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REVIEW PAPER

Research Trends in Sustainable Manufacturing: A Review and Future Perspective based on Research Databases

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Abstract

Sustainable manufacturing has become of great importance in various fields include manufacturing, mechanical engineering, materials science, environmental science, and energy science. In this paper, we analyzed and reviewed the research trends of sustainable manufacturing technologies and suggested future perspective. Specifically, the state-of-the-art and historical trajectory of sustainable manufacturing are analyzed using data obtained from the Web of Science library and the Journal Citation Reports (JCR). Selected journals and research categories are evaluated by the number of publications, the number of citations, impact factor (IF), and H-indices. To suggest future perspectives on sustainable manufacturing research, growth rate of each research objects are evaluated and historically followed. Sustainable manufacturing is likely to be change in its nature in the era of digital transformation. It is expected to provide the status and future of research trends of sustainable manufacturing to the both manufacturing researchers and journal publishers.

Keywords Sustainable manufacturing · Green manufacturing · Research database · Impact factor · H-index

1 Introduction

A growing number of researchers are focusing "sustainability" as an important objective in the field of manufacturing and engineering [1–5]. This trend has reached well beyond the small niche of those who traditionally focused on "green", and now resulted many prominent researches. Hence, sustainable manufacturing has become not only environmentally or eco-friendly manufacturing but also considers socially responsible manner in a broad sense [6]. Today, topics and keywords of sustainable manufacturing have expanded includes environmental impact, personnel health, operational safety, waste management, energy consumption, and manufacturing cost.

In definition, sustainable manufacturing is the creation of manufactured products through economical processes that minimize negative environmental impacts while conserving energy and resources [7]. 21st century manufacturing under the condition of environmental shift and deficiency of energy and resources accelerates the growth of sustainable manufacturing [8]. Following the trends to sustainable manufacturing, researchers make efforts to develop technologies for new paradigm of manufacturing [9–21].

Academia is one of the areas where the interest in sustainable manufacturing is growing explosively. Figure 1 shows the increasing number of journal publications which is the most significant indicator in academia in the field of sustainable manufacturing by time from 2008 to 2017. Totally, 341 journal papers in 2008 increased more than 5 times and reached to 1722 journal papers in 2017. Moreover, there was not even a single year of decline in journal paper publications from 2008 to 2017. In view of explosive growth of journal papers to date, interest in sustainable manufacturing in academia is likely to continue to increase.

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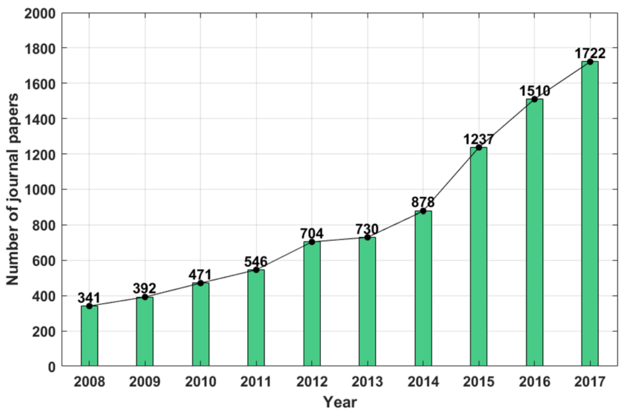

Fig. 1 The number of journal publications with the keyword '(sustain* OR green) AND manufacturing' between 2008 and 2017. Data were obtained from the Web of Science on May 2018

One of the major reasons for high growth rate of interest in sustainable manufacturing is legislation initiatives as previous work [22–25]. United Nations (UN)'s sustainable development agenda called the Sustainable Development Goals (SDGs) [26], and Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC) from 21st session of the Conference of the Parties to United Nations Convention (COP21) are representative example of legislation [27]. They have commons into oppose environmentally destroyable methods of manufacturing, encourage participation of both parties and non-parties include developing countries, and suggest specific action plan.

