Jurnal Teknologi

Full Paper

MICROPLASTICS FROM WASTEWATER TREATMENT PLANTS: A BIBLIOMETRIC ANALYSIS

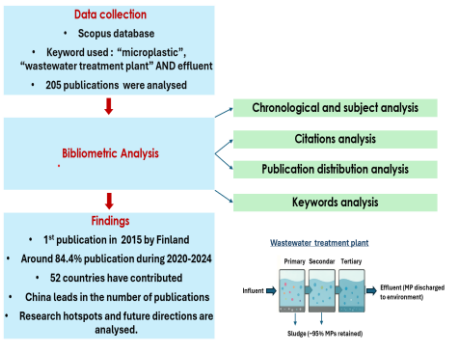
T. H. F. Aagani[a]*, S. Azman[a,f], M.Z. Mohamed Najib[a], Mazni Mat Zin[b], Nur Afifah binti A.Rahman[a], Zainab Haider Mussa[c], Fouad Fadhil Al-Qaim[d], Issa Farhan Deyab[e], Ilya Khairanis Othman[a,f]

[a]Department of Water and Environmental Engineering, Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia
[b]Centre of Civil Engineering Studies, College of Engineering, Universiti Teknologi MARA Johor Branch, Pasir Gudang Campus, 81750 Masai, Johor, Malaysia
[c]College of Biotechnology, Al-Qasim Green University, Al-Qasim, Iraq
[d]Department of Chemistry, Faculty of Science for Women, University of Babylon, PO Box 4, Hilla, Iraq
[e]Medical Physics Department, Al-Mustaqbal University, 51001 Hillah, Babil, Iraq
[f]Centre for River and Coastal Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

Article history
Received
10 February 2025
Received in revised form
29 July 2025
Accepted
3 August 2025
Published Online
16 June 2026

*Corresponding author
harriedfathima@graduate.utm.my

Graphical abstract



Abstract

Microplastics (MPs) in wastewater treatment plants (WWTPs) have received significant attention from researchers in recent years as WWTPs are a vital pathway for leaching MPs into the environment. This study employs bibliometric analysis to explore the evolution and emerging trends in research on MPs from WWTPs. This is achieved by employing a range of bibliometric techniques to analyse literature and to identify the publication pattern, prominent authors, journals, and countries contributing to the research in this field. A total of 205 research publications were analysed in this study based on the main keywords such as "microplastics" and "WWTP" and effluent". The scholars were not interested in MPs in WWTPs before 2015. However, around 84.4% of articles were published from 2020 to 2024, showing the rapid development in the related field. China leads in the number of publications. Currently, 52 countries have contributed to this field of study. The hotspots in the research area are specified based on keyword clustering analysis. This comprehensive analysis is crucial for enhancing our understanding of the fate and existence of MPs in WWTPs and their effluent. This study also provides the perspective for future studies related to MPs in WWTPs.

Keywords: Microplastic, Wastewater treatment plant, pollution, effluent, Bibliometric analysis

Abstrak

Kewujudan mikroplastik (MP) dalam loji olahan air sisa (WWTP) telah mendapat perhatian yang signifikan daripada penyelidik sejak beberapa tahun kebelakangan ini kerana WWTP merupakan laluan utama bagi pelepasan MP ke persekitaran. Kajian analisis bibliometrik ini bertujuan untuk

memberikan pemahaman yang jelas tentang keadaan semasa penyelidikan mengenai MP dalam WWTP. Ini dicapai dengan menggunakan pelbagai teknik bibliometrik untuk menganalisis literatur serta mengenal pasti corak penerbitan, pengarang terkemuka, jurnal dan negara yang menyumbang kepada penyelidikan dalam bidang ini. Sebanyak 205 penerbitan penyelidikan telah dianalisis dalam kajian ini berdasarkan kata kunci utama seperti "mikroplastik" dan "WWTP" dan "Effluen". Didapati bahawa para penyelidik tidak menunjukkan minat terhadap MP dalam WWTP sebelum tahun 2015. Namun, sekitar 84.4% artikel telah diterbitkan dari 2020 hingga 2024, yang menunjukkan perkembangan pesat dalam bidang kajian ini. China mendahului dari segi bilangan penerbitan dalam bidang berkaitan. Sehingga kini, 52 negara telah menyumbang kepada kajian ini. Tumpuan utama dalam bidang penyelidikan ini telah dikenal pasti berdasarkan analisis pengelompokan kata kunci. Analisis menyeluruh ini adalah penting untuk meningkatkan pemahaman kita tentang keadaan dan kewujudan mikroplastik dalam WWTP dan efluennya. Kajian ini juga memberikan perspektif untuk kajian masa depan berkaitan MPs dalam WWTP.

Kata kunci: Mikroplastik, Loji olahan air sisa, pencemaran, efluen, Analisis bibliometrik

1.0 INTRODUCTION

Massive consumption and application of plastic in every industry in the world have made a huge accumulation of plastic waste in the environment [1]. Plastics which are synthetic organic polymers made from petroleum oil, natural gas, coal, or converted natural products [2], are popular due to their nature of being lightweight, versatile, and durable [3]. However, the downside of this durability is its persistence in the environment, leading to long-term accumulation [4]. The United Nations Environment Program (UNEP) has stated that the annual plastic generation is 400 million tons [5]. Moreover, only 9% of plastic waste has been recycled, 12% of it has been incinerated and the remaining 79% of plastic waste has accumulated in the environment [6].

