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REVIEW ARTICLE

Bibliometric analysis and an overview of the application of the non-precious materials for pyrolysis reaction of plastic waste

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Abstract Huge plastic consumption and depletion of fossil fuels are at the top of the world's environmental and energy challenges. The scientific community has tackled these issues through different approaches. Catalytic pyrolysis of plastic wastes to valuable products has been proved as a sustainable route which fits with the circular economy aspects. The design of catalytic materials is the central factor for performing the catalytic conversion of plastic wastes. This review aims to conduct a Bibliometric analysis of the pyrolysis of plastic wastes and non-precious-based catalysts by mapping research studies over the last fifty years. The analysis was developed via VOSviewer and RStudio tools. It showed the historical progress regarding plastic waste pyrolysis to produce valuable products and chemicals worldwide. The research shows that the top five countries with the highest citations and publications in this field were Spain, China, England, the USA and India. The Journal of Analytical and Applied Pyrolysis had the most comprehensive coverage of plastic

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waste. The relationship between the catalyst and the mechanism of plastic waste can influence the production yield and selectivity. The research gap and underrepresented research topics were identified, and previous research studies on developing non-precious-based catalysts that were most relevant to the current topic were reviewed and discussed. The challenges and perspectives on catalyst preparation and development for material complexity were critically discussed. Challenges of previous studies and directions for future research were provided. This report might guide the reader to take a general look at plastic waste valorization by pyrolysis and easily understand the main challenges.

1. Introduction

The continuing expansion of the industry has resulted in an increasing global demand for plastics, making them a necessary commodity for maintaining current standards of living (Lopez et al., 2017). Around 1.5 million tons of plastic were generated worldwide in 1950, and 348 million tons were produced in 2017 (Ito et al., 2019, Wang et al., 2021). By 2050, it is predicted that 12 billion metric tons of trash will be dumped in landfills worldwide at the current rate of waste management (Geyer et al., 2017). Thus, plastic trash constitutes a severe environmental danger due to the rising quantities of plastic garbage produced yearly, the absence of proper recycling methods, and efficient waste management facilities (Seay 2022). The operation of plastic waste disposal is costly and harmful to the environment because of the emission of smells and byproducts that pollute the environment and harm human health (Alabi et al., 2019, Letcher 2020). Thus, plastic waste problems result from poor trash management and recycling infrastructure, particularly in developing nations. Burning these wastes releases toxic pollutants harmful to the ecosystem, including polychlorinated biphenyls, toxic free radicals, heavy metals, polycyclic aromatic hydrocarbons, dioxins, phosgene, dust, and pose a risk of human cancer, mutagenicity, and neurological complications.

Many solutions have been put out to make use of waste plastics, particularly for the generation of energy and fuels, to prevent resource waste and environmental degradation. Associated with other systems like anaerobic absorption and other biochemical and chemical conversion methods, thermal decomposition with measured oxidation aids in lesser contaminant emissions. It provides feedstock versatility, efficiency, scalability, high throughput, and product uniformity (Kunwar et al., 2016, Déparrois et al., 2019, Wang et al., 2021). Thermochemical disposal methods such as pyrolysis offer significant and diverse opportunities for producing fuels and value-added chemicals from plastic waste (Lopez et al., 2018) while minimizing unsustainable practices such as incineration and landfilling (Wang et al., 2021). One of the most popular technologies for converting trash into valuable fuels is pyrolysis. The thermal and physical properties of waste-to-fuel are comparable to those of fuels derived from petroleum (Lima et al., 2004, Intarapong et al., 2016).

In pyrolysis, catalysts play a critical role and are being explored in great detail. A significant benefit of the pyrolysis process catalyst is its ability to use less time and energy. When a catalyst is used, pyrolysis is known as catalytic thermal cracking or catalytic pyrolysis; when it is not used, it is known as non-catalytic pyrolysis. Various catalysts, such as magnesium (Mg) (Dong et al., 2022), iron (Fe) (Jagodzińska et al., 2022), cobalt (Co) (Lee et al., 2022), cerium (Ce) (Wang et al., 2022), and nickel (Ni) (Jagodzińska et al., 2022) have been improved and employed in pyrolysis reaction to improve plastic-to-fuel viability. Those materials also apply to various plastic wastes, such as LDPE, HDPE, ABS, PC, PS, PTFE, etc., which in many cases have synergistic effects that promote pyrolysis.

Despite numerous exploration publications representing the promise of combined pyrolysis with co-feeding, catalysis, and pretreatment for enhancing the plastic waste conversion system, product feature, and high-value chemical synthesis, there are very few reviews on this subject. We could only identify 10 research items, as shown in Table 1, according to our understanding and Web of Science (WoS) database search requirements. We combined the title search with keywords like "catalyst", "plastic", and "waste" and the topic search with terms like "review". In this study, we used a combination of bibliometric methods to perform a visual analysis and evaluate the publications quantitatively and qualitatively in the field of nanocatalysts for the pyrolysis reaction of plastic waste from 1970 to 2022. This allowed us to identify the research status and trend of various research topics, address research gaps, investigate country and author collaborations, and analyze the evolution of the word dynamics map over time. Rstudio and VOSviewer software were employed to conduct the bibliometric study. In addition to bibliometric analysis, the manuscript provides an overview of the previous literature on the application of non-precious active metals such as Co, Ce, Fe, Mg, and Ni for the pyrolysis reaction of plastic waste. Existing challenges and future viewpoints applied to suggestions of the current study are established, and summaries were also proposed. This study is useful for scientists and the plastics industry to boost manufacturing and might serve as a guide to promote more research more favorably. Some potential benefits for plastic industries include converting waste into valuable products (such as biofuels, chemicals, and carbon black) and reducing raw material costs. Using plastic waste as a feedstock for catalytic pyrolysis can help to reduce the cost of raw materials, as waste materials may be less expensive than virgin materials. This can help to lower the overall cost of manufacturing and increase competitiveness in the market. Other industrial benefits are growing sustainability by converting waste materials into valuable products rather than disposing of them in a landfill or other waste treatment facility and potential for innovation. Catalytic pyrolysis is an emerging technology that is still being researched and developed. As such, it presents opportunities for innovation and the development of new products and processes. This can help to drive innovation in the plastics industry and increase competitiveness in the market. Moreover, the bibliometric analysis of keywords like "catalyst", "plastic", and "waste" can be helpful for scientists and serve as a valuable guide to promote more research by providing insight into research trends, evaluating the impact and influence of research, and identifying opportunities for collaboration and productivity.

2. Bibliometric analysis

We employ bibliometric methodology, which uses quantitative methods to analyze bibliometric and bibliographic data (Pritchard 1969). The Web of Science Core Collection is the most reliable worldwide citation database because of the data's thorough review and curation. WoS contains more extensive scientific citations than other databases like Scopus, emphasizing more recent sources (Adriaanse and Rensleigh 2013). One of the strengths of WoS is its emphasis on more recent sources, as it was established later than some other databases, such as

Table 1 Summary of published articles (1970–2022) in the WOS database by merging the title search to keywords such as “catalyst”, “plastic”, and “waste” and topic search to keywords like “review”.

No.	Year	Main focus	Ref.
1	2012	“Developing advanced catalysts for the conversion of polyolefinic waste plastics into fuels and chemicals” ● The catalytic cracking of polyolefins over solid acids was explored. ● The role of catalysts in synthesizing fuels and chemicals and the employed reaction systems were reviewed.	Serrano et al. (2012)
2	2020	“Review of catalyst materials in achieving the liquid hydrocarbon fuels from municipal mixed plastic waste (MMPW)” ● Catalytic pyrolysis technology’s most recent advancements and issues in producing viable hydrocarbon fuels from municipality-mixed plastic trash were reviewed. ● Gaps between catalytic pyrolysis and conventional-thermal pyrolysis technology were found.	(Moorthy Rajendran et al., 2020)
3	2021	“Experimental study on catalytic pyrolysis of plastic waste using low-cost catalyst” ● The feasibility of using fly ash as a catalyst in the pyrolysis of HDPE and LDPE plastic waste was investigated. ● The physicochemical characteristics of the collected oil were assessed and contrasted with those of the useable polymerized forms of diesel and gasoline fuels.	(Nalluri et al., 2021)
4	2021	“Deactivation and Regeneration of Zeolite Catalysts Used in Pyrolysis of Plastic Wastes-A Process and Analytical Review” ● The oxidative processes for catalyst renewal are examined. ● The reviewer discussed the state of oxidation treatments at the time and listed the benefits and cons of each technique.	(Daligaux et al., 2021)
5	2021	“Progress on catalyst development for the steam reforming of biomass and waste plastics pyrolysis volatiles: A review” ● The essential components of the pyrolysis-reforming of biomass and waste plastics were examined. ● The effects of synthesis techniques, pyrolysis-reforming conditions, and catalytic materials on the process performance were investigated.	(Santamaria et al., 2021)
6	2021	“Co-pyrolysis of biomass and plastic wastes: A review on reactants synergy, catalyst impact, process parameter, hydrocarbon fuel potential, COVID-19” ● The development of co-pyrolysis and its potential for treating plastic and biomass wastes were evaluated. ● During co-pyrolysis, the synergistic effects of biomass and plastic were explored.	(Ansari et al., 2021)
7	2022	“Chemical recycling of plastic waste for sustainable material management: A prospective review on catalysts and processes” ● Comprehensive summaries and evaluations of the research on using catalysts in diverse thermochemical processes are provided.	(Huang et al., 2022)
8	2022	“Jet fuel produced from waste plastic with graphite as a catalyst” ● To determine whether pyrolysis can convert a mixture of waste plastics into a resource. ● Using activated carbons (graphite) as a catalyst, waste plastic is transformed into jet fuel through catalytic pyrolysis.	(Ali et al., 2022)
9	2022	“Pyrolysis Combined with the Dry Reforming of Waste Plastics as a Potential Method for Resource Recovery-A Review of Process Parameters and Catalysts” ● The most recent research on the topic is summarized in this review. ● Review and discussion are given on the impact of process variables, catalyst type, and feedstock.	(Pawelczyk et al., 2022)
10	2022	“Prospective review for development of sustainable catalyst and absorbents from biomass and application on plastic waste pyrolysis” ● The current study aims to describe the processes used to handle plastic trash through thermal, catalytic, and microwave pyrolysis. ● Under thermal pyrolysis, the impact of operational factors such as temperature, time, feedstock types, and product yield is explored.	(Rex et al., 2022)
11	2022	“Bibliometric analysis and an overview of the application of the nanocatalysts for pyrolysis reaction of plastic waste” ● The bibliometric analysis provided up-to-date materials, expertise in emerging developments, and interest in catalysts, plastic, and waste. ● The various advantages of pyrolysis were thoroughly discussed. ● The presence and effects of plastic waste on the environment were explored. ● Investigation of the publication trend and country collaboration and co-authorship. ● Authors and occurrence network studies. ● Subject category distribution for the literature. ● Review the nanomaterials used in the pyrolysis process for some detected papers. ● Challenges of previous studies and directions for future research were provided.	Current research

Scopus (ScientificPublications 2022). Furthermore, WoS’s citation analysis is more thorough and offers better visuals than Scopus’s citation analysis (Falagas et al., 2008). Overall, the comprehensive coverage, quality content, cited reference searching, user-friendly interface, and widespread use make the Web of Science a valuable resource for researchers and scholars (Levine-Clark and Gil 2009, Salisbury 2009). Herein we choose the WoS database to attain the data for our research and bibliometric analysis. After engaging the topic search criteria and using keywords such as "catalyst", "plastic", and "waste" on 25th/Sep/2022, we could find 1767 research items from 1970 to 2022. We selected all "Document Types" and did not limit them to a specific publication type. The types of documents were article, proceeding paper, review articles, early access, book chapters, meeting abstracts, editorial material and corrections; however, there was no patent in the search. We also included all research areas, all authors, all MeSH headings and qualifiers, and all publication sources. We did not exclude anything in terms of organisms, major concepts, conferences or meeting titles, funding agencies, group or corporation authors, editors, countries or regions, affiliations, and research domains. We downloaded the plain text file of the top 1000 highest-cited articles, exported the full record of the plain text file, and analyzed them by Rstudio and VOSviewer software. After employing VOSviewer and the biblioshiny function of the Rstudio, we have developed the bibliographic coupling of the countries, citations and publication reports, word cloud analysis, Sankey diagram, co-occurrence network map, growth of word dynamics map, trends of research topics, visualization map of co-authorship, thematic evolution map, and visualization map of country co-authorship.

