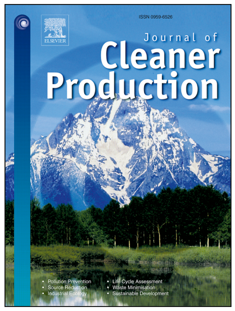
Journal Pre-proof



Bibliometric analysis of research trends on the thermochemical conversion of plastics during 1990–2020

Roomana Khatun, Huan Xiang, Yang Yang, Jiawei Wang, Güray Yildiz

PII: S0959-6526(21)02586-5

DOI: https://doi.org/10.1016/j.jclepro.2021.128373

Reference: JCLP 128373

To appear in: *Journal of Cleaner Production*

Received Date: 19 April 2021

Revised Date: 7 July 2021

Accepted Date: 17 July 2021

Please cite this article as: Khatun R, Xiang H, Yang Y, Wang J, Yildiz Gü, Bibliometric analysis of research trends on the thermochemical conversion of plastics during 1990–2020, *Journal of Cleaner Production* (2021), doi: https://doi.org/10.1016/j.jclepro.2021.128373.

CRediT authorship contribution statement

Roomana Khatun: Investigation, Formal analysis, Writing - Original Draft; **Huan Xiang**: Formal analysis, Writing - Review & Editing; **Yang Yang**: Supervision, Writing - Review & Editing, Funding acquisition; **Jiawei Wang**: Supervision, Writing - Review & Editing, Funding acquisition, **Güray Yildiz**: Writing - Review & Editing, Funding acquisition

Bibliometric analysis of research trends on the thermochemical conversion of plastics during 1990 – 2020

Roomana Khatun [a], Huan Xiang [a], Yang Yang [a], Jiawei Wang [a*], Güray Yildiz [b]

a. Energy and Bioproducts Research Institute (EBRI), Aston University, Birmingham, B4 7ET, UK

b. Department of Energy Systems Engineering, Izmir Institute of Technology, Urla 35430, Izmir, Turkey

Corresponding author: Jiawei Wang (j.wang23@aston.ac.uk)

Bibliometric analysis of research trends on the thermochemical conversion of plastics during 1990 – 2020

Roomana Khatun [a], Huan Xiang [a], Yang Yang [a], Jiawei Wang [a*], Güray Yildiz [b]

a. Energy and Bioproducts Research Institute (EBRI), Aston University, Birmingham, B4 7ET, UK

b. Izmir Institute of Technology, Faculty of Engineering, Department of Energy Systems Engineering, 35430, Urla, Izmir, Turkey

Abstract

The aim of this bibliometric analysis was to evaluate the trends in literature and the impact of publications that have been published during the period 1990 – 2020, in the field of thermochemical conversion of plastics, namely gasification, liquefaction and pyrolysis. SCOPUS was used and data was vetted via MS Excel, with analysis being completed via MS Excel and VOSViewer. A total of 1705 publications were used in the study, and China was identified as the most productive country. Pyrolysis was the most researched technology with over 88% of publications, while liquefaction accounted for less than 3% of the total publications. Across all three technologies, polyethylene (PE) was the most commonly occurring type of plastic. Journal of Analytical and Applied Pyrolysis had the highest number of publications and total citations. However, Energy Conversion and Management had a higher impact factor and higher average citations per publication. University of Alicante was identified as the most productive university with a total of 45 publications, while University of Leeds was the most commonly cited with an average of 65 citations per publication. The keyword analysis showed that co-pyrolysis with biomass and catalytic pyrolysis are gaining increased interests.

Keywords

Bibliometric Analysis, Gasification, Liquefaction, Plastic, Pyrolysis, Thermochemical Conversion

1. Introduction

Large scale production of plastic began in the 1950s, almost three decades after Bakelite was manufactured. The first synthetic plastic was produced in 1907 (Geyer et al., 2017). The plastics with the highest production rates include, but not limited to polyethylene (PE), polypropylene (PP), polyvinylchloride (PVC), polyethylene terephthalate (PET), polyurethane (PUR), and polystyrene (PS) (Geyer et al., 2017). There is a huge problem when it comes to the handling of plastic solid waste. It is estimated that cumulative plastic production up to 2017 was 8.3 metric billion tons, only 9% of which has been recycled, and a further 12% incinerated. There have been over 6.3 billion tonnes of plastic waste accumulated in the past 60 years, and 79% of this has been landfilled or accumulated in the natural environment (Geyer et al., 2017).

There are four main routes for plastic recycling. Primary methods are to reintroduce waste plastic in the production of similar plastic products. Secondary methods, known as mechanical recycling, involve the extrusion, processing, and conversion of waste plastic before being blended with virgin polymers. Tertiary methods alter the waste plastic's chemical structure and produce feedstock materials for plastic production of energy recovery. Finally, quaternary methods, known as energy recovery, are when the waste plastic undergoes combustion and steam, electricity or heat is recovered (Al-Salem et al., 2010). Thermochemical conversion technologies lie between tertiary and quaternary methods – the chemical structure of plastics is often altered for a range of uses, including plastic formation to energy recovery via the liquid and gas fractions. These technologies include gasification, liquefaction, and pyrolysis.

Gasification is defined as the thermal treatment of organic matter, which can convert plastic solid waste in the presence of low levels of oxygen. In ideal conditions, the products from gasification would be high calorific value gases and completely combusted char (Al-Salem et al., 2009). High operating temperatures are required for the gasification of plastic solid waste, typically higher than 600 °C (Brems et al., 2013). However, it is not uncommon to use temperatures as high as 1200 – 1500 °C (Al-Salem et al., 2009). Liquefaction commonly occurs at temperatures up to 500°C, with pressures up to 271 bar (Pei et al., 2012; Yuan et al., 2009). The conditions used directly affect the range of products, including solid residue, gas, and oils of varying concentration (Williams and Slaney, 2007). Pyrolysis is a technique that can be used to treat long-chain organic material. The operating temperatures vary from 350 – 900 °C, and the products include solid char, wax, condensable hydrocarbon oil, and gas with high calorific value (Antelava et al., 2019).

A bibliometric analysis is a statistical method in which citation data within a field of research is used to draw conclusions about the output and influence within the research area and identify emerging trends. There are two main types of bibliometrics: descriptive bibliometric allows research outputs to be considered by a nation, institution or by an individual, while evaluative bibliometric considers parameters such as citation data to see the influence of a paper, individual or institution. It is important to note that the influence does not directly relate to the quality of the paper (McBurney et al., 2002). In the research area of waste plastic, previous bibliometric studies have been focused on the pollution of plastic particles, from nano- to microplastics, including the presence of plastic particles in the environment (Sorensen and Jovanović, 2021), the development of microplastics (Zhou et al., 2021) and the issue of microplastics in marine ecosystems (Pauna et al., 2019). Others have carried out bibliometric studies on waste management, such as the management of plastic waste (deSousa, 2021) and the research trends on solid waste reuse and recycling (Li et al., 2018). With respect to the thermal conversion of waste, there are existing bibliometric studies on the trends of research on waste-to-energy incineration (Wang et al., 2016) and solid waste research (Fu et al., 2010). While there has been bibliometric analysis on topics such as plastic as a pollutant, waste management and the thermal treatment of waste, there is yet no bibliometric analysis that considers the trends in the thermochemical conversion technologies of plastic solid waste.

The purpose of this study was to conduct a bibliometric analysis on the thermochemical conversion technologies of plastic waste – namely gasification, liquefaction, and pyrolysis.

Publications between 1990 and 2020 were considered and quantitatively analysed. It allowed trends of research in the field over the past 30 years to be discovered and critically explored. Key countries and researchers in the progression of the thermochemical conversion technologies were identified. More importantly, gaps in the research field within thermochemical conversion technologies were identified, allowing specialised research to be conducted in the future.

2. Methodology

Data for this bibliometric analysis was collected via Scopus. Fig. 1 displays the methodology flowchart. The searches were carried out in a single day in January 2021 and limited to the range of years (1990 – 2020) and the subject areas (Material Science, Engineering, Chemistry, Chemical Engineering, Energy and Environmental Science). Searches were then limited by document type and language, with Articles and English, respectively.

A total of nine keywords were used in the initial search ((gasification OR liquefaction OR pyrolysis) AND (polyethylene OR polypropylene OR polyvinylchloride OR polyethylene terephthalate OR polyurethane OR polystyrene)). The number of initial citations and the number of citations after each limitation applied were recorded. When there were more than 2000 citations for a search, the search parameters were updated and restricted by year to ensure the total citations was less than 2,000 in order to extract the full CSV data.

The citations were exported from Scopus to Microsoft Excel in a CSV format. The data was then checked to ensure there were no citations with insufficient information. The citation data was vetted by searching for the occurrences of the keywords in the title, abstract and keywords. When the search keywords were present in two of these parameters, the citation was kept while all other citations were removed. The citation files were collated into a single excel to remove duplicates. The citation data was organised into different groups depending on the thermochemical conversion technology and the type of plastics included in the article, as well as the institution and the first author's geographical location. A list of citations based on each parameter was obtainable and used for VOSviewer visualisation analysis. VOSviewer is a free software tool for constructing and visualising bibliometric networks, developed by Nees Jan van Eck and Ludo Waltman. VOSviewer version 1.6.15 was used in the study. Network maps were used to create maps to display citation analysis of journals, co-authorship analysis of authors, and overlay visualisation was used to show trends over time.

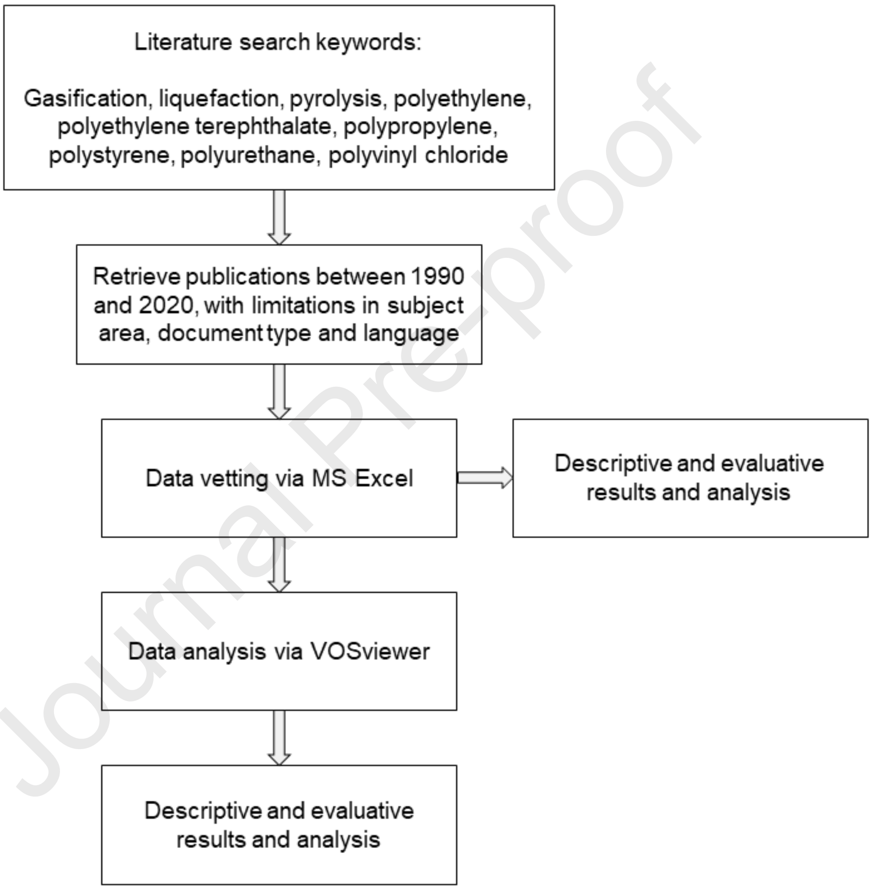


Fig. 1. Methodology flowchart.

3. Results and discussion

The results of the bibliometric analysis on thermochemical conversion technologies of plastics from 1990 – 2020, based on Scopus citation data, are discussed in this section. A total of 1705 papers were used in this bibliometric analysis, all of which were research articles and in English. This section focuses on various factors such as the output of publications by country and the type of conversion technology. Key journals and institutions are also analysed to identify the key contributors in this field of research and key authors and the most influential papers.

3.1. Overview of publications

This section focuses on the overall output of publications by country and by the type of thermochemical conversion technology or type of plastic.