However, several legislative actions are not only reason for efforts toward sustainable manufacturing [7, 28]. Economically speaking, high growth rate of interest in sustainable manufacturing is a natural result. The incremental increase of productivity is not able to follow the rapidly improving standard of quality of living in developing countries. Furthermore, digital transformation reinforces the importance of how to supply raw materials and energy to manufacture and operate largely increased demands on products and energy which intensify the importance of sustainable manufacturing. Therefore, sustainable manufacturing is now as an irreversible global trend in the field of manufacturing and engineering. According to United States Environmental Protection Agency, growing number of companies are treating sustainability as an importance objective in their strategy and operations to increase growth and global competitiveness [29]. It also defined 5 reasons why companies are pursuing sustainability.

- Increase operational efficiency by reducing costs and waste.
- Reach new customers and increase competitive advantage.
- Strengthen brand and reputation and build public trust.
- Build long-term business viability and success.
- Respond to regulatory constraints and opportunities.

Likewise, the industry is seeing a proliferation of sustainable manufacturing, which is due to a much more diverse and complex reason than existing reasons. Companies move forward along the path to sustainability by improving performance and reducing their resource.

This review concludes with an evaluation of research trends in sustainable manufacturing area based on research databases. We investigate historical trajectory and state-of-the-art sustainable manufacturing technologies published in recent 5 years [30]. Research databases obtained from the Web of Science library [31] and the Journal Citation Reports (JCR) [32] were used for analysis. H-index, impact factor (IF), number of citation, and number of published articles were used as evaluation method for importance of each subject. Finally, it is expected that the review will contribute to discussions on the future perspective of sustainable manufacturing technologies.

2 Analysis of Sustainable Manufacturing Research Trends

Research papers and articles in the area of sustainable manufacturing and its applications were analyzed. As publishing trends can provide milestones for future perspectives in terms of academic researchers, various factors of the publications were reviewed include nations, journals, articles, and keyword with individual journals also being reviewed. Data from 2010 to 2017 was analyzed for longitudinal study of research trends of sustainable manufacturing by time series.

There are several indicators for evaluation of academic results, the number of published articles, number of citations, IF and the H-index were used as evaluation parameters in this work similar to that of a previous work [23]. In general, the number of published articles was assumed to correlate with the importance of the journal and research subject, and the numbers of citations was assumed to correlate with the attention received from other researches.

IF is a measure reflecting the yearly average number of citations to recent articles published in that journal. Herein, IF was used as an important indicator for evaluation of performance of journal. Lastly, H-index is used for evaluation of categories in sustainable manufacturing. It is also a widely used indicator to evaluate individual scholars or research category to evaluate both productivity and the impact of a body of work.

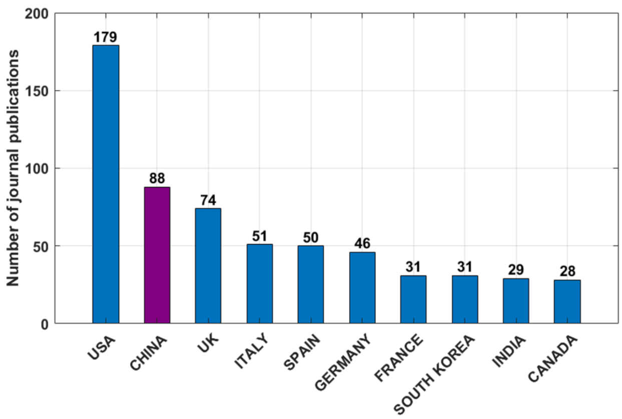

Fig. 2 The 10 countries that published the most articles on sustainable manufacturing in 2013. Data were obtained from the Web of Science on May 2018

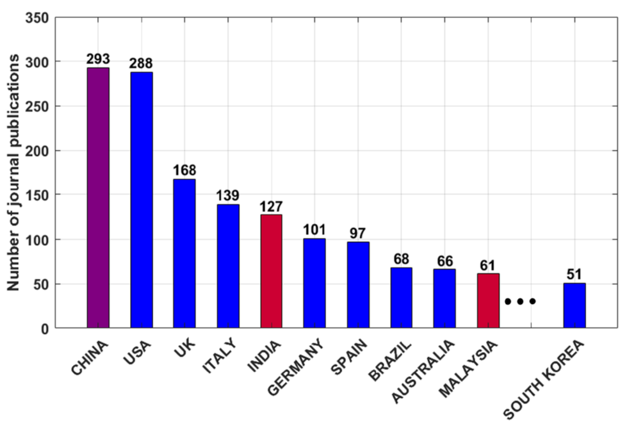

Fig. 3 The 10 countries that published the most articles on sustainable manufacturing in 2017. Data were obtained from the Web of Science on May 2018

Figure 2 and Fig. 3 show the 10 countries that have published the most journal articles related to sustainable manufacturing in 2013 and 2017 respectively. Hence, they represent global trend at that time but also historical trajectory of sustainable manufacturing. The most journal publications were from the United States and China, followed by the United Kingdom, Italy, Spain, etc., in 2013. However, China exceeds the United States in the number of journal publications and took first place in 2017. It is a remarkable achievement of China considering the difference of more than double in 2013. In addition, the prominence of Asian countries was also remarkable. Specifically, India, ranked ninth in 2013, ranked fifth in 2017 and Malaysia, which was out of the ranking in 2013, ranked tenth.

Table 1 shows top 6 journals in the field of sustainable manufacturing. At first, we selected all journals in 'Green & Sustainable Science & Technology' journal category. However, these journals also covered the topic which is not directly related to sustainable manufacturing include 'Chemistry, Multidisciplinary', and 'Argonomy'. Hence, we excluded above categories and limited them in the 'Energy & Fuels', 'Engineering, Environmental' and 'Engineering, Manufacturing', which are representative categories of journal related to sustainable manufacturing. Top ranked journal was "Renewable & Sustainable Energy Reviews" with IF of 9.184 in 2017. "International Journal of Precision Engineering and Manufacturing-Green Technology" ranked sixth with IF of 3.774 in 2017.

As Table 1 indicated only the current status of various research journals, historical changes in selected research journals are discussed in Figs. 4 and 5. As interest of sustainable manufacturing increases, most of journals except few show continuous increase in both of citation number and IF. Specifically, "IEEE Transactions on Sustainable Energy" shows highest growth rate of citation numbers, while "Renewable & Sustainble Energy Reviews" shows the highest growth rate of IF. It also ranked first in the citation numbers like in terms of IF. "International Journal of Precision Engineering and Manufacturing-Green

Table 1 Top 6 journals covered 'Energy & Fuels', 'Engineering, Environmental', and 'Engineering, Mechanical' in 'Green & Sustainable Science & Technology' in Journal Citation Report (JCR) journal category in 2017

Rank	Title	IF	Category
1	Renwable & Sustainable Energy Reviews	9.184	Energy & Fuels
2	IEEE Transactions on Sustainable Energy	6.235	Energy & Fuels Engineering, Electrical & Electronic
3	Journal Of Cleaner Production	5.651	Engineering, Environmental Environmental Sciences
4	Renewable Energy	4.900	Energy & Fuels
5	International Journal of Greenhouse Gas Control	4.078	Energy & Fuels Engineering, Environmental
6	International Journal of Precision Engineering and Manufacturing-Green Technology	3.774	Engineering, Manufacturing Engineering, Mechanical

Data were obtained from JCR on May 2018

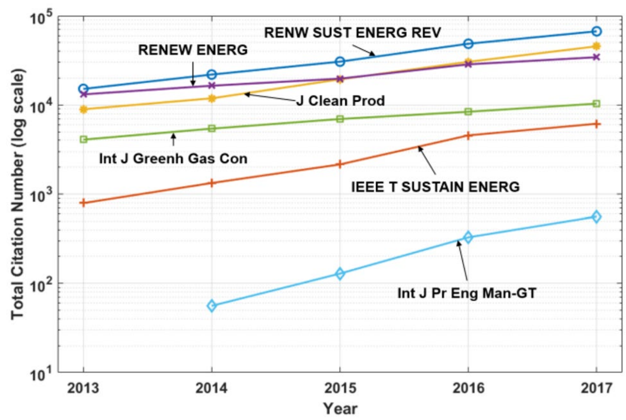

Fig. 4 The citation numbers of top 6 journals covered 'Energy & Fuels', 'Engineering, Environmental', and 'Engineering, Mechanical' in 'Green & Sustainable Science & Technology' in Journal Citation Report (JCR) journal category between 2013 and 2017. Data were obtained from JCR on May 2018

