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Sustainability in Numbers by Data Analytics

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Abstract

For a successful delivery of the United Nations Sustainable Development Goals (UNSDGs) and to track the progress of UNSDGs as well as identify the gaps and the areas requiring more attention, periodic analyses on the "research on sustainability" by various countries and their contribution to the topic are inevitable. This paper tracks the trends in sustainability research including the geographical distribution on sustainability research, their level of multi-disciplinarity and the cross-border collaboration, their distribution of funding with respect to the UNSDGs, and the lifecycle analyses. Cumulative publications and patents on sustainability could be fitted to an exponential function, thereby highlighting the importance of the research on sustainability in the recent past. Besides, this analytics quantifies cross-border collaborations and knowledge integration to solve critical issues as well as traditional and emerging sources to undertake sustainability research. As an important aspect of resource sustainability and circular economy, trends in publication and funding on lifecycle assessment have also been investigated. The analytics present here identify that major sustainability research volume is from the social sciences as well as business and economics sectors, whereas contributions from the engineering disciplines to develop technologies for sustainability practices are relatively lower. Similarly, funding distribution is also not evenly distributed under various SDGs; the larger share of funding has been on energy security and climate change research. Thus, this study identifies many gaps to be filled for the UNSDGs to be successful.

Keywords Sustainability impact · Sustainable development goals · Interdisciplinary collaboration · Interdisciplinary research · Lifecycle analysis

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Introduction

Sustainability has long been linked to resources and climate [1, 2]; however, the COVID-19 pandemic [3–6], as well as certain statistics, such as the doubling of waste each decade [7, 8], the Great Pacific Garbage Patch [9–11], etc., gives rise to concerns over the sustainability of humanity itself. The sustainability topic has been refined and enhanced through decades; the latest is the announcement of the United Nations' Seventeen Sustainability Development Goals (UNSDGs) on 1 Jan 2016. Since the industrial revolution, the science and technology–enabled mass production and supply of an exceptional range of goods and services have helped billions of people around the world to lead a modern life; however, this was at the expense of the environment due to the atmospheric, land, and ocean pollution that resulted [1]. The COVID-19 pandemic will punctuate the year 2020 in the history of humankind as it affected the ways of living in all continents and disrupted the future. Unfortunately, all these have been linked to human activity by disturbing nature's ecological balance via overexploitation of terrestrial resources [12]. A recent study reveals that the global human-made mass (such as roads, bridges, automobiles, etc.) will exceed all living biomass on planet Earth; the year 2020 is the cross-over point where the human-made mass or anthropogenic mass equals all living biomass [13].

The topic of sustainability links to over 500 definitions or keywords [14]. These include the following: SDGs; Paris Agreement and nationally determined contributions; circular economy and minimizing circularity gap as well as related terms such as closing the waste loop, end-of-life management of waste, ban on single-use plastics, ban on export of solid waste, design out waste, emissions reduction targets, recycling targets, etc. [15–21]; sustainability gap [2]; energy efficiency and more renewable energy in the energy mix [22–24]; water efficiency [25, 26]; materials efficiency [27, 28]; supply chain resilience and efficiency [29–35]; decarbonization efforts including low-carbon economy, carbon trading, low-carbon materials, low-carbon products, low-carbon services, green economy, carbon footprint reporting carbon tax [36–39]; green financing and related terminologies such as extended produced responsibility (EPR), environmental product declarations (EPD), energy efficiency targets, eco-design, eco-labeling, Environmental, Social & Governance (ESG) reporting, and packaging agreement [40–47]; lifecycle assessment and related terms such as lifecycle costing and lifecycle engineering [48–51]; renewable and sustainable materials; electronic waste (E-waste); design for recycling; design for reuse; regeneration of depleted resources; ethical sourcing of materials; and eliminating hazardous materials. Thus, sustainability is a process of maintaining the original state of the land, waters, and atmosphere for the benefit of mankind and future generations via revitalizing biodiversity, reducing natural pollution, elimination of waste, overcoming sea level rise, and reducing greenhouse gas emissions [2, 52]. In response to these efforts on sustainability, several countries have announced their positive commitments to the carbon neutrality, i.e., net zero emissions of greenhouse gases and design out waste to promote the sustainability agenda in recent years [36]. The European Union, the USA, the UK, South Korea, and Japan have committed to carbon neutrality by 2050, and China by 2060. India has recently announced carbon neutrality by 2070. Several well-known and large market capitalization companies in all sectors of the economy have pledged to reduce their carbon footprints. Besides, to ensure resource sustainability and environmental protection, a circular economy has been suggested as the remedy for the future, which is expected to create a more performant economic model that prioritizes resilience and sustainability [15–20].