3.1.1. Publications by country

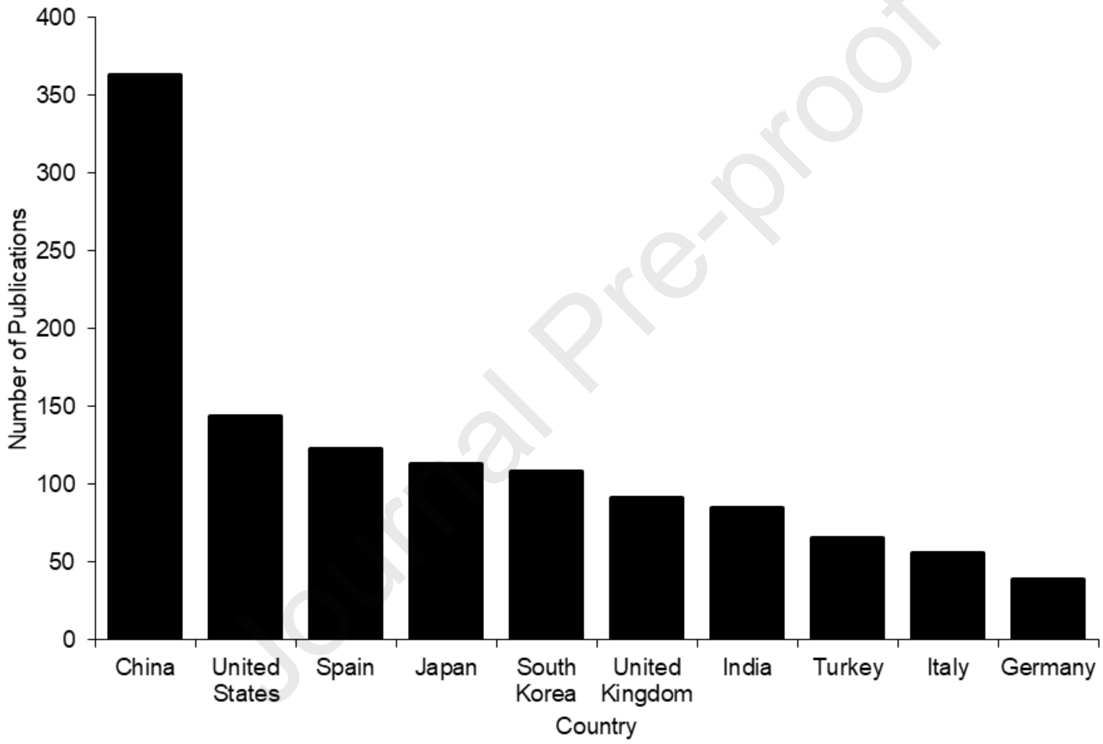


Fig. 2. Top 10 most productive countries.

Fig. 2 shows the ten countries with the highest number of publications in the research area of plastic conversion technologies. The country has been obtained based on the first listed author for each publication.

A total of 1705 publications have been included in this study, with contributions from 71 different countries. The 10 countries displayed in Fig. 2, account for a total of 1187 publications, almost 70% of the global total.

Funding data from China, European Union, United Kingdom, and the United States have been collected, and projects with the keywords: ‘plastic’ AND ‘liquefaction’ or ‘gasification’ or ‘pyrolysis’ were recorded. The following databased were used: Chinese Funding Agency, Community Research and Development Information Service (CORDIS), Engineering and Physical Sciences Research Council (EPSRC) and the National Science Foundation (NSF). China had the most funding in these projects, with an increase in the total funding over time. Despite the US having more publications in this field, the UK projects have had twice as much funding. The EU had the greatest amount of funding but covers a wide range of countries.

From a total of 365 publications affiliated with China, a total of 87 had no funding information. 172 publications were funded, or co-funded by the Nation Natural Science Foundation of China, while a further 30 was supported by Fundamental Research Funds for the Central Universities and 18 by National Basic research program of China. A large number of these publications (77%) were published after 2014, displaying a recent interest in thermochemical conversion of plastic in China.

More than half of US publications (73 publications) did not have funding data available, however the National Science Foundation have funded, or co-funded 10 publications, and the Department of Energy provided funding for 9 publications.

63% of publications from Spain had funding data available, which were both on a national and local level. Ministry of economy (MINECO) funded 22 publications, Spanish National Science Foundation (CICYT) funded 17 publications and Ministry of Science and Innovation (MICINN) funded 11 publications. Also, Eusko Jaurlaritza provided funding for 19 publications, and Generalitat Valenciana for 11 publications. There was a wide range of funding in Spain, and often multiple sources of funding for each publication, displaying the collaborations between different national and local bodies.

Only 40% of publications from Japan had funding information available. 18% of all publications were funded by Japan Society for the Promotion of Science. 33% of South

Korea's publications had no funding data available, whereas 30% of them was funded, or co-funded by the National Research Foundation of Korea.

46% of UK publications had funding data available. Among them, 13 publications were funded by the Engineering and Physical Sciences Research Council. The remaining publications were either funded by institutions within the UK or from other countries.

Only 30% of publications from India had funding details available. 10 of them were funded, or co-funded by the Department of Science and Technology and a further 8 by the Government of Kerala, suggesting an increased focus in the region of Kerala compared to the rest of the country. Only 30% of the publications from Turkey had funding details available. The Scientific and Technological Research Council of Turkey (TÜBİTAK), the largest funding contributor for publications from Turkey, funded or co-funded 7 publications. In Germany, on the other hand, Deutscher Akademischer Austauschdienst (DAAD) funded or co-funded 5 publications. For Italy, a majority of funded publications (with funding details available in publications) were institutional level. Although almost 39% of publications from Germany had funding details available, there were no key funders identifiable from this list.

The United States (130 kg/year) and the United Kingdom (99 kg/year) and South Korea (88 kg/year) have been identified as the three countries with the highest plastic waste generation per capita in 2016 (Law et al., 2020). When the population is not considered, the United States (320 million metric tons), India (277 million metric tons) and China (220 million metric tons) have the greatest amount of plastic waste generation in 2016 (Law et al., 2020).

This shows that research output, to a good extent is linked to research funding and waste generation. Although there is insufficient funding data available for every publication included in this study, it is evident that those with national funding support have more publications, compared to countries where only institutional funding is reported. The five countries which have the highest waste generation, with and without considering the population, have all been identified within the top 10 most productive countries.

3.1.2. Publications by technology

Table 1.
Distribution of publications by technology.

Technology	Number of Publications	Percentage
Gasification	156	8.76%
Liquefaction	50	2.81%
Pyrolysis	1575	88.43%

Table 1 shows the occurrences of the thermochemical conversion keywords in the titles of the final list of publications. From 1705 publications, the thermochemical conversion technology keywords appeared a total of 1785 times, indicating that approximately 4% of papers used a combination of thermochemical conversion technologies. 87% of the papers with more than one technology focused on both gasification and pyrolysis, which could be due to the similarities in the operating conditions. While pyrolysis takes place in an inert atmosphere, the low oxygen level in gasification is controlled to prevent combustion.

A high proportion of publications focused on pyrolysis, which can be classed as a flexible conversion technology (Maafa, 2021) due to the wide range of products (gas, liquid and solid residue/char), which depend on reaction conditions (Basu, 2018). A limitation with gasification is the formation of tar, which is a low-value product (Panepinto et al., 2016), and liquefaction products often require extremely high pressure but can yield up to 60% oil and 70% gas (Ramdoss and Tarrer, 1998).

3.1.3. Publications by plastic type

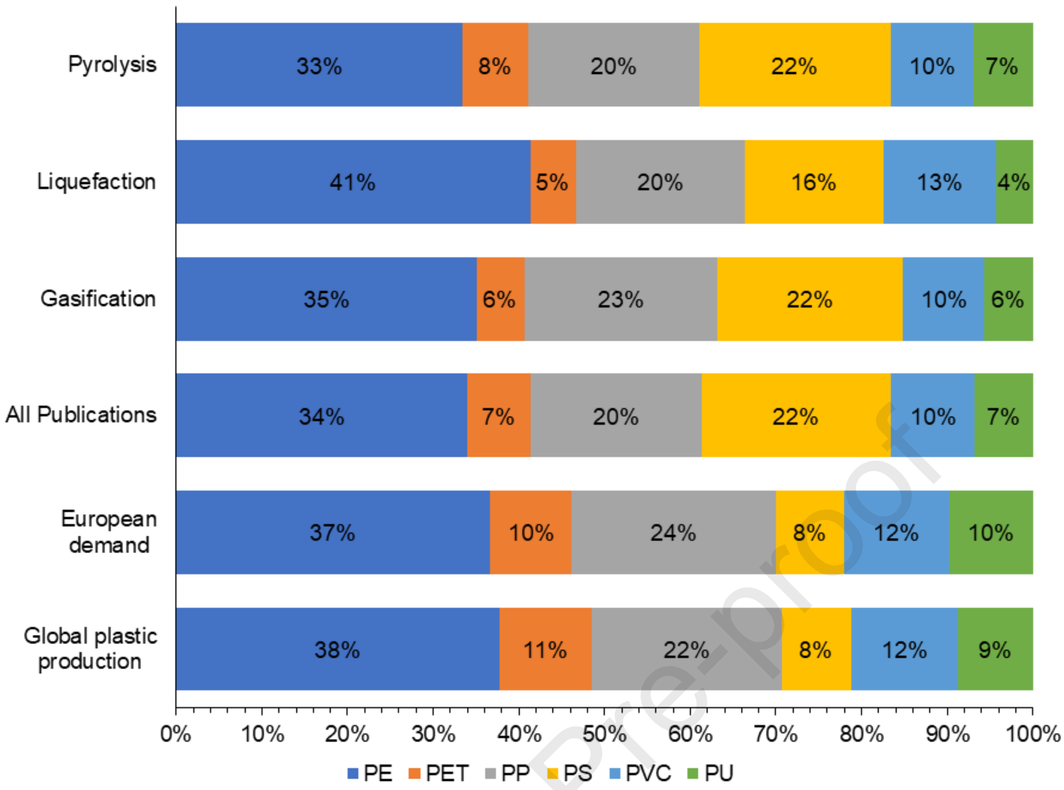


Fig. 3. Distribution of publications by plastic type.

Studies on the thermochemical conversion of plastics are often based on the types of plastic most found in waste, which is dependent on plastic demand and production. Fig. 3 shows the types of plastics stated in the title of publications and how they compare to the overall plastic demand in Europe and Globally. Polyethylene and polypropylene account for over 50% of the research in this field, while publications on polystyrene are significantly higher with respect to the European demand and global production. The global production values are almost identical to the European demand values, indicating that these six types of plastic are used in similar proportions worldwide. At present, it is thought that polystyrene is easier to dispose of than recycle due to the problems encountered during the separating and clearing stage. There is also an increase in the use of polystyrene, which originates from improved technology and the associated waste from electrical and electronic equipment (WEEE) (Maafa, 2021). While all three thermochemical conversion technologies have a higher proportion of publications compared to the distribution of polystyrene in both global production and European demand, the values for pyrolysis and liquefaction are over two times the production and demand values. Under isothermal pyrolysis conditions, it is possible to obtain up to 96.40% oil from polystyrene, with a further 3.60% gas (Kim et al., 1999). The pyrolysis of polystyrene reduces the amount of plastic being landfilled, and it also allows the valorisation of waste by obtaining the styrene monomer (Arandes et al., 2003). While the valorisation of polystyrene seems promising based on these factors, it is important to note that most research was carried out on a small scale. When such processes are scaled up, the problems occurred during the recycling of polystyrene, such as separating and cleaning of materials, could be big challenges for the pyrolysis or liquefaction of polystyrene. However, if the gas and liquid products are more valuable than the recycled materials, it may be a good investment for commercial companies.

3.2. Output of publications

This section focuses on the output of publications with respect to each type of thermochemical conversion technology.

