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REVIEW ARTICLE

Contribution of carbon footprint research towards the triple bottom line of sustainability

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Abstract

Carbon footprint (CF) research has received increasing attention in recent years, as evidenced by a rise in publications and citations, reflecting a growing concern for the environmental impact of human activities. However, the alignment of this scientific literature with the three dimensions of sustainability performance provided by the TBL paradigm (people, planet, and profit) has received limited attention. This study addresses this research gap by undertaking a large-scale bibliometric analysis of 9032 Web of Science (WoS) publications from 1992 to 2020. At the macro (journals) and micro (papers) levels, a methodology approach to classify research publications according to TBL dimensions was designed. The results indicate that the output and impact of CF research are balanced with respect to the environmental (planet) and economic (prosperity/profit) dimensions, while the social impact is balanced with respect to the people+profit dimensions. Other than that, "Affordable and Clean Energy" (3761 publications) and "Climate Action" (3091 publications) are the most frequently represented (and interconnected) objectives. The results obtained contribute to a greater understanding of the contribution of CF research to the attainment of the SDGs.

Keywords Sustainability · Sustainable development goals · Carbon footprint · Triple bottom line · Bibliometrics · Scientometrics

Introduction

Carbon footprint research

Carbon dioxide (CO2) emissions increased almost 3.6 times, from 9,463,838 kilotons (kt) in 1960 to 34,344,006 kt in 2019, especially in upper-middle-income countries (Lozano 2022a). This has raised concerns about the effect on the environment and the quality of life for future generations (WCED 1987). Monitoring and assessing the carbon footprint (CF) is an essential strategy for reducing greenhouse gas (GHG) emissions.

According to Wiedmann and Minx (2008), "The carbon footprint is a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product." According to this definition, a carbon footprint (CF) is the total quantity of greenhouse gases (such as carbon dioxide)

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released into the atmosphere by organizations, individuals, or countries.

In the struggle against climate change, reducing GHG emissions is one of the objectives. The Paris Climate Agreement, which was drafted in 2015, provides a comprehensive framework for reducing GHG emissions based on the voluntary commitments of the world's nations (Paris Agreement 2015). This historic agreement committed the world to "limiting temperature increases to 1.5 degrees Celsius" above pre-industrial levels, but the actual objective is 2 degrees (Liu et al. 2022). The Paris Climate Agreement established for the first time the connection between sustainable development and climate change. The United Nations Framework Sustainable Development Goals examined the relationships between climate change, economic, environmental, and social development in greater detail. The 2030 Agenda for Sustainable Development includes a set of 17 sustainable development goals (SDGs hereafter) with 169 specific targets (United Nations 2019), with SDG13 grouping actions to combat the effects of climate change.

From a bibliometric standpoint, the CF phenomenon has been analyzed from a research standpoint. Yue et al. (2020) identified 698 Web of Science (WoS) (2007–2019) publications. Based on a keyword clustering method, these authors determined that CF research is an interdisciplinary discipline, with the primary topics being CF calculation methods, research scales, energy, and agriculture. Similarly, Xie et al. (2020) analyzed 668 highly cited papers and 6680 journal articles published in WoS between 1996 and 2018. Their findings indicate that life-cycle assessment is one of the field's most important topics. Li et al. (2021) analyzed 283 indexed articles and conference proceedings from WoS (2010–2019). Life-cycle assessment, environmental performance and carbon management, greenhouse gas emissions, design, system, and sustainability were identified through their work. Similar research was conducted by Chen et al. (2021), who examined 9848 WoS (2006–2020) records. According to their findings, CF research has its own spatial and temporal organization, cooperation intensity, and knowledge hierarchy. Wu et al. (2022) compared Chinese (n=673) and non-Chinese (n=3755) scientific literature indexed in WoS (2007–2020), demonstrating that the impact of non-Chinese articles is more prominent, systematic, and mature than that of Chinese articles. Geographical differences have an impact on the nature of CF research, according to their findings. However, there is a dearth of research on the social aspects of CF research, which would help us comprehend the societal impact of this endeavor.

The triple bottom line

The triple bottom line (TBL) was established to help construct a connection between basic issues of the sustainability phenomena and three major sustainability performance dimensions: environmental, economic, and social, in other words, integrating economic and social aspirations into the environmental sphere to reinforce and widen the environmental agenda (Elkington 1994). As a result, the TBL paradigm allows us to view any form of sustainability issue through the lens of three primary stakeholders: social restrictions (people), economic effect (profit), and environmental implications (planet).

The TBL paradigm has been recognized by the research community as an essential holistic lens for addressing sustainability concerns (Lozano 2022a). The literature has also adapted the TBL paradigm. Tremblay et al. (2020) broadened this paradigm to the 5Ps (people, planet, prosperity, peace, and partnership), and other variations of this model have been proposed (for example, the 6Ps, which adds place and participation to the original five dimensions, and the 7Ps (proposed by Farooq et al. 2021), which includes profit alongside with participation). However, rather than being employed in academic research, the TBL framework has received more attention from practitioners and managers (for example, for some firms as a framework for reflecting their actions and commitment to SD, e.g., reporting). There is a large study deficit relating to TBL components (e.g., their interlinkages) in the scholarly literature.

While the TBL approach has been widely used in business and management fields (Alhaddi 2015; Tseng et al. 2020; Lozano 2022b; Pereira 2021) and various methods for their evaluation (e.g., indicators (Neri et al. 2021)) utilized, its incorporation into bibliometric studies has been slow. The majority of bibliometric studies have focused on TBL as the object of study (e.g., Tseng et al. 2020), with the exception of Bautista-Puig et al. (2022). Bautista-Puig and colleagues classified TIA's (tools, initiatives, and approaches) output in each sustainability dimension based on keywords, by comparing theory (i.e., the definition of TIAs) to its implementation into academic research (i.e., research output).

Just as the TBL dimensions allow us to analyze the impact of the activities of organizations around the world in terms of sustainability, analyzing scientific publications (in this case, CF research) based on these dimensions would allow measuring the social components of the research output in terms of sustainability, as well as facilitating lay public and citizen understanding of sustainability-related scientific contributions.

To the best of our knowledge, however, no bibliometric analysis of research papers categorized according to the characteristics of the TBL paradigm has ever been conducted.

Objectives

The purpose of this paper is to look at how CF research contributes to the three pillars of the TBL paradigm (profit, people, and planet). To address this goal, the following

specific research questions have been defined: (1) what are the main characteristics of the CF research, including annual scientific output, impact, main journals, institutions, and countries? (2) What is the contribution of CF research to the TBL paradigm?

Methods

Data collection

For the purposes of this study, we collected data from WoS. Using this database, the keyword "carbon footprint*" was searched in the title, abstract, and keywords (author and publication keywords) fields from Clarivate Analytics' Web of Science (WoS) Core Collection (SCI, SSCI, A&HCI) covering the period 1992–2020, including all the publication types.

This process was carried out between May and August of 2022 and a total of 9032 publications were collected. For each publication, the following aspects were considered: year of publication, publication type, times cited (WoS core), WoS category, keywords, highly cited status, country-level affiliation, institution-level affiliation, and source title. For journals, the Journal Impact Factor (JIF), 5-Year JIF, and journal quartile were collected from WoS and Journal Citation Reports (JCR), 2021 edition.