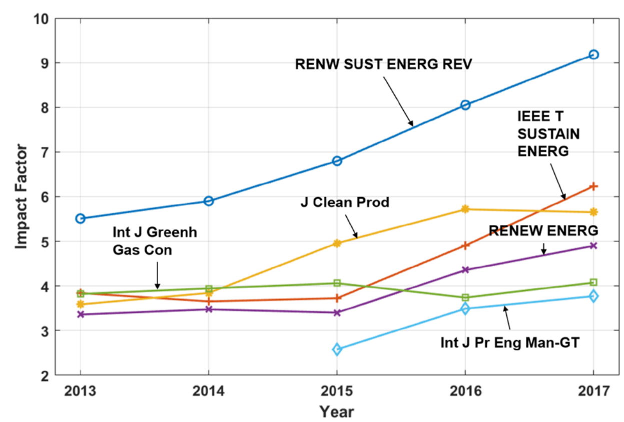

Fig. 5 The impact factor of top 6 journals covered 'Energy & Fuels', 'Engineering, Environmental', and 'Engineering, Mechanical' in 'Green & Sustainable Science & Technology' in Journal Citation Report (JCR) journal category between 2013 and 2017. Data were obtained from JCR on May 2018

Technology" also shows high growth rate in both citation numbers and impact factor.

Table 2 shows 10 most-cited articles in 2013–2014. We found articles that had keyword with 'sustain manufacturing' or 'green manufacturing' and refined them in category of engineering and manufacturing. Most of the articles were reviews. Articles form Samuel H. Huang et al., in 2013, "Additive manufacturing and its societal impact: A literature review" has the highest citation members of 238. International journal of production economics published 4 top cited papers in top 10 cited articles.

Four of top 10 cited papers have keywords of "additive manufacturing" in title. Also, most of cited papers are focusing on advanced manufacturing technologies including 3D printing which is one kind of additive manufacturing. By this time, researchers focused on advanced manufacturing process technology which can save energy or raw materials to reduce energy and resources consumption. In other words, sustainable manufacturing in 2013–2014 was primarily concerned with hardware innovation.

Table 3 shows 10 most-cited articles in 2016–2017. All the evaluation methods and data obtaining sources were identical from what we had for Table 2. Hence, we can discuss the research trends of sustainable manufacturing in terms of keywords. Big data analytics, supply chain management, and decision making algorithm are newly-emerging keywords for sustainable manufacturing in 2016–2017.

With the advent of Industry 4.0, sustainable manufacturing has been also changing [52, 53]. Conventionally, sustainable manufacturing was primarily limited to hardware and manufacturing process, it is now focusing on software innovation. The biggest changes in topic and keyword in sustainable manufacturing are the utilization of data and algorithm in sustainable manufacturing. The representative applications of data and algorithm in sustainable manufacturing are process understanding and optimization of resource usage. First, data measured by several sensors help understanding process itself and total supply chain which includes single process. Moreover, these understanding derive the environmental impact of operations systematically. The result obtained by process understanding is used as a basis for optimization of resource usage. This information previously dispersed across different formats is trying to make out the end-to-end impact of their operations throughout the value chain.

Overall, we showed that the attraction for sustainable manufacturing is increasing. Also, it is verified by increasing numbers of journal publications in sustainable manufacturing. However, the trends of sustainable manufacturing are gradually changing in detail such as most published counties and citation numbers and impact factor of journals. Furthermore, the topics and keywords that are mainly discussed in sustainable manufacturing are also changing.