3.2.1. Gasification publications

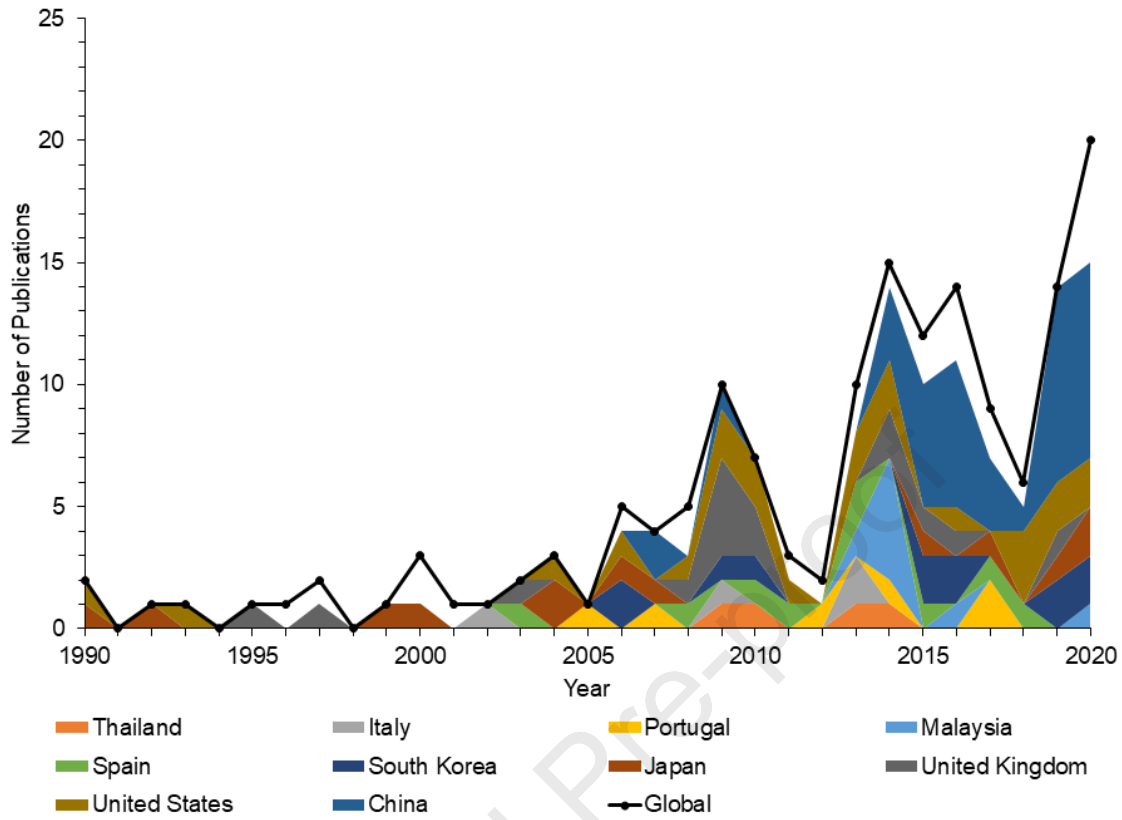


Fig. 4. Most productive countries in gasification research from 1990 – 2020.

Fig. 4 shows the output of the gasification publications by country since 1990, with only the top 10 most productive countries being displayed. There is an overall positive trend in the number of publications, with a majority of the publications having a first author from the same ten countries. There is little deviation between the output of these 10 countries and the global output on a yearly basis. The remaining 18 countries with publications in gasification have less than three publications across the 30-year research period, with 13 of them having only one publication.

It is evident that Malaysia's contributions in gasification research are largely limited to a four-year window, between 2013 to 2016. This coincides with key events which took place in Malaysia, such as the introduction of 'no plastic bag campaign day', launched by the Ministry of Domestic Trade, Cooperative and Consumerism (MDTCC) in January 2011. A recent study comments on the attitudes of a sample group of the Malaysian Impact to observe the change in consumer behaviours during the campaign. The introduction of an MYR 20 cent charge for plastic bags on Saturday had an impact on shopping trends. There was a 30% reduction in the volume of Saturday sales. However, there was a significant increase in Sunday sales (Zen et al., 2013). This shows that rather than dealing with plastic waste, it was easier to change habits. There was also a plastic import ban in Malaysia in 2012, which is another potential reason for increased research to deal with plastic waste as a nation.

There were apparent dips in the number of publications in gasification research, 1998 (0 publications), 2005 (1 publication), 2012 (2 publications), 2018 (6 publications), which are all 6 – 7 years apart. Rather than a sign of reduced interest in this area of research, the reduced number of publications could be due to the end of funding for projects or simply the completion of a project before a new research area was investigated.

In 2020, there was a significant number of publications from countries that have not already been recognised in this field. The displacement of waste due to China's import ban could be one of the factors behind the interest in gasification from a larger number of countries, but it is too early to see the full impact of this.

3.2.2. Liquefaction publications

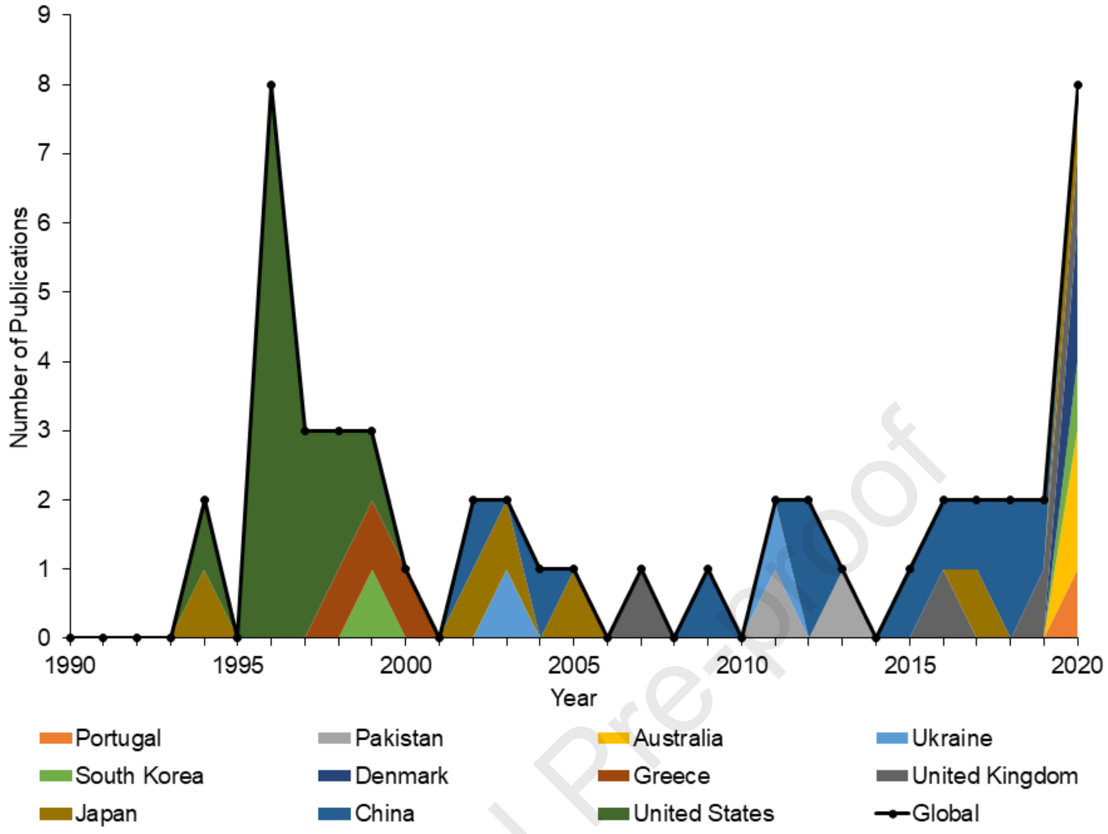


Fig. 5. Most productive countries in liquefaction research from 1990 – 2020.

There have only been 11 counties with interest in liquefaction in 1990 – 2020. Unlike the other thermochemical conversion technologies, there is no deviation between the leading nations and global publications. From Fig. 5, it is clear the United States had a strong interest in liquefaction research during the years of 1996 – 1999, with a total of 14 publications. Half of these had funding or affiliations with the US Department of Energy, indicating that the use of liquefaction was seen as a potential technology to produce energy via liquid fuel, rather than to directly combat the problem of plastic solid waste. While this only considers the first authors, when looking at the United States contributions after 2000, with respect to multiple authors per paper, the United States is not involved in liquefaction of plastics research. Since 2000, a majority of the papers correspond to China, with more than half of China's contributions limited to the years of 2015 – 2019, which received funding from Science

Federations, indicating the research was not restricted to the purpose of waste valorisation but for plastic waste management.

3.2.3. Pyrolysis publications

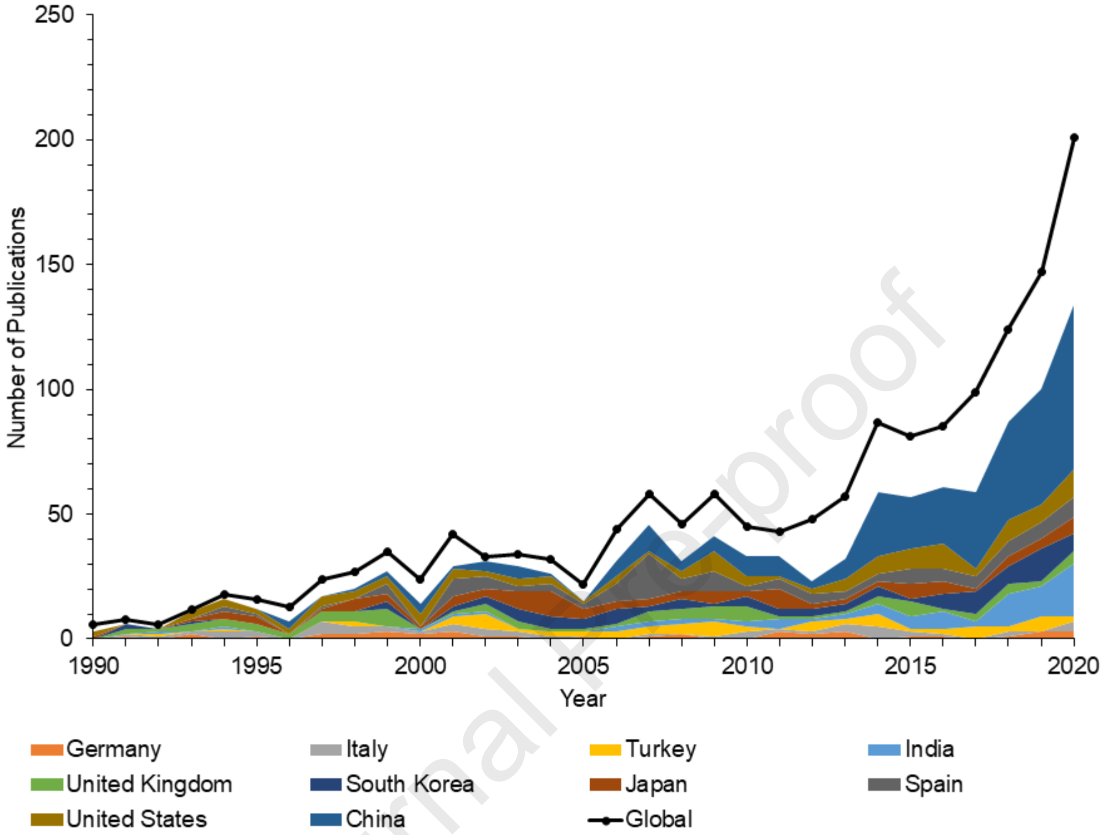


Fig. 6. Most productive countries in pyrolysis research from 1990 – 2020.

In pyrolysis research, the output of publications has been steadily growing over the past 30 years. Fig. 6 shows countries with a minimum of 40 publications in pyrolysis research. The ten counties displayed published a majority of the publications until 2011. Pyrolysis research has publications from 71 different countries, indicating the global effort in this area of research.

Similar to the gasification publications, there are dips that can be observed in Fig. 6. However, these are not as regular as the gasification publications. The main dips were in 2000 (27 publications) and 2005 (24 publications). Again, this is likely to be due to the end of a project or the end of funding. 2008 appears to be a dip (49 publications), but this is in comparison to 2007 (61 publications), with 29.51% of this (18 publications) from Spain. To put this into context, in 2006, Spain contributed 14.58% of the global total (7 publications) and in

2008 contributed 12.24% of the global total (6 publications). From the years 1997 to 2005, the mass of plastic waste produced per year in Spain increased by approximately 51.68%, from around 1027 tonnes per year to 1558 tonnes per year. This alone would be a highly concerning and motivating factor for increased research in methods to deal with plastic waste. The Spanish “Comisión de Investigación Científica y Tecnológica” was only acknowledged as funding 25% of the publications in 2006 and 2008. However, in 2007 77% of the publications had government funding.

Gasification and pyrolysis follow a similar trend with the number of total papers increasing over time. For gasification, the rate of change steadily increases over time from 1990 (2 publications) to 2020 (20 publications). However, for pyrolysis, the number of papers steadily increases from 1990 (9 publications) to 2014 (105 publications), at which point the number of publications increases rapidly from 2015 (95 publications) to 2020 (238 publications). In the past five years, research in pyrolysis has increased by a factor of 2.5.