In addition, PlumX (https://plumanalytics.com) was used to attain the publications' broader social impact by collecting mentions from news, policy reports, and social networking sites (Mendeley and Twitter) for each of the 11,452 publications with a DOI (83.4% of all the publications collected).

TBL dimensions

Correspondence between subject categories and TBL dimensions at the journal level

A thematic analysis was used to determine the main themes of the CF research from WoS (1992–2020) and their relationship to sustainability. First, we used Elkington's (1994) TBL framework (people planet, and profit) and later expanded these three main categories with the 2030 UN Agenda, including the 17 Sustainable Development Goals (SDGs). We utilized the wedding cake structure of Rockström and Sukhdev (2016) in order to place the 17 SDGs within the TBL framework.

The WoS categories assigned to each publication for the period starting 1992 to 2020 were used. A total of 217 research categories were identified within the WoS data set. A classification schema was designed by Author 1 (senior cataloger and expert in sustainability) and agreed upon by the other authors of the study (see Table 5). The classification was determined by assigning each category to the primary pillar based on the authors' expertise. For example, categories related to economics were classified under "Profits," while those pertaining to sociology are classified under both "People" and "Fisheries" are classified under "Planet." Based on this schema, we listed the 17 SDGs under each TBL category based on Rockström and Sukhdev (2016). According to this framework, the WoS categories related to the SDGs 6, 13, 14, and 15 were assigned to "planet"; categories related to the SDGs 1, 2, 3, 4, 5, 7, 11, and 16 were assigned to "people"; and categories related to the SDGs 8, 9, 10, and 12 were finally assigned to the "profit" component of TBL paradigm. The SDG-TBL correspondences used are offered in Table 1.

Correspondence between keywords and TBL dimensions at the article level

The OSDG API (https://osdg.ai) was employed to classify all the scientific output at the article level into the different SDGs. This open-source tool was utilized to identify any SDG-related relevant content, except for SDG17 "Partnership" (due to the complexity and uncertainty inherent to this tool). The OSDG workflow involves two stages. In the first stage, machine learning (ML) models trained on data collected through the OSDG Community Platform (CP) are used to screen texts and provide preliminary SDG labels. The CP, a citizen science project, generated high-quality labeled data through a tagging exercise (with more than 2000 worldwide volunteers). The second stage utilizes the OSDG ontology/keyword map, which combines various existing initiatives and approaches to verify the initial labels. To assign a specific SDG label, both the ML models and the ontology approach must agree, and the corresponding SDG must account for at least 10% of all SDG-related content within the document (see more details in Pukelis et al. 2022). The abstracts of all the CF papers were imported to the OSDG tool. A total of 7508 publications (83.2%) have at least one SDG assigned by the tool with a maximum of 3 SDGs assigned (58% of the papers have one goal assigned; 37% have two SDGs, and 5% have three SDGs). Once all the records were classified into the SDGs, the authors classified each of the SDGs into the TBL main pillars (see Table 1 for SDG-TBL correspondences).

A co-occurrence keywords network map was performed through VOSviewer (https://www.vosviewer.com) in order to study the relations between the different SDGs, in terms of SDGs sharing similar keywords across the publications within the scientific landscape on CF research.

Table 1 Correspondence between TBL dimensions and UN SDGs

TBL	SDG	SDG Scope
Planet (environment)	6	Ensure availability and sustainable management of water and sanitation for all
	12	Ensure sustainable consumption and production patterns
	13	Take urgent action to combat climate change and its impacts
	14	Conserve and sustainably use the oceans, seas and marine resources for sustainable development
	15	Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss
People (society)	1	End poverty in all its forms everywhere
	2	End hunger, achieve food security and improved nutrition and promote sustainable agriculture
	3	Ensure healthy lives and promote well-being for all at all ages
	4	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
	5	Achieve gender equality and empower all women and girls
Profit (economy; prosperity)	7	Ensure access to affordable, reliable, sustainable and modern energy for all
	8	Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all
	9	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation
	10	Reduce inequality within and among countries
	11	Make cities and human settlements inclusive, safe, resilient and sustainable

SDG17, "Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development", is placed on the top of the wedding cake structure

Source: Rockström and Sukhdev (2016)

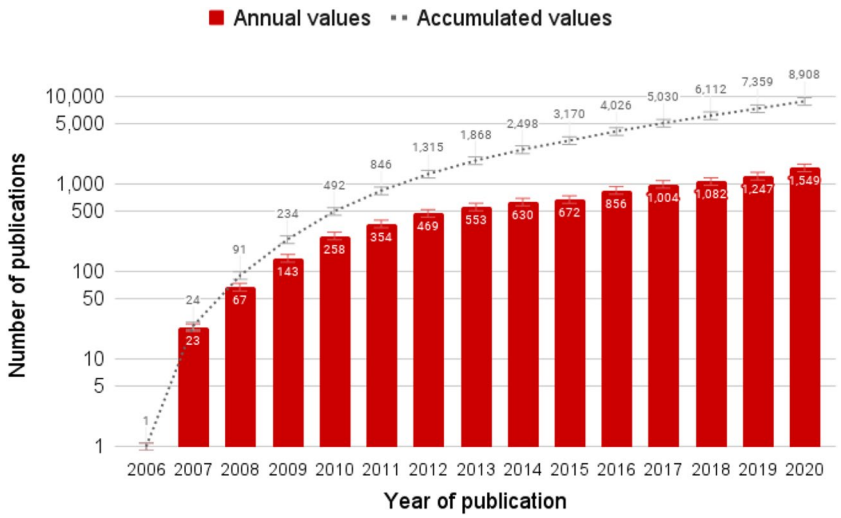

Fig. 1 Carbon footprint research output over the years (2006–2020). Source: self-elaborated from WoS. Note: 12 publications have no value on the date of publication metadata field. Publications from 2021 onwards are filtered out, as WoS indexation was not fully completed when data was extracted

Results

Carbon footprint research output

This section seeks to provide a basic overview of the current state of CF research and how the academic research output has changed dramatically over the past period (1992 to 2020), with a specific focus on its main producers (countries, institutions) and journals. This data would allow better contextualizing of the contribution of the CF research to the SDGs via the TBL dimensions.

Examination of the WoS database reveals a total output of 9031 publications about CF, with a substantial annual increase. The trend data start increasing around the year 2006 and then dramatically accelerates in 2009 (143 publications), achieving a maximum value in 2020 (1549 publications), a year in which 17.4% of the total output was published (Fig. 1).