The publications and typical citations per year of the works that have been reviewed are shown in Fig. 1. Annual papers and citations, in general, demonstrated an increasing tendency, with the great majority of these papers being articles, particularly in the last six years. For the period 1970–2022, the number of citations far exceeds the number of records of the publications. The citations began in 1993, and the year with the most citations (10930) was 2021. It should be stated that the saved amount of published items and citations in 2022 was 267 and 9241, respectively; this is because records for nine months of a year were available by the end of the retrieval date (25th Sep 2022). Citations enable academics to recognize the contributions of other authors and researchers in the catalyst, plastic, and waste field of study.

Fig. 1 presents a bibliographic coupling analysis of the countries included in the study with an overlay visualization. Bibliographic coupling refers to the relationship between two works citing the same third work in their bibliographies, indicating that they may deal with a similar subject matter. When two papers cite one or more other documents, they are said to be bibliographically connected. For this analysis, the maximum number of countries per document was set at 25, and the minimum number of records for a country was set at 5. Of the 56 countries included in the study, 28 met these thresholds. This coupling analysis also provides a visual representation of the cooperation between countries based on scientific maps. The total strength of the bibliographic coupling links for each country was considered concerning the other countries, with overall citation counts weighting the frames. The scores are subjective based on each country's typical number of citations (the total citation count for a country is divided by that country's number of publications). Larger frames indicate greater overall citations, while different colors signify varying levels of typical citations. The lines between countries represent links between these countries, with closer and thicker lines indicating greater co-authorship between the linked countries. With a substantial dissimilarity, the top country in this list was Spain, with 75 publications, 6271 citations, and 29,573 total link strength. For the other countries, the first records are the number of publications, the second is the number of citations, and the third is their total link strengths. The

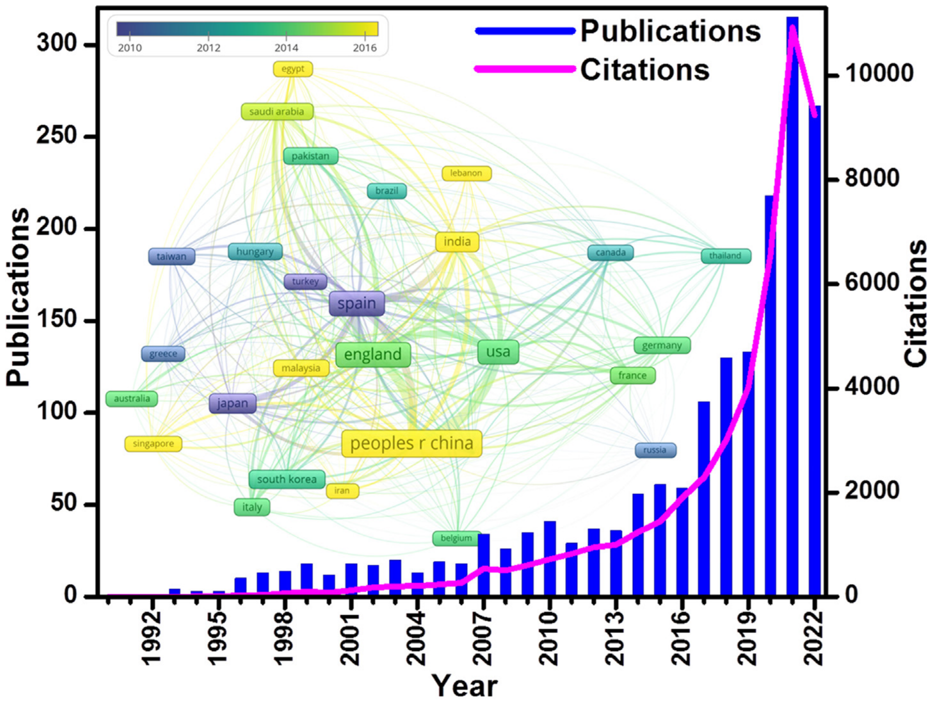

Fig. 1 WoS citation and publication yearly trends for the topic search of "catalyst", "plastic", and "waste" along with bibliographic coupling of the countries (overlay visualization) from 1970 to 2022 as per 25th Sep 2022.

other countries were; China (98; 5658; 29245), England (77; 5815; 28441), USA (70; 6757; 24050), India (37; 2384; 16623), Saudi Arabia (14; 1413; 9392), Japan (37; 2353; 7668), Canada (7; 865; 6599), France (14; 950; 5724), Poland (15; 1040; 5685), Malaysia (14; 2017; 5597), Germany (11; 1426; 5383), Italy (20; 1090; 5141), Pakistan (14; 692; 4939), South Korea (24; 1323; 4930), Egypt (7; 510; 4202), Hungary (14; 889; 3931), Taiwan (11; 514; 3455), Singapore (10; 721; 3407), Thailand (6; 418; 3314), Iran (5; 212; 2427), Belgium (5; 489; 2298), Turkey (8; 392; 2089), Greece (10; 988; 1893), Brazil (9; 482; 1854), Australia (9; 582; 1839), Lebanon (5; 233; 1745), and Russia (5; 384; 738). The colors in Fig. 1 show the publications years regarding the countries of origin. The yellowish frames reveal that China, India, Iran, Singapore, Malaysia, Lebanon, and Egypt have the most recent publications in this field. Table 2 shows the top countries according to total link strength.

To condense the view of our research topic related to catalysts, plastic, and waste, we developed the word cloud, and the overview can be seen in Fig. 2. A word cloud, also known as a tag cloud, is a graphic illustration of text statistics in the form of labels. The present research addresses the nanocatalysts for pyrolysis reaction of plastic waste trend identification challenge by generating insights on catalysts for pyrolysis recycling of plastic waste, using the available research items across the WoS database. Fig. 2 shows a word cloud of the text of the 50 most popular words base on the level of frequency. The frequency level refers to the number of times a particular word appears in the analyzed text. The most repeated words are "degradation", "pyrolysis", "high-density polyethylene", "polypropylene", "polyethylene", "conversion", "cracking", and "plastics". This could be seen as substantial in a study about the experiences of degradation because research appears to be process-driven authors who deliberate and carefully select their research on plastic waste and catalysts. Particularly, the term "degradation" was a leading descriptor for how articles framed their research and findings. A qualitative analysis showed that keywords such as "catalysts," "acid," "zeolite," and "silica-alumina" were used significantly less frequently in research on plastic waste recycling and catalytic pyrolysis reactions. A graphic like this one, therefore, aids in understanding the vast variability and complexity of the articles for research in catalysts, plastic, and waste.

Table 2 The top countries ranked according to the total link strength.

Country	Publications	Citations	Total link strength
Spain	75	6271	29,573
China	98	5658	29,245
England	77	5815	28,441
USA	70	6757	24,050
India	37	2384	16,623
Saudi Arabia	14	1413	9392
Japan	37	2353	7668
Canada	7	865	6599
France	14	950	5724
Poland	15	1040	5685
Malaysia	14	2017	5597
Germany	11	1426	5383
Italy	20	1090	5141
Pakistan	14	692	4939
South Korea	24	1323	4930
Egypt	7	510	4202
Hungary	14	889	3931
Taiwan	11	514	3455
Singapore	10	721	3407
Thailand	6	418	3314
Iran	5	212	2427
Belgium	5	489	2298
Turkey	8	392	2089
Greece	10	988	1893
Brazil	9	482	1854
Australia	9	582	1839
Lebanon	5	233	1745
Russia	5	384	738

A Sankey diagram is a standard graphic representation to depict the proportion of research topics based on keywords for each country and the source of the papers and to display a flow from one data set to another. Nodes and links are the terms used to describe the linked objects and relationships. Herein, to illustrate the percentage of study subjects for each country and the relevance of the papers they mentioned, a three-field Plot (Sankey diagram) of Country, Keyword, and Year of Publication of the cited references was developed. By utilizing broader rectangles to represent more frequent occurrences and many thick inflows and outflows to represent more links, this map summarizes the relative significance of themes, the research nation, and the journals in which the works were published. As seen in Fig. 3, most articles have focused on advancing pyrolysis techniques for recycling plastic waste. The analysis established that the "pyrolysis", "catalyst," and "plastic waste" keywords in machining operations had been used most frequently by different countries and journals. The main interests of catalytic pyrolysis of plastic waste researchers in China are pyrolysis and catalyst development. The most frequent topic of research in the UK are pyrolysis and plastic. Most papers discussing the mentioned topics have been published in China, the UK, India, the US, and Spain. The main research topics in Turkey, France, Poland, Egypt, Germany, and Brazil are HDPE, polypropylene, carbon nanotube, and biomass. Among the journals, the *Journal of Analytical and Applied Pyrolysis* produced studies with the broadest coverage of the various author keywords and countries. Nevertheless, "catalyst" and "plastic waste" were covered more comprehensively by *Energy Conversion and Management*. Other journals such as *Waste Management, Chemical Engineering Journal, Journal of Cleaner Production*, and *Applied Catalysis B-Environmental* have also been used by many countries to publish research articles that primarily contain keywords such as pyrolysis, catalytic pyrolysis, catalysts, and plastic waste.

The theme evolution of the research area is quantified and shown using a technique that combines performance analysis and scientific plotting to identify and display theoretical subdomains. Fig. 4 demonstrates the evolution of keywords in two altered periods (1992–2017 and 2018–2022). The inclusion index is inversely correlated with the arrow thickness. The box size corresponds to how frequently the topic appears in the literature. Keywords "hydrogen-production and degradation" are essential keywords as these show up in both stages; however, "emissions", "biomass gasification", "mechanical properties", and "depolymerization" has only shown up in the

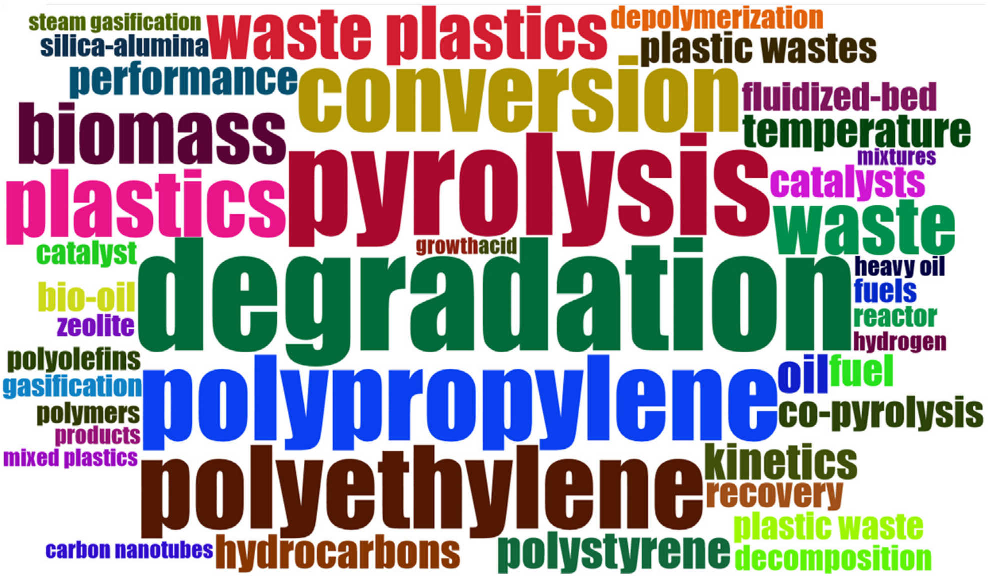

Fig. 2 Word cloud analysis with Rstudio for word frequencies, number of words = 50.