A key similarity between liquefaction and pyrolysis, as displayed in Figs. 7 and 8, is the rapid increase in papers from 2019 to 2020. For liquefaction, the number of publications increased 4-fold from 2 publications to 8 publications. These publications were from 6 different countries (Australia, Denmark, Japan, Portugal, South Korea, and the United Kingdom), which is the greatest number of countries to release publications on liquefaction in the same year. Portugal (1 publication), Australia (2 publications), and Denmark (2 publications) had not published papers on liquefaction of plastic waste at any point prior to 2020. For pyrolysis, there is a notable point at which the gap between the 10 countries with the most publications and the global publications becomes much larger. Prior to 2012, the largest difference was in 2009 (17 publications). In 2012 this value increased (25 publications), the difference fluctuated between 24 and 47 between 2013 and 2019 and reached a maximum in 2020 (67 publications). This increase pairs with China’s plastic import ban (China was the largest importer of plastic waste), which was announced in 2017 and came into practice in 2018. There is no surprise that the announcement of China’s ban leads to an increase in the research of thermochemical conversion of plastic waste. However, the full impact of the ban in terms of the quantity of waste that has been displaced and the drive for increased research can be observed in the years to come.

Another important observation is the output of publications from China. While for liquefaction, China has released publications throughout the 30-year period, but in gasification and pyrolysis research, there was a clear increase from 2013. As discussed earlier, China was the leading contributor to this type of research with 371 publications across the 30-year period. A majority of these (256 publications) were related to pyrolysis and published between the years 2014 and 2020. While other countries were involved in research across a majority of the 30-year period, the number of publications were at the same volume in comparison with China.

3.3. Journal analysis

3.3.1. Output of journals

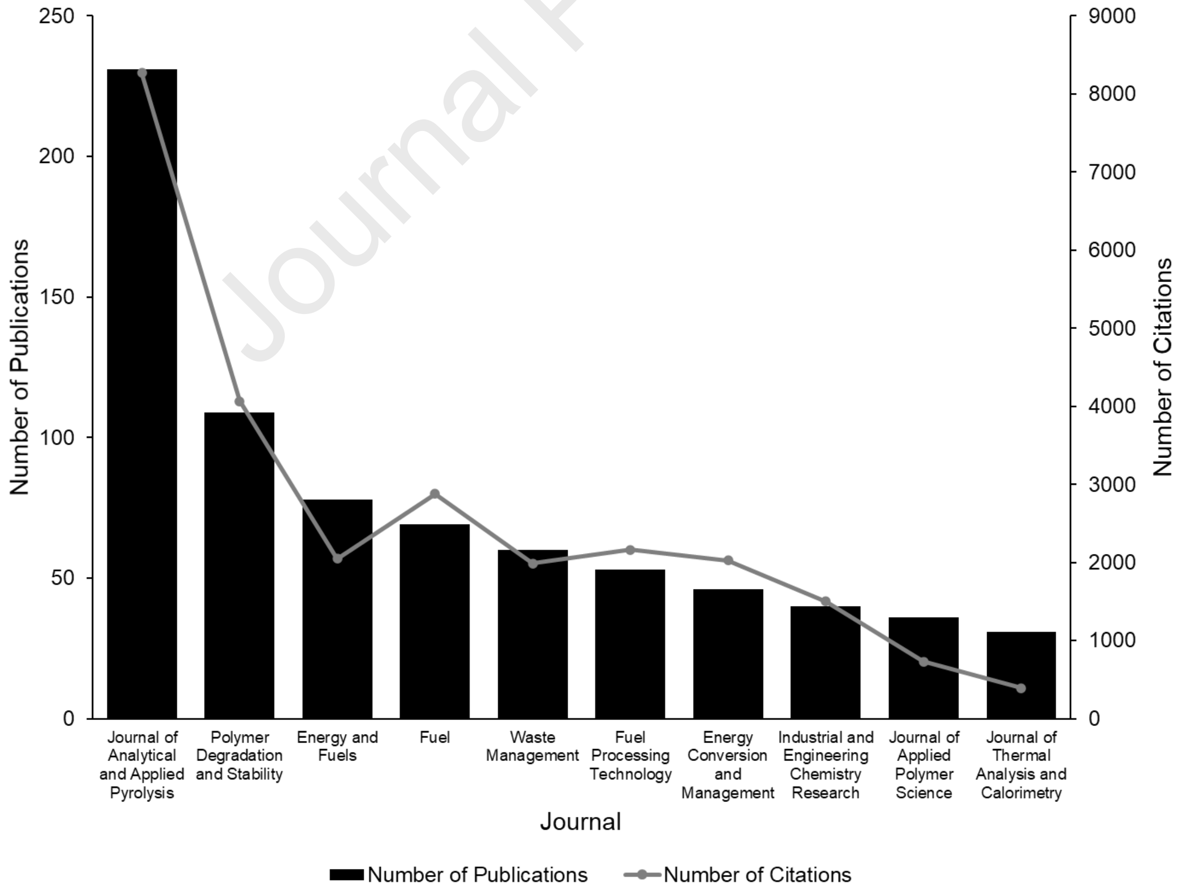


Fig. 7. Top ten most active journals.

There are several ways in which journals can be ranked: by output of publications, number of citations, or impact factor. Fig. 7 shows the ten journals with the highest volume of publications and the total number of citations. The named journals have published a total of 753 publications out of 1705 publications. The remaining publications have been published in over 300 journals. Journal of Analytical and Applied Pyrolysis (231 publications) is almost as productive as the next three journals combined: Polymer Degradation and Stability (109 publications), Energy and Fuels (78 publications) and Fuel (69 publications).

The number of citations and the number of publications are strongly linked, as shown in Fig. 7, with some exceptions. Fuel has a total of 2880 citations across 69 publications, while Energy and Fuels has only 2046 citations over 78 publications. The average citations per publication is much higher for the Fuel (41.74) in comparison with Energy and Fuels (26.23). The journal with the highest citations per publication from this list is Energy Conversion and Management (44.11), while the lowest is the Journal of Thermal Analysis and Calorimetry (12.61). The impact factor of a journal is another way the show the impact a journal has in a field of research. In this case, the impact factors vary significantly from the average trends observed using number of publications and the number of citations.

3.3.2. Impact of journals

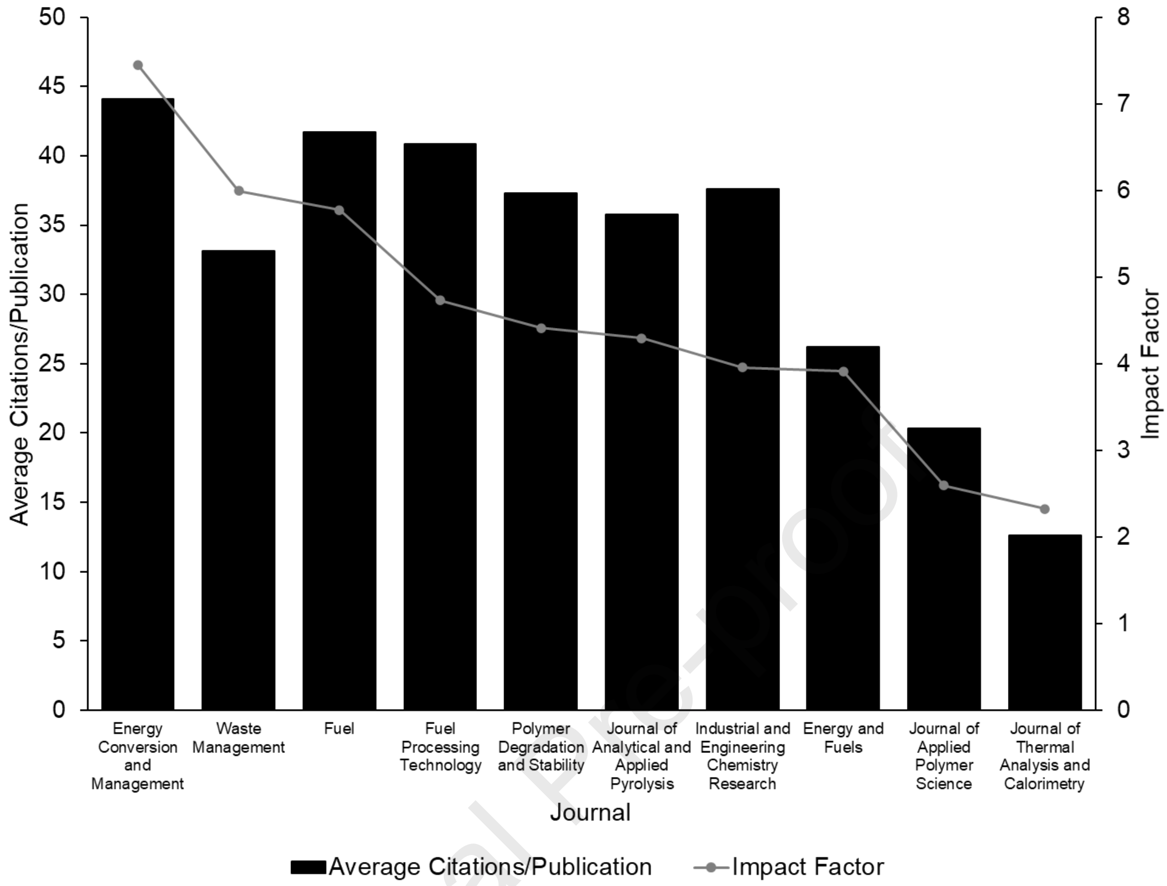


Fig. 8. 5-year impact factor of 10 most productive journals.

Fig. 8 shows the relationship between the 5-year impact factor of the journals and the average citations per publication for each journal. There is a small correlation between the impact factor and the average citations per publication. It is important to note that the average citations per publication have been calculated based on one single research area, which only makes up a small percentage of each journal's publications. Energy Conversion and Management has the highest impact factor (7.447) and also has been recognised as the one having the highest average citations per publication (44.11) based on thermochemical conversion of plastic publications. Similarly, within the top ten most productive journals, Journal of Thermal Analysis and Calorimetry has the lowest impact factor (2.325) and the lowest average number of citations per publication (12.61). Most of the journals have a lower impact factor compared to the average citations per publication, which is likely due to the narrow area of research. However, this difference could suggest that thermochemical conversion publications are more highly cited than other research areas. Another key difference is the time frame used to obtain the values – the impact factor is based on citation data over the past 5 years, while the average citations have been calculated for all publications in each journal across the whole 30-year research period.

Figs. 7 and 8 show that the influence of a journal depends on the parameters which are being selected. While the impact factor shows the reputation and quality of the research in a journal, the number of publications and the number of citations focus on the topics being studied in this bibliometric analysis.

3.3.3. Citation analysis of journals

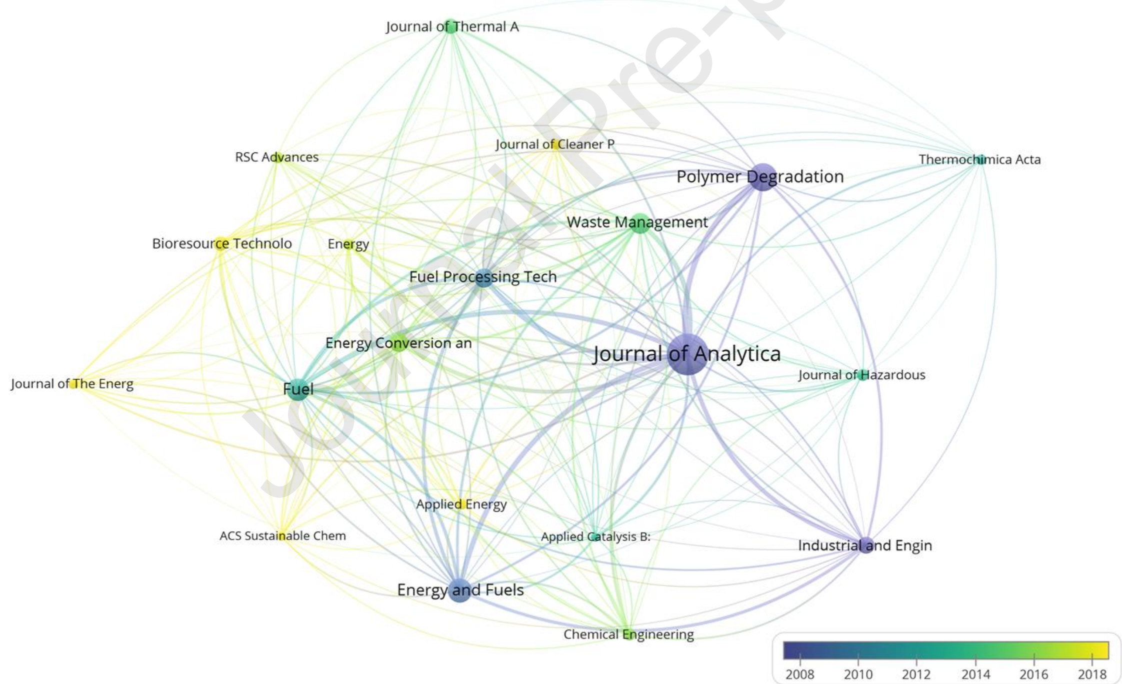


Fig. 9. Citation analysis of journals. Different colours indicate the average year of publications, the size of the circles indicates the number of publications, and the thickness of the lines represents the link strength among the journals.