Considering the immense and the growing importance of sustainability worldwide, we have attempted to capture sustainability research trends via numbers and infographics by analyzing data from the Springer Nature database. As the sustainability agenda applies equally to the entire human population of the planet, it is mandatory to periodically analyze the engagement of various countries and their contribution to the topic not only to track the progress but also to identify gaps and areas requiring more attention to successfully deliver UNSDGs. Therefore, this communication specifically analyzes the statistics of research publications, patents, and funding sources of research on the sustainability as well as life-cycle analysis. This analytics also considers their geographical distribution, their level of multi-disciplinarity and cross-border collaboration, and their distribution of funding with respect to the UN's Sustainable Development Goals (SDGs). Cumulative publications and patents could be fitted to an exponential function and highlighting the importance of the research on sustainability in the near future. Besides, this analytics quantifies cross-border collaborations and knowledge integration to solve critical issues as well as traditional and emerging sources to undertake sustainability research. Based on these findings, this paper identifies five pillars of sustainability research, viz. which is expected to the way forward for sustainability agenda. We identify major gaps both in terms of publications and funding, which are to be addressed to ensure success of UNSDGs.

Method

The data for this study has been obtained from SN Insights (2020) [53], which is a database including a substantial number of indexed academic publications, datasets, patents, grants, and policy documents. By searching the data on 10 Nov 2020 using the keywords "sustainability OR circular economy OR low-carbon economy OR green economy OR life-cycle analysis," authors have generated the following analyses and infographics in various dimensions. The data thus generated has been analyzed statistically without using any filters. The parameters analyzed are (a) the statistics of research publications; (b) the generation of intellectual property; (c) the disciplinarity of research, i.e., how extensively different disciplines are joined for better impact; and (d) the country-wise funding priority. In all the infographics, henceforth, we use the term "sustainability" to encompass all searches based on these five keywords.

Key Findings

Figure 1a is the cumulative number of sustainability publications during 2011–2020, which illustrates an exponential trend and suggests the growing importance of this subject. Over the past 10 years, a total of 5,879,000 sustainability-related publications have appeared in the scientific literature. This also implies that the research funding agencies and the organizations are prioritizing sustainability research in recent years. In response to this exponential increase in publications, the number of intellectual properties filed/sealed also shows an exponential trend (Fig. 1b). A geographical distribution of the sustainability publications is presented in Fig. 1c; these data indicate that the USA, Canada, and Europe contribute over 40% of the total sustainability publications so far. The data also show that the shares of sustainability research by larger economies and populations such as China and India are relatively lower (4 and 2%, respectively). Obviously, the sustainability efforts