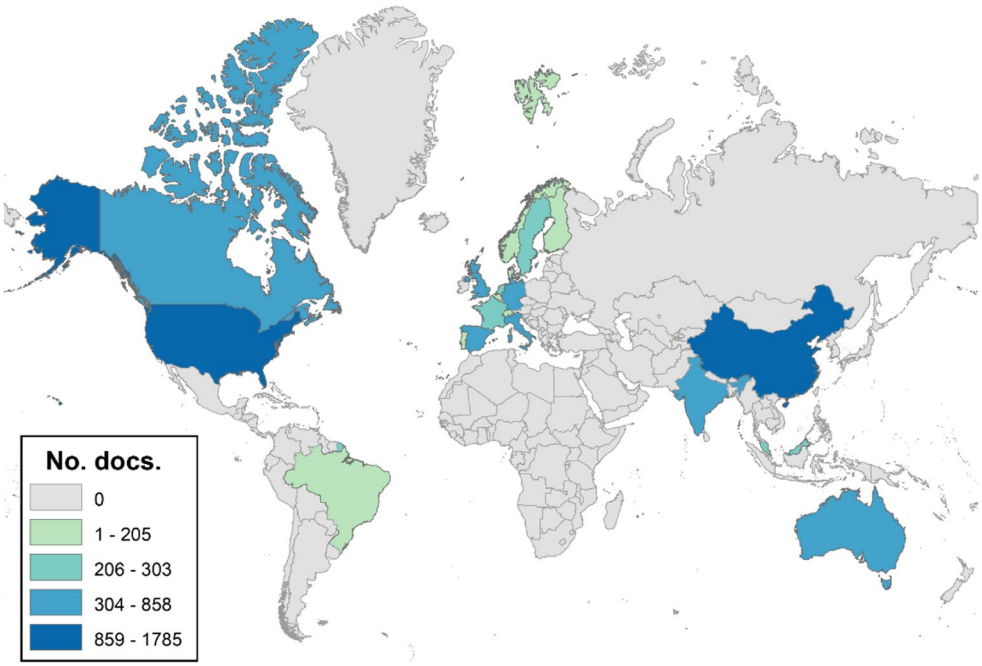

Fig. 2 Geographic distribution of top 20 scientific publications by country. Note: self-elaborated from WoS data. Map energized with ArcGis (https://www.arcgis.com)

Since the signing of the Kyoto Protocol in 1997, a large temporal gap has been observed between the framework agreement on climate change and the rise of research on CF research. A tentative explanation of its cause might be related to multiple historical events such as China becoming the world's largest GHG emitter in 2006, and the following year's 4th IPCC report (IPCC 2007), warning that the serious effects of global warming are evident. In 2009, experts warned that damage from climate change was arriving at a faster pace than it was anticipated (for example, see Steffen 2009).

The WoS dataset covers the diverse geographic extent of 128 countries, among which the USA (1785 papers; 19.76% of the output) and China (1167 publications, 12.92%) are the most productive nations publishing about CF, followed by the UK (858; 9.50%), Australia (584; 6.47%), Spain (563; 6.23%), and India (549; 6.08%) (Fig. 2). In this context, the specific interests of countries or regions, such as the USA, People's Republic of China, or Europe, to produce CF research may vary. Regulations and governmental policies may influence the CF scientific productivity of the countries as well.

In terms of top CF research-producing institutions, only seven organizations surpass the 100 publications in the research field. RLUK Research Libraries UK (with 610 documents) and N8 Research Partnership (229) lead the output. Both belong to a group of British universities (e.g., N8 Research Partnership is a collaboration of the eight most research-intensive Universities in the North of England). Similarly, it is followed by the University of California System in the USA (157), which also integrates different campuses (with 1,867,429 documents in WoS). Not surprisingly, the Chinese Academy of Sciences (CAS), one of the world's largest research organizations (with 61,700 scientists and 965,029 documents in WoS), appears in fourth position (145 publications), followed by the Norwegian University of Science Technology (NTNU), in Norway (122). The top 20 most productive institutions in CF research are available in Table 6.

The Journal of Cleaner Production (JCP) is the leading journal with the highest output of papers in CF research (829 papers), followed by *Sustainability* (263), and *the International Journal of Life Cycle Assessment* (161). *JCP* and *Sustainability* are highly prolific and specialized journals that cover a wide range of sustainability topics (see Bautista-Puig et al. 2021). *The International Journal of Life Cycle Assessment* is a less productive journal focused on Life Cycle Assessment. Not surprisingly, out of the top 20 publication venues, 14 journals were ranked in the Journal Citation Reports' first quartile, showing that the topic is being published in prestigious venues. Equally noteworthy is that 12 journals (60%) out of the top 20 are published by Elsevier, an influential publisher in the field. Descriptive data related to these top journals such as publisher, number of publications, 2021 Impact Factor, 5-Year Impact Factor, and JCR quartile is available in Table 7.

Table 2 Most frequently used WoS categories in carbon footprint research

Web of Science categories	Record count	TBL dimension	% of 9031 records	% of 19,120 category fields
Environmental Sciences	2835	Planet	31.4	14.8
Green & Sustainable Science & Technology	1970	Planet	21.8	10.3
Engineering, Environmental	1653	Planet	18.3	8.6
Energy & Fuels	1258	Profit	13.9	6.6
Environmental Studies	811	People	9.0	4.2
Engineering, Electrical & Electronic	613	Profit	6.8	3.2
Engineering, Chemical	532	Profit	5.9	2.8
Engineering, Civil	519	Profit	5.7	2.7
Construction & Building Technology	482	Profit	5.3	2.5
Materials Science, Multidisciplinary	473	Profit	5.2	2.5
Economics	314	Profit	3.5	1.6
Telecommunications	285	People	3.2	1.5
Computer Science, Information Systems	267	Profit	3.0	1.4
Water Resources	234	Planet	2.6	1.2
Computer Science, Theory & Methods	225	Profit	2.5	1.2
Chemistry, Multidisciplinary	221	Profit	2.4	1.2
Engineering, Mechanical	215	Profit	2.4	1.1
Food Science & Technology	214	Profit	2.4	1.1
Management	189	Profit	2.1	1.0
Engineering, Industrial	188	Profit	2.1	1.0

self-elaborated from WoS data

Table 3 Evolution of the number of publications per period and TBL paradigm

TBL dimension	2016–2020	2011–2015	2006–2010	2001–2005	1992–2000	Total	%
Planet	3291	1349	215	0	0	4855	41.7
People	1302	620	139	0	0	2061	17.7
Profit	2896	1528	300	0	0	4724	40.6

total values are not offered, because each paper could present a multi-classification of WoS categories, containing categories of different TBL dimensions

Source: self-elaborated from WoS data

TBL dimensions

Categories and TBL dimensions

A total of 195 categories were identified in the WoS dataset. Within these categories, planet (environment) attains 8728 publications with 42 WoS categories, profit (prosperity) attains 7944 publications with 69 WoS categories, and people (society) dimension attains 2448 publications with 84 WoS categories. As can be seen from Table 2, the people dimension covers more WoS categories, albeit it appears in a lower number of publications. On the other hand, the planet dimension shows the opposite behavior with a significant number of publications in a lower number of WoS categories. Specifically, the Environmental Sciences (2835 publications; 31.4%), Green and Sustainable Science and Technology (1970; 21.8%), and Engineering Environmental (1653; 18.3%) are the WoS categories with a higher number of research outputs on this topic (Table 2), all of them belonging to the planet dimension.

The evolution of each TBL dimension is offered in Table 3, where we can observe a significant increase in the number of publications aligned with planet (from 1349 publications to 3291 publications) and profit (from 1528 publications to 2896) in the last two periods analyzed. Considering the whole period, only the 17.7% of WoS categories are related to the public dimension.