Fig. 9 displays the citational analysis of journals. The journals displayed have a minimum of 10 publications, and the 20 journals with the highest link strength, as determined by

VOSViewer have been selected. From Fig. 9, it is clear that publications are cited regardless of the journal they have been published in. Journals with a lower average year tend to have a higher average link strength, as they are more established within the field and likely have a higher number of publications. The nodes represent the number of publications, and in this case Journal of Analytical and Applied Pyrolysis is identified as the most productive journal.

Journals with the lowest average year, largely on the right-hand side of the map, include Energy and Fuels, Journal of Analytical and Applied Pyrolysis and Polymer Degradation and Stability. These journals focus on pyrolysis or polymer materials and energy as a whole. Journals with an average publication year close to 2015 show the introduction of waste management as a topic, while publications with an average year of publication between 2015 and 2020 are focused on Bioresources and Sustainable Energy. This shows a shift in trends from the earlier parts of the research period to the latter. While early studies were often published in journals related to energy and fuel research, new publications consider co-processing, using not only plastic but also biomass and coal alongside plastic. Catalytic methods are also introduced in the last 10 years, evidenced by the changes in keywords used as evidenced in Table 6. Overall, this shows that while earlier studies may have been with the intention of waste valorisation or energy production, the purpose of studies in this field has changed over time. It was firstly to deal with the problem of plastic waste, and then changed to utilise renewable materials such as microalgae and biomass in the thermochemical conversion of plastics to see their influence on product yields and distributions.

3.4. Institutional analysis

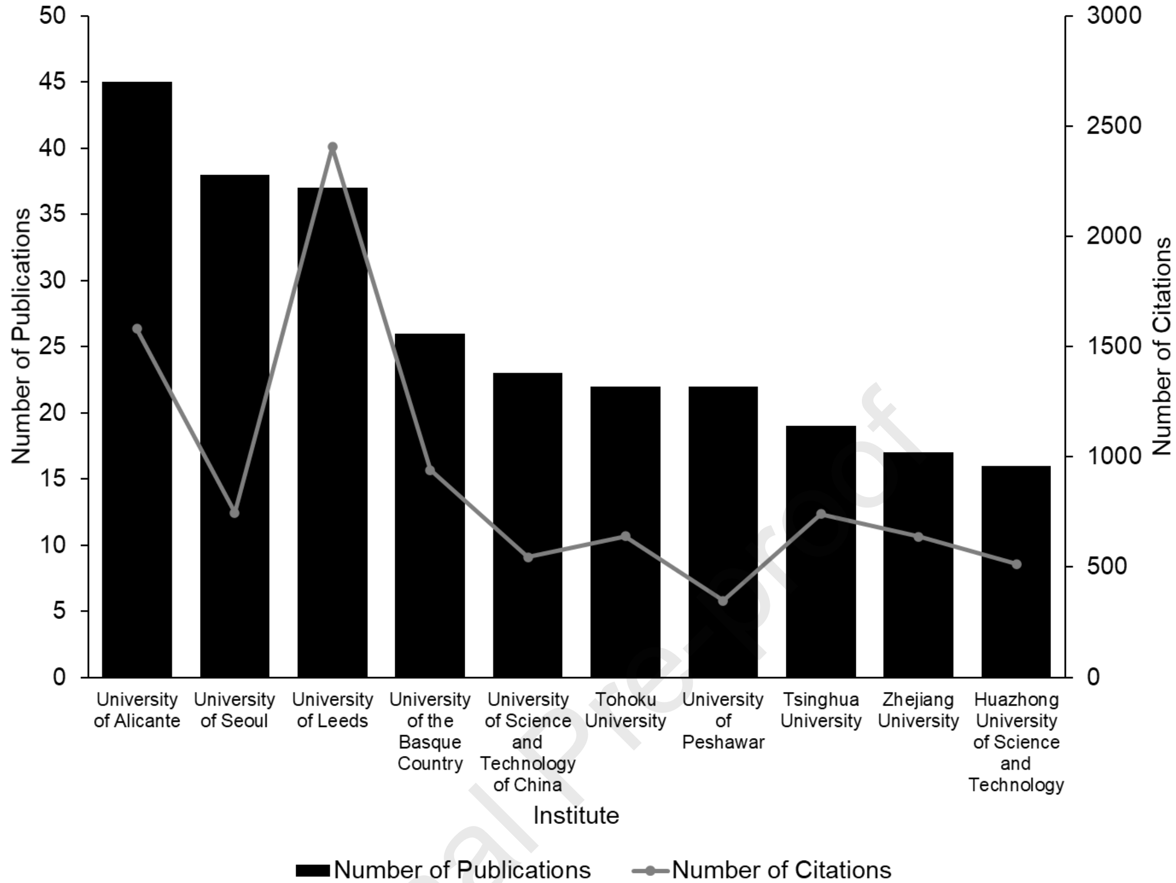


Fig. 10. Top ten most active institutions.

Fig. 10 displays the institutions with the highest number of publications across the 30-year period, and the number of publications per institute is determined by the first listed author. From the ten institutions with the greatest number of publications, a majority of the first authors' corresponding institutions (four) are located within China. All other countries have only one leading institute. Although Spain has the 3rd highest number of publications, the University of Alicante has published the highest number of publications in this field, accounting for 36% of Spain's total publications. Despite the United States having the 2nd highest number of publications, there are not any US institutions on this list. This indicates that the research carried out in the US is being conducted by many different institutions. The figure also shows the number of citations per institution. From this, it is evident that the University of Leeds is extremely influential in thermochemical conversion technologies of plastic waste with a significantly high number of citations, i.e. 2405 compared to those for all other institutions displayed, which range from 348 to 1581. Key academic staff in the top ten most active institutions and their research area and equipment are summarised in Table S1 in the supplementary information. Most of the research in these institutions was carried out at a microgram level using thermogravimetric analysers, tandem μ-reactors and pyroprobes and at a gram level using bench-scale fixed bed reactors, fluidised bed reactors and conical spouted bed reactors with one or multiple stages.

3.5. Author analysis

3.5.1. Co-authorship analysis

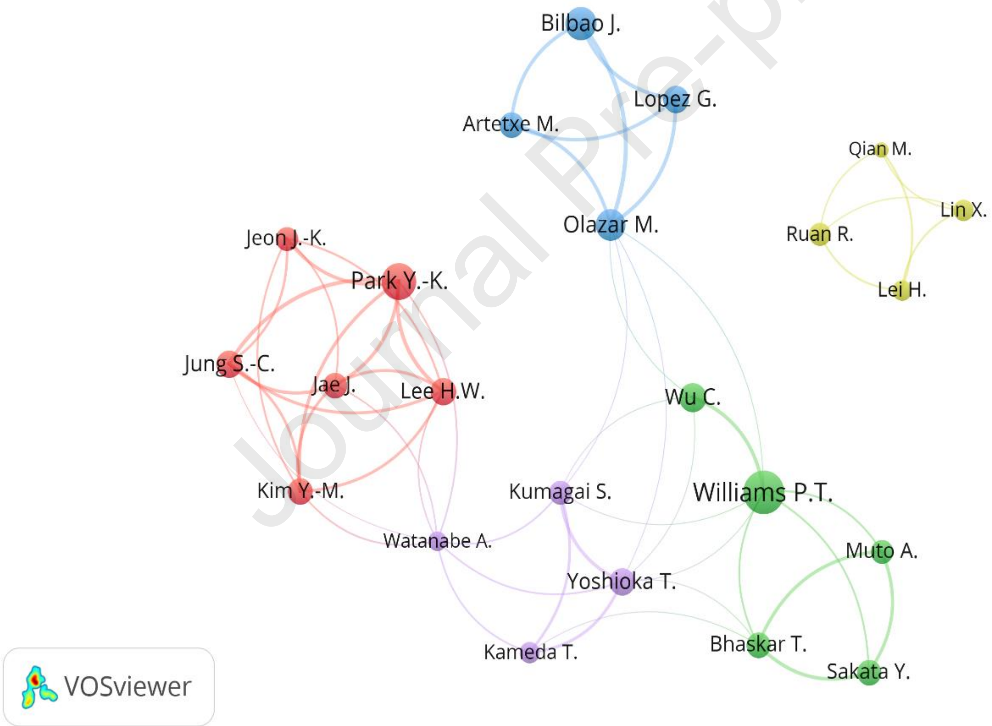


Fig. 11. Co-authorship map of authors which indicates the authors that cooperate in the field of thermochemical conversion of plastics. The size of the node indicates the total number of publications each author has contributed to. The thickness of the line between two nodes indicates the number of publications the authors have published together. The colour represents regions of publications.

Fig. 11 shows a co-authorship analysis of authors who have published at least six publications. This is not exclusive to the first listed author. There are clear research networks that are generally based on location, as shown by the different colours in the network, with green indicating the United Kingdom, India and Japan, purple indicating Japan, red corresponding to South Korea, blue representing Spain and yellow representing China and the United States. This shows that many nations are interlinked when conducting and publishing research, however, it is also important to note that China has not got strong links with any of the other clusters in the visualisation. This is simply due to the low number of authors that can be represented in an effective manner. Another key feature is the strength within clusters, particularly Spain and South Korea. These authors have thicker lines indicating they collaborate on a majority of publications as a group. With the size of the node representing the number of publications, it is clear that Williams P.T, Bilbao J, and Park Y.-K are the most productive authors in this network. More detailed information about the authors listed in Fig. 11 is presented in Table S2 in the supplementary information.

3.5.2. Citation analysis of authors

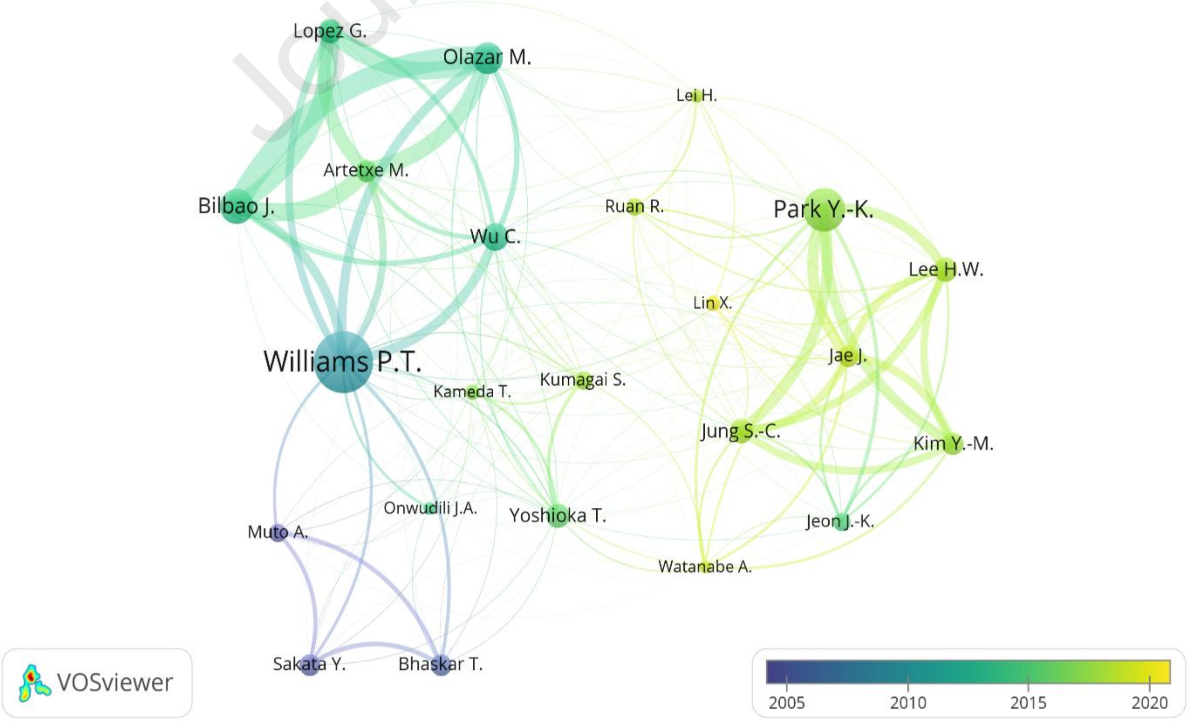


Fig. 12. Citation analysis of authors. The size of the nodes represents the number of publications of each author. The thickness between two nodes indicates the total number of citations between each node – where one node cites the other. The citation links have no direction. The colour of the node represents the average year of publication for each author.