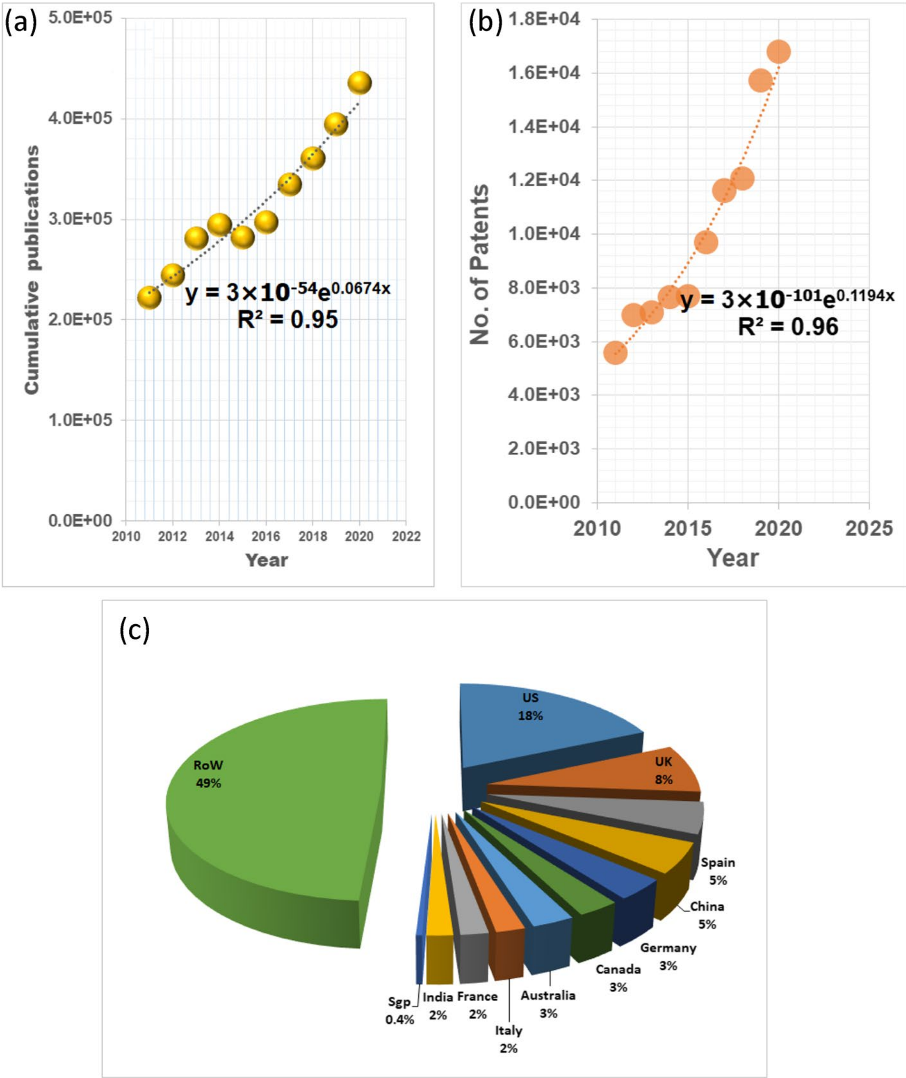
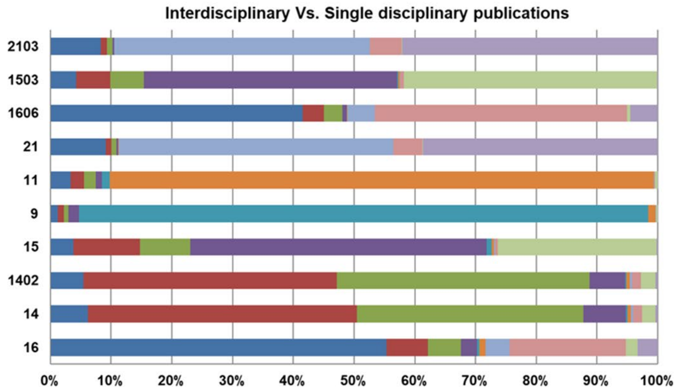


Fig. 1 Statistics on the yearly **a** publications and **b** number of patents filed/sealed during 2011–2020. The filled spheres/circles are the actual data points, and the dotted line is an exponential fit. The fitted function and the goodness of fit are also included in the figures. **c** Country-wise fraction of publications out of 5879 K total publications over the past 10 years

have a better impact if larger economies and populations have major shares in the statistics shown in Fig. 1c.

We have further investigated the nature of sustainability research, the results of which are shown in Fig. 2. The results suggest that more than 60% of the total sustainability publications are multidisciplinary or cross-field. Multidisciplinary implies that researchers from different disciplines work together, each drawing on their disciplinary knowledge, in order to develop things and services for real-life applications [54]. Cross-disciplinary



	16	14	1402	15	9	11	21	1606	1503	2103
16 Studies in Human Society	965,904	119,468	95,285	46,532	6,243	16,529	69,317	335,601	32,908	58,126
14 Economics	119,468	860,144	722,905	134,986	5,792	10,599	7,553	28,194	43,298	7,268
1402 Applied Economics	95,285	722,905	722,905	101,758	3,746	9,658	5,941	25,062	42,974	5,925
15 Commerce, Management, Tourism and Services	46,532	134,986	101,758	600,996	9,463	4,751	2,285	5,562	322,166	2,100
09 Engineering	6,243	5,792	3,746	9,463	499,425	6,330	193	22	1,462	167
11 Medical and Health Sciences	16,529	10,599	9,658	4,751	6,330	440,065	119	713	2,135	113
21 History and Archaeology	69,317	7,553	5,941	2,285	193	119	344,840	36,581	528	294,565
1606 Political Science	335,601	28,194	25,062	5,562	22	713	36,581	335,601	4,591	36,571
1503 Business and Management	32,908	43,298	42,974	322,166	1,462	2,135	528	4,591	322,166	526
2103 Historical Studies	58,126	7,268	5,925	2,100	167	113	294,565	36,571	526	294,565

Fig. 2 Cross-field (interdisciplinary) publications vs mono-discipline (single disciplinary) sustainability publications. The top panel is the graphical representation of the data shown in the bottom panel. The numbers in the ordinate and colors used for the data in the graph are defined in the data table in the bottom panel. The abscissa refers to the percentage of publications in each single disciplinary and interdisciplinary domain. The data was obtained from the Springer Nature database on 10 Nov 2020

means viewing one discipline from the perspective of another. Another terminology often used is interdisciplinary, which involves integrating knowledge and methods from different disciplines using a real synthesis of approaches. Transdisciplinary involves creating a unity of intellectual frameworks beyond the disciplinary perspectives. All these approaches are necessary for accelerating sustainability solutions [55]. This is also in line with the observations of another study by Clarivate Analytics (2020). For more than 10 years, Clarivate Analytics has been identifying the most highly cited researchers in the world [56]. A total of 6389 researchers were named Highly Cited Researchers in 2020. Among them, about 3896 researchers (~60% of the total 6389) are in specific fields, and 2493 researchers (~40% of the total 6389) were identified for their cross-field performance. Even though the practice of identifying highly cited researchers has been there for some time, only since 2018 did Clarivate Analytics start identifying the researchers with cross-field impact. The trend suggests that the cross-field research is gaining traction in recent years and underscores that cross-fields as well as multidisciplinary approaches are necessary for providing sustainability solutions [57].

As displayed by the data in Fig. 2, the social sciences (humanities, history, and archeological and political sciences) are dominating the research volume on sustainability followed by economics and business. In contrast, the contributions from engineering science as well as the medical and healthcare sectors are considerably inferior to those of the social sciences and economic sectors. Obviously, the efforts from the social science sectors placed significant awareness on sustainability, which put forward many policies in effect to preserve the planet's ecosystem for survival of its habitat. Similarly, the research insights from the economics and business sectors put forward the transition from linear to circular economy and urge the societies to keep the resources in use, which not only has significant economic impact but contributes to social and ecological domains also. These two dominant sectors, i.e., humanities and business and economics, contributed significantly to the multidisciplinary (cross-field) areas in addition to significant contribution to their corresponding single disciplinary subjects. Significant efforts are now required from the engineering and healthcare domains for the actual impact of the policies. For example, for complete transition from linear to circular economies, the materials and device recycling and reusing technologies need a significant number of innovations. Given the statistics that the waste production doubles in every decade and only few ideas are currently in place on recycling and reusing, implementing sustainability and circular economy policies without significant efforts from the engineering sectors will end up in vain.

The intensity of transnational collaboration in the sustainability research has also been investigated for the top 10 most contributing countries (Fig. 3). As can be seen from Fig. 3, sustainability research is primarily being carried out within the country, and only a marginal amount of transnational cooperation is taking place. Interestingly, most of the sustainability research collaboration is currently happening within the same countries, i.e., over 80% of the sustainability research in the USA is through internal collaboration between the

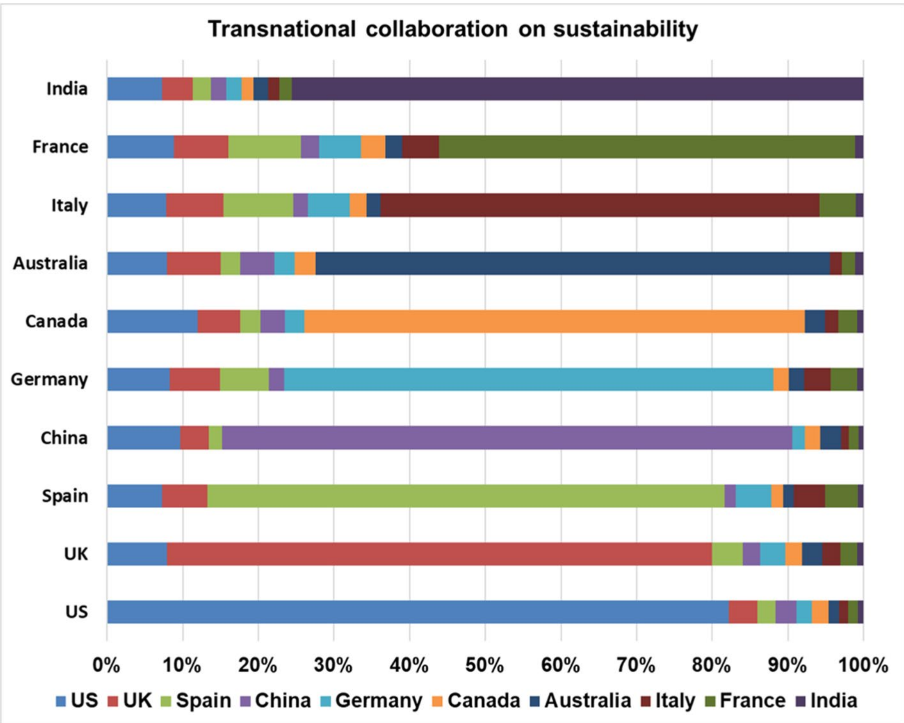


Fig. 3 Transnational collaboration publications in *Sustainability*. The data was obtained from the Springer Nature database on 10 Nov 2020

institutes within the USA and the transnational collaborations with other top 10 contributors are very nominal. We would point out that knowledge integration not only is required within various subject areas but also requires transnational collaboration for the successful implementation of SDGs as sustainability is a topic beyond geographical borders.

Figure 4 captures the major funders of sustainability research around the world and their correlations with the UN SDGs. Each row indicates the different sources of research funding. The columns represent the ten most focused UN SDGs. They are no. 1—no poverty, no. 3—good health and well-being, no. 4—quality education, no. 7—affordable and clean energy, no. 8—decent work and economic growth, no. 10—reduced inequalities, no. 11—sustainable cities and communities, no. 12—responsible consumption and production, no. 13—climate action, and no. 16—peace, justice, and strong institutions. Obviously, affordable and clean energy (SDG #7) and climate action (SDG #13) are the domains that received significant funding. Given the significant impact of SDG #11 (sustainable cities and communities) on the economy [52], although it appears as the next majorly funded initiative, the share needs to be significantly improved. Research on some of the basic SDGs, such as eradication of poverty (SDG #1), quality education (SDG #4), etc., is inferiorly funded.

It is generally agreed that every country, city, company, institution, and organization must take concrete measures to reduce emissions by 45% by 2030 compared with 2010 levels [1], and the universities have a key part to play in finding the solutions [58–62].

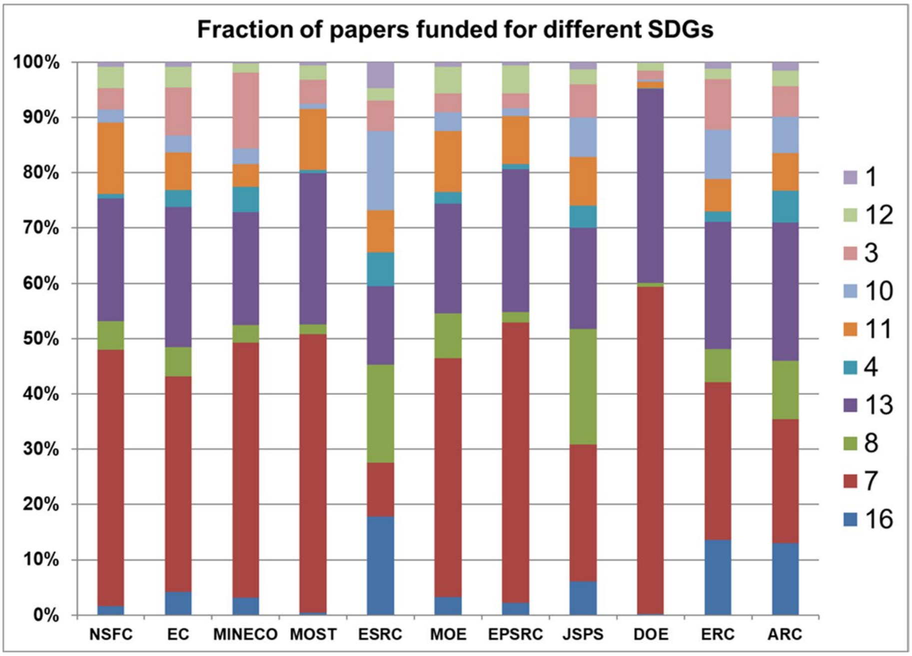


Fig. 4 Sustainability research funding sources and connections to the UN SDGs. National Natural Science Foundation of China (NSFC); European Commission (EC); Ministry of Economy, Industry and Competitiveness (MINECO); Ministry of Science and Technology of the People's Republic of China (MOST); Economic and Social Research Council (ESRC); Ministry of Education of the People's Republic of China (MOE); Engineering and Physical Sciences Research Council (EPSRC); Japan Society for the Promotion of Science (JSPS); United States Department of Energy (DOE); European Research Council (ERC); Australian Research Council (ARC). The data was obtained from the Springer Nature database on 10 Nov 2020

Therefore, we have also investigated sustainability-focused higher education grants. In general, the support for the sustainability-focused higher education research is growing (Fig. 5a). Higher education grants are monetary awards for educators who are in the process of pursuing or planning to pursue a degree in any given discipline. The grants are provided by foundations, corporate entities, and federal governments. The assessment units are usually the educational services. This encouragement is also evidenced by the growing number of sustainability-focused higher education journal papers over the past 10 years (Fig. 5b).

Finally, the trends in publication, funders, and top ten countries contributing to one of the important aspects of resource sustainability and circular economy, which is lifecycle analysis or lifecycle assessment (LCA), have also been investigated. LCA is often referred to as a "cradle-to-grave analysis," which examines the impacts from raw material extraction (cradle) through product lifetime and its various implications on health and environment (make and use) to the disposal (grave) [48–51]. Implementation of a circular economy is expected to transform the "cradle-to-grave analysis" into "cradle-to-cradle analysis" because the resources will be in use for an extended period of time. The analysis hereby also determines that, in line with the publications and patents, lifecycle analysis also follows an exponential trend (Fig. 6a). The organizations and countries promoting these activities are in Fig. 6b and c, respectively. Consistent with the trends in the overall research on sustainability, the institutions in the USA and Europe own the major share (85%) in the LCA activities also. China and India are the only Asian