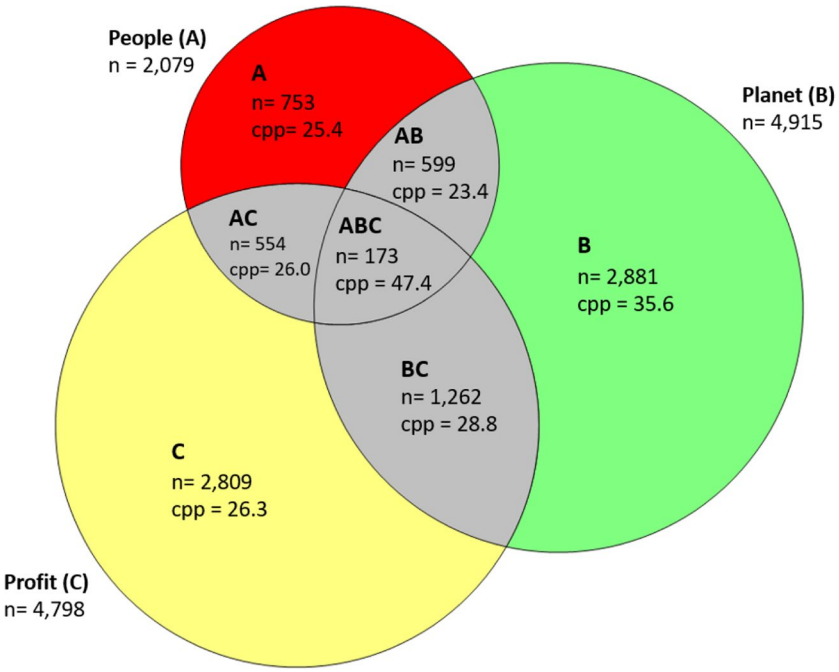

Fig. 3 Veen diagram including the number of publications about carbon footprint and the TBL dimensions associated. *N*, number of publications; CPP, average number of citations received. Source: self-elaborated from WoS data

Given the multi-classification scheme of the WoS categories, one publication can be assigned to more than one TBL dimension. The interrelation between TBL dimensions is offered in Fig. 3. As can be observed, the profit-planet profile (1435 publications including AB and ABC relations) constitutes the most frequent TLB interrelation, followed by the profit-people profile (727 publications, including AC and ABC interrelations). A low percentage of publications (1.9%; *n*= 173) attain all three TBL dimensions.

The predominance of publications only assigned to planet or to profit is evidenced by data from 2010 to 2020. Indeed, the publications combining these two dimensions (planet+profit) stand out as the third most frequent publication (Fig. 4). Publications assigned only to people are less frequent, as previously shown in Table 3.

Each TBL profile attains a different citation-based impact. Those publications related to all three dimensions achieve the highest average value (47.4 citations per publication), while the people+planet publications achieve the lowest (23.4). In general terms, those publications including a WoS category assigned to the planet dimension achieve higher citation impacts (Fig. 3).

When analyzing the mentions from non-academic publications and social networking sites, the people+planet combination is the TBL profile achieving the highest average mention values for news, policies, and tweets mentions. In any case, the Altmetrics data prevalence (number of publications with at least one mention) is low, especially for patent mentions.

The citation-based impact of these publications has increased over the years, especially in terms of the number of papers achieving the condition of highly cited papers (HCP). The accumulated number of HCPs increased from 10 in 2012 to 143 in 2020 (Fig. 5). As the condition of HCP depends entirely upon the year of publication and the main category assigned to the specific publication, these results show that the recent research on CF has achieved a remarkable impact.

The WoS categories assigned to these HCP reflect a strong impact of profit (43 highly cited publications) and planet (39). This observation is aligned with the previous findings from Table 3 and Fig. 4. Obviously, the citation patterns of each discipline might influence these results.

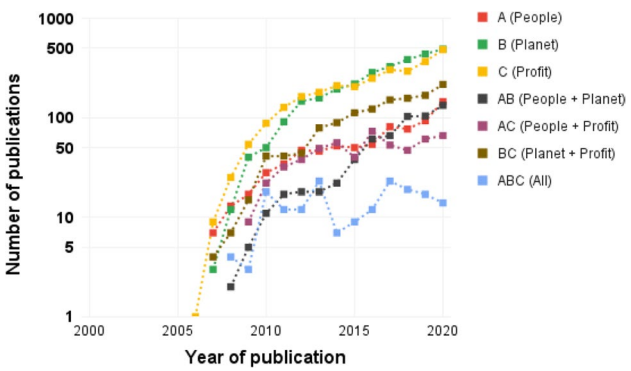

Fig. 4 Venn diagram including the number of publications about carbon footprint research and the TBL dimensions associated. Note: self-elaborated from WoS data

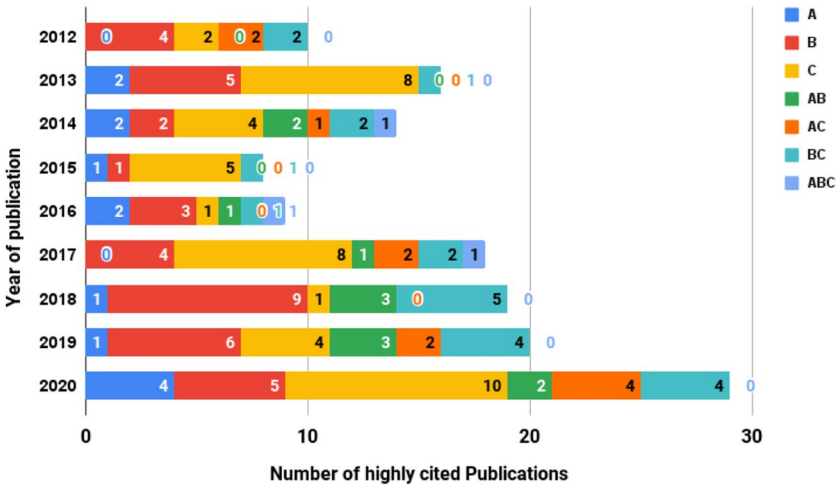

Fig. 5 Number of highly cited publications on carbon footprint research by year (2012–2020) and TBL dimension. Source: self-elaborated from WoS data

Keywords and TBL dimensions

In this section, we analyzed the contribution of the CF research to sustainability at the article level through the OSDG tool, using the keywords assigned to the articles instead of the categories assigned to the journals where the CF research is published.

As regards the SDGs, the SDG7 "Affordable and Clean Energy" represents 50.09% (3761 publications) of the total output assigned (7508), followed by SDG13 "Climate Action" (3091; 41.17%), "SDG9" Industry (1020; 13.59%), and SDG12 "Responsible Consumption" (994, 13.24%). As regards the TBL dimensions, prosperity encompasses 66.40% (4985 unique publications) of the total output, followed by planet with 57.82% (4341) and people with 7.51% (564). From the former, SDG7 "Affordable and Clean Energy" stands out with 3761 publications (50.09%) assigned, while SDG13 "Climate Action" is the goal addressed more in the planet dimension (Fig. 6). This suggests that CF research is linked to the use of clean energies and duty of care for the environment.