Fig. 12 shows the citation analysis of the most cited authors. From the top 30 entries, 23 unique names are shown from 1705 publications, and with over 4065 unique authors. The number of connections to other authors is referred to as Links, while the total link strength refers to the strength of a link of one item with other items. In this case of citation links between researchers, the links attribute indicates the number of citation links of a given researcher with other researchers. The total link strength attribute indicates the total strength of the citation links of a given researcher with other researchers (adapted from manual). Fig. 12 is a small sample of the citations between authors and gives an insight into how collaborative research within this field is. From Fig. 12 it is evident that the authors on the left-hand side of the network are more established authors with a lower average year of publication, while those on the right have a more recent average year of publication. This shows the shift in research and the volume of citations between researchers who are newer in this field of research. More detailed information about the authors listed in Fig. 12 is presented in Table S2 in the supplementary information.

3.6. Cited analysis of publications

Table 2

Most cited gasification publications.

Title	Reference	Journal	Institute	Country	Cited by
Generalized pyrolysis model for combustible solids	(Lautenberger and Fernandez-Pello, 2009)	Fire Saf. J.	UC Berkeley	USA	196
Hydrogen production by steam gasification of polypropylene with various nickel catalysts	(Wu and Williams, 2009)	Appl. Catal. B	UL	UK	155
Syngas production from catalytic gasification of waste polyethylene: Influence of temperature on gas yield and composition	(He et al., 2009)	Int. J. Hydrog. Energy	HUST	China	146
Characteristics of syngas from co-gasification of polyethylene and woodchips	(Ahmed et al., 2011)	Appl. Energy	UMD	USA	117
A study of the flammability reduction mechanism of polystyrene-layered silicate nanocomposite: Layered silicate reinforced carbonaceous char	(Gilman et al., 2006)	Polym. Adv. Technol.	BFRL	USA	115
Air gasification of polypropylene plastic waste in fluidized bed gasifier	(Xiao et al., 2007)	Energy Convers. Manag.	SEU	China	113
Effect of catalysts in the quality of syngas and by-products obtained by co-gasification of coal and wastes. 1. Tars and nitrogen compounds abatement	(Pinto et al., 2007)	Fuel	INETI	Portugal	95
Investigation of coke formation on Ni-Mg-Al catalyst for hydrogen production from the catalytic steam pyrolysis-gasification of polypropylene	(Wu and Williams, 2010)	Appl. Catal. B	UL	UK	87
Control of steam input to the pyrolysis-gasification of waste plastics for improved production of hydrogen or carbon nanotubes	(Acomb et al., 2014)	Appl. Catal. B	UL	UK	86
Fluidized bed thermal degradation products of HDPE in an inert atmosphere and in air-nitrogen mixtures	(Mastral et al., 2003)	J. Anal. Appl. Pyrolysis	UNIZAR	Spain	86

NIST: National Institute of Standards and Technology; UC Berkeley: University of California, Berkeley; HUST: Huazhong University of Science and Technology; UMD: University of Maryland; BFRL: Building and Fire Research Laboratory; SEU: Southeast University; INETI: Instituto Nacional de Engenharia, Tecnologia e Inovação; UL: University of Leeds; UNIZAR: University of Zaragoza

Table 3

Most cited liquefaction publications.

Title	Reference	Journal	Institute	Country	Cited by
Analysis of products from the pyrolysis and liquefaction of single plastics and waste plastic mixtures	(Williams and Slaney, 2007)	Resour. Conserv. Recy.	UL	UK	135
Coliquefaction of Waste Plastics with Coal	(Taghiei et al., 1994)	Energy & Fuels	UKY	USA	91
Direct liquefaction of waste plastics and coliquefaction of coal-plastic mixtures	(Feng et al., 1996)	Fuel Process. Technol.	UKY	USA	73
Thermal degradation/hydrogenation of commodity plastics and characterization of their liquefaction products	(Murty et al., 1996)	Fuel Process. Technol.	UKY	USA	46
Depolymerization-liquefaction of plastics and rubbers. 1. Polyethylene, polypropylene, and polybutadiene	(Shabtai et al., 1997)	Energy & Fuels	UoU	USA	45
Co-liquefaction of microalgae and synthetic polymer mixture in sub- and supercritical ethanol	(Pei et al., 2012)	Fuel Process. Technol.	HNU	China	42
Liquefaction of mixed plastics containing PVC and dechlorination by calcium-based sorbent	(Bhaskar et al., 2003)	Energy & Fuels	OU	Japan	41
Co-liquefaction of Makarwal coal and waste polystyrene by microwave-metal interaction pyrolysis in copper coil reactor	(Hussain et al., 2011)	J. Anal. Appl. Pyrolysis	AWKUM	Pakistan	38
Co-production of bio-oil and propylene through the hydrothermal liquefaction of polyhydroxybutyrate producing cyanobacteria	(Wagner et al., 2016)	Bioresour. Technol.	UoB	UK	34
Mechanism study of iron-based catalysts in co-liquefaction of coal with waste plastics	(Wang and Chen, 2002)	Fuel	SDUST	China	31

UL: University of Leeds; UKY: University of Kentucky; UoU: University of Utah; HNU: Hunan University; OU: Okayama University; AWKUM: Abdul Wali Khan University; UoB: University of Bath; SDUST: Shandong University of Science and Technology

Table 4

Most cited pyrolysis publications.

Title	Reference	Source title	Institute	Country	Cited by
Pyrolysis characteristics and kinetics of municipal solid wastes	(Sørum et al., 2001)	Fuel	NTNU	Norway	397
Chemical recycling of plastic wastes made from polyethylene (LDPE and HDPE) and polypropylene (PP)	(Achilias et al., 2007)	J. Hazard. Mater.	AUTH	Greece	292
Kinetic study on the thermal degradation of polypropylene and polyethylene	(Bockhorn et al., 1999)	J. Anal. Appl. Pyrolysis	KIT	Germany	271
Identification of polymer types and additives in marine microplastic particles using pyrolysis-GC/MS and scanning electron microscopy	(Fries et al., 2013)	Environ. Sci. Process Impacts	UOS	Germany	267
Pyrolysis of municipal plastic wastes for recovery of gasoline-range hydrocarbons	(Demirbas, 2004)	J. Anal. Appl. Pyrolysis	SÜ	Turkey	241
Thermal degradation behaviors of polyethylene and polypropylene. Part I: Pyrolysis kinetics and mechanisms	(Aboulkas and Bouadili, 2010)	Energy Convers. Manag.	UCA	Morocco	238
Kinetics of the low-temperature pyrolysis of polyethene, polypropene, and polystyrene modeling, experimental determination, and comparison with literature models and data	(Westerhout et al., 1997)	Ind. Eng. Chem. Res.	UT	Netherlands	236
Fluidised bed pyrolysis of low density polyethylene to produce petrochemical feedstock	(Williams and Williams, 1999)	J. Anal. Appl. Pyrolysis	UL	UK	231
A study of the products of PVC thermal degradation	(McNeill et al., 1995)	Polym. Degrad. Stab.	Glas	UK	218
Thermogravimetric characteristics and kinetic of plastic and biomass blends co-pyrolysis	(Zhou et al., 2006)	Fuel Process. Techol.	TU	China	213

NIST: National Institute of Standards and Technology; NTNU: Norwegian University of Science and Technology; AUTH: Aristotle University of Thessaloniki; KIT: Karlsruhe Institute of Technology; UOS: University of Osnabrueck; SÜ: Selçuk University; UCA: Université Cadi Ayyad; UT: University of Twente; UL: University of Leeds; Glas: University of Glasgow; TU: Tianjin University.

Tables 2, 3 and 4 display the most influential papers in each of the three different types of thermochemical conversion technologies. The publications have been selected based on the total number of citations.

For gasification, all listed publications have been published during the second half of the research period, indicating that recent publications are more influential, in comparison with publications before 2005. For liquefaction and pyrolysis publications the publications are spread over most of the 30-year period. The low number of papers in liquefaction research could explain the low citations, and the low average citations per year for the publications. Four of the liquefaction papers focused on co-liquefaction, highlighting that this thermochemical conversion is usually used for plastic paired with another material.

For pyrolysis research, all publications have over 200 citations, which is more than 2 times higher than the least cited one in gasification (86 citations), and around 7 times higher compared to the least cited liquefaction publication (31 citations). This displays the strong interest and dominance of pyrolysis as a thermochemical conversion technology when considering the treatment of plastic waste.

Tables 2, 3 and 4 show that there are two types of publications that would lead to a high citation. One type of publication is about novel processes, while another type is about reaction kinetics and mechanism. For gasification, pioneer papers on novel processes such as steam gasification (Wu and Williams, 2009), air gasification (Xiao et al., 2007), catalytic gasification (He et al., 2009), co-gasification with biomass (Ahmed et al., 2011), pyrolysis-gasification coupling (Acomb et al., 2014), all have received high interests. For liquefaction, most of the highly cited publications were on the co-liquefaction process, clearly indicating that co-liquefaction is the most promising process in the relevant research area. For pyrolysis, six out of the ten most-cited publications were about reaction kinetics and mechanism.

The most cited recent publications, which were published in 2016 and after, give a better view on the future direction in the research area. As shown in Table 5, three keywords are noticeable, i.e., plastic waste types, co-pyrolysis, and catalytic pyrolysis. These keywords have pointed out one challenge and two potential solutions of thermochemical conversion of plastic waste. Chemically recycle plastic waste with a variety of mixed plastic types and additives is always a challenge. Different plastics have different properties and thus lead to different products (Miandad et al., 2017a). Heteroatoms, such as chlorine, may seriously affect the quality of the products and the lifetime of the equipment. Therefore, the sorting and pretreatment of plastic waste are extremely important. Co-pyrolysis of plastic waste with other waste streams, especially biomass, provide a promising route for waste management as multiple waste streams are consumed as feedstock which could lead to significant waste reduction (Abnisa and Wan Daud, 2014). Among the ten most cited recent publications, there are examples of co-pyrolysis of plastic waste with paper waste (Chattopadhyay et al., 2016; Chen et al., 2016), cellulose (Kim et al., 2016), lignin (Fan et al., 2017; Jin et al., 2016) and rice straw (Kai et al., 2017). All six papers have demonstrated a strong synergistic effect between biomass and plastics during the pyrolysis. The yields of liquid and gas products and the aromatics and olefin production are affected by the interaction of biomass and plastics. Comparing to thermal pyrolysis, catalytic pyrolysis offers numerous advantages, including lower reaction temperature, shorter reaction time, better quality products and reduced need for further upgrading (Miandad et al., 2016). Catalysts were used in five of the ten most cited recent publications. Zeolites, such as ZSM-5 (Fan et al., 2017; Kim et al., 2016; Ratnasari et al., 2017), Y-type zeolite (Kim et al., 2016) and natural zeolite (Miandad et al., 2017b), were the most commonly used. Metal oxides (Fan et al., 2017) and supported metal catalysts (Chattopadhyay et al., 2016) were also investigated. Based on the analysis of the ten most cited recent publications, it is clear that co-pyrolysis and catalytic pyrolysis are the current trend in the research area of the thermochemical treatment of plastic waste.

Table 5

Most cited recent publications since 2016.

Title	Reference	Source title	Institute	Country	Cited by
Effect of plastic waste types on pyrolysis liquid oil	(Miandad et al., 2017a)	Int. Biodeterior. Biodegradation.	KAU	Saudi Arabia	116
Fast microwave-assisted catalytic co-pyrolysis of lignin and low-density polyethylene with HZSM-5 and MgO for improved bio-oil yield and quality	(Fan et al., 2017)	Bioresour. Technol.	NU	China	85
Catalytic co-pyrolysis of paper biomass and plastic mixtures (HDPE (high density polyethylene), PP (polypropylene) and PET (polyethylene terephthalate)) and product analysis	(Chattopadhyay et al., 2016)	Energy	BIT	India	82
Catalytic pyrolysis of waste plastics using staged catalysis for production of gasoline range hydrocarbon oils	(Ratnasari et al., 2017)	J. Anal. Appl. Pyrolysis	UL	United Kingdom	80
Catalytic Copyrolysis of Cellulose and Thermoplastics over HZSM-5 and HY	(Kim et al., 2016)	ACS Sustain. Chem. Eng.	UoS	South Korea	78
Time and temperature depended fuel gas generation from pyrolysis of real world municipal plastic waste	(Singh and Ruj, 2016)	Fuel	CSIR-CMERI	India	74
Evaluation of the co-pyrolysis of lignin with plastic polymers by TG-FTIR and Py-GC/MS	(Jin et al., 2016)	Polym. Degrad. Stab.	SEU	China	71
Co-pyrolysis of waste newspaper with high-density polyethylene: Synergistic effect and oil characterization	(Chen et al., 2016)	Energy Convers. Manag.	NFU	China	67
Plastic waste to liquid oil through catalytic pyrolysis using natural and synthetic zeolite catalysts	(Miandad et al., 2017b)	Waste Manage.	KAU	Saudi Arabia	64
Study on the co-pyrolysis of rice straw and high density polyethylene blends using TG-FTIR-MS	(Kai et al., 2017)	Energy Convers. Manag.	DUT	China	63

KAU: King Abdulaziz University; NU: Nanchang University; BIT: Birla Institute of Technology; UL: University of Leeds; UoS: University of Seoul; CSIR-CMERI: CSIR-Central Mechanical Engineering Research Institute; SEU: Southeast University; NFU: Nanjing Forestry University; DUT: Dalian University of Technology.

