A Review of Global Research Trends on Sustainable Manufacturing

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1 Introduction

Despite having been used interchangeably in many cases, the terms 'Sustainable Development (SD)' and 'Sustainability' are inherently distinct—SD is the pathway to succeed in sustainability, that is the ideal dynamic state [1, 2]. A majority of the scientific community has been incorporating SD into the field of manufacturing, considering the growing global interest in the phenomenon as "Our Common Future [3]" drawn by the World Commission on Environment and Development, in 1987. The interest grew even larger following the revelation that our common future is intensively influenced by the manufacturing sector as revealed at the Earth Summit, Rio de Janeiro, Brazil in 1992 [4]. From that point on, the field has experienced numerous revolutions complying to the fact that being sustainable has greater benefits.

Being the core of all industrial economies, it was outlined that the manufacturing sector must be made sustainable with the aim of preserving the high standards of living already attained by industrialized societies and for enabling the sustainable achievement of the same standards of living by other developing societies. Thus,

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there is always a need for sustainable manufacturing development due to a number of prevailing issues such as the depletion of non-renewable resources, more stringent environmental and occupational safety/health regulations, and the growing penchant for environmentally-friendly products, among many others [5, 6, 7, 8]. Sustainable manufacturing entails the manufacturing of more sustainable products—energy-efficient, eco-friendly, and socially-responsible—by using sustainable processes and systems, i.e., those which produce minimal adverse environmental impacts, conserve energy and natural resources, are harmless to people, and are economically viable [9, 10, 11, 12]. However, according to [13], "there are many insufficient attempts, including a partially integral approach, almost all fall short because they largely deal with products and processes, but fail to stress the interconnectivity among the three integral elements involved in manufacturing (products, processes and systems), and show the basis for sustainable value creation an economic growth (p. 104)". This condition—a need for the development of sustainable products, processes, and systems—and the fact that this topic is dramatically receiving a great deal of attention from practitioners and researchers, thereby draws our fundamental question: how has research on sustainable manufacturing evolved in recent years?

To address the question, the current research carried out a Bibliometric or Scientometric analysis, which can expedite the review's process of research trends in the literature concerning the subject and subsequently give guidelines and directions for further investigations. This would contribute to providing up-to-date overview of the topic, including the possible implications for facilitating the complexities involved in the area of sustainable manufacturing. The methodological approach has been effectively employed since its inception in the early literature (i.e., [14, 15] which presented a description of Bibliometric research, up to its adoption in very recent studies [16, 17, 18, 19, 20, 21]. By using this method, the current study is primarily aimed at accomplishing the following objectives:

1. To present the past and present progress of the literature published on "sustainable manufacturing" and also its interchangeable term "sustainable production".
2. To characterise the most contributing countries to the understudied theme.
3. To recognise the core journals having a significant contribution to the subject.
4. To determine the highly contributing academic institutions to the under-researched topic.
5. To identify the prolific authors contributing considerably to developing the area.
6. To outline common terminology, research topics and in-depth insights.

Accordingly, this article is organized as follows: Sect. 1.2 clarifies the research methodological approach and the procedure of this study, Sect. 1.3 delivers findings of this overview and discusses the results according to the aforementioned objectives, and, finally, Sect. 1.4 provides the reader with a sense of closure on the topic.

2 Methods

Bibliometric analysis is a methodological approach which is applied to investigate the research trends in specific areas and outline the directions of such research through analysing the academic databases outputs [16, 22] according to co-occurrence, co-citation, co-author, co-word, and bibliographic coupling [17, 21]. Thus, this method has been carried out to examine global research trends in the area of sustainable manufacturing.

The data for this study was extracted from Scopus until May, 2021. However, the Scopus database is prominently regarded as the largest indexer of global research content, including titles from more than 5,000 publishers worldwide, e.g., Springer, ScienceDirect, Taylor & Francis, Emerald, Wiley, etc. [18, 23]. The bibliometric software and VOSviewer were accordingly used to statistically scrutinise the descriptive data including annually scientific production, most frequent keyword, and providing visualization for co-word analysis [19, 24].

2.1 Criteria for the Review

Similar to [25] and Guraja et al. [26], the documents considered for this review are limited to article, abstract report, book, book chapter, business article, conference paper, conference review, data paper, editorial, erratum, letter, multimedia, note, press release, report, retracted, review or short survey that were written only in English. We took into account all types of sources, book, book series, conference proceeding, journal, multi-volume reference works, newsletter, press release, report, and trade journal.