According to review and analysis of research trends of sustainable manufacturing, we discussed on future perspectives of sustainable manufacturing in next section based on research databases. Moreover, specific technologies were selected and categorized from the perspective of manufacturing engineers.

3 Future Perspectives of Sustainable Manufacturing Research Trends

As discussed in the previous chapters, sustainable manufacturing are getting attention worldwide. The concerns on sustainable manufacturing were also reflected in journal citation

Table 2 The 10 most-cited articles with keyword '(sustain* OR green) AND manufacturing' published in 2013–2014

Title	Journal	Citations
Additive manufacturing and its societal impact: A literature review [33]	Int J Adv Manuf Technol	238
Barriers analysis for green supply chain management implementation in Indian industries using analytic hierarchy process [34]	Int J Prod Econ	145
Product variety management [35]	CIRP Ann Manuf Technol	134
Additive manufacturing: A framework for implementation [36]	Int J Prod Econ	109
Hybrid flow shop scheduling considering machine electricity consumption cost [37]	Int J Prod Econ	93
A review of engineering research in sustainable manufacturing [9]	J Manuf Sci E-T ASME	75
A new approach to the design and optimisation of support structures in additive manufacturing [38]	Int J Adv Manuf Technol	70
Green supply chain performance measurement using fuzzy anp-based balanced scorecard: A collaborative decision-making approach [39]	Prod Plan Control	66
Turning sustainability into action: explaining firms' sustainability efforts and their impact on firm performance [40]	Int J Prod Econ	64
A comparison of energy consumption in bulk forming, subtractive, and additive processes: review and case study [41]	Int J Precis Eng Manuf-Green Tech	63

Data were obtained from Web of Science on August 2018

Table 3 The 10 most-cited articles with keyword '(sustain* OR green) AND manufacturing' published in 2016–2017

Title	Journal	Citations
Big data analytics in logistics and supply chain management: certain investigations for research and applications [42]	Int J Prod Econ	72
The evolution and future of manufacturing: A review [43]	J Manuf Syst	59
The impact of big data on world-class sustainable manufacturing [44]	Int J Adv Manuf Technol	33
An integrated DEMATEL-ANP approach for renewable energy resources selection in Turkey [45]	Int J Prod Econ	22
Sustainable supply chain management in emerging economies: Trade-offs between environmental and cost performance [46]	Int J Prod Econ	22
Direct Metal Additive Manufacturing Processes and Their Sustainable Applications for Green Technology: A Review [47]	Int J Precis Eng Manuf-Green Tech	22
A hybrid group leader algorithm for green material selection with energy consideration in product design [48]	CIRP Ann Manuf Technol	22
Carbon emissions and energy effects on a two-level manufacturer-retailer closed-loop supply chain model with remanufacturing subject to different coordination mechanisms [49]	Int J Prod Econ	21
The relationship between green supply chain management and performance: A meta-analysis of empirical evidences in Asian emerging economies [50]	Int J Prod Econ	19
Product recovery optimization in closed-loop supply chain to improve sustainability in manufacturing [51]	Int J Prod Res	19

Data were obtained from Web of Science on August 2018

report and web of science database. In the web of science, category of 'Green & Sustainable Science & Technology' was first created in 2015. In this section, trends related to sustainable manufacturing are analyzed with different categories to discuss the future perspectives. Representative categories of journal related to sustainable manufacturing were selected. They are 'Energy & Fuels', 'Engineering, Mechanical', 'Engineering, Environmental', 'Engineering, Manufacturing', 'Engineering, Industrial' and 'Green & Sustainable Science & Technology'. The trajectories of the total citation, number of articles and impact factor of these categories from 2013 to 2017 are analyzed and compared as shown in Fig. 6. Data of the 'Green & Sustainable Science & Technology' category is shown only for 3 years. All of the six categories related to sustainable manufacturing shows increase rate in both number of article and total citation. 'Energy & Fuels' shows the largest number of articles and total citation which means large number of researches are carried out with attentions.