3.7. Keyword analysis

Table 6 summaries the changing trend of the keywords in the last three decades. In gasification papers, the top three keywords have remained constant for the past two decades, i.e. gasification, polyethylene and hydrogen, however the total occurrences have either doubled or tripled. Pyrolysis has moved from 9th to 5th and stayed constant at 5th from 2000, indicating the strong link between these thermochemical conversion technologies and the similarities between these work. The rank of steam gasification is evidently increasing, moving from 10th to 9th between 2000 – 2009 and 2010 – 2019. The most recent keywords indicate an interest in co-gasification techniques, especially for plastic and biomass.

Table 6

Keyword analysis.

	1990-1999 Keywords	2000-2009 Keywords	2010-2019 Keywords
	Gasification		
Rank	9 Publications	36 Publications	95 Publications
1	Alumina (1)	Gasification (16)	Gasification (29)
2	Catalysis (1)	Polyethylene (8)	Polyethylene (22)
3	Char (1)	Hydrogen (5)	Hydrogen (17)
4	Decomposition (1)	Polypropylene (5)	Plastic waste (15)
5	Gas formation (1)	Pyrolysis (5)	Pyrolysis (15)
6	Gasification (1)	Catalyst (4)	Waste (12)
7	Polyethylene (1)	Nickel (4)	Biomass (11)
8	Polyvinyl chloride (1)	Waste (4)	Co-gasification (7)
9	Pyrolysis (1)	Polyvinyl chloride (3)	Steam (7)
10	Waste plastics (1)	Steam (2)	Polypropylene (6)
	Liquefaction		
Rank	20 Publications	9 Publications	14 Publications
1	Liquefaction (5)	Co-liquefaction (3)	Co-liquefaction (4)
2	Co-Liquefaction (4)	Waste plastics (2)	Copper (2)
3	Waste plastics (4)	-	Hydro-liquefaction (2)
4	Polyethylene (3)	-	Liquefaction (2)
5	Catalysts (2)	-	Microalgae (2)
6	Coal (2)	-	Microwave (2)
7	Lignite (2)	-	Phase (2)
8	-	-	Plastic (2)
9	-	-	Polyethylene (2)
10	-	-	Polystyrene (2)
11	-	-	Supercritical Water (2)
	Pyrolysis		
Rank	166 Publications	397 Publications	822 Publications
1	Pyrolysis (44)	Pyrolysis (135)	Pyrolysis (279)
2	Polystyrene (24)	Polyethylene (62)	Polyethylene (139)
3	Polyethylene (12)	Polystyrene (37)	Copyrolysis (94)

4	Polyvinylchloride (10)	Kinetics (36)	Plastic waste (84)
5	Gas chromatography (6)	Polypropylene (26)	Polystyrene (79)
6	Kinetics (6)	Thermal degradation (25)	Polypropylene (74)
7	Pyrolysis gc-ms (6)	Thermogravimetric analysis (24)	Catalytic pyrolysis (68)
8	Mass spectroscopy (4)	Polyvinylchloride (24)	Kinetics (66)
9	Polyurethane (4)	Plastic waste (21)	Biomass (53)
10	Thermal decomposition (3)	Polyurethane (15)	Zeolite (48)

Due to the limited number of papers in liquefaction research, there have not been enough keywords to rank from 1 – 10. Between 2010 – 2019, 11 keywords are displayed due to only one word being applicable if a frequency of two was dismissed. Early liquefaction research appears to use coal as a catalyst. In contrast, in more recent publications, it appears that co-liquefaction and hydro-liquefaction are preferred, using biomass such as microalgae, and supercritical water, respectively.

Pyrolysis keywords indicate the constant growth of research in this thermochemical conversion technology. The frequency of the highest-ranked keyword has increased by a factor of 6 from the first decade to the last decade. The most commonly used plastic, polystyrene and polyethylene ranked the 2nd and 3rd in all decades except the last one – polystyrene went from the 3rd ranking to the 5th. There was a strong focus on analytical methods in the first 20 years of research, evidenced by terms such as *gas chromatography, pyrolysis gc-ms, mass spectroscopy, and thermogravimetric analysis.* In the last decade of publications, as with gasification and liquefaction, there has been increased research in co-pyrolysis and catalytic pyrolysis. This is supported by the appearance of biomass and zeolite, being the rank of 9 and 10, respectively. The co-pyrolysis with biomass is progressive as it is addressing the possibility of using renewable resources to generate pyrolysis products which traditionally would have been only derived from plastic feedstock. However, using biomass may decrease the capacity of plastic waste that can be processed, which will ultimately add to the problem of plastic solid waste. Conversely, the introduction of zeolite and catalytic pyrolysis could increase the capacity by reducing the process time and improve the quality of the liquid product. Therefore, the catalytic co-pyrolysis with biomass, ensures the process is sustainable, while also addressing the problem of plastic solid waste.

4. Conclusions

Three decades of literature on thermochemical conversion technologies of plastic waste has been analysed in this study, to show the research trends in three different types of thermochemical conversion technologies, gasification, liquefaction, and pyrolysis.

The key findings were as follows:

In the past three decades, a total of 71 countries have contributed to the research on the thermochemical conversion treatment methods of plastic solid waste. However, a majority of the contributions are from 10 key countries, with China accounting for 21.58% of the total publications.

Pyrolysis has been the most heavily researched thermochemical conversion technology, with 88.43% of publications, and publications from all 71 countries included in the study.

The number of publications is linked to funding with the most productive countries receiving both national and local funding, as well as projects funded by academic institutions.

Research is in a very defining stage at the moment, should interest increase significantly in the next few years. Co-pyrolysis with biomass and catalytic pyrolysis are gaining increased interests. It is clear that the import of plastics ban announced by China since 2017 is a key factor for increased research, and the next few years of research will show the true impact of this. Due to this displacement of such large volumes of plastic waste, it is likely that publications will increase in immediate years as each nation seeks solutions on how to manage and valorise the domestic or imported displaced plastic waste.

Acknowledgements

The work was supported by an Institutional Links grant (No. 527641843), under the Turkey partnership. The grant is funded by the UK Department for Business, Energy and Industrial

Strategy together with the Scientific and Technological Research Council of Turkey (TÜBİTAK; Project no. 119N302) and delivered by the British Council.

CRediT authorship contribution statement

Roomana Khatun: Investigation, Formal analysis, Writing - Original Draft; **Huan Xiang**: Formal analysis, Writing - Review & Editing; **Yang Yang**: Supervision, Writing - Review & Editing, Funding acquisition; **Jiawei Wang**: Supervision, Writing - Review & Editing, Funding acquisition, **Güray Yildiz**: Writing - Review & Editing, Funding acquisition

References

Abnisa, F., Wan Daud, W.M.A., 2014. A review on co-pyrolysis of biomass: An optional technique to obtain a high-grade pyrolysis oil. Energy Convers. Manag. 87, 71–85. https://doi.org/10.1016/J.ENCONMAN.2014.07.007

Aboulkas, A., Bouadili, A. El, 2010. Thermal degradation behaviors of polyethylene and polypropylene. Part I: Pyrolysis kinetics and mechanisms. Energy Convers. Manag. 51, 1363–1369.

Achilias, D.S., Roupakias, C., Megalokonomos, P., Lappas, A.A., Antonakou, E. V, 2007. Chemical recycling of plastic wastes made from polyethylene (LDPE and HDPE) and polypropylene (PP). J. Hazard. Mater. 149, 536–542.

Acomb, J.C., Wu, C., Williams, P.T., 2014. Control of steam input to the pyrolysis-gasification of waste plastics for improved production of hydrogen or carbon nanotubes. Appl. Catal. B Environ. 147, 571–584. https://doi.org/https://doi.org/10.1016/j.apcatb.2013.09.018

Ahmed, I.I., Nipattummakul, N., Gupta, A.K., 2011. Characteristics of syngas from co-gasification of polyethylene and woodchips. Appl. Energy 88, 165–174. https://doi.org/10.1016/j.apenergy.2010.07.007

Al-Salem, S.M., Lettieri, P., Baeyens, J., 2010. The valorization of plastic solid waste (PSW) by primary to quaternary routes: From re-use to energy and chemicals. Prog. Energy Combust. Sci. 36, 103–129. https://doi.org/https://doi.org/10.1016/j.pecs.2009.09.001

Al-Salem, S.M., Lettieri, P., Baeyens, J., 2009. Recycling and recovery routes of plastic solid waste (PSW): A review. Waste Manag. https://doi.org/10.1016/j.wasman.2009.06.004

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. Environ. Manage. 64, 230–244. https://doi.org/10.1007/s00267-019-01178-3

Arandes, J.M., Ereña, J., Bilbao, J., López-Valerio, D., de la Puente, G., 2003. Valorization of the Blends Polystyrene/Light Cycle Oil and Polystyrene−Butadiene/Light Cycle Oil over HZSM-5 Zeolites. Ind. Eng. Chem. Res. 42, 3700–3710. https://doi.org/10.1021/ie030045j

Basu, P., 2018. Biomass Gasification Pyrolysis and Torrefaction.

Bhaskar, T., Uddin, M.A., Kaneko, J., Kusaba, T., Matsui, T., Muto, A., Sakata, Y., Murata, K., 2003. Liquefaction of mixed plastics containing PVC and dechlorination by calcium-based sorbent. Energy & fuels 17, 75–80.

Bockhorn, H., Hornung, A., Hornung, U., Schawaller, D., 1999. Kinetic study on the thermal degradation of polypropylene and polyethylene. J. Anal. Appl. Pyrolysis 48, 93–109. https://doi.org/https://doi.org/10.1016/S0165-2370(98)00131-4

Brems, A., Dewil, R., Baeyens, J., Zhang, R., 2013. Gasification of plastic waste as waste-to-energy or waste-to-syngas recovery route. Nat. Sci. 05, 695–704. https://doi.org/10.4236/ns.2013.56086

Chattopadhyay, J., Pathak, T.S., Srivastava, R., Singh, A.C., 2016. Catalytic co-pyrolysis of paper biomass and plastic mixtures (HDPE (high density polyethylene), PP (polypropylene) and PET (polyethylene terephthalate)) and product analysis. Energy 103, 513–521. https://doi.org/10.1016/J.ENERGY.2016.03.015

Chen, W., Shi, S., Zhang, J., Chen, M., Zhou, X., 2016. Co-pyrolysis of waste newspaper with high-density polyethylene: Synergistic effect and oil characterization. Energy Convers. Manag. 112, 41–48. https://doi.org/10.1016/J.ENCONMAN.2016.01.005

Demirbas, A., 2004. Pyrolysis of municipal plastic wastes for recovery of gasoline-range hydrocarbons. J. Anal. Appl. Pyrolysis 72, 97–102. https://doi.org/10.1016/j.jaap.2004.03.001

deSousa, F.D.B., 2021. Management of plastic waste: A bibliometric mapping and analysis. Waste Manag. Res. 0, 0734242X21992422. https://doi.org/10.1177/0734242X21992422

Fan, L., Chen, P., Zhang, Y., Liu, S., Liu, Y., Wang, Y., Dai, L., Ruan, R., 2017. Fast microwave-assisted catalytic co-pyrolysis of lignin and low-density polyethylene with HZSM-5 and MgO for improved bio-oil yield and quality. Bioresour. Technol. 225, 199–205. https://doi.org/10.1016/J.BIORTECH.2016.11.072

Feng, Z., Zhao, J., Rockwell, J., Bailey, D., Huffman, G., 1996. Direct liquefaction of waste plastics and coliquefaction of coal-plastic mixtures. Fuel Process. Technol. 49, 17–30. https://doi.org/https://doi.org/10.1016/S0378-3820(96)01036-3

Fries, E., Dekiff, J.H., Willmeyer, J., Nuelle, M.-T., Ebert, M., Remy, D., 2013. Identification of polymer types and additives in marine microplastic particles using pyrolysis-GC/MS and scanning electron microscopy. Environ. Sci. Process. Impacts 15, 1949–1956. https://doi.org/10.1039/C3EM00214D