The SDG7 "Affordable and Clean Energy" and SDG13 "Climate Action" are the most interrelated SDGs in the CF research literature (link strength equals to 1183), as the co-occurrence keyword map of the goals interrelations shows (Fig. 7). Other significant connections that we observed are as follows: SDG9 "Industry, Innovation and Infrastructure"/SDG7 "Affordable and Clean Energy" (312); SDG12 "Consumption and Production"/SDG7 "Affordable and Clean Energy" (235); SDG12 "Responsible Consumption and Production"/SDG13 "Climate Action" (link strength of 220).

Discussion

The purpose of this work is to give a large-scale bibliometric examination of CF research and its contribution to the fundamental pillars of sustainability. Only a few studies, as noted in the introduction, have incorporated the TBL into their research strategy. As a result, this work contributes to the debate by offering a methodology approach for delineating theme analysis in greater detail (at the journal and article levels). These findings are discussed further below:

Carbon footprint research output

The results of this study suggest that, although CF research has a long tradition (the term was coined by Wackernagel and Rees 1996, and the IPPC group was established under the United Nations in 1989), there is a substantial amount of research published only after 2009, although the "carbon footprint" keyword does not begin to appear in the literature until 2006, as the results have shown. These results are in line with other studies in literature: Chen et al. (2021) observed a growth of 32% in the period from 2009 to 2019. Li et al. (2021) calculated a growth of 75% (2010–2019), and Shi and Yin (2021) obtained a growth of 91.34% (2009–2019).

These latter authors further suggested this period as a "rising phase" of CF research. This also coincides with the building blocks of climate change (e.g., Kyoto Protocol 1997; Paris Climate Agreement, 2015) and raising public awareness and engagement (e.g., 2007 Nobel Peace Prize on a climate change documentary).

Origin of carbon footprint research

The results of this study confirm the observations of Chen et al. (2021) and Li et al. (2021). The core research forces are mainly from Europe, North America, and Asia, and the most productive countries are the USA, China, the UK, Australia, and Spain. Similarly, the Chinese Academy of Sciences (Republic of China) is one of the top 5 leading organizations, followed by the University of California System

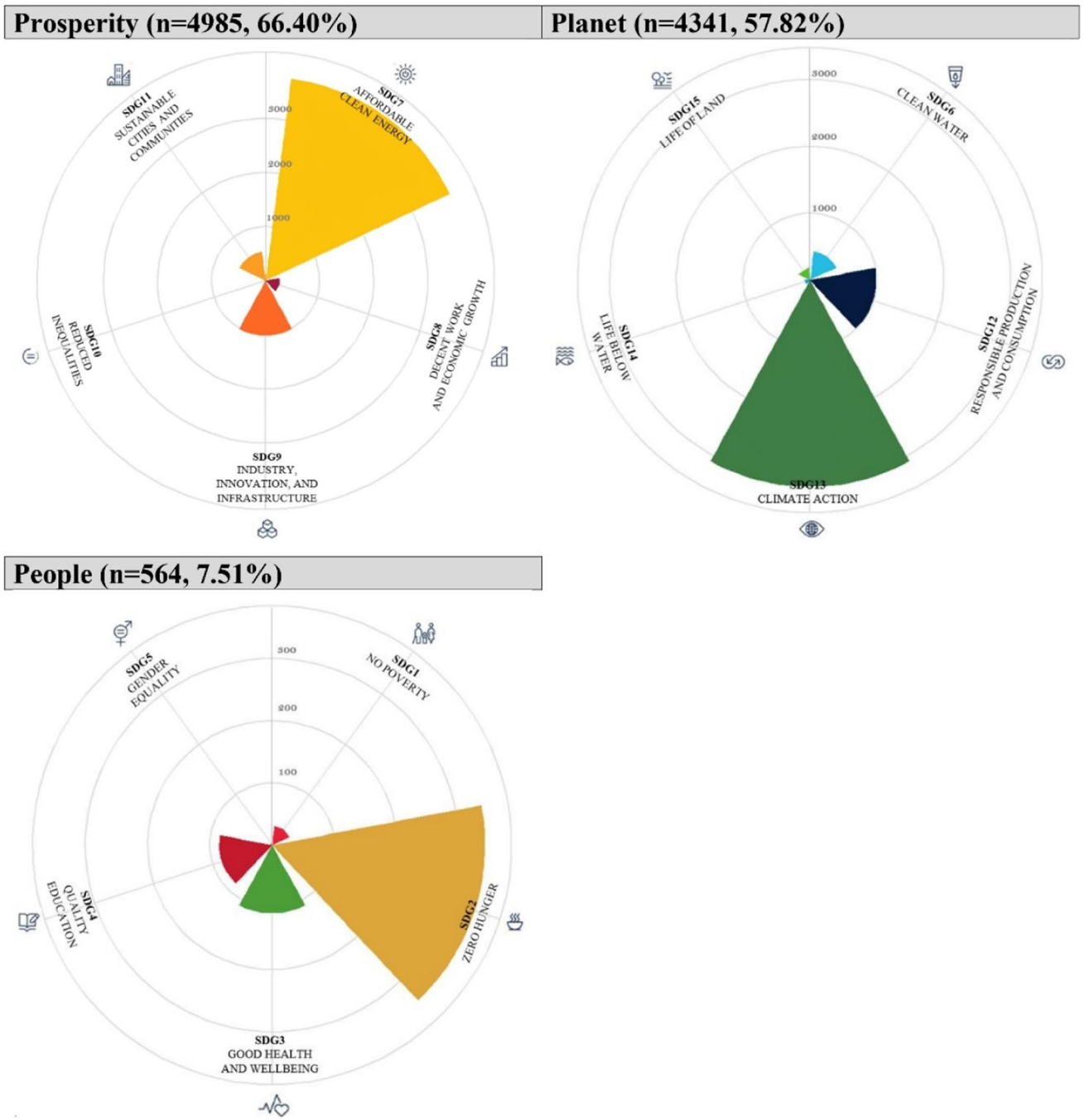

Fig. 6 Distribution of SDGs by main pillars (profit/prosperity, planet, and people). Source: self-elaborated from WoS data and the OSDG tool (https://osdg.ai)

(USA), which is also aligned with the results provided by Chen et al. (2021). While some of these institutions stand among the most prolific research organizations in the world, some others have a clear specialization on the topic (e.g., Norwegian University of Science Technology (NTNU), namely strategic research areas and departments).

