav et al., 2021). Environmental sciences are the second most common field of researchers involved in LCA in Poland, Czechia, and Slovakia. On the other hand, in Hungary, environmental sciences are in third place and the second most widespread field is computer science. In Poland and Czechia, energy is in third place, while in Slovakia it is the field of social sciences. Table 8 lists the top ten subject areas in which V4 scientists working on LCA are active.

TABLE 8. Subject areas in which authors from V4 countries publish articles on LCA

Subject area	V4	Share [%]	Poland	Czechia	Hungary	Slovakia
Engineering	804	48	367	251	147	72
Environmental Science	582	35	337	149	75	43
Energy	424	25	267	96	58	23
Computer Science	265	16	80	50	117	22
Material Sciences	194	12	99	58	23	20
Social Science	181	11	69	63	32	28
Mathematics	169	10	98	23	42	16
Business, Management and Accounting	154	9	86	43	22	12
Chemical Engineering	127	8	62	25	33	13
Earth and Planetary Sciences	104	6	57	27	8	18

Source: own work.

The same analysis was done for 20 highly cited papers listed in Table 7. A total number of 13 papers were involved in the subject of engineering. The same number of papers were involved in the subject area of energy. The subject area of environmental science contains 12 papers. That's a similar situation to the group of all articles on LCA published by authors from the V4. Only two other subject areas (business, management and accounting) have more than two papers, with seven papers, and mathematics with four papers.

Keyword co-occurrence analysis

Keywords often reflect the aim and focus of the study. The authors used a total of 3,977 keywords. Figure 5 shows the links between 45 keywords that were used at least 10 times in the analyzed articles (Table 9). The diameter of the circle represents the occurrence of the keyword – the larger the circle is, the more often the keyword occurs. Co-occurrence relationships of two keywords are shown by a line connecting two circles. Circle colors indicate distinct clusters, and cluster structure is determined by the interaction between keywords, culminating in clusters of highly connected keywords. As can be seen, the keyword "life cycle assessment" is surrounded by many other keywords. Some of these keywords are similar; for example, for one term such as life cycle assessment, authors use other different notation variants such as LCA, life-cycle assessment, etc. Figures 6 and 7 show links between keywords that were used at least ten times in articles by Polish (Fig. 6) and Czech (Fig. 7) authors. Figures for Hungarian and Slovak authors are not presented because Hungarian authors met the limit of ten uses of only five keywords (life cycle assessment – 66×; product lifecycle management – 29×; LCA – 16×; product modeling – 16×; sustainability – 14×) and Slovak authors only four keywords (life cycle assessment – 41×; LCA – 24×; environmental impact – 16×; sustainability – 10×).

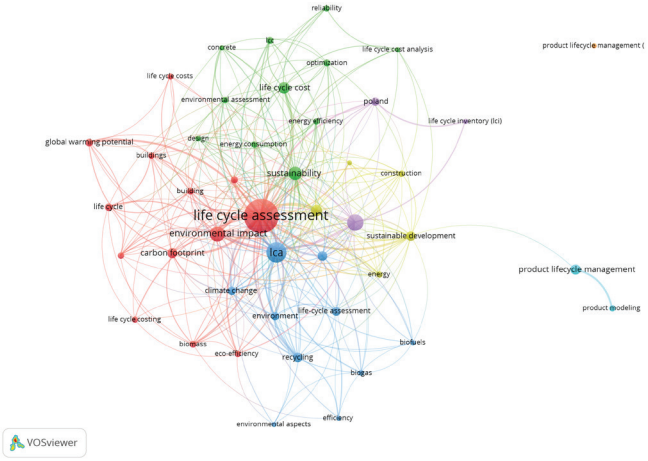

FIGURE 5. Co-occurrence analysis of LCA publication keywords published by V4 authors (keywords used at least 10 times are included)

Source: own work based on Scopus data.

TABLE 9. Most frequently used keywords

Keyword	Number of occurrences	Keyword	Number of occurrences
life cycle assessment	412	construction	16
lca	147	energy	16
life cycle assessment (lca)	94	energy efficiency	16
environmental impact	84	life cycle costing	16
sustainability	65	life cycle costs	16
life cycle cost	49	product modelling	16
circular economy	46	reliability	16
product lifecycle management	38	eco-efficiency	15
carbon footprint	37	energy consumption	15
recycling	35	environmental assessment	15
sustainable development	34	buildings	14
environmental impacts	33	greenhouse gases	14
life-cycle assessment	28	biogas	12
climate change	26	design	12
poland	25	concrete	11
environment	24	efficiency	11
global warming potential	20	biofuels	10
life cycle	20	environmental aspects	10
optimization	19	life cycle cost analysis	10
waste management	19	life cycle inventory (lci)	10
building	18	product lifecycle management (plm)	10
biomass	17	renewable energy sources	10
lcc	17		

Source: own work.