It is also mentioned that utilising the quotation marks (“”) is essential to discover the exact phrases and to eschew lemmatization and synonym features of Scopus [20]. All the documents were filtered via article title, abstract and keywords to minimise duplication and undefined documents (without author’s name). For data consistency, data from May 2021 onwards were not taken into account in this study.

2.2 Search Approaches for the Selection

The first search string used to analyse includes the keyword of “sustainable manufacturing (henceforth called as Sus-Man)”, which resulted in a total of 1954 documents. The applied query was as follows: (TITLE-ABS (“sustainable manufacturing”)) AND PUBYEAR < 2021 OR PUBDATETXT ((“January 2021” OR “February 2021” OR “march 2021” OR “April 2021” OR “May 2021”)) AND (EXCLUDE (PUBYEAR, 2022)) AND (LIMIT-TO (LANGUAGE, “English”)). Then, the search

string proceeds with the same course by replacing the term of "sustainable production" (henceforth called as Sus-Pro), resulting in a large number of 6392 documents from the Scopus database.

Next, the second part involves a combination of above search strings in an in-depth analysis, but it was limited to only journal and article types; however, the most common study designs for word search "sustainable production" OR "sustainable manufacturing" (henceforth called as Sus-Man/Pro) were journal articles (n = 4802, 58%). The query used was: (TITLE-ABS ("sustainable production" OR "sustainable manufacturing")) AND (LIMIT-TO (SRCTYPE, "j")) AND (LIMIT-TO (DOCTYPE, "ar")) AND PUBYEAR < 2021 OR PUBDATETXT (("January 2021" OR "February 2021" OR "march 2021" OR "April 2021" OR "May 2021")) AND (EXCLUDE (PUBYEAR, 2022)) AND (LIMIT-TO (LANGUAGE, "English")).

3 Results and Discussion

This section is completed through the procedure with the adopted methods according to the research objectives, as presented in Sect. 1.1. It discusses the detailed analyses and findings on each objective in an orderly manner in the ensuing segments.

3.1 Past and Present Progress of Research Interest

This segment presents the emerging trends in "sustainable production (Sus-Pro)" and "sustainable manufacturing (Sus-Man)" to provide a general outline of documents according to the author's keywords. As shown in Fig. 1, throughout the past forty-two years from 1979 to 2021, the research interest in Sus-Pro has acquired growing attention. An analysis of the temporal trend of the number of publications for Sus-Man was also performed. Interestingly, the keyword of Sus-Man is very common in Malaysia, which is ranked 11th among core contributing countries (outlined in Sect. 3.2). As a case in point, this term is commonly used by four prominent engineering/technology-based universities, which were found among the top fifteen contributors to the topic (explained in Sect. 3.4)—Universiti Teknikal Malaysia, Universiti Teknologi Malaysia, Universiti Tun Hussein Onn Malaysia, and Universiti Utara. However, the term 'sustainable manufacturing' was first reported after 13 years of publishing the oldest article, entitled "Markets for Alaskan oil", which had been aimed at developing the USA's economic, environmental, and national security goals [27].

The results show the research on this sustainable paradigm has considerably progressed, in particular, in the new millennium. A remarkable number of 857 documents were published on Sus-Pro in 2020 alone compared to 256 documents for Sus-Man (Fig. 1). The analyses indicate that the combination of publications on both Sus-Man and Sus-Pro (i.e., Sus-Man/Pro) were continuously increased every year