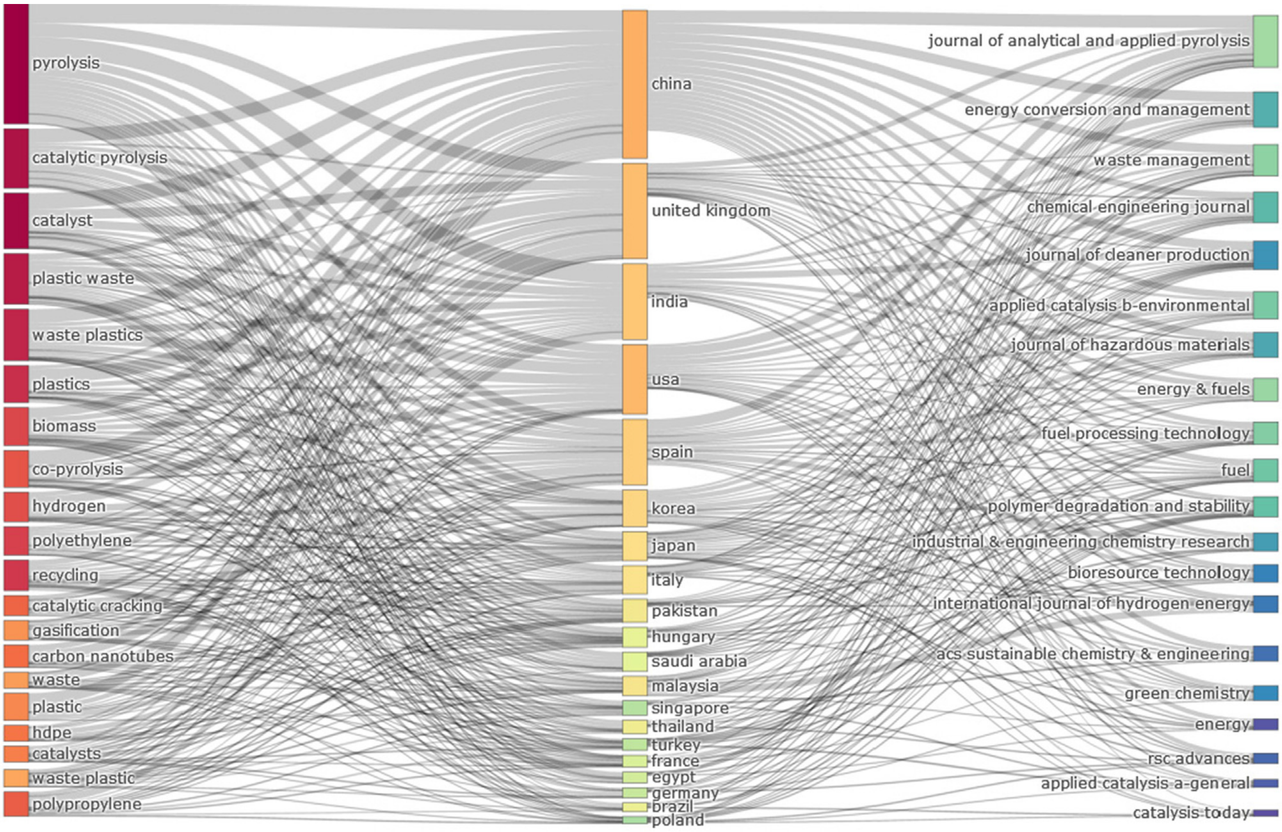

Fig. 3 A three-field Plot (Sankey diagram) of country (middle), Keyword (left), and Source (right) of publication for research in catalyst, plastic, and waste with number of items = 20.

first stage. In the second period, the newly labeled themes contain a study of more complexity. In the second period, new research areas such as "kinetics", "high-density polyethylene", "chemical-vapor-deposition", and "ring-opening polymerization" themes have stood out. Research related to degradation contributes to scientific advancements in catalysts, plastic, and waste, but they are closely linked to non-noble materials such as nickel and emission issues. Consequently, one essential definition of a thematic region is a community of themes that have emerged throughout distinct sub-periods. However, it is

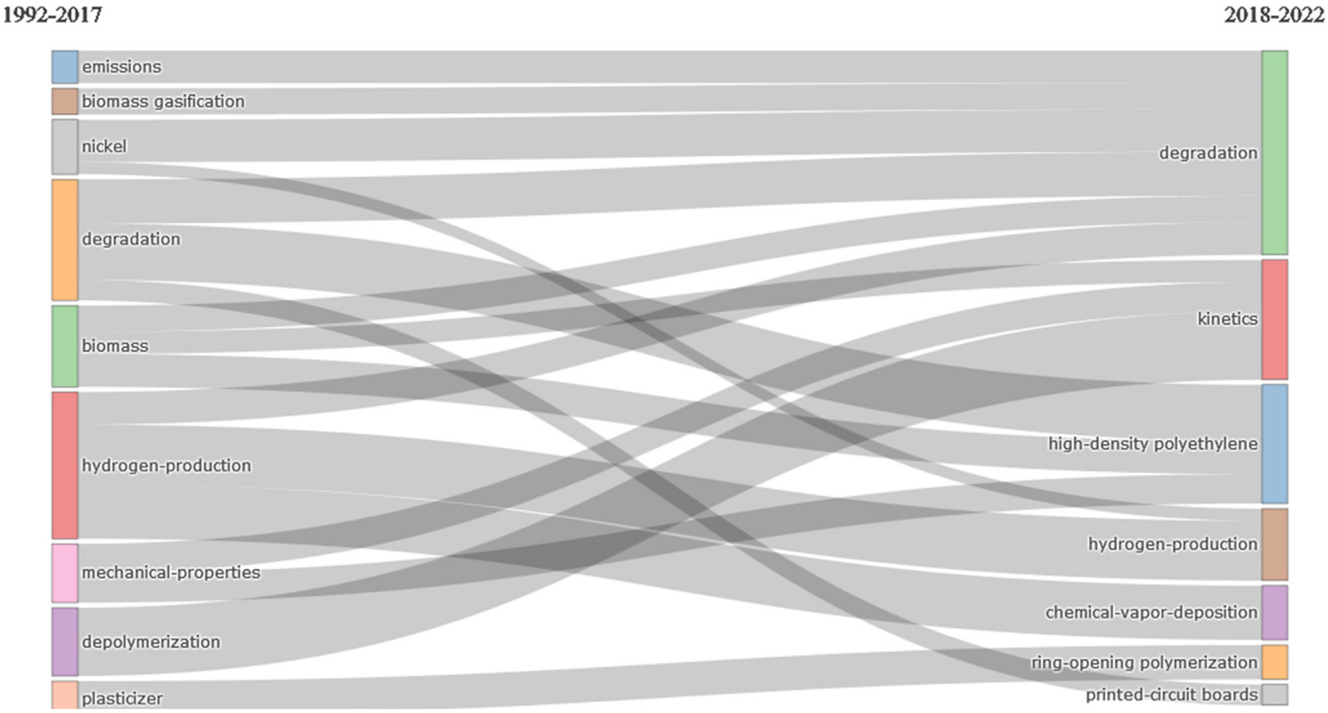

Fig. 4 Thematic evolution map of keywords from 1992 to 2022 with respect to catalyst, plastic and waste.

challenging to distinguish whether an investigation is conducted by individuals or by several countries in combined advantages based on the word cloud (Fig. 2), three fields plot (Fig. 3), and thematic evolution map (Fig. 4). Thus, we developed the global cooperation map (Fig. 5) and co-occurrence network visualization (Fig. 7) to illustrate research collaborations and possible synergies between the two fields.

The co-authorship network of countries was shown using VOSviewer software to evaluate the global co-authorship of the nations that published articles in the catalyst, plastic, and garbage categories. Fig. 5 depicts the joint work of countries with the minimum number of documents of a country as 5, with a minimum number of citations as zero. Out of 68 countries, 37 countries (frames) and 176 co-authorships comprise the catalyst, plastic, and waste co-authorship network (links) that met the threshold. The frames' sizes correspond to the keywords' frequency, with larger frames denoting more frequent use. The length and thickness of the edges reveal how closely the two frames interact with one another. The colors of the frames in Fig. 5a show the cluster to which the countries belong. As seen in Fig. 5a and Table 3, the most projecting countries (publications; citations; and total link strength) on the map include China (218; 7380; 142), England (120; 6511; 97), USA (113; 7506; 73), Spain (115; 6880; 41), France (26; 1121; 38), India (86; 3115; 36), Malaysia (32; 2278; 34), Japan (65; 2788; 33), Saudi Arabia (26; 1573; 31), and South Korea (60; 1927; 30).

Furthermore, a yearly overlay map has been developed because it is a specific type representing data over time, with each year described as a separate layer or map. Overlay yearly maps can be used to visualize trends and patterns in data over time, to compare data between different years, and to identify changes or trends in the data over time. The yellowish frames (Fig. 5b) show that the most recent publications in this field are from Indonesia, Singapore, Nigeria, Malaysia, Switzerland, North Ireland, Netherlands, Belgium, Egypt, Oman, and New Zealand.