Furthermore, 'Energy & Fuels' and 'Green & Sustainable Science & Technology' shows the highest impact factor. It means that energy and fuels are the main approach

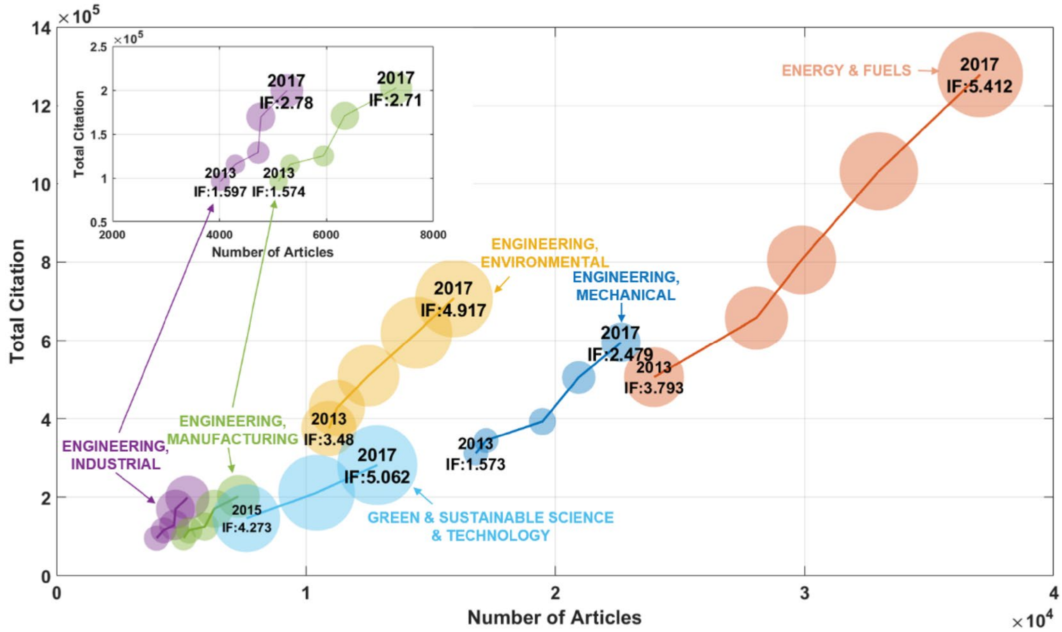

Fig. 6 Trajectories of total citation (y axis), number of articles (x axis), and impact factor (radius of circle) by time of six representative categories of journal related to sustainable manufacturing. Data were obtained from Web of Science and Journal Citation Report (JCR) on August 2018

to solve the manufacturing issue towards green technology. Also, 'Engineering, Industrial' and 'Engineering, Environmental' shows steepest increase rate. It is expected that the research on the area of industrial engineering and environmental engineering will get more attentions and impacts in near future.

In order to investigate changes of research areas in details, keywords related to sustainable manufacturing were selected. The current data and the previous data were compared. The data between 2010 and 2014 were obtained from the paper by Yoon et al. [23] published in 2016. Data between 2013 and 2017 were collected from the Web of Science on May 2018. Figure 7 shows the trend of the number of published articles and their H index.

Except for 'Biomaterials' which shows slight decrease, research area related to sustainable manufacturing shows increase rate in both number of journal articles and H-index. As described in the previous literature [30], they are all in the stage between early stage and developed state. In early stage, research related to the area starts by few researchers with little attention. In the emerging state, the number of researchers in the field increases and it begins to attract more attentions. Most of research area related to sustainable manufacturing seems additional increases will be followed.