Figure 5 shows several automatically generated clusters based on the co-occurrence of keywords according to the VOS methodology (van Eck & Waltman, 2007). The first cluster (red) focuses on the LCA of buildings and its impact on global warming. The second cluster (green) focuses on the impact of energy consumption and the improvement of energy efficiency. The third cluster (blue) focuses on the sustainability of biogas and biofuels. These three clusters are the largest, and each contains at least 10 keywords. However, most keywords are interconnected with keywords in other clusters, so the above interpretation of the focus of individual clusters should be considered significantly simplistic. The fourth cluster (yellow) focuses on the circular economy, renewable energy resources, and sustainability of buildings and constructions. The fifth cluster (purple) is not sector-specific, but deals with LCA in Poland. If the first five clusters can be said to be closely interconnected, then the last two clusters (light blue and orange) are relatively independent and deal with product life cycle management.

Figure 6 shows generated clusters for publication authored by authors from Poland. The main topics for authors from Poland are sustainability, eco-efficiency, and improving energy consumption and its impact on carbon footprint and global warming. The next topics are circular economy, recycling, waste management, and sustainable use of biomass.

Figure 7 shows generated clusters for publication authored by authors from Czechia. The topics of circular economy, recycling, and climate change are similar to those in Poland. On the other hand, there are far fewer keywords meeting the selection criteria, which may be due to the significantly smaller number of publications in which Czech authors participated.

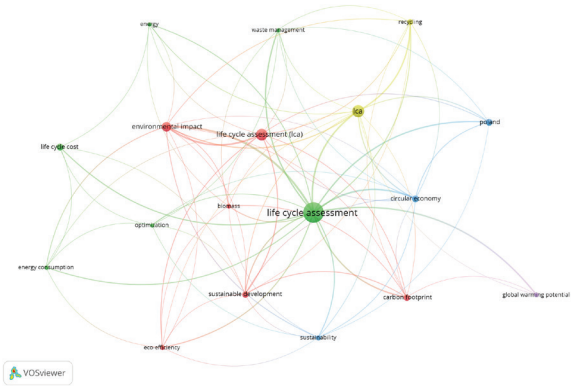

FIGURE 6. Co-occurrence analysis of LCA publication keywords published by authors from Poland (keywords used at least 10 times are included)

Source: own work based on Scopus data.

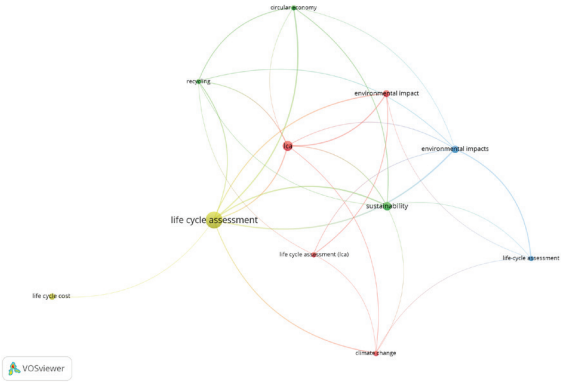

FIGURE 7. Co-occurrence analysis of LCA publication keywords published by authors from Czechia (keywords used at least 10 times are included)

Source: own work based on Scopus data.

The main funding organization

Most publications do not have the research support stated. The most important support providers are the European Union and its programs, such as Horizon. The most important supporters with 20 or more supported publications include agencies and ministries from all V4 countries (Table 10).

TABLE 10. Most important funding agencies

Funding agency	State	Number of publications
European Commission	EU	132
Horizon 2020 Framework Programme	EU	59
Narodowe Centrum Badań i Rozwoju (National Center for Research and Development)	Poland	43
Ministerstvo Školství, Mládeže a Tělovýchovy (Ministry of Education, Youth and Physical Education)	Czechia	36
European Regional Development Fund	EU	35
Ministerstwo Edukacji i Nauki (Ministry of Education and Science)	Poland	33
Grantová Agentura České Republiky (Technology Agency of the Czech Republic)	Czechia	33
Vedecká Grantová Agentúra MŠVVaŠ SR a SAV (Scientific Grant Agency of the Ministry of Education, Science and Research of the Slovak Republic and the Slovak Academy of Sciences)	Slovakia	28
Nemzeti Kutatási, Fejlesztési és Innovációs Alap (National Research, Development and Innovation Fund)	Hungary	22
Technologická Agentur České Republiky (Technology Agency of the Czech Republic)	Czechia	21
Seventh Framework Programme	EU	21
UK Research and Innovation	UK	20

Source: own work.

Limitations and uncertainties of the study

This study has several limitations. First, the study was limited to Scopus data, so publications that are not indexed in this database but in other ones (such as Web of Science) are not included. As an example, an article by the author of this paper (Ansorge & Beránková, 2017) was published in the European Journal of Sustainable Development and is not indexed in Scopus. Authors from V4 countries will most probably also publish part of their research in national journals that are not indexed in prestigious international databases. An example

is the articles by Vladimír Kočí (Kočí et al. 2019; Kráľová et al., 2020), who is the most active Czech author.