Co-authorship is a relationship in which two or more researchers collaborate to publish their findings on a particular subject. As a result, co-authorship networks may be considered collaboration networks made up of scholars who show their collaboration. Fig. 6 displays a co-occurrence linkage diagram produced from the authors' publications, and Table 4 lists the top authors based on the total link strength. In co-authorship networks, frames stand in for researchers, frames size for co-occurrence weight, color, and proximity correspond to the networked relationship clustering, and the names of authors (text) are comprised in a map. The illustration shows the network of co-authorship associations between 126 authors (out of a total of 3192 authors), with the maximum number of authors per document set at 25 and the minimum number of records per author set at 5. Authors who co-occur more frequently tend to be closer in the visualization, while clusters reflect groupings of closely linked authors. The red group includes authors (publications; citations; and total link strength) such as Paul T. Williams (46; 2507; 82), Chunfei Wu (26; 1480; 47), Han-Ping Chen (9; 680; 32), Dingding Yao (10; 563; 28), and so on. This cluster is linked with the white, blue, and purple ones. The second cluster is the green one that includes scholars, namely Gartzen Lopez (21; 1445; 100), Aitor Arregi (10; 375; 56), Martin Olazar (28; 1809; 126), and so on. This cluster is strongly connected with all other clusters (except the purple one). The third cluster depicted in blue comprises Javier Bilbao (35; 2074; 145), who has collaboration and linkages between light blue, yellow, and red clusters. In terms of publication years, as mentioned in the overlay visualization view of the VOSviewer, Dingding Yao (10; 563; 28), Ningbo Gao (7; 318; 7), Laura Santamaria (5; 95; 25), Alazne Gutierrez (6;

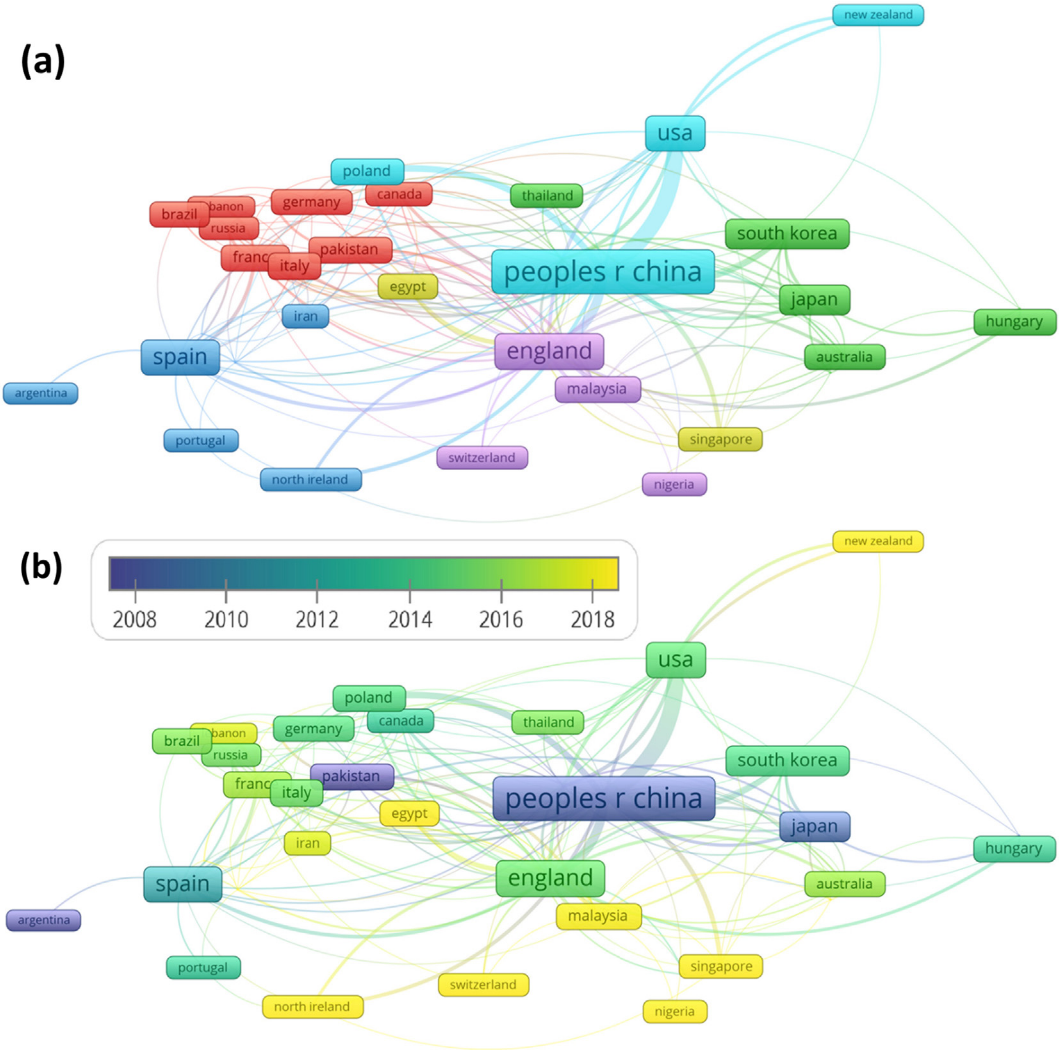

Fig. 5 VOSviewer (a) network visualization and (b) overlay map of country co-authorship.

Table 3 The top countries ranked according to the total link strength of countries' co-authorship.

Country	Publications	Citations	Total link strength
China	218	7380	142
England	120	6511	97
USA	113	7506	73
Spain	115	6880	41
France	26	1121	38
India	86	3115	36
Malaysia	32	2278	34
Japan	65	2788	33
Saudi Arabia	26	1573	31
South Korea	60	1927	30

127; 23) have published the most recent publications in the field of catalyst, plastic, and waste.

For the analysis of large documents and keywords in the WoS database, we conducted the co-occurrence networks map by the VOSviewer software, and the illustration is shown in Fig. 7. Co-occurrence is a term that describes the frequent occurrence, shared existence, and proximity of related keywords on the WoS database. Co-occurrence may contain words roughly similar and associated with the same subject. It is a content analysis method that creates semantic visual maps that show the cognitive structure of the subject under investigation using author keywords. The analysis of the keywords related to our search generated 3538 results. Of these results, only 186 met the threshold when we set each keyword's minimum number of occurrences at 10. The output results are organized into four clusters to facilitate clear visualization of the connections among the keywords, which are represented by nodes and links. This allows for a better understanding of the relationships between the keywords and the patterns within the data. A method similar to modularity-based clustering is used to group the keywords (Waltman et al., 2010, Andersen et al., 2020); each term is examined and put in the cluster where it co-occurs most frequently, shown by color. The node size reflects the centrality of the keywords, the line thickness reflects the frequency with which keyword pairs appear together, and the link joining of the two nodes signifies the relationship between the two keywords. The 10 most occurring keywords (with occurrences; total link strength) is pyrolysis

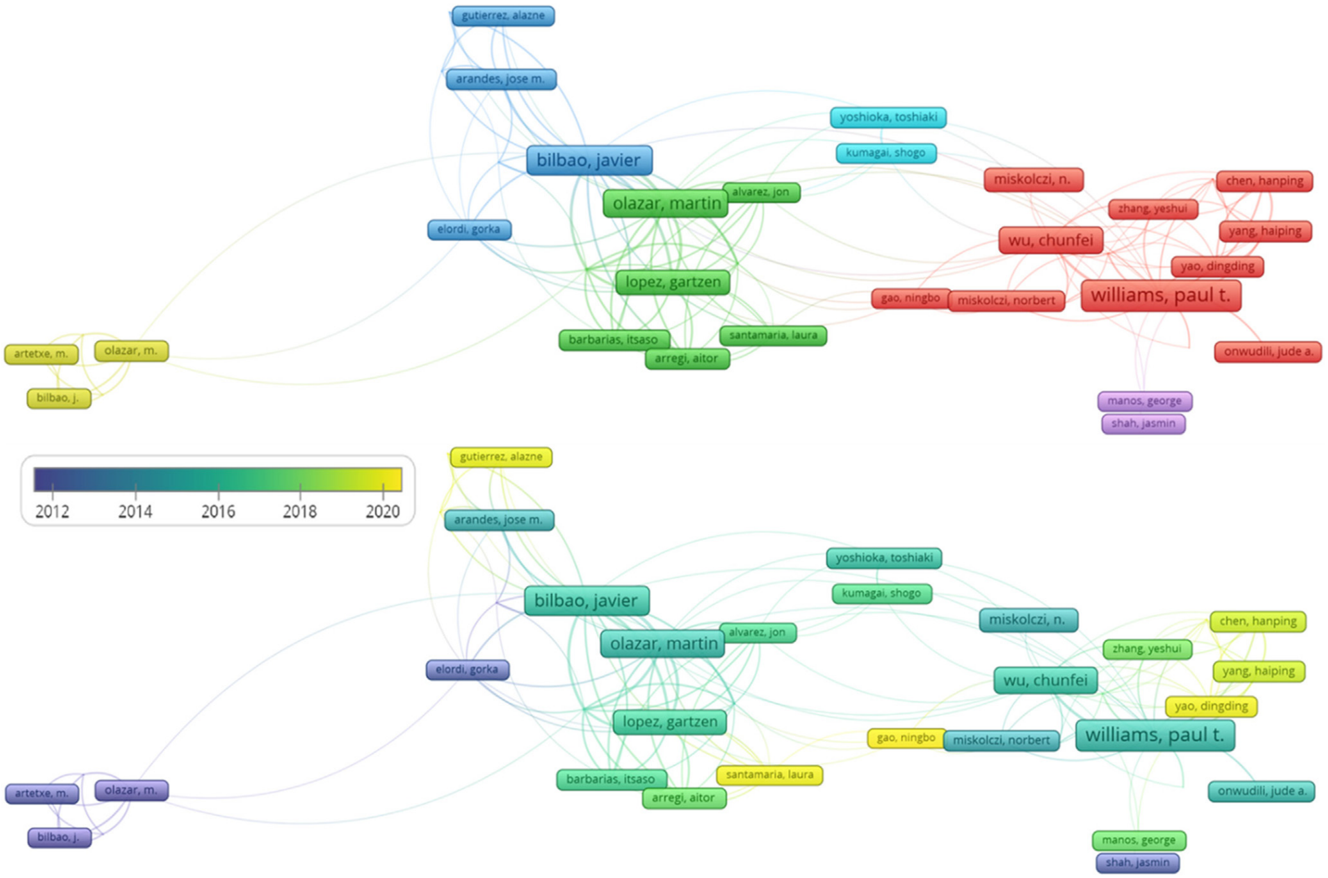

Fig. 6 VOSviewer network and overlay visualization map of co-authorship using author names.

Table 4 Top 20 authors base on total link strength.

Author	Publications	Citations	Total link strength	h-index
Javier Bilbao	35	2074	145	88
Martin Olazar	28	1809	126	81
Roger Ruan	22	666	103	75
Gartzen Lopez	21	1445	100	59
Maite Artetxe	19	1342	94	36
Paul T. Williams	46	2507	82	87
Hanwu Lei	16	888	67	37
Tao Tang	16	597	59	60
Aitor Arregi	10	375	56	22
Xuecheng Chen	12	436	56	42
Jiang Gong	12	431	54	41
Maider Amutio	11	1090	52	47
Itsaso Barbarias	9	391	50	14
Ewa Mijowska	10	339	50	53
Xin Wen	9	349	50	33
Yunfeng Zhao	7	228	49	39
Jia Wang	7	123	47	14
Chunfei Wu	26	1480	47	49
Jie Liu	8	340	46	45
Moriko Qian	8	314	46	21

(325; 2414), degradation (212; 1605), polypropylene (180; 1504), polyethylene (184; 1398), plastics (171; 1219), high-density polyethylene (154; 1204), cracking (144; 1184), biomass (142; 1045), conversion (133; 1044), and waste plastics (148; 998). It is clear that there are research clusters that the researcher directs when authors focus on a specific part of the pyrolysis (green cluster), catalyst (red cluster), plastic waste (yellow cluster), and biomass utilization (blue cluster). The