Fu, H., Ho, Y., Sui, Y., Li, Z., 2010. A bibliometric analysis of solid waste research during the period 1993-2008. Waste Manag. 30, 2410—2417. https://doi.org/10.1016/j.wasman.2010.06.008

Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. Sci. Adv. 3, e1700782. https://doi.org/10.1126/sciadv.1700782

Gilman, J.W., Jr., R.H.H., Shields, J.R., Kashiwagi, T., Morgan, A.B., 2006. A study of the flammability reduction mechanism of polystyrene-layered silicate nanocomposite: layered silicate reinforced carbonaceous char. Polym. Adv. Technol. 17, 263–271. https://doi.org/https://doi.org/10.1002/pat.682

He, M., Xiao, B., Hu, Z., Liu, S., Guo, X., Luo, S., 2009. Syngas production from catalytic gasification of waste polyethylene: Influence of temperature on gas yield and composition. Int. J. Hydrogen Energy 34, 1342–1348. https://doi.org/10.1016/j.ijhydene.2008.12.023

Hussain, Z., Khan, K.M., Basheer, N., Hussain, K., 2011. Co-liquefaction of Makarwal coal and waste polystyrene by microwave–metal interaction pyrolysis in copper coil reactor. J. Anal. Appl. Pyrolysis 90, 53–55. https://doi.org/https://doi.org/10.1016/j.jaap.2010.10.002

Jin, W., Shen, D., Liu, Q., Xiao, R., 2016. Evaluation of the co-pyrolysis of lignin with plastic polymers by TG-FTIR and Py-GC/MS. Polym. Degrad. Stab. 133, 65–74. https://doi.org/10.1016/J.POLYMDEGRADSTAB.2016.08.001

Kai, X., Li, R., Yang, T., Shen, S., Ji, Q., Zhang, T., 2017. Study on the co-pyrolysis of rice straw and high density polyethylene blends using TG-FTIR-MS. Energy Convers. Manag. 146, 20–33. https://doi.org/10.1016/J.ENCONMAN.2017.05.026

Kim, B.-S., Kim, Y.-M., Lee, H.W., Jae, J., Kim, D.H., Jung, S.-C., Watanabe, C., Park, Y.-K., 2016. Catalytic Copyrolysis of Cellulose and Thermoplastics over HZSM-5 and HY. ACS Sustain. Chem. Eng. 4, 1354–1363. https://doi.org/10.1021/ACSSUSCHEMENG.5B01381

Kim, Y.S., Hwang, G.C., Bae, S.Y., Yi, S.C., Moon, S.K., Kumazawa, H., 1999. Pyrolysis of polystyrene in a batch-type stirred vessel. Korean J. Chem. Eng. 16, 161–165. https://doi.org/10.1007/BF02706830

Lautenberger, C., Fernandez-Pello, C., 2009. Generalized pyrolysis model for combustible solids. Fire Saf. J. 44, 819–839.

Law, K.L., Starr, N., Siegler, T.R., Jambeck, J.R., Mallos, N.J., Leonard, G.H., 2020. The United States contribution of plastic waste to land and ocean. Sci. Adv. 6. https://doi.org/10.1126/sciadv.abd0288

Li, N., Han, R., Lu, X., 2018. Bibliometric analysis of research trends on solid waste reuse and recycling during 1992–2016. Resour. Conserv. Recycl. 130, 109–117. https://doi.org/https://doi.org/10.1016/j.resconrec.2017.11.008

Maafa, I.M., 2021. Pyrolysis of polystyrene waste: A review. Polymers (Basel). https://doi.org/10.3390/polym13020225

Mastral, F.J., Esperanza, E., Berrueco, C., Juste, M., Ceamanos, J., 2003. Fluidized bed thermal degradation products of HDPE in an inert atmosphere and in air-nitrogen mixtures. J. Anal. Appl. Pyrolysis 70, 1–17. https://doi.org/10.1016/S0165-2370(02)00068-2

McBurney, M.K., Novak, P.L., Novak, P., 2002. Reflections on Communication What Is Bibliometrics and Why Should You Care?

McNeill, I.C., Memetea, L., Cole, W.J., 1995. A study of the products of PVC thermal degradation. Polym. Degrad. Stab. 49, 181–191. https://doi.org/https://doi.org/10.1016/0141-3910(95)00064-S

Miandad, R., Barakat, M.A., Aburiazaiza, A.S., Rehan, M., Ismail, I.M.I., Nizami, A.S., 2017a. Effect of plastic waste types on pyrolysis liquid oil. Int. Biodeterior. Biodegradation 119, 239–252. https://doi.org/10.1016/J.IBIOD.2016.09.017

Miandad, R., Barakat, M.A., Aburiazaiza, A.S., Rehan, M., Nizami, A.S., 2016. Catalytic pyrolysis of plastic waste: A review. Process Saf. Environ. Prot. 102, 822–838. https://doi.org/10.1016/J.PSEP.2016.06.022

Miandad, R., Barakat, M.A., Rehan, M., Aburiazaiza, A.S., Ismail, I.M.I., Nizami, A.S., 2017b. Plastic waste to liquid oil through catalytic pyrolysis using natural and synthetic zeolite catalysts. Waste Manag. 69, 66–78. https://doi.org/10.1016/J.WASMAN.2017.08.032

Murty, M.V.S., Rangarajan, P., Grulke, E.A., Bhattacharyya, D., 1996. Thermal degradation/hydrogenation of commodity plastics and characterization of their liquefaction products. Fuel Process. Technol. 49, 75–90. https://doi.org/https://doi.org/10.1016/S0378-3820(96)01040-5

Panepinto, D., Senor, A., Genon, G., 2016. Energy recovery from waste incineration: economic aspects. Clean Technol. Environ. Policy 18, 517–527. https://doi.org/10.1007/s10098-015-1033-7

Pauna, V.H., Buonocore, E., Renzi, M., Russo, G.F., Franzese, P.P., 2019. The issue of microplastics in marine ecosystems: A bibliometric network analysis. Mar. Pollut. Bull. 149, 110612. https://doi.org/https://doi.org/10.1016/j.marpolbul.2019.110612

Pei, X., Yuan, X., Zeng, G., Huang, H., Wang, J., Li, H., Zhu, H., 2012. Co-liquefaction of microalgae and synthetic polymer mixture in sub- and supercritical ethanol. Fuel Process. Technol. 93, 35–44. https://doi.org/https://doi.org/10.1016/j.fuproc.2011.09.010

Pinto, F., Lopes, H., André, R.N., Gulyurtlu, I., Cabrita, I., 2007. Effect of catalysts in the quality of syngas and by-products obtained by co-gasification of coal and wastes. 1. Tars and nitrogen compounds abatement. Fuel 86, 2052–2063. https://doi.org/https://doi.org/10.1016/j.fuel.2007.01.019

Ramdoss, P.K., Tarrer, A.R., 1998. High-temperature liquefaction of waste plastics. Fuel 77, 293–299. https://doi.org/https://doi.org/10.1016/S0016-2361(97)00193-2

Ratnasari, D.K., Nahil, M.A., Williams, P.T., 2017. Catalytic pyrolysis of waste plastics using staged catalysis for production of gasoline range hydrocarbon oils. J. Anal. Appl. Pyrolysis 124, 631–637. https://doi.org/10.1016/J.JAAP.2016.12.027

Shabtai, J., Xiao, X., Zmierczak, W., 1997. Depolymerization−Liquefaction of Plastics and Rubbers. 1. Polyethylene, Polypropylene, and Polybutadiene. Energy & Fuels 11, 76–87. https://doi.org/10.1021/ef960076+

Singh, R.K., Ruj, B., 2016. Time and temperature depended fuel gas generation from pyrolysis of real world municipal plastic waste. Fuel 174, 164–171. https://doi.org/10.1016/J.FUEL.2016.01.049

Sorensen, R.M., Jovanović, B., 2021. From nanoplastic to microplastic: A bibliometric analysis on the presence of plastic particles in the environment. Mar. Pollut. Bull. 163, 111926. https://doi.org/https://doi.org/10.1016/j.marpolbul.2020.111926

Sørum, L., Grønli, M.G., Hustad, J.E., 2001. Pyrolysis characteristics and kinetics of municipal solid wastes. Fuel 80, 1217–1227. https://doi.org/https://doi.org/10.1016/S0016-2361(00)00218-0

Taghiei, M.M., Feng, Z., Huggins, F.E., Huffman, G.P., 1994. Coliquefaction of Waste Plastics with Coal. Energy & Fuels 8, 1228–1232. https://doi.org/10.1021/ef00048a010

Wagner, J., Bransgrove, R., Beacham, T.A., Allen, M.J., Meixner, K., Drosg, B., Ting, V.P., Chuck, C.J., 2016. Co-production of bio-oil and propylene through the hydrothermal liquefaction of polyhydroxybutyrate producing cyanobacteria. Bioresour. Technol. 207, 166–174. https://doi.org/https://doi.org/10.1016/j.biortech.2016.01.114

Wang, L., Chen, P., 2002. Mechanism study of iron-based catalysts in co-liquefaction of coal with waste plastics. Fuel 81, 811–815. https://doi.org/https://doi.org/10.1016/S0016-2361(01)00201-0

Wang, Y., Lai, N., Zuo, J., Chen, G., Du, H., 2016. Characteristics and trends of research on waste-to-energy incineration: A bibliometric analysis, 1999–2015. Renew. Sustain. Energy Rev. 66, 95–104. https://doi.org/https://doi.org/10.1016/j.rser.2016.07.006

Westerhout, R.W.J., Waanders, J., Kuipers, J.A.M., van Swaaij, W.P.M., 1997. Kinetics of the Low-Temperature Pyrolysis of Polyethene, Polypropene, and Polystyrene Modeling, Experimental Determination, and Comparison with Literature Models and Data. Ind. Eng. Chem. Res. 36, 1955–1964. https://doi.org/10.1021/ie960501m

Williams, P.T., Slaney, E., 2007. Analysis of products from the pyrolysis and liquefaction of single plastics and waste plastic mixtures. Resour. Conserv. Recycl. 51, 754–769. https://doi.org/10.1016/j.resconrec.2006.12.002

Williams, P.T., Williams, E.A., 1999. Fluidised bed pyrolysis of low density polyethylene to produce petrochemical feedstock. J. Anal. Appl. Pyrolysis 51, 107–126. https://doi.org/https://doi.org/10.1016/S0165-2370(99)00011-X

Wu, C., Williams, P.T., 2010. Investigation of coke formation on Ni-Mg-Al catalyst for hydrogen production from the catalytic steam pyrolysis-gasification of polypropylene. Appl. Catal. B Environ. 96, 198–207. https://doi.org/https://doi.org/10.1016/j.apcatb.2010.02.022

Wu, C., Williams, P.T., 2009. Hydrogen production by steam gasification of polypropylene with various nickel catalysts. Appl. Catal. B Environ. 87, 152–161.

https://doi.org/10.1016/j.apcatb.2008.09.003

Xiao, R., Jin, B., Zhou, H., Zhong, Z., Zhang, M., 2007. Air gasification of polypropylene plastic waste in fluidized bed gasifier. Energy Convers. Manag. 48, 778–786. https://doi.org/10.1016/j.enconman.2006.09.004

Yuan, X., Cao, H., Li, H., Zeng, G., Tong, J., Wang, L., 2009. Quantitative and qualitative analysis of products formed during co-liquefaction of biomass and synthetic polymer mixtures in sub- and supercritical water. Fuel Process. Technol. 90, 428–434. https://doi.org/https://doi.org/10.1016/j.fuproc.2008.11.005

Zen, I.S., Ahamad, R., Omar, W., 2013. No plastic bag campaign day in Malaysia and the policy implication. Environ. Dev. Sustain. 15, 1259–1269. https://doi.org/10.1007/s10668-013-9437-1

Zhou, L., Wang, Y., Huang, Q., Cai, J., 2006. Thermogravimetric characteristics and kinetic of plastic and biomass blends co-pyrolysis. Fuel Process. Technol. 87, 963–969. https://doi.org/10.1016/j.fuproc.2006.07.002

Zhou, M., Wang, R., Cheng, S., Xu, Y., Luo, S., Zhang, Y., Kong, L., 2021. Bibliometrics and visualization analysis regarding research on the development of microplastics. Environ. Sci. Pollut. Res. 28, 1–15. https://doi.org/10.1007/s11356-021-12366-2

Research on thermochemical conversion of plastic was characterised.

Academic cooperation relationships were studied.

Trends of research emphases were obtained from the changes of keywords.

Hotspots and research trends were discussed as a useful reference for future studies.

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: