Vol. 25 No.1 (Januari 2024) 010-019
e-ISSN 2548-6101 p-ISSN 1411-318X

Jurnal Teknologi Lingkungan

Journal Homepage: ejournal.brin.go.id/JTL

How Important is the Life Cycle Assessment (LCA) Study of Plastic Waste? Use of Bibliometric Analysis to Reveal Research Positions and Future Directions

Seberapa Pentingkah Studi Penilaian Siklus Hidup (LCA) tentang Sampah Plastik? Penggunaan Analisis Bibliometrik untuk Mengungkap Posisi dan Arah Masa Depan dari Penelitiannya

ZULWELLY MURTI[1*], RIANA Y. H. SINAGA[1], MULYONO MULYONO[1], GEBY OTIVRIYANTI[1], SOEN STEVEN[1,2], MAYA L. D. WARDANI[1], NURUS S. LAILI[1], ANITA YUSTISIA[1], ERNIE S. A. SOEKOTJO[1], VIONITA LUKITARI[1], MUHAMMAD SUDIONO[1], ADIK A. SOEDARSONO[3], DIAN P. DEWANTI[4]

[1] Research Center For Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency (BRIN), KST BJ Habibie, South Tangerang, Banten 15314, Indonesia
[2] Biomass Technology Workshop, Faculty of Industrial Technology, Institut Teknologi Bandung, Sumedang 45363, Indonesia
[3] Research Center For Process and Manufacturing Industry Technology, National Research and Innovation Agency (BRIN), KST BJ Habibie, South Tangerang, Banten 15314, Indonesia
[4] Research Center for Environmental and Clean Technology, National Research and Innovation Agency (BRIN), KST BJ Habibie, South Tangerang, Banten 15314, Indonesia
* zulw001@brin.go.id

INFORMASI ARTIKEL

Histori artikel:
Diterima 4 Oktober 2023
Disetujui 19 Desember 2023
Diterbitkan 31 Januari 2024

Kata Kunci:
Penilaian siklus hidup (LCA)
Sampah plastik
Bibliometrik
Pirolisis
Keberlanjutan

ABSTRAK

Timbulan dan pembuangan sampah plastik menjadi masalah global yang semakin rumit dan perlu diatasi. Studi ini bertujuan untuk melakukan analisis bibliometrik dari penilaian siklus hidup (LCA) tentang sampah plastik. Data dari tahun 2013 hingga 2022 dikumpulkan dari Scopus dan Web of Science. Data yang telah dikumpulkan kemudian digabungkan dan dihapus duplikasinya menggunakan R v.4.2.3 dan R studio v.3.8.6. Setelah itu, data dianalisis dan divisualisasikan dengan bantuan Biblioshiny. Data yang dianalisis meliputi publikasi tahunan artikel ilmiah, kontribusi berdasarkan negara, kata kunci yang relevan berdasarkan peta pohon, pola pertumbuhan penelitian, pengelompokan topik, posisi penelitian berdasarkan peta tematik, dan peta struktur konseptual dalam cakupan kata kunci terkait. Tren publikasi tahunan menunjukkan pertumbuhan substansial dari 30 artikel pada tahun 2013 menjadi 631 artikel pada tahun 2022, yang menandakan kesadaran dan perhatian terhadap permasalahan sampah plastik. Tiongkok, Amerika Serikat, dan Italia memimpin publikasi tahunan sekaligus sebagai negara-negara yang paling banyak dikutip artikel-artikelnya, mengingat status mereka sebagai produsen plastik terbesar di dunia. Kata kunci yang paling relevan dari peta pohon juga ditampilkan adanya integrasi yang kuat antara upaya daur ulang plastik dan LCA dalam pengelolaan dampak lingkungan dengan kata kunci yang menonjol antara lain daur ulang, LCA, pengelolaan sampah, sampah plastik, dampak lingkungan, dan ekonomi sirkular. Studi ini pada akhirnya memberikan wawasan mendalam mengenai posisi penelitian dan arah masa depan terkait studi LCA tentang sampah plastik, yang semakin meningkat karena pentingnya pengelolaan sampah plastik berkelanjutan. Kajian ilmiah dalam bidang ini diharapkan terus berkembang untuk mendukung kesadaran dan komitmen seluruh pemangku kepentingan dalam mengatasi permasalahan sampah plastik di seluruh dunia.

ARTICLE INFO

Article history:
Received October 4th 2023
Accepted December 19th 2023
Published January 31st 2024

ABSTRACT

The generation and disposal of plastic waste become an increasingly complicated global concern that needs to be overcome. This study aims to conduct a bibliometric analysis of life cycle assessment (LCA) studies on plastic waste. Data from 2013 to 2022 were collected from Scopus and Web of Science. Collected data were merged and deduplicated using R v.4.2.3 and R studio v.3.8.6. Afterward, data were analyzed and visualized by Biblioshiny.

Keywords:
LCA,
Plastic waste,
Bibliometric,
Pyrolysis,
Sustainability

The analyzed data encompass scientific production output, contributions by country, relevant keywords by tree map, research growth pattern, topic clustering, research position by thematic map, and conceptual structure map within this scope. The annual publications trend denotes a substantial growth from 30 articles in 2013 to 631 articles in 2022, signifying awareness and attention towards plastic waste issues. China, the United States, and Italy have led annual publications as well as the most cited countries, given their status as the world's largest plastic producers. The most relevant keywords from the tree map also show a strong integration between plastic recycling efforts and LCA in managing the environmental impact with prominent keywords including recycling, LCA, waste management, plastic waste, environmental impact, and circular economy. This study finally provides profound insights into research positions and future direction related to LCA studies on plastic waste, which are escalating at the forefront because of the importance of sustainable plastic waste management. Scientific studies in this domain are expected to continuously grow to support the awareness and commitment of all stakeholders in addressing plastic waste issues worldwide.

1. INTRODUCTION

1.1 Background

Plastics are among the most widely used materials in the world (Geyer et al., 2017). As many as 390.7 million tons of plastic were produced in 2021 worldwide (Chamas et al., 2020; Kumar et al., 2021; Pandey et al., 2023; Plastics Europe and EPRO, 2022). Its extensive use as packaging material (Eissenberger et al., 2023; Ncube et al., 2021; Rhodes, 2018), transportation (Chauhan et al., 2022), agricultural tools (Wanner, 2021), and various other products has led to a significant annual enhancement in plastic production (Alegado et al., 2021; Murti et al., 2022). However, excessive usage without proper waste management has negative impacts on the environment and human life (Evode et al., 2021; Rodrigues et al., 2019). Plastic waste accumulates in oceans (Masura et al., 2015; Napper & Thompson, 2020; Rhodes, 2018), rivers (Abidin & Steven, 2021b, 2021a; Mai et al., 2020), and landfills which become a serious threat to terrestrial and marine ecosystems (Thushari & Senevirathna, 2020). In addition, some types of plastics can release hazardous substances from their additives or monomers that can endanger human health (Geyer et al., 2017; Li et al., 2021; Liu et al., 2020).

One approach to quantify the negative impacts of plastic waste is to perform a life cycle assessment (LCA) (Alhazmi et al., 2021; Anshassi & Townsend, 2021; Neo et al., 2021; Santos et al., 2022). This analysis considers the environmental impacts of the production, usage, and waste-processing phases of plastics. By performing LCA, the life cycle of plastic waste and its impact on the environment can be determined. Several studies have been carried out in this field. Schwarz et al. (2021) performed an LCA study to achieve a circular economy in plastic recycling. As much as 73% of CO_2 equivalent can be reduced by sorting and recycling the 15 most used plastics in Europe.

In the meantime, LCA helped to find the most suitable option for plastic waste management in Singapore. Khoo (2019) found that mechanical recycling is not proper but thermochemical conversion through pyrolysis and gasification offers a more attractive solution. Besides, Barjoveanu et al. (2023) found that separating PET trays from bottle waste is imperative to avoid contamination during recycling and to recover a greater amount of PET. Research progress in the plastic waste LCA has been reviewed to present improvements to future waste management (Alhazmi et al., 2021). An analysis of chemical recycling LCA literature highlighted two different approaches to treating plastic waste (Davidson et al., 2021).

LCA of mixed plastic waste end of life was compared specifically between India and Indonesia with several treatments and technologies (Neo et al., 2021), whilst LCA of specific plastic waste has also been reported, for example, high-density polyethylene, polylactic acid, and polyethylene terephthalate bottles (Gandhi et al., 2021; Gironi & Piemonte, 2011). However, the body of literature on bibliometric analysis of various plastic waste LCA is still lacking, thus to investigate the research positions and future directions, a bibliometric analysis is needed. It is an analytical approach for evaluating the quality and quantity of scientific publications in a particular field with the least cost involved (Hasan et al., 2023; Islam et al., 2022).

The quantitative examination of bibliographic data, such as citations and publications, to assess the effect and significance of scientific research is known as bibliometrics. It is frequently used in academics and scientific research to evaluate the productivity, visibility, and influence of academics, journals, institutions, and research topics (Baas et al., 2020). In this study, bibliometric analysis focuses on assessing the citation impact and quality of papers published in the journal (García-Villar & García-Santos, 2021). Measuring metrics such as the number of citations a journal has received, the average number of citations per article, the h-index (a measure of both productivity and impact), and the journal's impact factor (a metric indicating the average number of citations received per article published in the journal) are examples of such metrics (Andersen, 2018).

1.2 Research Objectives

According to the previous explanation, this study aims to provide an overview of the development patterns and future prospects of LCA of sustainable plastic waste. To achieve this goal, this study analyzes the identification of publication trends annually, leading research countries, highest cited countries, most relevant frequent keywords, and the growth and focus of research. Besides, this study also generates co-occurrence relationships between keywords, thematic maps, conceptual structure maps, and related topic trends using LCA on sustainable plastic waste in order to exhibit research positions, trends, emerging research themes, and future directions.

This study consists of four main parts. The first part introduces background and research objectives related to the LCA of plastic waste. The second part addresses methodology, which includes data collection, analysis,

visualization, and methodological framework. The third part describes findings, which are divided into performance analysis and science mapping. It also explains the discussion of the LCA of plastic waste and policy recommendations. Finally, the fourth section summarizes the conclusions, limitations, and directions for future research.

2. METHODOLOGY

Along with the immense impact of scientometrics for exploring, analyzing, and predicting academic literature, the bibliometric approach was selected for this study. In bibliometric techniques, there are two main categories, i.e. performance analysis and science mapping (Cobo et al., 2011; Sharifi et al., 2021). Performance analysis compares the performance of researchers, institutions, or countries in a particular scientific field. It was realized by identifying publication trends annually, leading research countries, highest cited countries, most relevant frequent keywords, and growth and focus of research.

The second category, science mapping, encompasses techniques used to map the structure of science in a particular scientific field. Science mapping aids in identifying trends and directions of knowledge development and serves as a tool to assist in decision-making. The science mapping analysis applied in this study consisted of co-occurrence relationships between keywords, thematic mapping, conceptual structure mapping, and topic trends.

2.1 Data Collection

Data was collected from two widely used and well-recognized databases in academia and research, namely Scopus and Web of Science (WoS) (Zhu & Liu, 2020). The search and export process was done without specialized software but utilizing each database website directly therein. The inputted keywords for both databases were similar, including "lifecycle assessment" OR "life cycle assessment" OR "life-cycle assessment" OR "lifecycle analysis" OR "life cycle analysis" OR "life-cycle analysis" AND "Plastic Waste".

The time range was 10 years, starting from 2013 to 2022. The criteria for selecting the published article findings include subject area (environmental science), document type (article), source type (journal), and language (English). The search results showed that 1,887 articles were obtained from Scopus and 104 from WoS.

2.2 Data Analysis

After collecting the datasets from the two databases, they were combined. The merging of the datasets was performed using R version 4.2.3 and R Studio version 3.8.6, with the datasets exported in the BibTeX file format. Simple programming codes were utilized to combine both datasets, identify and remove duplicate data, and generate a refined and combined dataset. There were 102 duplicate articles, resulting in a final dataset of 1,889 articles available for analysis.

Several aspects of bibliometric data were applied to explore the LCA study on plastic waste. After extracting, combining, and refining complete information from Scopus and WoS, this study employs the aspects of overview, country, document, word, and conceptual structure within Biblioshiny to conduct visual analysis.

2.3 Data Visualization and Methodological Framework

Many tools can be utilized to visualize bibliometric data, as reported by many other researchers (Moral-Muñoz et al., 2020). Nevertheless, this study employed R Studio Software, which contains the Bibliometrix package with web-based application visualizations called Biblioshiny (Alviz-Meza et al., 2023). Figures and tables were used to present the findings and interpret them based on the most highlighted and prominent issues. The presented data and graphics are categorized into two distinct classifications: performance analysis, which emphasizes the evaluation of quantitative indicators of scholarly productivity, and science mapping, which focuses on the visualization and analysis of structural and conceptual relationships among scholarly publications (Farooq, 2023; Gaviria-Marin et al., 2019).

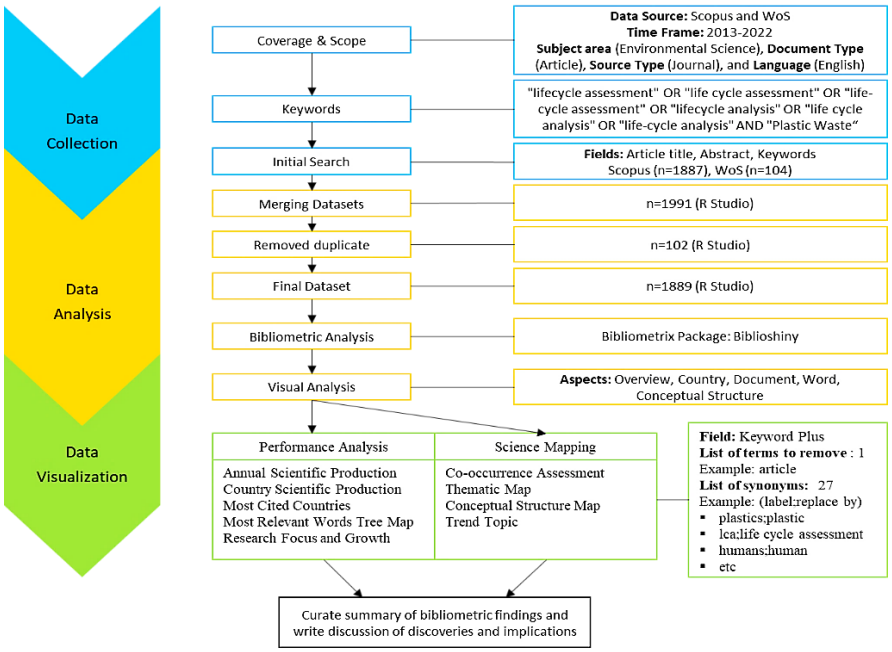

Figure 1. Methodological framework

The performance analysis in this study encompasses various dimensions, including annual scientific production, country scientific production, most-cited countries, most relevant word tree maps, and research focus and growth. Additionally, the science mapping aspect is comprised of co-occurrence assessment, thematic map, conceptual structure map, and trend topic analysis. The fields considered for analysis involve keyword plus (Wu et al., 2023), wherein a list of terms to remove is applied, consisting of a single term, namely "article". Furthermore, a list of synonyms encompassing 27 pairs of words was used. Noteworthy examples include the substitution of "plastics" with "plastic", "LCA" with "life cycle assessment", and "humans" with "human", among others. This study follows the structured methodological framework of the bibliometric studies conducted by Donthu et al. (2021) with some necessary adjustments, as illustrated in Figure 1.

3. RESULTS AND DISCUSSION

3.1 Parameters of Significance from the LCA Study on Plastic Waste

The graph in Figure 2 represents the scientific output related to the LCA study on plastic waste. It encompasses the number of articles published in 2013 to 2022. The data demonstrated a significant augmentative trend in the number of annual published articles. This growth in publications indicates rising interest and attention from researchers toward the topic. In 2013, only 30 articles were published. Likewise, there was a salient surge of published articles in 2018, with 112 articles, which continued to grow exponentially until its peak in 2022 (631 articles, 21-fold enhancement). This pattern is reinforced by the global plastic production which always annually intensified from 2 million tons in 1950 to more than 390 million tons in 2022 due to the intense market demand after 2000 (Alegado et al., 2021).

The multiplication of articles also reflects the integral role of LCA in developing sustainable solutions to plastic waste problems. By utilizing LCA, researchers can evaluate the environmental and social impacts of plastic production and waste management processes, as well as identify areas where improvements can be made to mitigate adverse effects (Alhazmi et al., 2021; Antelava et al., 2019). In other words, more research conducted in this field raises the prospect of alleviating the environmental and social impacts of plastic waste.

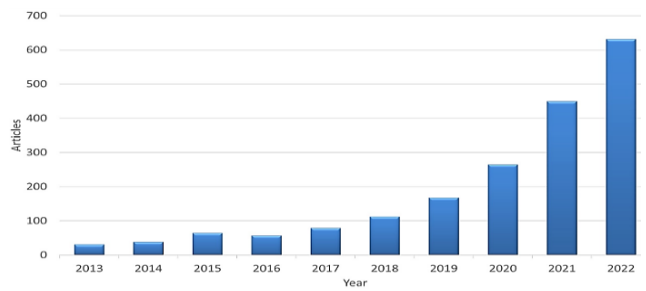

Figure 2. Annual scientific production

However, the abundant amount of publications may also interpret that concerns regarding plastic waste issues remain an important and complex matter (Nielsen et al., 2020). Cooperation across industrial sectors and scientific disciplines is required to address this problem. Moreover, continuing research in the field of LCA of plastic waste can constitute a vital component of sustainable solutions (Eissenberger et al., 2023). Hence, it is imperative to continue observing and supporting research in this area to accomplish the goals of sustainable development for plastic waste management.

Table 1 demonstrates the frequency of scientific publications regarding this topic based on the country. The data exhibits an emerging interest in the LCA study on plastic waste. The majority of the research is led by China, with a frequency of 273, followed by United States and Italy, with frequencies of 150 and 138, respectively. The United Kingdom and India also have significant research outputs with frequencies of 107 and 91, successively. Spain, Germany, and Australia have moderate research output with frequencies above 60. South Korea, Brazil, Netherlands, Belgium, and Canada have frequencies between 42 and 45. A cluster of countries with frequencies between 30 and 41 include Malaysia, Japan, Denmark, Sweden, Iran, and Turkey.

Furthermore, it is observed that both developed and developing countries demonstrate significant interest in conducting this research. Notably, several developing countries, such as India, Brazil, and Malaysia, have high frequencies of scientific output that even exceed several developed countries like Denmark, Sweden, and France. This means that developing countries are paying more attention to researching global environmental issues, although developed countries are still leading. China, the United States, and leading countries in Europe are the top contributors. This can be attributed to the fact that they are currently among the world's largest producers of plastics. Data from Plastics Europe and the European Association of Plastics Recycling and Recovery Organizations in 2020 indicate that China contributed 32%, North America 19%, and Europe 15% to global plastics production. The three combined regions produce 67% of the world's plastics (Plastics Europe and EPRO, 2022).

Table 1. Most countries' scientific production

Country	Frequency	Country	Frequency
China	273	Belgium	41
United States	150	Canada	41
Italy	138	Malaysia	41
United Kingdom	107	Japan	38
India	91	Denmark	35
Spain	85	Sweden	31
Germany	70	Iran	30
Australia	60	Turkiye	30
South Korea	57	France	28
Brazil	45		

China has the greatest number of total citations, with 6,957 citations and an average of 23 citations per article, as outlined in Table 2. Denmark has the highest average citations per article at 49.7 citations despite having only 1,789 total citations. Other countries that also have relatively high average citations per article include Italy (46.1 citations per article) and the United Kingdom (35.9 citations per article). Countries such as India and Germany have low average citations per article, at 19.8 and 21.1 citations per article, in respective terms. Meanwhile, Indonesia is still not visible in all of these parameters since the independent plastic and

recycling industries have not been established and the use of sustainable plastics has not been well-encouraged.

Table 2. Most cited countries

Country	Total Citations	Average Article Citations
China	6957	23
Italy	6452	46.1
United States	3192	24.4
United Kingdom	3050	35.9
Spain	1809	22.1
Denmark	1789	49.7
India	1779	19.8
Australia	1647	27.9
Germany	1413	21.1
Belgium	1317	28

3.2 Research Focus and Growth

The frequency analysis of keywords in the form of a treemap can provide a clear depiction of research focus and growth in plastic waste management and the resultant environmental impacts, as well as associated global issues. As presented in a treemap visualization reveals that the terms with the highest frequency were recycling, life cycle assessment, and waste management (Figure 3).