The leading journals on CF research are also in line with previous studies (e.g., Li et al. 2021), which highlight the presence of journals ranked in prominent positions in the JCR quartiles. These journals, however, are generalist journals, which cover a wide spectrum of topics. As an example, *the Journal of Cleaner Production* (Elsevier)

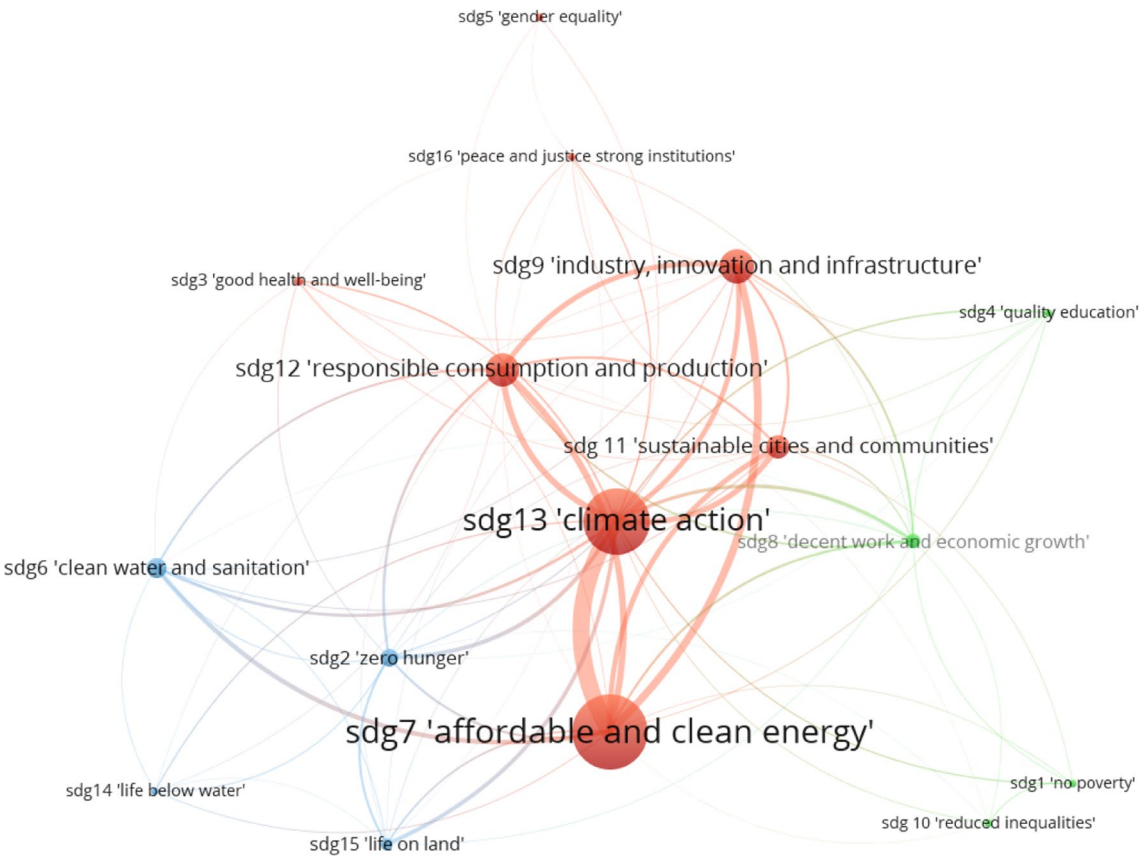

Fig. 7 Keywords co-occurrence map with SDG interrelations. Source: self-elaborated from WoS data; network powered with VOSviewer (https://www.vosviewer.com)

encompasses topics[1] such as education to reporting and assessment, among many others. Similarly, *Sustainability* (MDPI) is a mega-journal with a variety of topics, and a high number of special issues. In this vein, Repiso et al. (2021) found that a substantial number of works published in this journal (42.3%) have minimal or no relationship with the subject of sustainability in the Spanish context.

Delineation of sustainability in research

The results show that the publications' topics are related to the environmental and economic perspectives (planet, and profit or prosperity dimensions). This finding is evidenced using both levels of analysis (journal and article levels). While the journal level is led by planet (4915 unique publications; 54.4%), the article level is led by profit (4985 unique publications containing categories assigned to this dimension; 66.40%). This trend is even more obvious in the most recent years (see Table 3 and Fig. 4) and could be related to the fact that climate change has detrimental effects on economic sectors and threaten global prosperity (United Nations 2015).

The TBL interrelation analysis reveals that few publications (1.9%) include all three dimensions of the triple bottom line (TBL), indicating that research efforts are typically compartmentalized, as observed in previous studies (Lozano and Huisingh 2011). Notably, the profit-planet relationship is predominant. This discovery is not surprising given that profit has a major impact on carbon footprint (CF). Individuals'/households' contributions to global emissions and economic inequality are extensively investigated in the literature (see Chancel 2022), and this represents a new research hotspot (concurring with Yang and Meng 2019). Similarly, several publications investigate this interconnection at the organizational level (e.g., firms have mostly concentrated on the economic dimension, but they are becoming more aware of their critical role in sustainability and society, Lozano 2022a, b).

The inclusion of social (people) considerations within CF publications attaining higher alternative impact and interest (news, policies, and tweets) can be attributed to the practical implications and relevance of such publications to the lay public, potentially disseminated by policymakers,

[1] See: https://www.elsevier.com/__data/promis_misc/JCLP_image_aimsandscope.pdf

Table 4 Altmetric impact by TBL profile

Profile	DOIs	News count			Patents count			Policy count			Tweets count		
		P (%)	Avg.	Max	P (%)	Avg.	Max	P (%)	Avg.	Max	P (%)	Avg.	Max
A	1101	6.2	4.0	30	2.2	1.2	2	21.3	4.3	80	28.2	9.6	206
B	3849	6.9	8.1	205	1.2	1.4	10	22.2	4.2	56	27.4	16.4	1652
C	3106	7.3	6.7	177	1.4	1.2	3	22.2	4.9	176	26.8	12.9	1295
AB	843	6.8	7.7	83	1.3	1.0	1	23.2	4.5	123	27.4	12.2	368
AC	644	12.7	11.7	256	0.9	1.0	1	25.4	5.6	79	31.5	30.4	1552
BC	1565	7.7	5.4	89	1.0	1.2	2	24.8	2.9	36	28.5	10.8	365
ABC	344	6.4	4.2	21	3.0	1.1	2	20.8	3.3	21	23.3	6.4	118

P (%), data prevalence, that is, the percentage of publications that have received counts; *Avg.*, average number of mentions; *Max*, maximum value achieved

Source: self-elaborated from PlumX data. See "About PlumX metrics" for detailed information about each metric: https://plumanalytics.com/learn/about-metrics

companies, and media. The strong citation-based impact of profit can be attributed to the fact that economic considerations play a crucial role in shaping organizational policies related to CF (e.g., are expected to be accountable for their CF practices, not only in terms of regulatory compliance but also in meeting stakeholder expectations). Economic issues can have an impact on organizational and national investment decisions. These findings also support earlier research indicating that highly cited articles address economic issues (e.g., Tseng et al. 2020; Mishra et al. 2022).

In terms of the SDGs and their representation in the CF research data set, SDG7 and SDG13 are the goals that should be addressed more frequently in future literature. This is not surprising since SDG13 has specific indicators for reducing emissions (e.g., Indicator 13.2.2: total greenhouse gas emissions per year) whereas SDG7 is related to energy efficiency and the increased use of renewables for climate mitigation (e.g., International Council for Science 2015). In terms of connections, these SDGs have the highest interconnection degree. Improvement in energy efficiency is linked to the decline in the footprint-to-energy ratio (target 7.3) or the proportion of the population will increase the footprint (target 7.1) (He et al. 2022). Also, SDG13 has a relevant connection with responsible consumption (SDG12) (ensuring sustainable consumption contributes to mitigation, to the extent that pollution via the emission of emissions is concerned) and Industry SDG9 (e.g., climate change impacts on infrastructure or industry emissions).