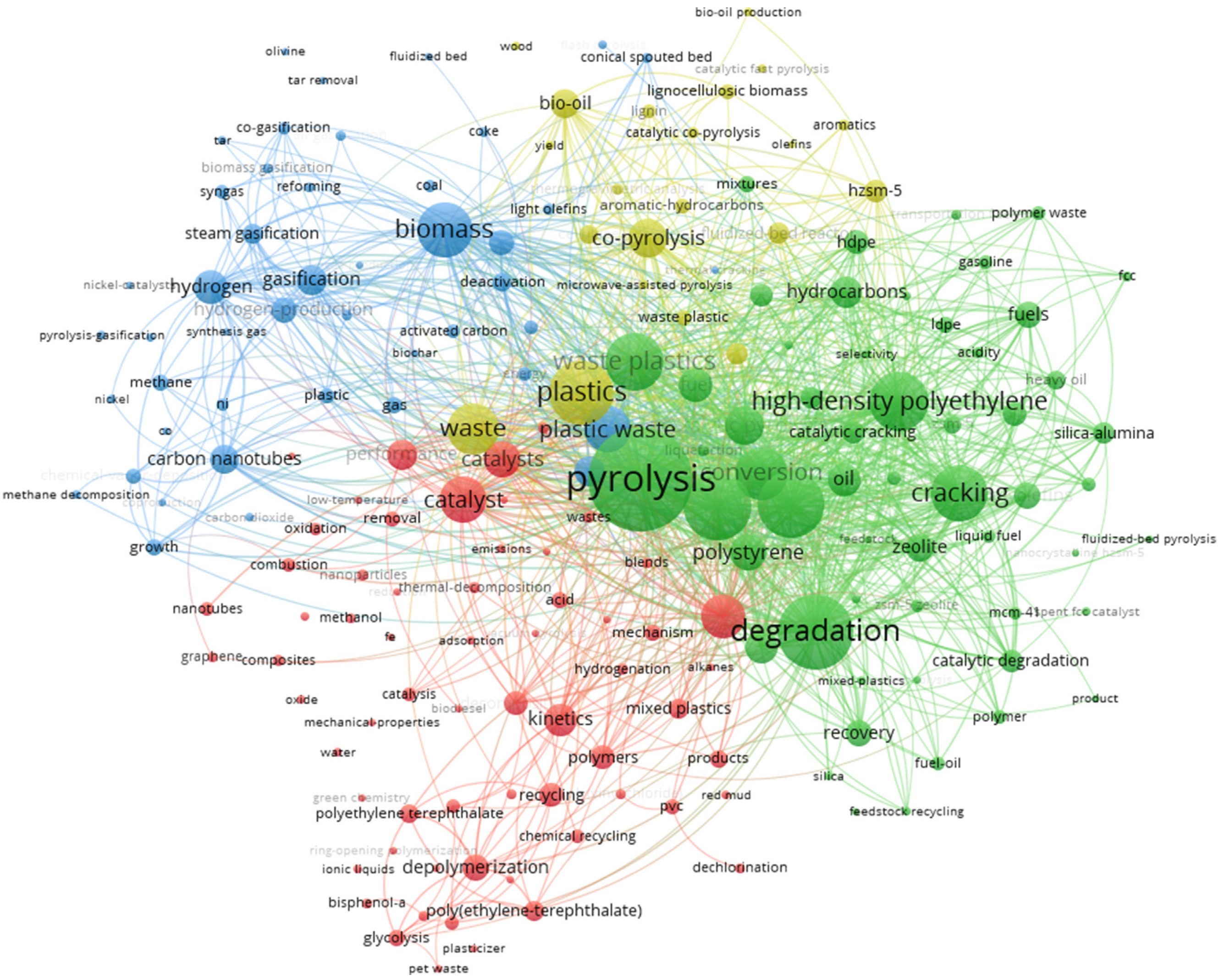

Fig. 7 Co-occurrence network map of keywords based on total link strength (Search criteria: Topic= "catalyst", "plastic", and "waste"; all keywords; minimum number of occurrence of a keyword = 10; 186 keywords met threshold; on 25th.September.2022).

detected keywords for the red cluster are "catalyst", "thermal degradation", "kinetics", "performance", "products", "low temperature", and "nanoparticles". After employing such keywords in the topic search of the WoS database, 78 published items were detected. The five top-cited papers were focused on the employment of ZnO nanoparticles (Bhatia and Verma 2017), Z-scheme $MoSe_2/CdSe$ (Wang et al., 2019), $Fe_2O_3/g\text{-}C_3N_4$ (Liu et al., 2019), Cerium-doped mesoporous TiO_2 nanoparticles (Xiao et al., 2006) for photocatalysis application, and nitrogen-doped graphene for metal-free catalytic oxidation (Indrawirawan et al., 2015). Another section of this cluster focuses on how thermal degradation can influence the catalytic pyrolysis reaction of plastic waste. The second cluster in green color mainly dealt with "pyrolysis", "polypropylene", "polyethylene", "high-density polyethylene", "cracking", "degradation", "conversion", and "waste plastics". After employing these keywords in the topic search of the WoS database, we could find 58 research items that mostly focused on research areas such as thermal degradation, silica-alumina, fuels, and polyolefins. The third cluster in blue detected keywords such as "hydrogen", "biomass", "gasification", and "carbon nanotubes". After employing such keywords in the WoS database topic search, the detected articles focused on nickel catalysts, tar, nanotube materials, steam gasification, and methane decomposition. Gong et al. (Gong et al., 2014), for eample, employed mixed catalysis of CuBr and NiO to convert polyethylene (PE), including HDPE, LDPE, and LLDPE, into high-value-added carbon nanomaterials (CNMs). Br radicals enhanced the creation of long, straight, and surface-smooth CS-CNTs by promoting the dehydrogenation and aromatization of LLDPE fragment radicals to produce a significant number of light hydrocarbons and a negligible amount of aromatics. Br radicals encouraged the random cleavage of HDPE, which produced short, winding, and surface-rugged CNFs by forming more long-chain olefins and fewer gas products and aromatics. The yellow cluster focused on "waste", "plastics", "co-pyrolysis", "bio-oil", and "HZSM-5". In accordance to the total link strength of this cluster, there is a lack of research in the field such as "seed oil", "microwave pretreatment", "municipal plastic film wastes", "carbon distributions", "mono-aromatics", and "mesoporocity development". It is important to note that keywords are frequently dispersed in two or more clusters inside a single publication, which leads to an intriguing phenomenon in keywords co-occurrence patterns or the degree to which various groups overlap. In general, studies related to catalysis (23; 188), nanocrystalline HZSM-5 (10; 91), Co (10; 76), nickel-catalysts (10; 69), and Fe (10; 47), were among the least frequent keywords. Thus, there is a lack of research on the mentioned keywords for catalysis reaction, especially in the pyrolysis process and non-noble materials.

Descriptive research has several benefits, one of which is the ability to examine data and provide a thorough grasp of the study topic. Determining how to research keywords through dynamic word growth in real-world situations is another advantage of descriptive research. A word dynamic-growth graph was created using the top frequent keywords to assess the keyword dynamics across the study period (1970–2022). Each word's repetition trend (i.e., how frequently it appears in the dataset throughout the search) represents occurrences. The most frequent top ten keywords are degradation (1994), pyrolysis (1876), high-density polyethylene (1358), polypropylene (1536), polyethylene (1417), conversion (1306), cracking (1566), plastics (1212), biomass (601), and thermal-degradation (909). Based on Fig. 8, the yearly growth curve and occurrence value of keywords are used to explain the evolution of those terms. According to the growth of the word dynamics map, the terms used the most frequently started to develop in 1991 and have risen ever since. In those years, "biomass", "thermal-degradation", "plastics", and "cracking" had high ranks of frequency, but the usage rates of these keywords declined in the lasted decade. It can also be seen that pyrolysis and degradation studies, in general, have seen the most prominent development. This number also shows that researchers' interest in catalytic plastic waste is growing in terms of high-density polyethylene, polypropylene, polyethylene, and conversion.

Research topic modeling is a data mining and machine learning technique that identifies and extracts the main topics or themes from a large corpus of text data. It is often used to analyze research papers, articles, and documents to discern trends and patterns in research activity over time. One way to track the trends of a particular research topic over time is to use topic modeling to analyze a large dataset of research papers or articles on the topic, and then plot the frequency of the identified topics over time. Thus, Fig. 9 presents a visual trend analysis of the top ten significant research subjects from 1997 to 2022. Over the past three years, research into microwave-assisted pyrolysis, polyethylene terephthalate (PET), alkenes, and solid wastes has grown significantly. Thus, it is essential to choose the keywords carefully, especially for innovative research. In addition to the bibliometric analysis, we also performed a literature review on non-precious active metals such as Mg, Fe, Co, Ce, and Ni for the pyrolysis reaction of plastic waste in the next section.

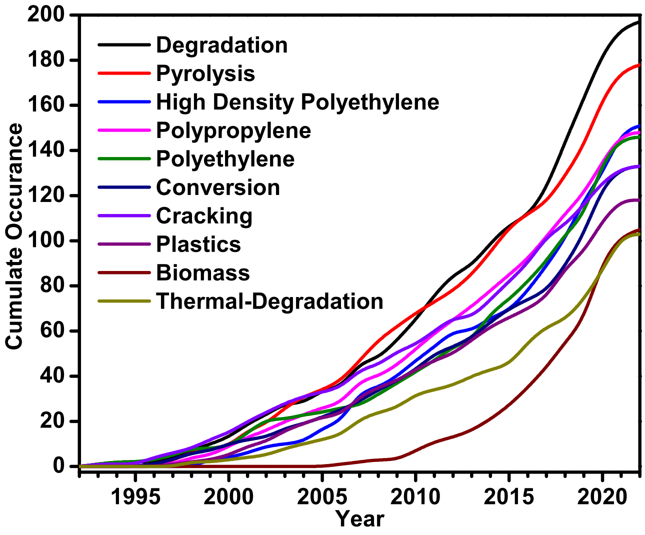

Fig. 8 Growth of word dynamics map over time.

3. Non-precious materials

Numerous single metals (including Co, Ni, Ce, Fe, and Mg) and their alloys, as well as metal phosphides, borides, and oxides, have recently been the subject of intensive research as low-cost and highly effective catalysts for the pyrolysis processes. After performing a title search using keywords such as "pyrolysis," "plastic," "waste," and "catalyst" and selecting the "Article" document type, 59 research items were identified. A summary of these studies is presented in Table S1. This section intends to highlight the application of a pyrolysis reaction based on non-noble nanoparticles as a catalytic helper for recycling plastic waste.