Electrical discharge machining (EDM) technologies had been almost completed before 10 years ago [54, 55]. However, the results have not been opened because the main research groups are the major machine companies. Only main concepts of them were applied for patents. Therefore,

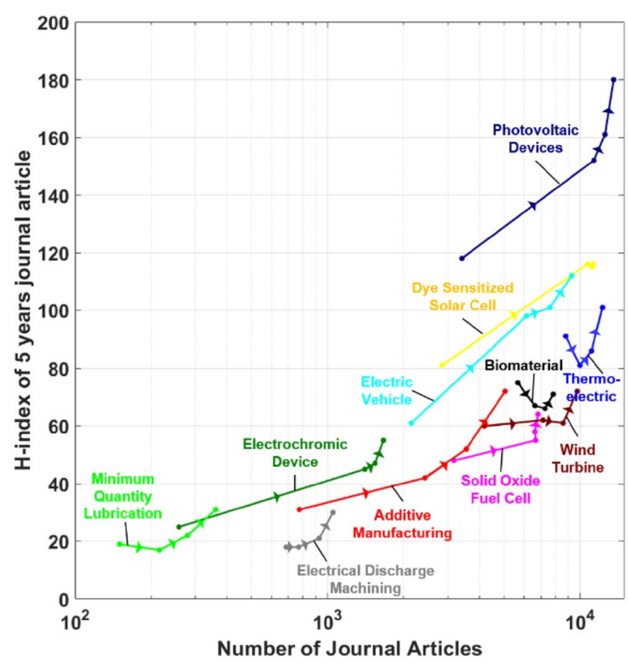

Fig. 7 H-index trajectory of the keywords related to sustainable manufacturing between 2010–2014, 2011–2015, 2012–2016 and 2013–2017. Data were obtained from Web of Science on May 2018

the general research topics are applications for advanced materials and investigations of the optimal machining conditions. As a results of the current EDM studies, their

H-indices have been increased but the number of articles have been decreased.

In Fig. 8, increase rates are compared. It is supposed that the change rate of H index is more important factor than that of total number of published paper to analyze the influence on the society. Additive manufacturing, electrochromic devices, minimum quantity lubrication (MQL), electric vehicle and EDM are the most influential research areas in sustainable manufacturing.

In the cutting process, most of lubricants have been carbide-based oil or water soluble chemicals [56–58]. The reasons why MQL stands out as an eco-friendly process are not only their low consumption of lubricants, but also usage of plant or ethanol-based liquid [59–61]. Following the research trends, we expected that of research trends of MQL and EDM are likely to show a similar pattern. Instead of development of advanced manufacturing process for MQL, applications to various materials using MQL are expected to occupy the majority.

Most important research area, which shows highest H-index change rate and increase rate of number of articles is additive manufacturing. Additive manufacturing gets a lot of attention in the recent 5 years to minimize the waste by using bottom up method [62–64]. Compared to top down methods where generation of waste is inevitable by cutting out the base material to get the desired features, bottom up methods could avoid the waste generation by print the materials as the desired feature shape [65–67]. As discussed in Sect. 2, even though the trend is leaning toward from hardware to software innovation recently, additive manufacturing is still in the developing stage and expected to grow in the next several years.

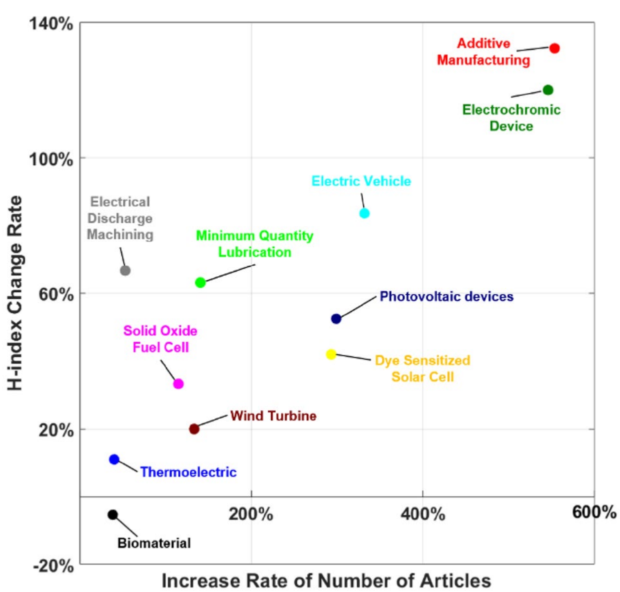

Fig. 8 H-index change rate trajectory of the keywords related to sustainable manufacturing between 2010–2014 and 2013–2017. Data were obtained from Web of Science on May 2018

Furthermore, electrochromic devices shows high increase rates. Electrochromic devices such as electrochromic windows on the building utilize the solar energy to reduce the energy loss [68–71]. Instead of fossil fuels, renewable energy such as photovoltaic, thermoelectric, wind turbine, etc. are widely studied and considered as a future energy sources without environmentally negative impact. The portion of renewable energy in manufacturing has increased and expected to increase more in the future.

Electric vehicles are also the keyword with both high H-index change rate and number of articles. The development of zero-emission vehicles has actively researched by academia and industry since the depletion of the fossil resources and the climatic change cause by carbon emissions are considered as urgent issues [72–74]. Hence, there are several efforts to reduce fuel consumption and emissions by the electrification of the automobile and the displacement of gasoline by alternative energy carriers. Consumer's interest in the environment, the efforts by car manufacturers, and government support will continue to develop the research of electric vehicles [75, 76].

Moreover, keywords of EDM and MQL shows high H-index increase rate. In the conventional manufacturing process, there are efforts to transform conventional machining to sustainable manufacturing process by reducing the energy and waste. For example, EDM increases the efficiency of the machining process and minimizes use of energy [77]. Also, MQL is studied to reduce the waste [78].

Based on research databases in the field of sustainable manufacturing, we identified three commonalities. First, sustainable manufacturing has been defined relatively accurately by focusing on several specific applications away from unclear and abstract concepts. This aspect is likely to continue by addressing sustainability in a coordinated and formal manner, rather than in an ad hoc and informal manner. Next, sustainable manufacturing is no longer a cost-saving measure but an essential tool for developing new core competencies. It is now producing environmentally friendly results through innovative processes, rather than the eco-friendly changes of existing processes. Finally, sustainable manufacturing requires a collaborative work with various researchers from a long term perspective. Recent research on sustainable manufacturing has largely been made up of a combination of multi-disciplines, and this aspect is likely to continue in the future.

4 Conclusions

In this review, researches pertaining to sustainable manufacturing were analyzed based on articles contained in research databases. Status quo and historical trajectory of sustainable manufacturing in recent was evaluated using the data obtained from the Web of Science library and JCR. To inform the discussion on future perspectives sustainable manufacturing, research journals and subject areas were evaluated using various methods include number of published articles, number of citations, IF and H-indices.

Researches on sustainable manufacturing in Asian countries have increased rapidly and begin to exceed conventionally countries with a well-established research infrastructure. In terms of journals, journal which had previously shown high impact factor and citation numbers, continued to dominate. Also, journal categories of sustainable manufacturing are showing an increasing trend while maintaining their rankings as a rule.

According to analysis, the research trends in sustainable manufacturing also follows the general trend in Industry 4.0. It seems that big data and their processing capabilities like decision making algorithm and deep learning will play an important role in the era of digital transformation also in the field of sustainable manufacturing. However, conventionally spotlighted topics include additive manufacturing and electrochromic devices likely to continue to strengthen.

Researches in the field of energy and fuels are the main approach to solve the limitation of manufacturing process and find the solution towards sustainable manufacturing process. Researchers are seeking ways for the environmentally friendly manufacturing process by using renewable energy or energy efficient and minimum waste generation processes. To this end, increasing number of research and attention are in the research area of additive manufacturing, electrochromic devices, electrical vehicle, MQL, etc.

This review provided insights into the current status of sustainable manufacturing, by suggesting evaluation methods and providing specific examples, and should also inform future perspectives. For the future, better evaluation methods include keyword analysis using artificial intelligence can provide a higher degree of understanding of the current status and future perspectives of the scientific research in the field of sustainable manufacturing researchers.

Beyond struggling with short-term survival, manufacturing should change their natures with environmental improvement and economically sustainable. To take important steps towards green growth which ensures future-oriented manufacturing, pioneering research manufacturing researchers is required.

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Compliance with Ethical Standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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