Limitations

The dataset was created using the WoS. As a result, all of the results are solely dependent on the database's coverage. There is strong evidence of WoS biases in terms of publications indexed (Mongeon and Paul-Hus 2016) and citations covered (Martín-Martín et al. 2018), particularly towards English-language journals, journal article types, and a few empirical disciplines, which may have distorted the results. Because the Social Sciences, Humanities, and Arts have limited coverage in WoS, CF research in the Profit and People categories may be underrepresented. This could explain some of the observations in Fig. 3. Furthermore, we propose that additional types of publications, such as grey literature about CF (e.g., reports), be included to create a more complete global picture. As a result, we are convinced that our findings cannot be generalized because they are limited to the CF study covered by WoS. Future research with larger samples from more diverse databases is required. Similarly, Altmetrics data were gathered from PlumX, a well-known and extensively utilized source in the scientific literature. While references from other data sources may change (Ortega 2018; Karmakar et al. 2021), the effects on the final results (see Table 4) are minimal.

We suggested a supplementary strategy for classifying CF scientific output towards the TBL paradigm at two levels in this study: (1) journal level (semi-automatic classification) and keyword level (using the OSDG tool). The journal-level analysis (via WoS categories) necessitates a manual match between WoS categories and TBL dimensions. When matching categories into one of the TBL dimensions, this manual analysis may involve inherent subjectivity. Furthermore, a category may be associated to more than one TBL dimension, and an article may be categorized under many TBL dimension categories, adding complexity to the method. Each category has been matched with only one TBL dimension for clarity and to be as thorough as possible.

The article-level analysis (via publication keywords) has been previously tested by Bautista-Puig et al. (2021). They utilized a very similar approach to the one used in this study (e.g., keyword classification of the papers to the main TBL pillars, by searching economic, environmental, and social terms). The main advantage of this method is the usage of a higher set of available keywords (+4000) and the availability of an enhanced system (e.g., machine learning models trained by

using the OSDG community dataset) to analyze data (Pukelis et al. 2022). This approach can be easily reproduced and can be considered for other databases (e.g., Dimensions, Scopus) or datasets (e.g., with the use of an API) for future studies. However, this method has its own limitations, which is that it depends on a keyword approach and, consequently, might not be able to capture the whole picture of CF research (e.g., if a paper does not include a specific keyword from the ontology, a goal cannot be assigned to the excerpt of text). Moreover, the previous editions of this tool presented here had some shortcomings such as the effects of academics and Western bias (Pukelis et al. 2022). As a result, the results of the two aforementioned analyses should be interpreted with caution.

Conclusions

This work presents a comprehensive bibliometric analysis of CF research, and the findings help scholars and decision-makers interpret and contextualize the results. In addition, this study proposes a new delineation method for analyzing sustainability contribution at both the macro (journals) and micro (papers) levels. For a thorough understanding of how research contributes to achieving the SDGs, specifically SDG13 and SDG7, among others, the development of reproducible methodologies for analyzing scientific literature is essential.

There are numerous implications of this investigation. When formulating policies pertaining to CF emissions and sustainability measures, policymakers and business leaders utilize the main findings to adopt a comprehensive (e.g., holistic) approach to sustainability. Moreover, by introducing a novel bifurcated methodology for elucidating the contributions of sustainability (e.g., of research output), these results provide valuable insights to researchers from various disciplines. In addition, the results of the interlinkages (e.g., poorly addressed holistic approach) indicate that research can improve their sustainability performance by better linking their dimensions; furthermore, the study's impact (in terms of citations and interest) provides opportunities for future research in the field.

Future studies should employ qualitative research methodologies (e.g., interviews) to identify drivers and more specific motivations to publish research in CF by geographic regions or countries (for instance, differences between OECD and non-OECD countries could be investigated). Other dimensions (such as participation and peace) and their interrelations could be investigated in terms of TBL. In addition, additional research could concentrate on the integration of alternative approaches to the identification of SDGs, such as Aurora (https://aurora-sdg.labs.vu.nl) or Elsevier (Rivest et al. 2021), in order to evaluate the reliability and robustness of the proposed techniques.

Appendix

Table 5 Classification schema to match WoS Categories with TBL lines

TBL	WoS category
Profit	Energy Fuels
Profit	Engineering Electrical Electronic
Profit	Engineering Chemical
Profit	Engineering Civil
Profit	Materials Science Multidisciplinary
Profit	Economics
Profit	Construction Building Technology
Profit	Chemistry Multidisciplinary
Profit	Computer Science Information Systems
Profit	Engineering Mechanical
Profit	Management
Profit	Food Science Technology
Profit	Computer Science Theory Methods
Profit	Engineering Industrial
Profit	Computer Science Interdisciplinary Applications
Profit	Engineering Multidisciplinary
Profit	Operations Research Management Science
Profit	Engineering Manufacturing
Profit	Transportation Science Technology

Table 5 (continued)

TBL	WoS category
Profit	Business
Profit	Computer Science Hardware Architecture
Profit	Metallurgy Metallurgical Engineering
Profit	Computer Science Artificial Intelligence
Profit	Architecture
Profit	Automation Control Systems
Profit	Mechanics
Profit	Polymer Science
Profit	Nanoscience Nanotechnology
Profit	Computer Science Software Engineering
Profit	Chemistry Applied
Profit	Materials Science Composites
Profit	Mining Mineral Processing
Profit	Electrochemistry
Profit	Materials Science Textiles
Profit	Optics
Profit	Remote Sensing
Profit	Business Finance
Profit	Mathematics Applied
Profit	Mathematics Interdisciplinary Applications
Profit	Chemistry Analytical
Profit	Engineering Petroleum
Profit	Mineralogy
Profit	Materials Science Characterization Testing
Profit	Engineering Aerospace
Profit	Materials Science Ceramics
Profit	Nuclear Science Technology
Profit	Engineering Biomedical
Profit	Instruments Instrumentation
Profit	Robotics
Profit	Computer Science Cybernetics
Profit	Imaging Science Photographic Technology
Profit	Chemistry Organic
Profit	Physics Atomic Molecular Chemical
Profit	Materials Science Biomaterials
Profit	Biochemical Research Methods
Profit	Materials Science Coatings Films
Profit	Acoustics
Profit	Chemistry Inorganic Nuclear
Profit	Astronomy Astrophysics
Profit	Spectroscopy
Profit	Radiology Nuclear Medicine Medical Imaging
Profit	Mathematical Computational Biology
Profit	Physics Fluids Plasmas
Profit	Physics Mathematical
Profit	Physics Multidisciplinary
Profit	Mathematics
Profit	Crystallography
Profit	Biophysics
Profit	Microscopy
Profit	Physics Particles Fields

Table 5 (continued)