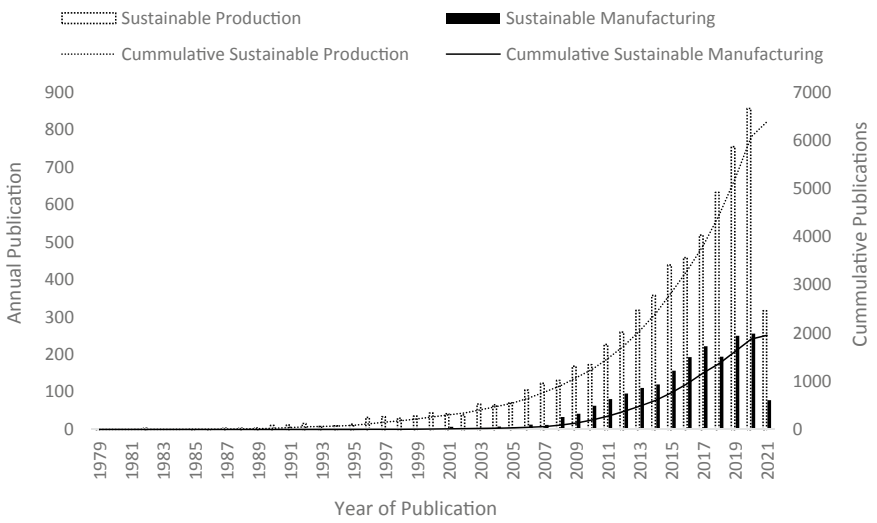

Fig. 1 Trend in publications over the years. Note: (i) Including all document type: article, abstract report, book, book chapter, business article, conference paper, conference review, data paper, editorial, erratum, letter, multimedia, note, press release, report, retracted, review paper, or short survey; (ii) Including all source type: book, book series, conference proceeding, journal, multi-volume reference works, newsletter, newspaper, press release, report, trade journal; (iii) 1954 documents on Sus-Man: (TITLE-ABS ("sustainable manufacturing")) AND PUBYEAR < 2021 OR PUBDATETXT (("January 2021" OR "February 2021" OR "march 2021" OR "April 2021" OR "may 2021")) AND (EXCLUDE (PUBYEAR, 2022)) AND (LIMIT-TO (LANGUAGE, "English")); (iv) 6392 documents on Sus-Pro: (TITLE-ABS ("sustainable production")) AND PUBYEAR < 2021 OR PUBDATETXT (("January 2021" OR "February 2021" OR "march 2021" OR "April 2021" OR "May 2021")) AND (EXCLUDE (PUBYEAR, 2022)) AND (LIMIT-TO (LANGUAGE, "English"))

since 2006, accordingly there was a dramatic growth in the cumulative total published documents hitherto. It is expected to continue to rise due to the unique intellectual contributor of Sus-Man/Pro to 'our common future'; however, it is unanimously accepted, after the Earth Summit [4], that being sustainable is more beneficial [17].

3.2 Core Contributing Countries

A total of 4802 journal articles published between 1979 and 2021on Sus-Man/Pro is dominated by developed and emerging countries. United States, China, India, the United Kingdom and Germany are the top five countries, respectively, as shown in Table 1. In terms of publication output, there is a huge gap between the top five countries identified. The United States tops the list with the publication of more than 800 research papers on the topic, followed by the United Kingdom and Germany at 4th and 5th places among developed countries, publishing less than 400 papers for the

Table 1 Country-wise growth of publications on sustainable manufacturing/production

Country	No. of articles[a]	National context
1. United States	817	Developed country
2. China	677	Emerging/developing country
3. India	470	Emerging/developing country
4. United Kingdom	341	Developed country
5. Germany	335	Developed country
6. Italy	291	Developed country
7. Brazil	231	Emerging/developing country
8. Netherlands	188	Developed country
9. Spain	181	Developed country
10. Australia	180	Developed country
11. Malaysia	172	Developing country

[a]Out of 4802 articles (document type) from journal (source type)

same time period. This is less than two times of the United States publication outputs, generally drawing attention to the environmentally harmful effects of manufacturing.

Nevertheless, it is interesting to look at the growth of publications on this area from the perspective of a developing country. Malaysia is the only developing country producing research outputs on Sus-Man/Pro after the top ten countries with 172 publications (Table 1). It is adjacent to Australia with less than 8 publications to be listed in the top ten based on its research outputs over the past years.

After conducting and merging the country profile and bibliometrics, the co-authorship analysis of countries provided 174 results. As such, we applied a threshold of a minimum of one document published per country and excluded any articles that co-authored more than 25 countries. A predetermined screening criterion was also used to screen and verify the list of countries. Unrelated terms such as "email", "university", etc. were discarded. Finally, a total of 139 countries were selected (Fig. 2).

As illustrated in Fig. 2, United States is the first core contributing country among others in all the parameters—total link strength (586), links (92), and documents (817, avg. pub. year: *ca.* 2014). The analyses also revealed that the most and recent co-author network is between United States and China. Based on the minimum link strength between countries, the first five countries, which had high collaborations with researchers from United States, are China, India, United Kingdom, Germany, and Australia. Meanwhile, the most co-author network for Malaysia was their regional neighbour, i.e., Indonesia. It is then followed by United Kingdom, Pakistan, and China.

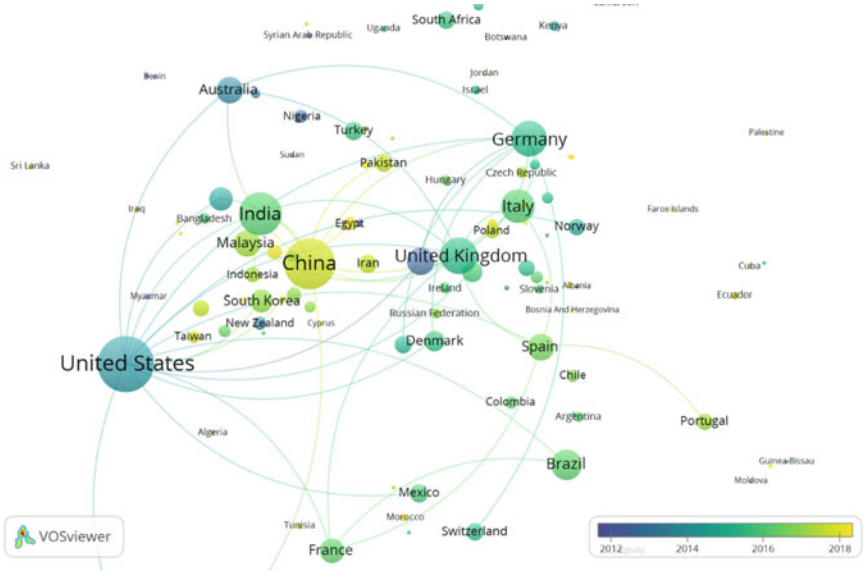

Fig. 2 Co-authorship network map of countries publishing on sustainable manufacturing/production

3.3 Core Contributing Journals

The findings indicate that 4802 articles are owned by 160 journals. The top 10 journals, with a share of 758 number of publications, are presented in Table 2. It is noticeable that six journals were from the United Kingdom and developing countries had none. The "*Journal of Cleaner Production*" published the maximum number of research articles on the understudied area, followed by the "*Sustainability"* and "*ACS Sustainable Chemistry and Engineering*".

Overall, 40% of the total research articles from the top 10 journals were published in the "*Journal of Cleaner Production*" (CiteScore 13.1), which remarkably includes the most cited article—[28]—among others (Table 2). The publication of research papers on this topic in these high-impact journals signifies the scientific community's growing interest and acknowledgement on the subject.

3.4 Core Contributing Academic Institutions

Research institutes from China has dominated the publications on research topic; Chinese Academy of Sciences (n = 89) and Ministry of Education China (n = 83). Starting with only 2 publications in 2012, Chinese Academy of Sciences had an incredible 89 published papers recently. With 172 publications in all, the Chinese

Table 2 Top 10 journals publishing research on sustainable manufacturing/production

Source title	Country	Publisher	Scopus Cite Score 2020	No. of articles[a]	Most cited article (times cited)
1. Journal of Cleaner Production	United Kingdom	Elsevier Ltd	13.1	305	[28] (503)
2. Sustainability	Switzerland	MDPI AG	3.9	155	[29] (131)
3. ACS Sustainable Chemistry and Engineering	United States	American Chemical Society	12.0	65	[30] (38)
4. Green Chemistry	United Kingdom	Royal Society of Chemistry	15.2	47	[31] (368)
5. International Journal of Advanced Manufacturing Technology	United Kingdom	Springer London	5.6	43	[32] (178)
6. International Journal of Production Research	United Kingdom	Taylor and Francis Ltd	10.8	33	[33] (84)
7. Bioresource Technology	United Kingdom	Elsevier Ltd	14.8	29	[34] (180)
8. Plos One	United States	Public Library of Science	5.3	28	[35] (218)
9. Procedia Manufacturing	Netherlands	Elsevier BV	13.1	28	[36] (65)
10. Biotechnology for Biofuels	United Kingdom	BioMed Central Ltd	9.9	25	[37] (93)

[a]Out of 4802 articles (document type) from journal (source type)

country is well ahead of other countries—see Table 3. About 55% of the publications from the top 10 research institutes come from emerging and developing countries, with more than 280 affiliated-published papers (Table 3). The continuously increasing publications from such countries is a clear sign that this field of research will only continue to grow in the near future.

Table 3 Top 10 research institutes working on sustainable manufacturing/production

Affiliation	Country	National context	No. of articles[a]
1. Chinese Academy of Sciences	China	Emerging/developing country	89
2. Ministry of Education China	China	Emerging/developing country	83
3. Wageningen University & Research	Netherlands	Developed country	78
4. USDA Agricultural Research Service	United States	Developed country	44
5. Universidade de Sao Paulo	Brazil	Emerging/developing country	44
6. United States Department of Agriculture	United States	Developed country	40
7. Empresa Brasileira de Pesquisa Agropecuária—Embrapa	Brazil	Emerging/developing country	35
8. Danmarks Tekniske Universitet	Denmark	Developed country	34
9. UNESP-Universidade Estadual Paulista	Brazil	Emerging/developing country	32
10. CNRS Centre National de la Recherche Scientifique	France	Developed country	32

[a]Out of 4802 articles (document type) from journal (source type)

3.5 Core Contributing Authors

Sekar Vinodh published a large number of articles on the topic with 18 research papers consistently every year since 2012, followed by two scientists, namely Fazleena Badurdeen and Norsiah Hami (Table 4). Interestingly, Norsiah Hami is the only scientist from developing country who was listed among the top three authors.

3.6 Common Terminology, Research Topics and In-Depth Insights

The investigation reveals that Sus-Man and Sus-Pro have been often applied interchangeably in the subject area of Engineering and Technology; however, there is also an inherent difference between them—'sustainable production' is a broader term that can be used in all subject areas. As shown in Fig. 3, 1034 out of 1954 documents were remarkably published on Sus-Man in the Engineering and Technology area

Table 4 Top 10 authors publishing on sustainable manufacturing/production

Author name	Institutions	Country	No. of articles[a]	Most cited article (times cited)
1. Vinodh, Sekar	National Institute of Technology Tiruchirappalli, India	India	18	[38] (64)
2. Badurdeen, Fazleena	University of Kentucky	United States	12	[8] (550)
3. Hami, Norsiah	Universiti Utara Malaysia	Malaysia	12	[39] (9)
4. Xu, Boqing	Tsinghua University	China	11	[40] (316)
5. Liang, Yu	Tsinghua University	China	10	[40] (316)
6. Gao, Liang	Huazhong University of Science and Technology	China	9	[41] (149)
7. Li, Lin	University of Illinois at Chicago	United States	9	[42] (147)
8. Pham, Duc Truong	University of Birmingham	United Kingdom	9	[43] (60)
9. Ocampo, Lanndon A	Cebu Technological University	Philippines	9	[44] (20)
10. Haapala, Karl R	Oregon State University	United States	8	[45] (73)

[a]Out of 4802 articles (document type) from journal (source type)

compared to 870 (out of 6392) documents for Sus-Pro, suggesting that 'sustainable manufacturing' is the most common term for such a subject area.

The co-occurrence analysis of keywords was accordingly performed for Sus-Man/Pro on a total of 4802 publications in 160 journals. A threshold of a minimum number of keywords occurrences equal to 5 was set. The analysis of Sus-Man/Pro resulted in 492 keywords out of a total of 13,466. Figure 4 displays the overlay visualization which is coloured differently based on the average publications' year. The overlay visualization ranges from white (old article) to dark purple (contemporary article). The dominant keywords based on total link strength were "sustainability" (612 total link strength), "sustainable manufacturing" (366), "sustainable development" (125) and "sustainable production" (118), respectively.

The analyses indicated that the links, total link strength, and occurrence for Sus-Man is ranked higher than Sus-Pro. Link is a connection or relation between two items (e.g., co-occurrence of keywords) while the total link strength is a weight

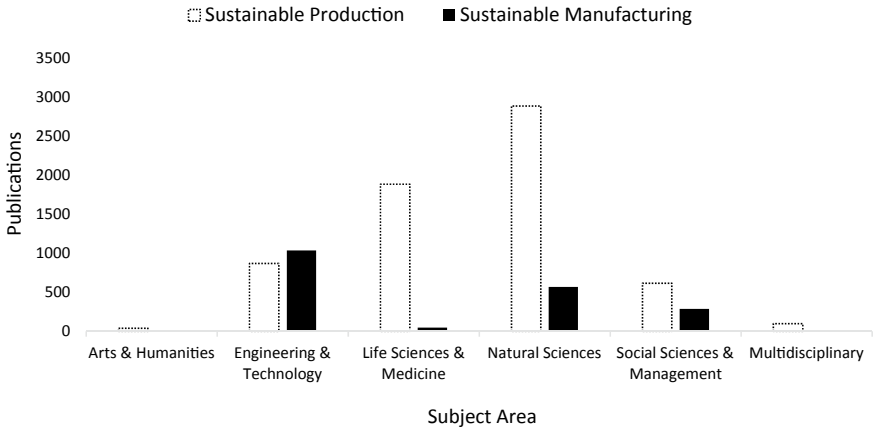

Fig. 3 Publications over the subject area

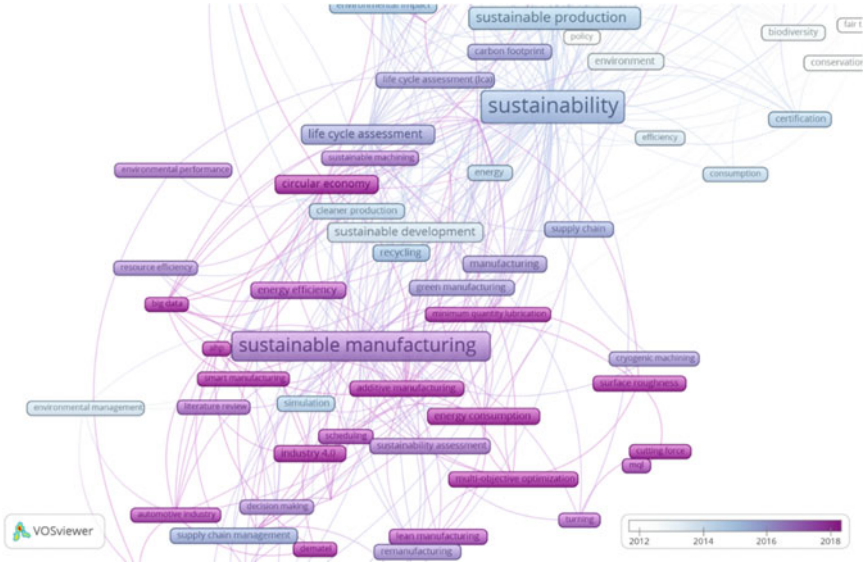

Fig. 4 Co-occurance network map of keywords from articles published on sustainable manufacturing/production

attribute to determine the cumulative strength of the links of an item with other items [24]. This could be explained by the fact that, the links and total link strength for Sus-Man are higher than Sus-Pro since it is a recent fascinated topic and thus more strongly connected to other emerging keywords such as 'Circular Economy' (total link strength: 72, avg. pub. year: 2018.9). The link between circular economy and sustainable manufacturing was well-argued by [13], who explained that circular

economy can be operationalised in manufacturing through applying the 6Rs—Reduce, Reuse, Recycle, Recover, Redesign and Remanufacture. Other connected emerging keyword include 'Industry 4.0' (total link strength: 48, avg. pub. year: 2019.4).

Table 5 lists the 10 most influential articles on Sus-Man, which were ranked using Scopus in terms of the highest citation. The article by [8] received the highest citation count of 550, providing the all-inclusive overview of the concept by exemplifying the dry, near-dry and cryogenic machining. It is preceded by [46] with 436 citations, who concluded that the initiation of a new technology may modify the description of "what is sustainable". Noticeably, there is a paper in the list of the 10 most influential articles with 213 citations—[47]—which was very recently reported, among others, on a fundamental query about "can industry 4.0 revolutionise the environmentally-sustainable manufacturing wave?"

These global research trends depict a growing need for sustainable manufacturing development to sustainably address challenges and issues related to ecosystem destruction and numerous other unsustainable paradigms. There were many significant efforts as such; however, the development is generally traced by compartmentalising the manufacturing's integral elements—product, process, and system (Fig. 5). This may be due to sustainable manufacturing is a complex systems problem [13], and which it is being relied highly on the analytical approaches that make learning and development through the reductionism thinking and mechanism interpretation.

Figure 5 manifests a visual representation of elements, where the union is created by overlapping products (value design), processes (value creation), and systems (value recovery) based on the 6R methodology to fulfil the TBL requirements [1]. The colour gold was employed to denote sustainable development, thereby ensuring that SD is the Golden Pathway to manufacturing sustainability. Therefore, new technologies together with other critical success factors [46, 47] and mental models, on which the manufacturing encompasses interrelated elements, with interconnected processes, units, norms, values, behaviours, individuals and groups, which are influencing and being influenced by one another, are requested to sustainable manufacturing development [17].

4 Conclusion

This article presents an analysis of the research trends in sustainable manufacturing area using a bibliometric analysis in the Scopus database, which is prominently considered as the major indexer of global scientific content. The data for the study was extracted until May 2021 based on the descriptive data of publication outputs and resulted in retrieving a total of 4802 journal articles reported between 1979 and 2021. The bibliometric method contributed to provide the structures and development in the sustainable manufacturing area so that the scientific community could penetrate the existing hierarchy of the publication in the context. The analyses revealed that publication growth was swift; the published documents were continuously increased

Table 5 10 most influential articles on sustainable manufacturing.

Rank	Authors (Year)	Title	Source title	Times cited
1	Jayal et al. [8]	Sustainable manufacturing: modeling and optimization challenges at the product, process and system levels	CIRP Journal of Manufacturing Science and Technology	550
2	Garetti and Taisch [46]	Sustainable manufacturing: trends and research challenges	Production Planning and Control	436
3	Jovane et al. [48]	The incoming global technological and industrial revolution towards competitive sustainable manufacturing	CIRP Annals—Manufacturing Technology	282
4	Joung et al. [49]	Categorization of indicators for sustainable manufacturing	Ecological Indicators	279
5	Sarkis [50]	Manufacturing's role in corporate environmental sustainability—concerns for the new millennium	International Journal of Operations and Production Management	276
6	Rusinko [51]	Green manufacturing: an evaluation of environmentally-sustainable manufacturing practices and their impact on competitive outcomes	IEEE Transactions on Engineering Management	243
7	Yan and Li [52]	Multi-objective optimization of milling parameters—the trade-offs between energy, production rate and cutting quality	Journal of Cleaner Production	229
8	Ijomah et al. [53]	Development of design for remanufacturing guidelines to support sustainable manufacturing	Robotics and Computer-Integrated Manufacturing	214
9	Jabbour et al. [47]	When titans meet—can industry 4.0 revolutionise the environmentally-sustainable manufacturing wave? The role of critical success factors	Technological Forecasting and Social Change	213
10	Faulkner and Badurdeen [9]	Sustainable Value Stream Mapping (Sus-VSM): methodology to visualize and assess manufacturing sustainability performance	Journal of Cleaner Production	209

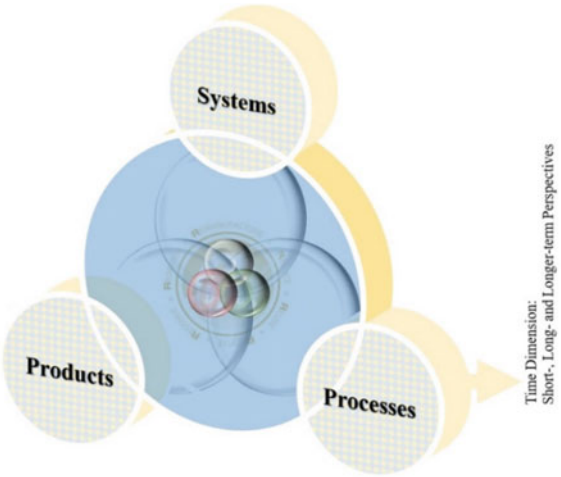

Fig. 5 Integral elements of sustainable manufacturing, from a general perspective to fully integrated perspective

every year since 2006. Core contributing countries, journals, academic institutions, and authors were also discovered. The United States and China are the countries in the top two, respectively, with an enormous number of publications and great collaboration networks. It may give an opportunity to investigators from other academic institutions and countries to widen their research collaborations. Furthermore, this study discussed some new areas considered for sustainable manufacturing which would be potential top topics for future research.

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