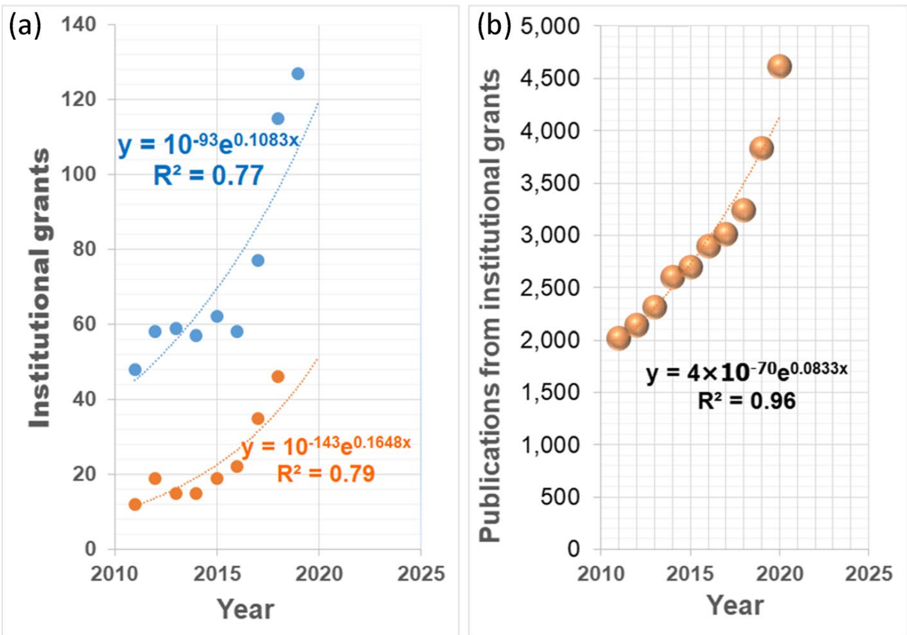


Fig. 5 **a** Growth of research grants by institutions of higher education and **b** growth of sustainability-focused higher education journal papers from higher education grants. The solid circles show the data points, and the dotted line is the exponential fit. The fitted equations and the reliability factors are also shown in the graph

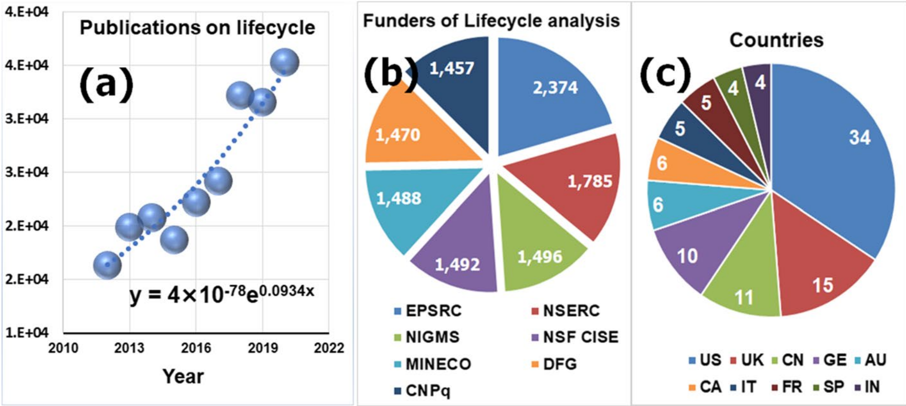


Fig. 6 **a** Number of yearly publications on lifecycle analysis during 2010–2020. The solid circles show the datapoints, and the dotted line is the exponential fit. **b** Top 7 funders of sustainability research; their total number of publications from each funder is shown in the representative segments. EPSRC stands for Engineering and Physical Sciences Research Council (UK), NSERC for Natural Sciences and Engineering Research Council (Canada), NIGMS for National Institute of General Medical Sciences (US), NSF CISE for the Directorate for Computer & Information Science & Engineering of NSF (US); MINECO for Ministry of Economy, Industry and Competitiveness (Spain), DFG for German Research Foundation, and CNPq for National Council for Scientific and Technological Development (Brazil). **c** Top ten countries funding lifecycle analysis research; the numbers in the segment refer to the percentage of contribution. US—United States of America, UK—United Kingdom, CN—China, GE—Germany, AU—Australia, CA—Canada, IT—Italy, FR—France, SP—Spain, and IN—India

countries entered in the list of top major contributors, but their share is limited to 15% even though nearly 60% of the world's total population live in this continent.

Thus, there is an urgent need for sustainability thinking in all areas of human endeavor. The data from the UNESCO Institute for Statistics (UIS) suggests that the global spending on research and development has reached US$1.7 trillion. Interestingly about ten countries account for 80% of the total global spending. The UIS has mentioned that countries have pledged to substantially increase R&D spending as well as the number of sustainability researchers by 2030, as part of the Sustainable Development Goals (SDGs). Moving forward, all products and services need to be reimagined for the health of planet Earth and its systems and beings and sustainability should be specified to include five typical aspects, viz., resource sustainability, environmental protection, social well-being, integration of knowledge from various disciplines to solve societal sustainability issues (knowledge integration), and waste as a resource (circular economy), as outlined in a recent editorial [63]. These five pillars of sustainability are schematically shown in Fig. 7; i.e., sustainability means reimagining all human actions responsibly on the Earth and its systems and all beings such that the new paradigm creates enormous jobs, economic growth, and social well-being.

Conclusions

In conclusion, this study identifies significant attention by the academic community on sustainability agenda worldwide; however, a small fraction of educationally and economically advanced countries is in the lead role. A significant bottleneck in this gap is the funding

Fig. 7 Five pillars of sustainability

for sustainability and lifecycle analyses in most countries, which adversely affects development and diffusion of multi- and transdisciplinary knowledge. In the following, we list the specific outcomes of this study.

1. The analytics presented here considered only the knowledge domain; we show that the academic activities in this area are still in the early stages as judged from the exponential growth in publications and patents.
2. Generating sustainability solutions requires multidisciplinary, cross-field, interdisciplinary, and transdisciplinary approaches. Henceforth, such approaches should be encouraged to mitigate the overemphasis of mono-disciplinary pursuits in vogue. There are tremendous scope and opportunities for new science and technology of atoms and molecules, materials, products, services, and economic models. The new paradigm provides for new jobs, economic growth, and the well-being of humans.
3. We identify that social sciences, business, and economics contribute a larger share in the research volume on sustainability, which increased public awareness, put many policies into effect, and initiated the transition from linear to circular economies. However, the contribution of the engineering sector is relatively lower. Significant attention is required to develop technologies from the engineering sector for the sustainability practice.
4. Funding distribution is also not seen to be uniform with respect to the UNSDGs. Energy security and climate change attracted significant funding, whereas research funding for some of the basic needs such as eradication of poverty, quality education, reduction of inequalities, etc. is significantly lower. Sustainability education should be pervasive in all disciplines of higher education so as to lower the sustainability gap of universities and equip graduates in leading us into a sustainable future.
5. In recent years, the sustainability R&D activities are growing though limited to a few countries centered in Europe and the Americas. Despite a larger human share in Asia, the investment on sustainability education and academic activities is relatively lower. In the future, it is likely that the sustainability R&D will gain momentum in more countries around the world.

6. Lifecycle analysis, one of the important components of a circular economy and sustainability, receives relatively poor funding from major economies, although its research volume is considerable.
7. The sustainability topic should be strengthened by considering the following five pillars: (i) resource sustainability, (ii) environmental protection, (iii) social well-being, (iv) knowledge integration to solve societal issues, and (v) implementing a circular economy for developing waste as a resource. Sustainability activities are to be reimaged such that human actions are responsible to the Earth and its systems and all beings.

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Author Contribution SR initiated the idea and drafted the manuscript; WH searched and secured the data and contributed to the initial draft and analytics; RJ contributed to the discussion, elaboration, processing, and visualization of data and revised the manuscript.

Data Availability The data that support the findings of this study are available from Digital Science's Dimensions platform, but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are, however, available from the authors upon reasonable request and with permission from Digital Science's Dimensions platform.

Declarations

Conflict of Interest Seeram Ramakrishna is the editor in chief of *Materials Circular Economy*; Wayne Hu is an editor of Engineering in Springer Shanghai; and Rajan Jose is the main editor of *Materials Circular Economy*.

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