TBL	WoS category
Profit	Quantum Science Technology
People	Environmental Studies
People	Telecommunications
People	Multidisciplinary Sciences
People	Regional Urban Planning
People	Transportation
People	Urban Studies
People	Hospitality Leisure Sport Tourism
People	Horticulture
People	Education Educational Research
People	Public Environmental Occupational Health
People	Agricultural Economics Policy
People	Development Studies
People	Nutrition Dietetics
People	Sociology
People	Social Sciences Interdisciplinary
People	Medicine General Internal
People	Education Scientific Disciplines
People	Political Science
People	International Relations
People	Information Science Library Science
People	Surgery
People	Public Administration
People	Area Studies
People	Urology Nephrology
People	Anesthesiology
People	Psychology Multidisciplinary
People	Statistics Probability
People	Health Policy Services
People	Ethics
People	Humanities Multidisciplinary
People	Law
People	Pharmacology Pharmacy
People	Art
People	Health Care Sciences Services
People	Demography
People	Anthropology
People	Communication
People	Ophthalmology
People	Social Issues
People	Archaeology
People	History Philosophy Of Science
People	Social Sciences Mathematical Methods
People	Critical Care Medicine
People	Primary Health Care
People	Psychology Social
People	Respiratory System
People	Nursing
People	Behavioral Sciences
People	Dentistry Oral Surgery Medicine
People	Emergency Medicine

Table 5 (continued)

TBL	WoS category
People	Genetics Heredity
People	Medicine Research Experimental
People	Pediatrics
People	Psychology Applied
People	Criminology Penology
People	Dermatology
People	History
People	Philosophy
People	Religion
People	Social Sciences Biomedical
People	Transplantation
People	Medical Ethics
People	Obstetrics Gynecology
People	Ergonomics
People	Gerontology
People	Linguistics
People	Oncology
People	Psychiatry
People	Substance Abuse
People	Tropical Medicine
People	Asian Studies
People	Cultural Studies
People	Geriatrics Gerontology
People	Medical Informatics
People	Paleontology
People	Parasitology
People	Psychology Clinical
People	Social Work
People	Sport Sciences
People	Audiology Speech Language Pathology
People	Cardiac Cardiovascular Systems
People	Chemistry Medicinal
People	Clinical Neurology
People	Endocrinology Metabolism
People	Family Studies
People	Film Radio Television
People	Hematology
People	Immunology
People	Language Linguistics
People	Literary Theory Criticism
People	Literature
People	Logic
People	Medical Laboratory Technology
People	Medicine Legal
People	Neuroimaging
People	Orthopedics
People	Otorhinolaryngology
People	Psychology Educational
People	Psychology Experimental
People	Reproductive Biology
People	Theater

Table 5 (continued)

TBL	WoS category
People	Virology
Planet	Environmental Sciences
Planet	Green Sustainable Science Technology
Planet	Engineering Environmental
Planet	Ecology
Planet	Water Resources
Planet	Agriculture Dairy Animal Science
Planet	Biodiversity Conservation
Planet	Thermodynamics
Planet	Agriculture Multidisciplinary
Planet	Biotechnology Applied Microbiology
Planet	Agronomy
Planet	Meteorology Atmospheric Sciences
Planet	Physics Applied
Planet	Chemistry Physical
Planet	Geosciences Multidisciplinary
Planet	Geography
Planet	Agricultural Engineering
Planet	Veterinary Sciences
Planet	Plant Sciences
Planet	Geography Physical
Planet	Forestry
Planet	Materials Science Paper Wood
Planet	Fisheries
Planet	Marine Freshwater Biology
Planet	Engineering Geological
Planet	Physics Condensed Matter
Planet	Soil Science
Planet	Biochemistry Molecular Biology
Planet	Biology
Planet	Zoology
Planet	Toxicology
Planet	Oceanography
Planet	Microbiology
Planet	Engineering Marine
Planet	Engineering Ocean
Planet	Geochemistry Geophysics
Planet	Geology
Planet	Limnology
Planet	Cell Biology
Planet	Entomology
Planet	Evolutionary Biology
Planet	Infectious Diseases
Planet	Ornithology
Planet	Mycology

Table 6 Top 20 institutions ranked by CF research between the year 2008 and 2020 (source: WoS)

Affiliations	Country	Record count	% of 9032
RLUK Research Libraries UK	United Kingdom	610	6.75
N8 Research Partnership	United Kingdom	229	2.54
University of California System	USA	157	1.74
Chinese Academy of Sciences	China	145	1.61
Norwegian University of Science Technology	Norway	122	1.35
Indian institute of technology system iit system	India	113	1.25
White Rose University Consortium	United Kingdom	110	1.22
State University System of Florida	USA	89	0.99
University of New South Wales Sydney	Australia	88	0.97
United States Department of Energy	USA	79	0.87
Swiss Federal Institutes of Technology	Switzerland	78	0.86
University of Sydney	Australia	77	0.85
Udice French Research Universities	France	70	0.78
University of Leeds	UK	67	0.74
University System of Ohio	USA	66	0.73
Centre National de la Recherche Scientifique	France	63	0.70
Hong Kong Polytechnic University	China	63	0.70
University of Manchester	UK	63	0.70
Wageningen University Research	Netherland	63	0.70
Universidade De Santiago De Compostela	Spain	61	0.68

Table 7 Top 20 core journals on carbon footprint research

Rank	Journal	Publisher	N.P.	2021 IF	5 Year IF	Quartile position
1	Journal of Cleaner Production	Elsevier	829	11.072	11.016	Q1
2	Sustainability	MDPI	263	3.889	4.089	Q2/Q3/Q4
3	International Journal of Life Cycle Assessment	Springer	161	5.257	6.803	Q2
4	Science of the Total Environment	Elsevier	139	10.754	10.237	Q1
5	Applied Energy	Elsevier	126	11.446	11.268	Q1
6	Construction and Building Materials	Elsevier	100	7.693	8.194	Q3
7	Energies	MDPI	96	3.252	3.333	N/A
8	Energy Procedia	Elsevier	96	N/A	N/A	Q2/Q1
9	Journal of Industrial Ecology	Wiley	85	7.202	7.945	Q1
10	Renewable Sustainable Energy Reviews	Elsevier	83	16.799	17.551	Q1
11	Environmental Science Technology	ACS	79	11.357	12.154	Q1
12	Resources Conservation and Recycling	Elsevier	72	13.716	13.543	Q1
13	Energy	Elsevier	62	8.857	8.234	Q1/Q2
14	Energy Policy	Elsevier	59	7.576	7.88	Q1
15	Ecological Indicators	Elsevier	58	6.263	6.643	Q1
16	Journal of Environmental Management	Elsevier	58	8.91	8.549	Q2
17	Environmental Science and Pollution Research	Springer	46	5.19	5.053	Q2
18	ACS Sustainable Chemistry & Engineering	Amer. Chemical. Soc.	44	9.224	9.458	Q1
19	Ecological Economics	Elsevier	44	6.536	7.3	Q1
20	Environmental Research Letters	IOP	44	6.947	8.414	Q1

Source: Journal Citation Reports (2021 edition)

N/A, not available; *Energy Procedia* discontinued 2020; *N.P.*, number of publications

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Visualization: NB, SA, and EO
Data collection: SA, CT, NB, and EO
Data analysis: SA and NB and EO and CT
Writing: SA and NB and EO and CT

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