3.1. Magnesium (Mg)

Magnesium oxide (MgO) is an inorganic salt of magnesium formed with ions of magnesium and oxygen. Because of its basicity, redox characteristics, electronic and crystalline structure, and usage as a heterogeneous catalyst for various chemical processes (including the dehydrogenation of short-chain alkanes, epoxidation of alkenes, dehydrogenation or dehydration of alcohols, etc.) (Aramendía et al., 2003, Elkhalifa and Friedrich 2018). Due to its potential chemical and electronic uses and unique magnetic, optical, electrical, thermal, mechanical, and chemical characteristics, MgO has drawn much attention. MgO's distinct physicochemical features, such as its exceptional refractive index, make it an environmentally benign, economically viable, and crucial nanoparticle for industry (El-Moslamy 2018, Khan et al., 2020). As an irreducible oxide with a highly electropositive cation (Mg^{2+}), MgO has an intriguing chemical property in that when oxygen vacancies occur; they are anion vacancies with trapped electrons (Calatayud et al., 2003). In terms of structure, MgO is an oxide with a rock-salt structure, which implies that five O_2 ions surround each Mg^{2+} ion on the surface. It has been noted that magnesium oxide has surface flaws such as edges, corners, and bends. These flaws contribute to breaking the chemical bonds of the adsorbed molecules, which might affect how well the MgO functions as a catalyst (Klabunde et al., 1996, Knözinger et al., 2000, Elkhalifa and Friedrich 2018). Applications for MgO powder include catalysts, additives for heavy fuel oils, semiconductors, anti-reflection coatings, and medicines (Julkapli and Bagheri 2016). As a non-toxic and biodegradable hybrid platform for bioimaging applications, Jitao et al. (Li et al., 2021) reported the production and characterisation of silk fibroin (SF) coated magnesium oxide

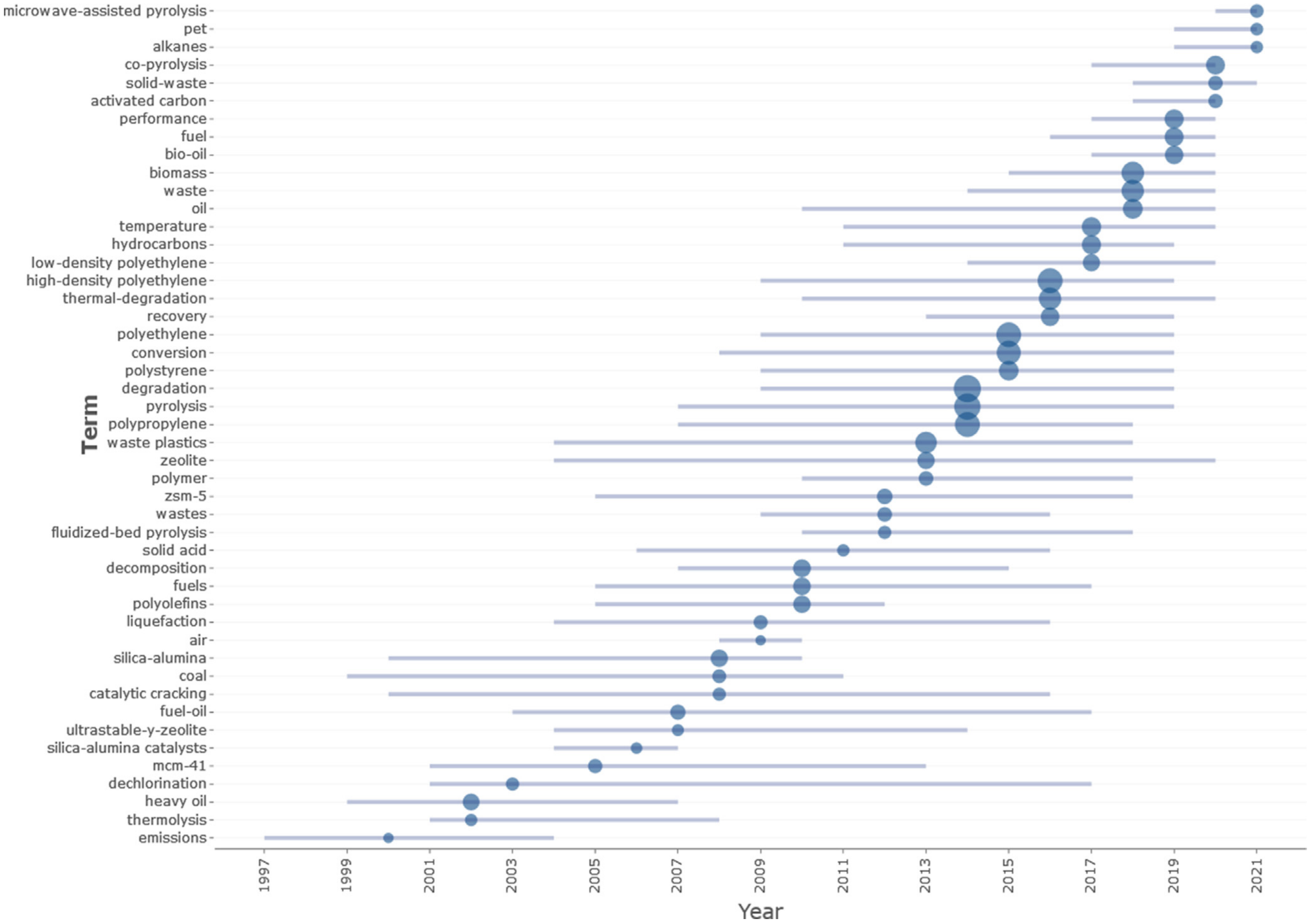

Fig. 9 Trends of research topic modeling over time.

(MgO) nanospheres with oxygen, Cr^{3+}, and V^{2+} associated optical defects. Fig. 10 shows the size and shape of MgO and MgO-SF spheres as determined by Field Emission Scanning Electron Microscopy (FESEM). In contrast to the bare MgO NPs, the MgO-SF spheres displayed a consistent spherical shape with less aggregation. The optical characteristics of the spheres revealed improved fluorescence and better quantum yield at two distinct excitation wavelengths. These complex optical structures, which combine fluorescent MgO and natural biopolymer silk, have the dual capabilities of drug delivery and bioimaging in addition to being biocompatible and biodegradable. Kuan and Huang (Kuan et al., 2013) demonstrated that CaO and MgO increase syngas output for the microwave pyrolysis of sugarcane bagasse, both of which are effective CO_2 adsorbents chemisorb CO_2 to generate $CaCO_3$ and $MgCO_3$ (Chanburanasiri et al., 2011, Jo et al., 2017). By chemisorbing CO_2, these catalysts lower CO_2 levels while facilitating water gas shift and reformation (Cheng et al., 2019). In summary, catalysts encourage secondary heterogeneous processes to increase syngas output during microwave pyrolysis of agricultural wastes (Zhang et al., 2015a, 2015b). After employing the "Magnesium oxide", "nano", "pyrolysis", "plastic", and "waste" keywords in the topic search of the WoS database, we could only detect three articles (Nahil et al., 2015, Abbood et al. 2020, Jia et al., 2020). Amal and Ibraheem (Abbood et al. 2020) employed MgO as a catalyst for carbon nanorod (CNRs) synthesis from plastic waste (PP), and the morphology of the sample were revealed by FESEM in Fig. 10(e and f). Large numbers of CNRs were discovered to have been produced. These nanorods have a carbon (25–46 nm) diameter and a length of a few micrometers. The XRD result confirms the ratio of the elements, which is shown in the result. The additional peaks seen in Energy Dispersive X-Ray Analysis (EDS) are related to the substrate and polymer additives utilized in the experiment. Jingbo et al. (Jia et al., 2020) applied Mg material to convert low density polyethylene (LDPE) and polypropylene (PP) into value-added carbon nanotubes (CNTs) and revealed that Mg causes an increment of metal support interaction with Ni metal. The work offered a method for designing and creating extremely effective catalysts to transform polymers into CNTs with additional value.

3.2. Iron (Fe)

Iron forms compound in various oxidation states and are the fourth most prevalent metal by mass in the Earth's crust. Iron (hydr)oxides are a common occurrence in nature and are easily manufactured. Some iron (hydr)oxides arise naturally and solely in the nanometer size range. Over the past several years, iron nanostructures have garnered much interest as great catalysts used in various fields. Iron can reduce the energy barrier

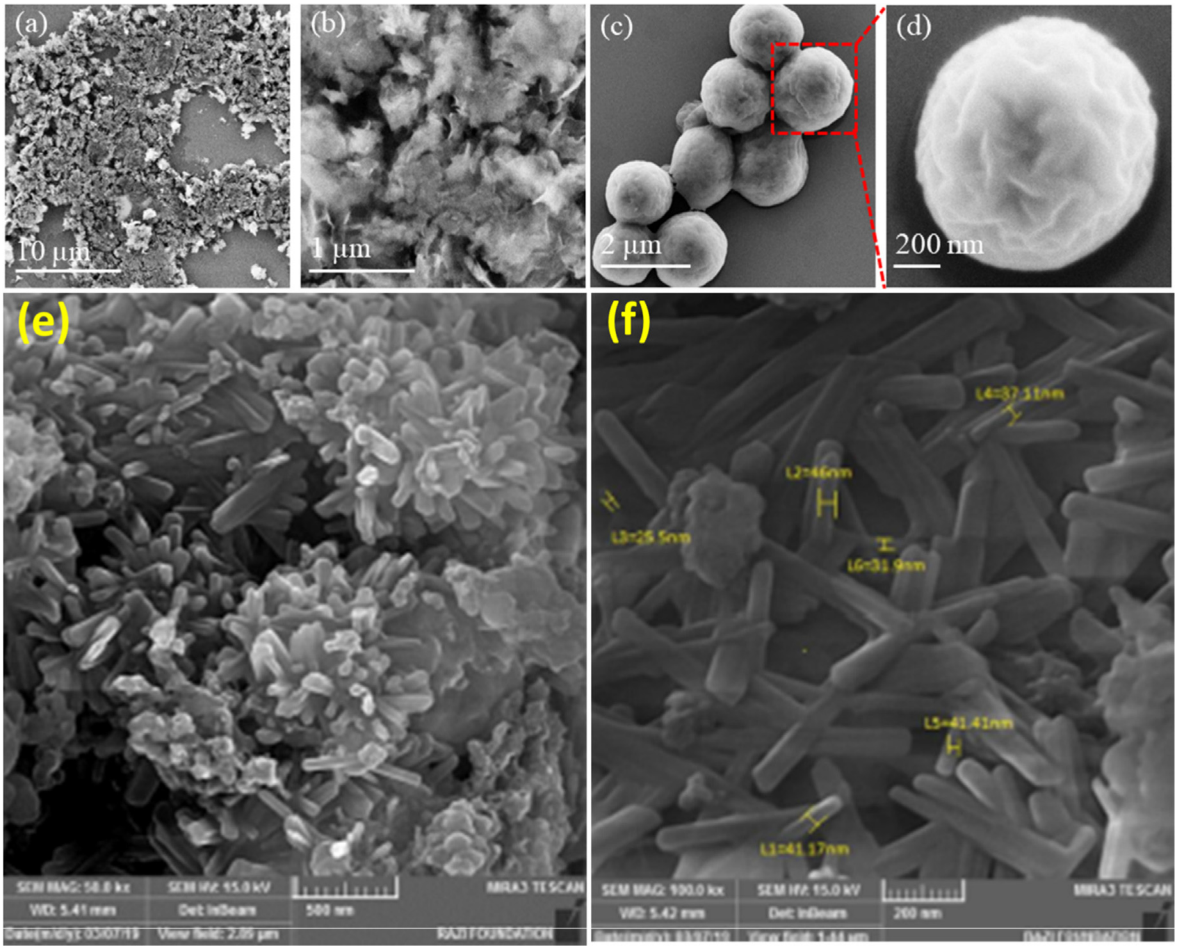

Fig. 10 FESEM micrographs of (a,b) MgO nanoparticles (NPs) and (c,d) MgO-SF spheres at different magnifications (Li et al., 2021); (e) FESEM image of CNRs grown on MgO at 500 nm and (f) at 200 nm (Abbood and et al. 2020).