Additionally, several reasonably relevant keywords include plastic waste, environmental impact, municipal solid waste, pyrolysis, sustainable development, circular economy, climate change, and greenhouse gases. This strengthens that plastic waste management remains the foremost concern in developing more sustainable technologies and methods (for example, landfill, pyrolysis, and incineration) (Escalante et al., 2022; Veksha et al., 2020). Moreover, mitigating the environmental impacts of plastic waste persists as a challenge to overcome (Armenise et al., 2021; Baran, 2020; Idumah & Nwuzor, 2019). Technology- and material-related terms are also evident in the analysis. They are polymer, polyethylene, and polyethylene terephthalates, signaling efforts to develop more eco-friendly alternative materials and reduce conventional plastic usage (Gandhi et al., 2021; Narancic & O'Connor, 2019).

In accordance with Figure 4, it can be seen that the utilization of LCA in plastic waste management has developed rapidly from year to year, as expressed by the number of related publication keywords that continue to enhance annually. In particular, there is a significant number of keywords used in 2022. Recycling, life cycle assessment, and waste management are the three main keywords that often appear, with recycling being the most widely discussed and rapidly evolving keyword since 2013. This reinforces that plastic recycling is an important factor for plastic waste management.

The escalating focus on sustainable development can also be seen in publications on LCA and plastic waste, which denotes that plastic waste management should be oriented towards efforts to maintain environmental sustainability. Likewise, the focus on alternative technologies for plastic waste processing can also be seen, particularly in pyrolysis and incineration technologies (Chen et al., 2021; Davidson et al., 2021; Kumar et al., 2021; Rhodes, 2018; Veksha et al., 2020). Unfortunately, publications on alternative technologies by means of biodegradation are still few, reflecting that further research is needed to develop alternative technologies or the route is less favored to be selected because of the long duration process (Bindar et al., 2022; Estevez et al., 2009; Jiang et al., 2014; Steven et al., 2021).

Figure 3. Most relevant words with tree map

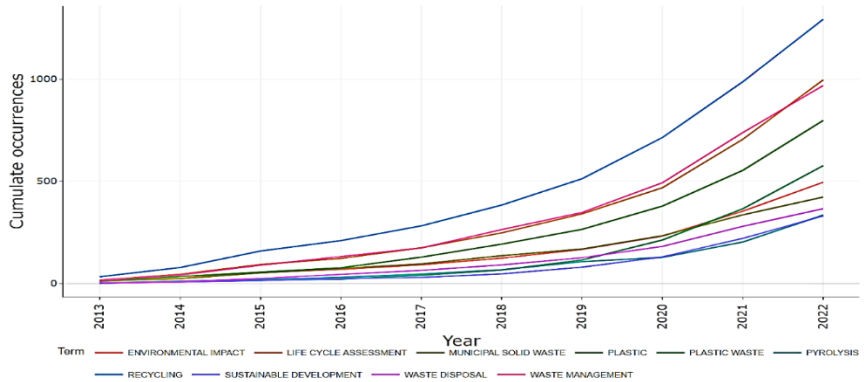

Figure 4. Growth pattern in research focus

3.3 Research Position Analysis

Figure 5 serves two clusters with different keywords, namely Cluster 1 (red) with 20 keywords and Cluster 2 (blue) consisting of 28 keywords. For each keyword, it can be seen that the most substantial values are recycling, plastic waste, and plastic in Cluster 1, whereas waste management, life cycle assessment, and environmental impact are dominant in Cluster 2. This implies that those keywords have a major influence on the co-occurrence network. According to the results of this analysis, it can be concluded that keywords that are more related to plastic recycling processes, products, and environment in the co-occurrence network are in Cluster 1, while keywords that are more related to waste management and policy are in Cluster 2.

The research position can be examined by thematic map, which is divided into four quadrants as plotted in Figure 6. The top left (niche) has many articles but little influence due to being isolated from certain themes. The top right (motor) has many influential articles. The bottom left (emerging or declining) has a few influential articles because it is still embryonic. The bottom right (basic) has a few articles but quite influential (Donthu et al., 2021). Based on the authors' keyword mapping, ten clusters are acquired. They are life cycle assessment, plastic, microplastic, municipal solid waste management, COVID-19, pollution, biochar, adsorption, sensitivity analysis, and 3D printing.

The "life cycle assessment" cluster includes the keywords of life cycle assessment, circular economy, and recycling. The "plastic" cluster includes the keywords plastic, plastic waste, and pyrolysis, both of which are the largest clusters and are directly related to the topic being discussed. Those two clusters are located close together. The "plastic" cluster is in the motor quadrant representing that keywords in this cluster are the main drivers in the development of science in this field. Research in this cluster is broad and has a major impact on the scientific literature. The "life cycle assessment" cluster is in the basic quadrant indicating that although the keywords in this cluster are not yet numerous, they have a meaningful influence on the scientific literature.

The "plastic" cluster highlights the focus on plastic waste issues and efforts to address their environmental impacts. The "life cycle assessment" cluster presents the central concept in assessing the environmental impact from plastic production to disposal stages. The connection between these two clusters is clearly seen in the term "plastic waste", which is linked to the concept of "life cycle assessment", implying the importance of the LCA approach in measuring the environmental impact of plastic waste management (Anshassi & Townsend, 2021). This analysis strengthens that the scientific literature is focused on integrating LCA concepts in efforts to manage plastic waste, encompassing reduction, recycling (Santos et al., 2022), and better environmental impact management (Alhazmi et al., 2021).

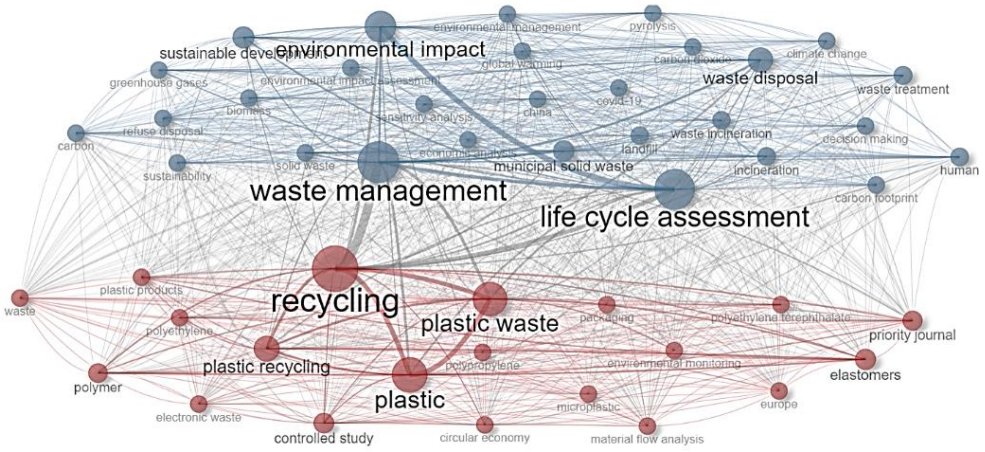

Figure 5. Research position by clustering in co-occurrence assessment

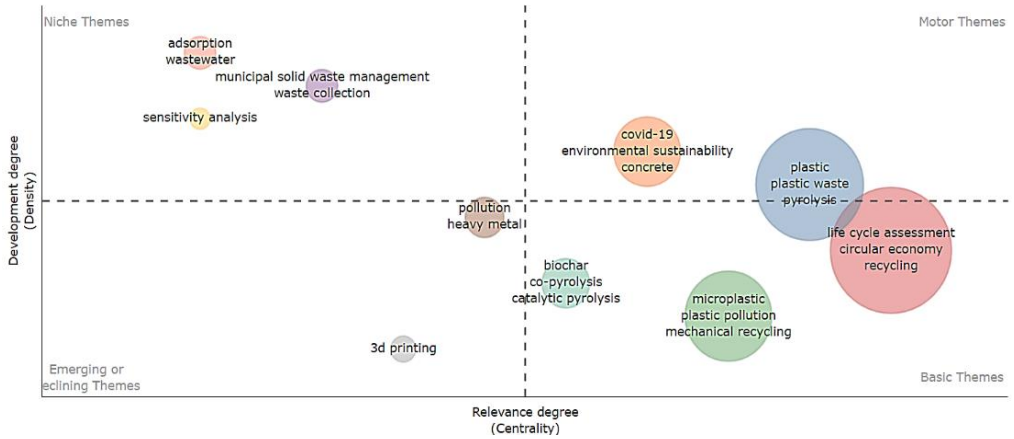

Figure 6. Research position by thematic map

The research position can also be analyzed by a conceptual structure map. This section provides two clusters that are differentiated between different topics, as seen in Figure 7. The first cluster consisted of topics such as recycling, plastic, plastic waste, plastic recycling, polymers, elastomers, circular economy, and packaging. This cluster is likely to discuss topics related to technology and innovation in plastic waste processing, including reprocessing, recycling, and use of alternative materials. The second cluster consisted of topics such as LCA, waste management, environmental impact, municipal solid waste, waste disposal, pyrolysis, sustainable development, incineration, solid waste, waste treatment, carbon dioxide, priority journal, waste incineration, landfill, sustainability, climate change, greenhouse gases, decision-making, carbon, environmental management, carbon footprint, sensitivity analysis, and environmental impact assessment. This cluster is intended to discuss broader topics related to the environmental impact of plastic waste processing, including LCA, waste management, waste treatment, and environmental impact assessment.

From these two clusters, it can be observed that LCA study on plastic waste topic is closely related to the second cluster. This signifies that research and studies on the environmental impact of plastic waste, as well as efforts to manage plastic waste in a more sustainable manner, are the main focus. Several topics appeared to have a strong relationship with this topic, such as waste management, waste disposal, sustainability, climate change, greenhouse gases, and environmental impact assessment. This suggests that LCA study on plastic waste is likely to be involved in various aspects of waste management and environmental conservation.

3.4 Trending Topics and Future Directions

From these two clusters, it can be observed that LCA study on plastic waste topic is closely related to the second cluster. This signifies that research and studies on the environmental impact of plastic waste, as well as efforts to manage plastic waste in a more sustainable manner, are the main focus. Several topics appeared to have a strong relationship with this topic, such as waste management, waste disposal, sustainability, climate change, greenhouse gases, and environmental impact assessment. This suggests that LCA study on plastic waste is likely to be involved in various aspects of waste management and environmental conservation.

Economic growth, escalating global population, and per capita consumption across the world are in line with the accumulation of plastic waste (Chen et al., 2021). The adverse repercussions of plastic waste have prompted widespread societal concerns owing to their potential to compromise the environment and improve human health (Mai et al., 2020; Napper & Thompson, 2020). It is also compounded by the fact that plastic waste requires years for degradation or decomposition, in contrast to other waste types (Babaremu et al., 2022). The predicament of plastic waste is a substantial environmental issue, prompting intensive research (de Sousa, 2021). The data show the inception of the plastic waste topic in the year 2020 until the present, totaling 553 occurrences. This is in contrast to other waste-related subjects, such as electronic waste, chemistry, forestry, and pollutants, which stopped in 2021.

The existence of plastic waste signifies the escalating global significance of plastic waste management, underscoring its status as a paramount concern in contemporary nations (Sun et al., 2022). This substantiates that the subject of LCA study on plastic waste is gaining substantial attention and is being rigorously examined across a spectrum of current articles, attesting to its gravity on a global scale (Antelava et al., 2019). The trend in LCA-related discourse concerning plastic waste highlights the mounting global importance of effective plastic waste management as an imperative point for all nations (Chauhan et al., 2022; Li et al., 2021). Furthermore, this emphasizes the need for joint linkage efforts to bring about change, especially gaining awareness and commitment from governments, institutions, and other stakeholders to continuously collaborate (Branscomb et al., 1999; Zhao et al., 2021).

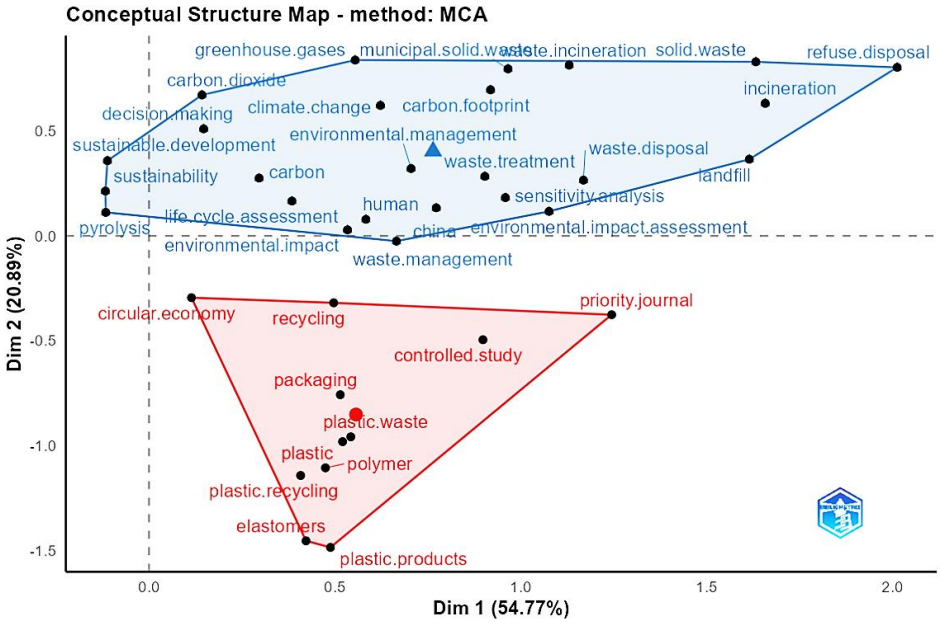

Figure 7. Conceptual structure map

4. CONCLUSION

In conclusion, this study has successfully achieved its objective of providing a comprehensive overview of the development patterns and future prospects of life cycle assessment (LCA) in the context of sustainable plastic waste. Through a thorough analysis of publication trends, leading research countries, citation patterns, and relevant keywords, the study has illuminated key aspects of the current research landscape. Additionally, the application of LCA has been instrumental in generating valuable insights through co-occurrence relationships, thematic maps, conceptual structure maps, and related topic trends. The scientific production related to LCA study on plastic waste has increased by 21-fold from 2013 to 2022. This shows interest and attention enhancement of researchers towards this topic, along with the growth in global plastic production and environmental problems due to plastic waste. Developed countries such as China, the United States, and Italy have the greatest scientific production and citation numbers due to being the largest plastic producers in the world. Several developing countries are also beginning to take a great interest in this topic. The most frequent keywords that appear include recycling, life cycle assessment, waste management, plastic waste, environmental impact, and circular economy. This implies that the current main research focus is on recycling efforts, plastic waste management, and environmental impact assessments through LCA methods. In addition, the themes of environmental sustainability and circular economy have drawn the attention of researchers in an effort to find long-term solutions to the problem of plastic waste. The integration between plastic recycling efforts and LCA to manage the environmental impact of plastic waste is also important. Overall, research trends and positions interpret that LCA and plastic waste have become the main focus because of the importance of globally sustainable plastic waste management. The future direction of this topic is expected to signify and support awareness of the efforts and commitment of various parties in dealing with the world's plastic waste problem.

ACKNOWLEDGMENTS

Mr. Soen Steven acknowledges the Postdoctoral Scheme at the Research Center for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency (BRIN), Indonesia 2023-2024. All authors are equally and fairly distributed in drafting, editing, and reviewing the manuscript, software providence, data processing, formal analysis, critical revising, and visualization.

REFERENCES

Abidin, A. Z., & Steven, S. (2021a). Plastic Marine Debris Study based on Indonesian Plastic National Balance (IPNB) and seashore approach. *IOP Conference Series: Materials Science and Engineering*, *1143*(1), 012048. https://doi.org/10.1088/1757-899X/1143/1/012048

Abidin, A. Z., & Steven, S. (2021b). Study on Indonesian Plastic Marine Debris Based on River Survey. *IOP Conference Series: Materials Science and Engineering*, *1143*(1), 012049. https://doi.org/10.1088/1757-899X/1143/1/012049

Alegado, J. E., Aliño, J. M., Chow, S. C. F., Diola, M. B. L., Jagath, P., Gamaralalage, D., Gurrero, L., Hengesbaugh, M., Hernandez, V., Ishimura, Y., Kato, M., Kim, E., Liu, C., Moinuddin, M., Moon, D., Okuno, M., Olsen, S. H., Pelogio, G., Pey, P., … Canh, V. D. (2021). Plastic Atlas: Facts and Figures about the World of Synthetic Polymers, Asia Edition. In *Heinrich Boell Stiftung Hong Kong Office, Break Free From Pacific Asia Pacific and Institute for Global Environmental Strategies*.

Alhazmi, H., Almansour, F. H., & Aldhafeeri, Z. (2021). Plastic Waste Management: A Review of Existing Life Cycle Assessment Studies. *Sustainability*, *13*(10), 5340. https://doi.org/10.3390/su13105340

Alviz-Meza, A., Orozco-Agamez, J., Quinayá, D. C. P., & Alviz-Amador, A. (2023). Bibliometric Analysis of Fourth Industrial Revolution Applied to Material Sciences Based on Web of Science and Scopus Databases from 2017 to 2021. *ChemEngineering*, *7*(1), 2. https://doi.org/10.3390/chemengineering7010002

Andersen, J. (2018). Preaward—Project Preparation. In *The European Research Management Handbook* (pp. 147–171). Elsevier. https://doi.org/10.1016/B978-0-12-805059-0.00006-7

Anshassi, M., & Townsend, T. G. (2021). Reviewing the Underlying Assumptions in Waste LCA Models to identify Impacts on Waste Management Decision Making. *Journal of Cleaner Production*, *313*, 127913. https://doi.org/10.1016/j.jclepro.2021.127913

Antelava, A., Damilos, S., Hafeez, S., Manos, G., Al-Salem, S. M., Sharma, B. K., Kohli, K., & Constantinou, A. (2019). Plastic Solid Waste (PSW) in the Context of Life Cycle Assessment (LCA) and Sustainable Management. *Environmental Management*, *64*(2), 230–244. https://doi.org/10.1007/s00267-019-01178-3

Armenise, S., SyieLuing, W., Ramírez-Velásquez, J. M., Launay, F., Wuebben, D., Ngadi, N., Rams, J., & Muñoz, M. (2021). Plastic waste recycling via pyrolysis: A Bibliometric Survey and Literature Review. *Journal of Analytical and Applied Pyrolysis*, *158*, 105265. https://doi.org/10.1016/j.jaap.2021.105265

Baas, J., Schotten, M., Plume, A., Côté, G., & Karimi, R. (2020). Scopus as a Curated, High-Quality Bibliometric Data Source for Academic Research in Quantitative Science Studies. *Quantitative Science Studies*, *1*(1), 377–386. https://doi.org/10.1162/qss_a_00019

Babaremu, K. O., Okoya, S. A., Hughes, E., Tijani, B., Teidi, D., Akpan, A., Igwe, J., Karera, S., Oyinlola, M., & Akinlabi, E. T. (2022). Sustainable Plastic Waste Management in a Circular Economy. *Heliyon*, *8*(7), e09984. https://doi.org/10.1016/j.heliyon.2022.e09984

Baran, B. (2020). Plastic Waste as a Challenge for Sustainable Development and Circularity in the European Union. *Ekonomia i Prawo*, *19*(1), 7. https://doi.org/10.12775/EiP.2020.001

Barjoveanu, G., Gadaleta, G., Santomasi, G., De Gisi, S., Notarnicola, M., & Teodosiu, C. (2023). Does PET Trays Sorting affect the Sustainability of Plastic Waste? An LCA and Cost-revenue Approach. *Science of The Total Environment*, *897*, 165222. https://doi.org/10.1016/j.scitotenv.2023.165222

Bindar, Y., Steven, S., Kresno, S. W., Hernowo, P., Restiawaty, E., Purwadi, R., & Prakoso, T. (2022). Large-scale Pyrolysis of Oil Palm Frond Using Two-Box Chamber Pyrolyzer for Cleaner Biochar Production. *Biomass Conversion and Biorefinery*. https://doi.org/10.1007/s13399-022-02842-1

Branscomb, L. M., Kodama, F., & Florida, R. (1999). Industrializing Knowledge: University-Industry Linkages in Japan and the United States. In *The MIT Press*.

Chamas, A., Moon, H., Zheng, J., Qiu, Y., Tabassum, T., Jang, J. H., Abu-Omar, M., Scott, S. L., & Suh, S. (2020). Degradation Rates of Plastics in the Environment. *ACS Sustainable Chemistry & Engineering*, *8*(9), 3494–3511. https://doi.org/10.1021/acssuschemeng.9b06635

Chauhan, V., Kärki, T., & Varis, J. (2022). Review of Natural Fiber-Reinforced Engineering Plastic Composites, Their Applications

in the Transportation Sector and Processing Techniques. *Journal of Thermoplastic Composite Materials*, *35*(8), 1169–1209. https://doi.org/10.1177/0892705719889095

Chen, H. L., Nath, T. K., Chong, S., Foo, V., Gibbins, C., & Lechner, A. M. (2021). The Plastic Waste Problem in Malaysia: Management, Recycling and Disposal of Local and Global Plastic Waste. *SN Applied Sciences*, *3*(4), 437. https://doi.org/10.1007/s42452-021-04234-y

Cobo, M. J., López-Herrera, A. G., Herrera-Viedma, E., & Herrera, F. (2011). An Approach for Detecting, Quantifying, and Visualizing the Evolution of a Research Field: a Practical Application to the Fuzzy Sets Theory Field. *Journal of Informetrics*, *5*(1), 146–166. https://doi.org/10.1016/j.joi.2010.10.002

Davidson, M. G., Furlong, R. A., & McManus, M. C. (2021). Developments in the Life Cycle Assessment of Chemical Recycling of Plastic Waste – A Review. *Journal of Cleaner Production*, *293*, 126163. https://doi.org/10.1016/j.jclepro.2021.126163

de Sousa, F. D. B. (2021). Management of Plastic Waste: A Bibliometric Mapping and Analysis. *Waste Management & Research: The Journal for a Sustainable Circular Economy*, *39*(5), 664–678. https://doi.org/10.1177/0734242X21992422

Donthu, N., Kumar, S., Mukherjee, D., Pandey, N., & Lim, W. M. (2021). How to Conduct A Bibliometric Analysis: An Overview and Guidelines. *Journal of Business Research*, *133*, 285–296. https://doi.org/10.1016/j.jbusres.2021.04.070

Eissenberger, K., Ballesteros, A., De Bisschop, R., Bugnicourt, E., Cinelli, P., Defoin, M., Demeyer, E., Fürtauer, S., Gioia, C., Gómez, L., Hornberger, R., Ißbrücker, C., Mennella, M., von Pogrell, H., Rodriguez-Turienzo, L., Romano, A., Rosato, A., Saile, N., Schulz, C., … Schmid, M. (2023). Approaches in Sustainable, Biobased Multilayer Packaging Solutions. *Polymers*, *15*(5), 1184. https://doi.org/10.3390/polym15051184

Escalante, J., Chen, W.-H., Tabatabaei, M., Hoang, A. T., Kwon, E. E., Lin, K.-Y. A., & Saravanakumar, A. (2022). Pyrolysis of Lignocellulosic, Algal, Plastic, and Other Biomass Wastes for Biofuel Production and Circular Bioeconomy: A Review of Thermogravimetric Analysis (TGA) Approach. *Renewable and Sustainable Energy Reviews*, *169*, 112914. https://doi.org/https://doi.org/10.1016/j.rser.2022.112914

Estevez, M., Vargas, S., Castaño, V. M., & Rodriguez, R. (2009). Silica Nano-particles Produced by Worms through a Bio-digestion Process of Rice Husk. *Journal of Non-Crystalline Solids*, *355*(14–15), 844–850.

Evode, N., Qamar, S. A., Bilal, M., Barceló, D., & Iqbal, H. M. N. (2021). Plastic Waste and Its Management Strategies for Environmental Sustainability. *Case Studies in Chemical and Environmental Engineering*, *4*, 100142. https://doi.org/10.1016/j.cscee.2021.100142

Farooq, R. (2023). Mapping the Field of Knowledge Management: a Bibliometric Analysis using R. *VINE Journal of Information and Knowledge Management Systems*, *53*(6), 1178–1206. https://doi.org/10.1108/VJIKMS-06-2021-0089

Gandhi, N., Farfaras, N., Linda Wang, N.-H., & Chen, W.-T. (2021). Life Cycle Assessment of Recycling High-Density Polyethylene Plastic Waste. *Journal of Renewable Materials*, *9*(8), 1463–1483. https://doi.org/10.32604/jrm.2021.015529

García-Villar, C., & García-Santos, J. M. (2021). Bibliometric Indicators to Evaluate Scientific Activity. *Radiología (English Edition)*, *63*(3), 228–235. https://doi.org/10.1016/j.rxeng.2021.01.002

Gaviria-Marin, M., Merigó, J. M., & Baier-Fuentes, H. (2019). Knowledge management: A Global Examination based on Bibliometric Analysis. *Technological Forecasting and Social Change*, *140*, 194–220. https://doi.org/10.1016/j.techfore.2018.07.006

Geyer, R., Jambeck, J. R., & Law, K. L. (2017). Production, Use, and Fate of All Plastics Ever Made. *Science Advances*, *3*(7). https://doi.org/10.1126/sciadv.1700782

Gironi, F., & Piemonte, V. (2011). Life Cycle Assessment of Polylactic Acid and Polyethylene Terephthalate Bottles for Drinking Water. *Environmental Progress & Sustainable Energy*, *30*(3), 459–468. https://doi.org/10.1002/ep.10490

Hasan, M., Abedin, M. Z., Amin, M. Bin, Nekmahmud, M., & Oláh, J. (2023). Sustainable Biofuel Economy: A Mapping Through Bibliometric Research. *Journal of Environmental Management*, *336*, 117644. https://doi.org/10.1016/j.jenvman.2023.117644

Idumah, C. I., & Nwuzor, I. C. (2019). Novel Trends in Plastic Waste Management. *SN Applied Sciences*, *1*(11), 1402. https://doi.org/10.1007/s42452-019-1468-2

Islam, M. M., Chowdhury, M. A. M., Begum, R. A., & Amir, A. A. (2022). A Bibliometric Analysis on The Research Trends of Climate Change Effects on Economic Vulnerability. *Environmental Science and Pollution Research*, *29*(39), 59300–59315. https://doi.org/10.1007/s11356-022-20028-0

Jiang, W., Luo, S., Liu, P., Deng, X., Jing, Y., Bai, C., & Li, J. (2014). Purification of Biosilica from Living Diatoms by A Two-Step Acid Cleaning and Baking Method. *Journal of Applied Phycology*, *26*, 1511–1518. https://doi.org/10.1007/s10811-013-0192-3

Khoo, H. H. (2019). LCA of Plastic Waste Recovery into Recycled Materials, Energy and Fuels in Singapore. *Resources, Conservation and Recycling*, *145*, 67–77. https://doi.org/10.1016/j.resconrec.2019.02.010

Kumar, R., Verma, A., Shome, A., Sinha, R., Sinha, S., Jha, P. K., Kumar, R., Kumar, P., Shubham, Das, S., Sharma, P., & Vara Prasad, P. V. (2021). Impacts of Plastic Pollution on Ecosystem Services, Sustainable Development Goals, and Need to Focus on Circular Economy and Policy Interventions. *Sustainability*, *13*(17), 9963. https://doi.org/10.3390/su13179963

Li, P., Wang, X., Su, M., Zou, X., Duan, L., & Zhang, H. (2021). Characteristics of Plastic Pollution in the Environment: A Review. *Bulletin of Environmental Contamination and Toxicology*, *107*(4), 577–584. https://doi.org/10.1007/s00128-020-02820-1

Liu, H., Wang, C., Zhang, J., Zhao, W., & Fan, M. (2020). Pyrolysis Kinetics and Thermodynamics of Typical Plastic Waste. *Energy & Fuels*, *34*(2), 2385–2390. https://doi.org/10.1021/acs.energyfuels.9b04152

Mai, L., Sun, X.-F., Xia, L.-L., Bao, L.-J., Liu, L.-Y., & Zeng, E. Y. (2020). Global Riverine Plastic Outflows. *Environmental Science & Technology*, *54*(16), 10049–10056. https://doi.org/10.1021/acs.est.0c02273

Masura, J., Baker, J., Foster, G., & Arthur, C. (2015). Laboratory Methods for the Analysis of Microplastics in the Marine Environment: Recommendations for Quantifying Synthetic Particles in Waters and Sediments. In *National Oceanic and Atmospheric Administration Marine Debris Program-U.S. Department of Commerce*.