The second limitation results from the choice of search query. LCA is currently a highly widespread methodology, so many authors use only the abbreviation "LCA" as a keyword. Another article by Vladimír Kočí can be mentioned as an example (Pavlů et al., 2019). The point is that the abbreviation LCA is not only used for "life cycle assessment", but also in medicine (LCA = lithocholic acid), mathematics (LCA group = locally compact Abelian group), statistics (LCA = latent class analysis), etc. The Scopus database indexes 472 publications with "LCA" in the keywords, title, or abstract, which were written by authors from V4 countries and do not meet the criteria of the search query used. A portion of these publications will probably also be focused on life cycle assessment.

The last limitation may result from the fact that many authors may not use some form of LCA notation in the title, keywords, or abstract, but their research may still relate to LCA or use LCA techniques. It may be cases where the authors used more general terms such as "life cycle analysis", "life cycle", and "life cycle thinking" or studies that consider individual impact indicators, such as water footprint, for example, the article by Jiří J. Klemeš (Jia et al., 2019).

Conclusions

LCA is a widespread tool for environmental impact assessment and one of the main tools to promote steps leading to the achievement of sustainable development. Research in this area is worldwide, and the V4 countries are no exception. Researchers from Poland are the most active, followed by researchers from Czechia and Hungary, and the least extensive LCA research is in Slovakia. The most active researchers are László Horváth and Imre J. Rudas from Hungary, whose more than 70 publications significantly exceed the number of publications of other V4 researchers. Dorota Burchart-Korol from Poland has 38 publications, and Jiří J. Klemeš and Vladimír Kočí from Czechia have 35 publications. The most active Slovak researcher is Silvia Vilčeková, with 20 publications. Three researchers from Poland have more than 20 publications.

The most cited publications in the field of LCA are those of Jiří J. Klemeš, who worked in Hungary and subsequently in Czechia. However, such international connectivity is rather an exception, as cooperation in LCA research within the V4 countries is not high (expressed by co-authorships). Only for Slovak researchers are the main collaborators researchers from Czechia and Poland.

At the same time, international cooperation within the LCA topic is widespread and includes countries from all continents, except Antarctica.

The most widespread subject area in which LCA research is conducted is engineering, followed by environmental sciences. In Hungary, second place belongs to computer science, although the importance of computer science in Hungary is not reflected in keywords. The main areas that (according to keywords) are connected with LCA are mainly the impact on the environment, sustainability, circular economy, and sustainable development.

Due to its popularity among Polish authors, Energies is the most significant journal for the dissemination of LCA research conducted in V4 countries; in the other V4 countries, the journal was used less frequently. Other widely used journals are the Journal of Cleaner Production, Sustainability, and the International Journal of Life Cycle Assessment.

LCA research is gaining increasing attention in the V4 countries, albeit slowly compared to other parts of the world. This suggests that LCA will play a key role in fulfilling European environmental legislation and achieving the Sustainable Development Goals. The study highlights current and potential future areas of interest for LCA research. The knowledge published via this study can serve not only researchers working in the field of LCA but also research managers who are managing research in this field.

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Summary

Life cycle assessment in the Visegrad Group: a bibliometric analysis. Purpose: Life cycle assessment (LCA) research has been going on for several decades. However, it is not obvious how the post-communist countries of Central Europe participate in LCA research. The aim of this paper is to gather knowledge on the recent progress of scientific research related to LCA in the Visegrad Group (Visegrad Four, V4). Methods: A bibliometric analysis was chosen for the evaluation. Studies published by authors with affiliations in the V4 countries were extracted from the Scopus database. Descriptive analyses were performed, such as analyzing the distribution of types of scientific papers, language, journals used, keywords, and research fields. Using the VOSviewer application, bibliometric mapping was performed to express the links between individual works. The most active authors from the V4 countries and the most influential articles were identified using citation analysis. Results and discussion: A total of 1,665 studies have been found. Almost all studies originate from engineering or environmental sciences. Poland is the most active in LCA research within the V4. However, the most active scientists are affiliated with Hungarian universities. Likewise, the most cited scientist carried out most of his research in LCA at universities in Hungary. Slovakia has the least developed LCA research. It has also been noted that there is a low level of collaboration among authors from V4 countries. Conclusions: The analysis demonstrated differences in LCA research within the V4. Nevertheless, LCA research is gaining popularity in all V4 countries, albeit slowly. At the same time, LCA is of fundamental importance, especially in the implementation of European environmental legislation in practice and in achieving the goals of sustainable development. The findings obtained through this analysis can serve not only researchers working in LCA research but also scientific managers in the management of research in this area.