in some processes by transitioning from one oxidation state to another, acting as a catalyst. However, it transforms back to its initial condition after the reaction, making it ready to begin again. Iron (hydr)oxides have been widely used as catalysts in various heterogeneous catalytic systems, including water splitting for hydrogen production, water–gas shift, steam reforming, the Fischer-Tropsch hydrocarbon synthesis, Haber-Bosch to produce ammonia, ethylbenzene dehydrogenation to produce styrene monomers, AOPs to oxidize pollutants in water and soil, and aerobic oxidation of organic compounds to produce new products for the fine chemical industry (Pereira et al., 2012). Geetu and Pethaiyan (Sharma and Jeevanandam 2013) synthesized FeO@Ag core–shell nanoparticles via the thermal decomposition method to reduce 4-nitrophenol and methylene blue, and the FESEM images are shown in Fig. 11 (a and b). When used to reduce 4-nitrophenol and methylene blue in an aqueous mixture, FeO/Ag core–shell nanosized samples show great promise as catalysts. The catalysts are very simple to separate using an outside magnet. Using silver nanoparticles to additional magnetic core materials might be made possible by extending the current synthetic strategy. Under uncontrolled pH circumstances and without Fe hydroxide precipitation, heterogeneous catalysis uses iron that is stabilized within the interlayer gap of the catalyst's structure to efficiently create hydroxyl radicals from the oxidation of hydrogen peroxide (Garrido-Ramírez et al., 2010). Yuxue and co-authors (Wei et al., 2020) synthesized hierarchically mesoporous iron oxide/graphene oxide (GO) compounds have been by a simplistic, one-step hydrothermal technique and used as Fischer–Tropsch synthesis (FTS) catalysts. Fig. 11 (c) provides a schematic representation of the hierarchically mesoporous catalysts. High C_{5+} selectivity and olefin: paraffin ratio is produced due to the increased porosity, which also encourages the rapid mass transfer of reactants and yields. This gives the gas a more straightforward entrance to the surface and improves the contact between reaction intermediates and active sites. Catalysts with a hierarchical mesoporous structure often exhibit faster reduction and carburization behaviors, promoting iron carbide production. This is because the metal-support contact is somewhat weaker in these catalysts. Catalysts with a hierarchically mesoporous structure, such as those made of iron supported on graphene oxide (Fe/G-N), often have larger surface areas, higher porosities, and more straightforward reduction and carburization behaviors compared to other types of catalysts. This provides more exposed surface sites for syngas adsorption and makes it easier for reactants to reach and products to be released from active sites with less resistance to mass transfer. Iron catalysts generate a high yield of CNTs when compared directly to other catalyst metals, even though all metals may make CNTs (Kong et al., 1998, Govindaraj et al., 1999, Tan et al., 2009, Liu et al., 2013). The impact of employing iron, cobalt, and nickel catalysts on the generation of CNT from chemical vapor deposition (CVD) of

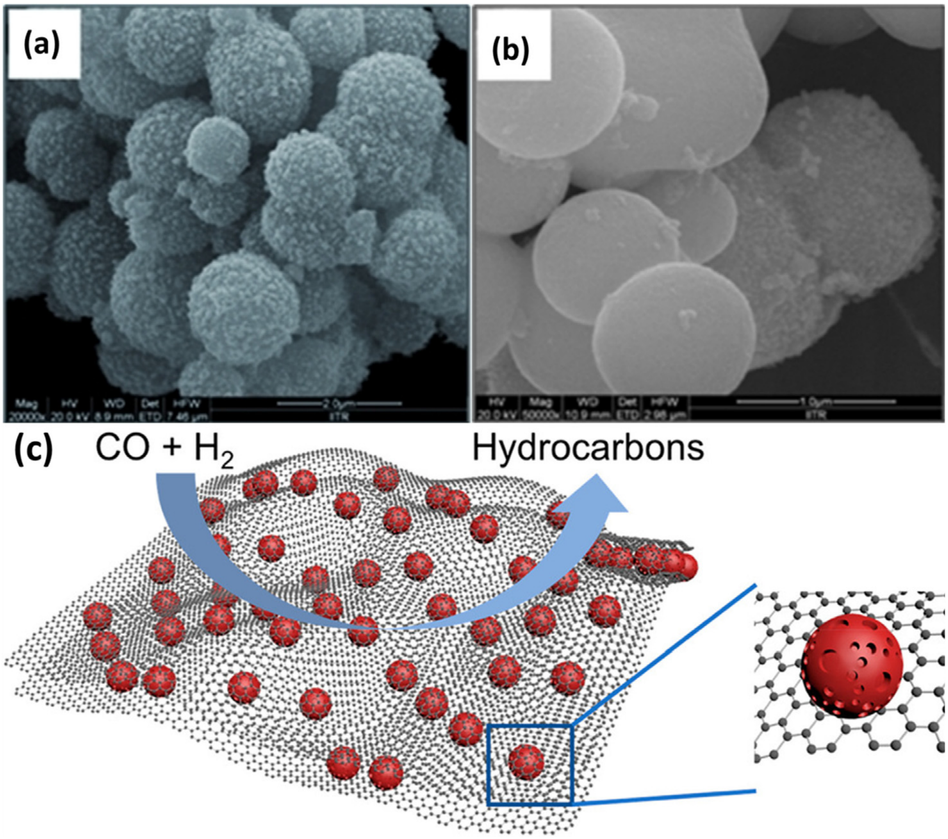

Fig. 11 (a) FESEM image of as-prepared iron oxide@Ag core–shell nanoparticles, (b) FESEM image of iron oxide@Ag core–shell nanoparticles prepared using different 0.25 mmol concentrations of silver acetate; (c) schematic drawing of the as-prepared hierarchically mesoporous graphene oxide-supported iron NPs catalysts. Reuse with permission from (Sharma and Jeevanandam 2013, Wei et al., 2020).

methane was examined by previous research (Liu et al., 2013). The increased carbon solubility of iron, which aids in forming carbon nanotubes, was credited with the iron catalyst's improved efficacy. Xiangyu et al. (Jie et al., 2020) employed iron-based catalysts as microwave susceptors for the rapid one-step process for the catalytic deconstruction of plastic waste. The highly efficient FeAlO$_x$ catalyst and microwave susceptor combined with incident microwaves can quickly extract over 97% of the hydrogen from plastic waste in 20 s. A possible solution to the growing problem of plastic waste is shown by the quick and selective generation of H$_2$ and carbon nanoparticles from the breakdown of plastics.

3.3. Cobalt (Co)

Good catalytic activity, great renewability, the high selectivity of heavy hydrocarbons, and low water–gas shift reaction activity are all benefits of the cobalt-based catalyst. Low-temperature Fischer-Tropsch synthesis may be carried out industrially using cobalt-based catalysts. Jun et al. (Chen et al., 2010) synthesized large Co$_3$O$_4$ nanocubes, β-Co(OH)$_2$ hexagonal nanodiscs, and nanoflowers via the hydrothermal method for the lithium storage capability and the morphologies of the uncalcined samples are shown in Fig. 12. According to the electrochemical tests, the nanoflower sample has the best performance and many reversible capabilities. Cobalt is the most advantageous metal for synthesizing long-chain hydrocarbons because of its high activity, excellent selectivity to linear paraffin, and low water–gas shift (WGS) activity. On an oxide support, Co metal particles are typically distributed as the catalyst (Tsakoumis et al., 2010). The fact that oxygen is rejected as water by cobalt catalysts significantly impacts their activity and selectivity (Blekkan et al., 2007). The use of cobalt-based catalysts during catalytic pyrolysis has been shown to increase reaction kinetics for the formation of syngas due to the known effectiveness of cobalt for dehydrogenation and deoxygenation (Kim et al., 2019, Jung et al., 2020). The carbon deposition process on cobalt metal is likely distinct from that of nickel metal (Budiman et al., 2012). It is also claimed that cobalt catalyst, particularly when supported by silica and alumina, has good temperature stability (Ferreira-Aparicio et al., 1998). We also found that the cobalt content in the Ni$_3$Co1 bimetallic catalyst supported on ZrO$_2$ was very effective in catalyzing the steam reforming of phenol (Nabgan et al., 2016). Jayeeta and co-workers (Chattopadhyay et al., 2016) studied the catalytic co-pyrolysis of biomass and plastics (HDPE, PP & PET) blends in the fixed-bed reactor using 40% Co/30%CeO$_2$/30%Al$_2$O$_3$ catalyst. Cobalt loading increased catalytic performance, with 40%Co/30%CeO$_2$/30%Al$_2$O$_3$ catalyst demonstrating the greatest performance. Its greater catalytic activity may be due to its higher surface area value and intensive peak production of CoO and Co$_3$O$_4$, indicating better metal dispersion during synthesis. Chanyeong et al. (Park et al., 2022), in another study, conducted catalytic pyrol-

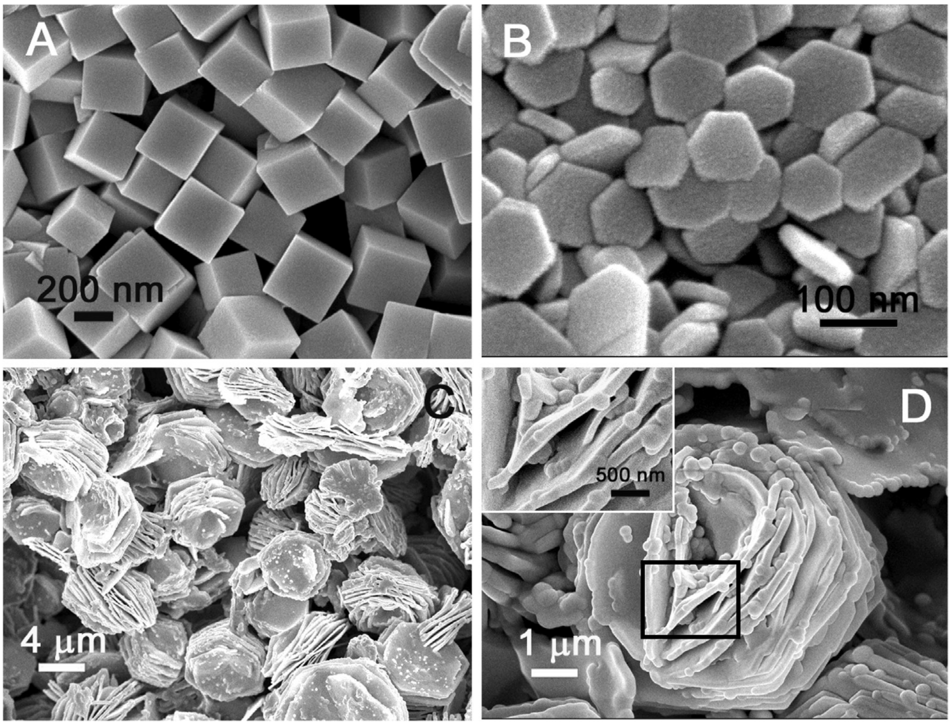

Fig. 12 FESEM images of Cobalt-based (A) nanocubes, (B) nanodiscs, and (C, D) nanoflowers. The inset in D shows the magnified illustration of the region marked by the black square (Chen et al., 2010).

ysis of polyester fiber using a cobalt oxide catalyst to increase the production of such high-value-added materials. The study showed that using cobalt oxide to pyrolyze polyester fibers (and maybe other soluble fibers and plastic materials) could help handle trash in a sustainable and environmentally beneficial way.

3.4. Cerium (Ce)

Over the past few decades, applications involving the environment and energy have generated significant interest in nanostructured CeO_2 due to its exceptional physical and chemical capabilities. CeO catalytic constituents are essential due to their high catalytic activity and are increasingly used in many catalytic systems. The enhanced activity of CeO_2 is responsible for the ceria-based materials employed in their investigation having a high sulfur tolerance and strong redox stability. More aspects, ranging from defect chemistry to structure-derived effects, were technologically revealed with the controlled production of nanostructured CeO_2. Thanks to their remarkable catalytic activities, which result from a rapid and efficient mutation of the oxidation state between Ce^{4+} and Ce^{3+}, cerium oxide nanoparticles (CeONPs) have drawn much interest (Xu and Qu 2014). The cerium atom may quickly and significantly alter its electrical state to suit its immediate surroundings. The lattice structure also reveals oxygen vacancies, or defects resulting from the loss of oxygen and its electrons and alternate between CeO_2 and $CeO_{2\text{-}x}$ during redox processes. CeO_2 is recognized as an excellent exogenous promoter combination with transition metal-based materials to obtain the best pyrolysis activity because of its unique structures and features. Additionally, in alkaline circumstances, CeO_2 has excellent mechanical stability and corrosion resistance, which helps to increase the structural robustness and endurance during pyrolysis reactions. Cerium is less studied, and many writers, especially those looking at recycling used catalysts for fluid catalytic cracking as cement additives, do not even measure such components (Ferella et al., 2016). Once used up, liquid catalytic cracking waste catalysts can be recycled in various ways, including as a cement and ceramic material additive, a component of asphalt mixes, casting sand, and steel production (Yoo 1998). According to the literature, the reduction of coke during the gasification of carbonaceous materials, including plastics, can be significantly aided by CeO_2-based catalysts (Yan et al., 2020). CeO_2 is the best support to reduce the creation of carbon in this situation and is also active in the water gas shift process (Asadullah et al., 2001, Lee et al., 2020). In an analytical pyrolyzer, Kuan et al. (Ding et al., 2018) developed a tandem catalytic bed of CeO_2 and HZSM-5 to increase the hydrocarbon output from the co-pyrolysis of maize stover (CS) and LDPE. Results showed that CeO_2 could take oxygen out of acids, aldehydes, and methoxy phenols, yielding a maximum amount of hydrocarbons of 85% and the most significant level of monocyclic aromatic selectivity of 73% in the tandem catalytic bed. This study provides insight into the more effective conversion of plastic waste and biomass residuals into value-added fuels and chemicals. Their studies provide insight into the more effective tandem catalytic bed of CeO_2 and HZSM-5 materials for converting both biomass residuals and plastic waste to value-added fuels and chemicals. The generation of gaseous products increased when Fe_2O_3/CeO_2 catalyst was used, in another study (Parparita et al., 2015), in the steam gasification of plastic, biomasses, and plastic/biomass composites, showing that the catalyst sped up the gasification process. In particular, the use of catalysts significantly boosted H_2 and CO_2 generation. Since the quantity of most gaseous products increased relative to the estimated values obtained by combining the amount for each component gasification, the synergistic impact of co-gasification of plastics and biomass on gas production rate was found. Shan et al. (Wu et al., 2021) synthesized Ni/CeO_2 core–shell catalysts with different shell thicknesses for hydrogen-rich syngas production from waste plastics in a two-staged fluidized bed reactor. They discovered that the CeO_2 shell prevented the coke produced during the reaction from covering the Ni core. Additionally, the $Ni@CeO_2$-0.5 catalyst's intimate contact between the shell and core may enhance the metal's synergistic impact and hence help to improve its catalytic performance.

3.5. Nickel (Ni)

Ni-based catalysts are the most commonly used in reforming and cracking reactions due to the C–C bond break capacity. Alumina has often supported Ni due to the material's ability to tolerate reactional conditions. According to previous research (Wu et al., 2013, Yao et al., 2016), Ni-based catalysts have strong reactivity for cleaving C–C and C–H bonds, making them useful for polymer reforming and cracking processes. Compared to Co/Al_2O_3 and Cu/Al_2O_3, Ni/Al_2O_3 showed stronger activity to produce multi-walled CNTs and had a larger H_2 yield (Zhang et al., 2015a, 2015b). Ni-based catalysts are the most promising for tar removal and syngas reforming due to their catalytic reactivity and financial benefits (Shen et al., 2014). Metal oxides (such as MgO and Al_2O_3) or natural materials are typically used to support nickel catalysts (e.g., activated charcoal, olivine, dolomite) (Le et al., 2009, Lee and Ihm 2009, Shen et al., 2014). Matthew et al. (Yung et al., 2016) employed a Ni/ZSM-5 catalyst for the catalytic pyrolysis of biomass. Over biomass: catalyst ratio of 1:1, the addition of nickel increased the total output of aromatic hydrocarbons and the conversion of pyrolysis vapor oxygenates. Additionally, independent of the Ni reduction state—pre-reduced Ni or unreduced NiO—the activity of nickel-modified ZSM-5 catalysts converged to the same level. The nickel-modified HZSM-5 catalyst has a particular enhancement effect on the selectivity of monocyclic aromatic hydrocarbons in the catalytic pyrolysis of LDPE (Zhou et al., 2022). The fact that metal-modified HZSM-5 has better anti-coking capabilities and generates less coke in the reaction than untreated HZSM-5 is another intriguing observation (Zhou et al., 2022). However, the coking and deactivation of Ni-based catalysts are challenging issues with the catalytic pyrolysis procedure. The active metal sites on the catalyst surface are covered by carbon deposition, reducing or deactivating the catalyst's activity. At high temperatures, the catalyst may also become inactive because of the encapsulation of the deposited carbon on metal particles and due to structural modifications such as pore collapse of the catalytic support and aggregation of active metal particles. Therefore, it is required to carry out the reuse experiment using Ni-loaded biochar catalysts to understand the catalytic deactivation process. According to research, adding the fitting addition to catalysts can retain the catalysts' stability while reducing the yield of amorphous carbon. According to several writers, Mo has been reported to be a promoter of the synthesis of CNTs, regardless of the metal catalysts (Pérez-Mendoza et al., 2005, Yahyazadeh and Khoshandam 2017, Yahyazadeh et al., 2022). According to research, adding the right addition to catalysts can retain the catalysts' stability while reducing the yield of amorphous carbon. According to previous research (Lamouroux et al., 2007, Dong et al., 2022), Mo has reportedly been viewed as a promoter of the synthesis of CNTs, regardless of the metal catalysts.

4. Challenges and perspectives

Despite ongoing efforts to improve the stability and efficiency of catalytic pyrolysis, there is a relative scarcity of research papers on the pyrolysis process for plastic waste recovery. This research could aid academics, scholars, politicians, and administrators construct a framework for converting plastic waste to liquid fuel by identifying collaborating authors who have played critical roles in the catalyst, plastic, and waste research field. Two methodological issues with this study's co-authorship analysis are the lack of an explanation for the association with co-authorship (Zupic and Čater 2014) and the subjective nature of visualization interpretation (Ramos-Rodríguez and Ruíz-Navarro 2004). The study utilized works exclusively from the WoS database. Future research would benefit from a more comprehensive bibliometric analysis, including additional databases such as Scopus. Only journal papers published in English were considered, a further limitation due to the need for native English-speaking authors to review the literature for inclusion criteria. The findings were based solely on systematic review and bibliometric analysis, without consideration of additional variables that may impact the study's conclusions, such as population size.

Despite the various potential applications of non-precious-based catalysts and nanocatalyst innovation, their development is still in its early stages. Hence, it is necessary to develop techniques to enhance the catalytic performance of the pyrolysis process for plastic waste. Scientists are currently exploring techniques to modify nanomaterials to enable their large-scale production and potential use in diverse applications, such as catalysis, energy storage, conservation, environmental remediation, and chromatographic separation. Further research is needed to investigate the significance of multimetallic catalysts in plastic waste pyrolysis reactions. Selectivity can be controlled by including metals in the catalyst and alloying elements, allowing several active metal species to have a stronger affinity for the pyrolysis process than a monometallic catalyst. Our recent study showed that compared to their mono- and bimetallic counterparts, trimetallic catalysts (Nabgan et al., 2023) exhibit improved catalytic activity, stability, durability, and recyclability. However, several issues must be resolved and thoroughly studied to develop their energy conversion potential fully. Regarding synthesis, accurately controlling the compositional ratio of metals using chemical techniques is challenging due to the varied reduction rates of metallic precursors, and identifying the dominant synergistic effect in ternary systems is also tricky.

5. Conclusions

The current status and research gaps in the non-precious materials for the pyrolysis reaction of plastic waste were revealed by a bibliometric investigation. This review included contemporary bibliometric studies by VOSviewer and RStudio software on catalytic pyrolysis reaction waste plastics on the topic search of keywords such as "catalyst", "plastic", and "waste" using WoS database in 1970–2022 are thoroughly discussed and critically evaluated. The most popular journals, most cited articles, productive nations, innovation trends in research, and network collaboration according to co-authorship based on the top 1000 furthermost referenced publications were identified by bibliometric analysis. In addition to developing the bibliographic coupling of the countries, the citations and publication reports, word cloud analysis, Sankey diagram, co-occurrence network map, growth of word dynamics map, trends of research topics, visualization map of co-authorship, thematic evolution map, and visualization map of country co-authorship, we have also developed the word dynamics map and the growth of word dynamics map. We have identified many gaps and future aspects in plastic waste recycling and catalytic pyrolysis reaction. Pyrolysis, degradation, polypropylene, polyethylene, and plastic were the most common keywords; however, studies on the minor common keywords, such as catalysis, nanocrystalline HZSM-5, Co, and nickel-catalysts, are lacking. The papers from the Journal of Analytical and Applied Pyrolysis were the ones that covered the most authors, nations, and keywords out of all the journals. According to the bibliographic coupling of the nations, Spain, China, England, the United States, and India were the top five nations with the most publications and citations in this field. The top cited studies on using non-precious active metals like Co, Ce, Fe, Mg, and Ni for the pyrolysis reaction of plastic waste have also been reviewed, and that's the second thing to mention. The synthesis of nanostructured materials has advanced significantly, but a wide range of associated applications has also increased considerably. However, it's also essential to reduce the difficulties in obtaining and processing valuable products from the thermal cracking of plastic waste. This paper aims to bridge the gap between theory and practice by summarizing current knowledge on the role of catalysts in the thermal cracking reaction of plastic waste, presenting new research directions related to plastic waste recycling, and providing suggestions for future scholars to further their understanding of the conversion of plastic waste into liquid fuels. We believe these results are effective because they offer an appealing potential solution for plastic waste in both industrial and scientific aspects. Verily, catalytic pyrolysis of plastic waste can be of great use to the plastics industry in a multitude of ways. It can convert waste into valuable products, reduce the cost of raw materials, increase sustainability, and hold innovation potential. Moreover, the bibliometric analysis of keywords such as "catalyst," "plastic," and "waste" can aid scientists and serve as a valuable guide to further research, offering insight into research trends, evaluating the impact and influence of research, and discovering opportunities for collaboration and productivity. Therefore, academics and industrial researchers must collaborate to develop effective, affordable energy materials and safer pyrolysis systems for the future to facilitate the real-world and widespread implementation of non-rare earth elements for achieving global sustainable development goals. Future research into non-precious materials' structural and chemical development and their potential uses will present exciting opportunities and difficulties for materials scientists and engineers. Critically, the issues have to do with several significant factors, including defect modification and scale-up synthesis monolithic device enabling, which significantly affect energy and environmental applications.

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Availability of data and materials

Not applicable.

CRediT authorship contribution statement

Walid Nabgan: Methodology, Investigation, Funding acquisition. **M. Ikram:** Software, Writing – review & editing. **M. Alhassan:** Formal analysis, Resources. **A.H.K. Owgi:** Data curation, Writing – review & editing. **Thuan Van Tran:** Conceptualization, Visualization. **L. Parashuram:** Methodology, Investigation. **A.H. Nordin:** Writing – review & editing. **Ridha Djellabi:** Writing – review & editing. **A.A. Jalil:** Conceptualization, Writing – review & editing, Supervision. **F. Medina:** Writing – review & editing, Supervision, Funding acquisition. **M.L. Nordin:** Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.arabjc.2023.104717.

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