Moral-Muñoz, J. A., Herrera-Viedma, E., Santisteban-Espejo, A., & Cobo, M. J. (2020). Software Tools for Conducting Bibliometric Analysis in Science: An Up-to-date Review. *El Profesional de La Información*, *29*(1). https://doi.org/10.3145/epi.2020.ene.03

Murti, Z., Dharmawan, Siswanto, Soedjati, D., Barkah, A., & Rahardjo, P. (2022). Review of the Circular Economy of Plastic Waste in Various Countries and Potential Applications in Indonesia. *IOP Conference Series: Earth and Environmental Science*, *1098*(1), 012014. https://doi.org/10.1088/1755-1315/1098/1/012014

Napper, I. E., & Thompson, R. C. (2020). Plastic Debris in the Marine Environment: History and Future Challenges. *Global Challenges*, *4*(6), 1900081. https://doi.org/10.1002/gch2.201900081

Narancic, T., & O'Connor, K. E. (2019). Plastic Waste as A Global Challenge: Are Biodegradable Plastics the Answer to the Plastic Waste Problem? *Microbiology*, *165*(2), 129–137. https://doi.org/10.1099/mic.0.000749

Ncube, L. K., Ude, A. U., Ogunmuyiwa, E. N., Zulkifli, R., & Beas, I. N. (2021). An Overview of Plastic Waste Generation and

Management in Food Packaging Industries. *Recycling*, *6*(1), 12. https://doi.org/10.3390/recycling6010012

Neo, E. R. K., Soo, G. C. Y., Tan, D. Z. L., Cady, K., Tong, K. T., & Low, J. S. C. (2021). Life Cycle Assessment of Plastic Waste End-of-life for India and Indonesia. *Resources, Conservation and Recycling*, *174*, 105774. https://doi.org/10.1016/j.resconrec.2021.105774

Nielsen, T. D., Hasselbalch, J., Holmberg, K., & Stripple, J. (2020). Politics and the Plastic Crisis: A Review throughout the Plastic Life Cycle. *WIREs Energy and Environment*, *9*(1). https://doi.org/10.1002/wene.360

Pandey, P., Dhiman, M., Kansal, A., & Subudhi, S. P. (2023). Plastic Waste Management for Sustainable Environment: Techniques and Approaches. *Waste Disposal & Sustainable Energy*, *5*(2), 205–222. https://doi.org/10.1007/s42768-023-00134-6

Plastics Europe and EPRO. (2022). Plastics – the Facts 2022. In *Plastics Europe AISBL*.

Rhodes, C. J. (2018). Plastic Pollution and Potential Solutions. *Science Progress*, *101*(3), 207–260. https://doi.org/10.3184/003685018X15294876706211

Rodrigues, M. O., Abrantes, N., Gonçalves, F. J. M., Nogueira, H., Marques, J. C., & Gonçalves, A. M. M. (2019). Impacts of Plastic Products Used in Daily Life on the Environment and Human Health: What is Known? *Environmental Toxicology and Pharmacology*, *72*, 103239. https://doi.org/10.1016/j.etap.2019.103239

Santos, J., Pizzol, M., & Azarijafari, H. (2022). Life Cycle Assessment (LCA) of Using Recycled Plastic Waste in Road Pavements: Theoretical Modeling. In *Plastic Waste for Sustainable Asphalt Roads* (pp. 273–302). Elsevier. https://doi.org/10.1016/B978-0-323-85789-5.00014-9

Schwarz, A. E., Ligthart, T. N., Godoi Bizarro, D., De Wild, P., Vreugdenhil, B., & van Harmelen, T. (2021). Plastic Recycling in A Circular Economy; Determining Environmental Performance Through an LCA Matrix Model Approach. *Waste Management*, *121*, 331–342. https://doi.org/10.1016/j.wasman.2020.12.020

Sharifi, A., Simangan, D., & Kaneko, S. (2021). Three Decades of Research on Climate Change and Peace: A Bibliometrics Analysis. *Sustainability Science*, *16*(4), 1079–1095. https://doi.org/10.1007/s11625-020-00853-3

Steven, S., Restiawaty, E., & Bindar, Y. (2021). Routes for Energy and Bio-Silica Production from Rice Husk: A Comprehensive Review and Emerging Prospect. *Renewable and Sustainable Energy Reviews*, *149*, 111329. https://doi.org/10.1016/j.rser.2021.111329

Sun, Y., Liu, S., Wang, P., Jian, X., Liao, X., & Chen, W.-Q. (2022). China's Roadmap to Plastic Waste Management and Associated Economic Costs. *Journal of Environmental Management*, *309*, 114686. https://doi.org/10.1016/j.jenvman.2022.114686

Thushari, G. G. N., & Senevirathna, J. D. M. (2020). Plastic Pollution in the Marine Environment. *Heliyon*, *6*(8), e04709. https://doi.org/10.1016/j.heliyon.2020.e04709

Veksha, A., Yin, K., Moo, J. G. S., Oh, W.-D., Ahamed, A., Chen, W. Q., Weerachanchai, P., Giannis, A., & Lisak, G. (2020). Processing of Flexible Plastic Packaging Waste into Pyrolysis Oil and Multi-Walled Carbon Nanotubes for Electrocatalytic Oxygen Reduction. *Journal of Hazardous Materials*, *387*, 121256. https://doi.org/10.1016/j.jhazmat.2019.121256

Wanner, P. (2021). Plastic in Agricultural Soils – A Global Risk for Groundwater Systems and Drinking Water Supplies? – A Review. *Chemosphere*, *264*, 128453. https://doi.org/10.1016/j.chemosphere.2020.128453

Wu, H., Cheng, K., & Li, C. (2023). Ferroptosis, Necroptosis, Pyroptosis, and Cuproptosis in Cancer: A Comparative Bibliometric Analysis. *Cell Death Discovery*, *9*(1), 238. https://doi.org/10.1038/s41420-023-01542-7

Zhao, C., Liu, M., Du, H., & Gong, Y. (2021). The Evolutionary Trend and Impact of Global Plastic Waste Trade Network. *Sustainability*, *13*(7), 3662. https://doi.org/10.3390/su13073662

Zhu, J., & Liu, W. (2020). A Tale of Two Databases: the Use of Web of Science and Scopus in Academic Papers. *Scientometrics*, *123*(1), 321–335. https://doi.org/10.1007/s11192-020-03387-8