Plastic particles that are less than 5mm [7] are known as MPs [8], have become a human-induced stressor affecting both terrestrial and aquatic ecosystems [9]. MPs can be classified into two types based on their origin: primary MPs and secondary MPs. Primary MPs are intentionally produced in micro sizes, and secondary MPs result from the degradation of larger plastic materials [10]. These are further classified by shape, including foams, fibres, films, and fragments [11]. Plastic breaks into small-sized particles without undergoing a complete degradation [12]. MPs are persistent due to their slow degradation [13] and insolubility in water [14], making their prevalence in the environment particularly challenging to address.

WWTPs are recognized as the main source that releases millions of MPs into the environment [15][16][17]. The plastic undergoes the physical abrasion, biofouling, and chemical oxidation-related weathering during the different stages of WWTPs which generate MPs [18]. Cunsolo [19] has mentioned that an average of 5.6 million MPs were emitted to the environment annually per person from the sewers and an estimated 6.5×10^8 MPa were released daily from seven WWTPs into Xiamen Bay [20]. Around 95% of MPs removed during treatment accumulate in sludge [21], while the remaining MPs are discharged as effluent into the surface waters, contributing to both aquatic and terrestrial pollution [22]. The efficiency of MP removal varies depending on treatment methods [19], with primary and secondary treatments achieving removal rates between 70% and 99% and 7% to 20%, respectively [23][24].

MPs could also act as carriers of pollutants and pathogens due to their hydrophobic properties [25]. Effluent from WWTPs is a significant pathway for bacterial attachment to MPs, facilitated by biofilm formation in the presence of high inorganic nutrient levels [26]. Core bacterial groups remain attached to the MPs and are discharged from WWTPs to the environment [27]. Their presence in the environment can lead to the interaction of MPs with terrestrial and marine biota [28].

Numerous studies have reported chronic toxicity of MPs in humans and other organisms due to prolonged exposure [29][30]. Furthermore, MPs have been found in the guts of aquatic organisms such as crab, fish, mussel, prawn, mud creepers, etc. [31][32][33]. MPs also disrupt the basic intestinal functions in both vertebrates and invertebrates, leading to a wide range of negative effects [34][35]. Desforges *et al*. [36] have found the presence of MPs in marine plankton and Schwabl *et al*. [37] have found MPs in human waste. Therefore, the presence of MPs poses a significant impact on living organisms in the environment.

There are several systematic reviews on MPs from WWTPs that focus on topics such as detection methods, removal efficiencies, or environmental impacts [38].

However, these reviews often lack a comprehensive quantitative assessment of the research landscape and its development over time. Growing concerns over the presence of MPs in sludge and effluent along with their ecological and health risks, highlight the need for a bibliometric approach to identify key contributors, influential publications, emerging research hotspots, and underexplored areas within this field of study. Bibliometric analysis offers a distinct and valuable perspective by systematically mapping research trends, collaboration networks, and knowledge gaps [39,40].

This study on bibliometric analysis is aimed at provide a clear understanding of the present state of research on MPs in WWTPs. This is achieved by employing a range of bibliometric techniques to analyse literature and to identify the publication pattern, prominent authors, journals and countries contributing to the research in this field.

2.0 METHODOLOGY

2.1 Collection and Screening

The data collection and screening related to this study were conducted using the Scopus database. Scopus provided the highest number of documents compared to Web of Science search and PubMed [41]. The keywords: ("microplastic", "WWTP" AND "effluent") were used for the search. The database has publications based on these keywords from 2015 to 2024. The bibliometric search began in 2015 because the first study on MPs in WWTPs was conducted by Talvitie in 2015[42]. There were around 397 publications. The documents were further screened based on the document type, subject area, language, publication stage, and source titles. Furthermore, the search was restricted to publications only in the English language. In addition to that, the journals published more than 10 articles related to MPs were taken into consideration to improve the accuracy of the data. Moreover, the subject areas were limited to Environmental sciences and Engineering. Then the screened search results yielded around 205 publications. Table 1 shows the search string used for the search of literature in the Scopus database and Figure 1 shows publications while avoiding unrelated fields [43]. The required documents were downloaded from the Scopus database on August 15th, 2024. Citation data was also downloaded, which is available in the Scopus Report feature.

2.2 Bibliometric Analysis

Bibliometric analysis involves quantitative methods for evaluating different aspects of scholarly literature, including publication patterns, citation relationships, author productivity, and journal impact factors [44][45]. This method of analysis is widely used in academic and research institutions to evaluate research productivity, identify emerging trends, and inform strategic decisions in funding allocation and policymaking. Suitable keywords must be entered for an effective literature search.

Table 1 The search string

Database	Search strings
Scopus	TITLE-ABS-KEY (microplastics, AND , "wastewater treatment plant" , AND effluent) AND PUBYEAR > 2014 AND PUBYEAR < 2025 AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "re")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (PUBSTAGE , "final")) AND (LIMIT-TO (SRCTYPE , "j")) AND (LIMIT-TO (EXACTSRCTITLE , "Science Of The Total Environment") OR LIMIT-TO (EXACTSRCTITLE , "Water Research") OR LIMIT-TO (EXACTSRCTITLE , "Environmental Pollution") OR LIMIT-TO (EXACTSRCTITLE , "Chemosphere") OR LIMIT-TO (EXACTSRCTITLE , "Marine Pollution Bulletin") OR LIMIT-TO (EXACTSRCTITLE , "Environmental Science And Pollution Research") OR LIMIT-TO (EXACTSRCTITLE , "Journal Of Hazardous Materials") OR LIMIT-TO (EXACTSRCTITLE , "Journal Of Environmental Management") OR LIMIT-TO (EXACTSRCTITLE , "Chemical Engineering Journal") OR LIMIT-TO (EXACTSRCTITLE , "Water Science And Technology"))

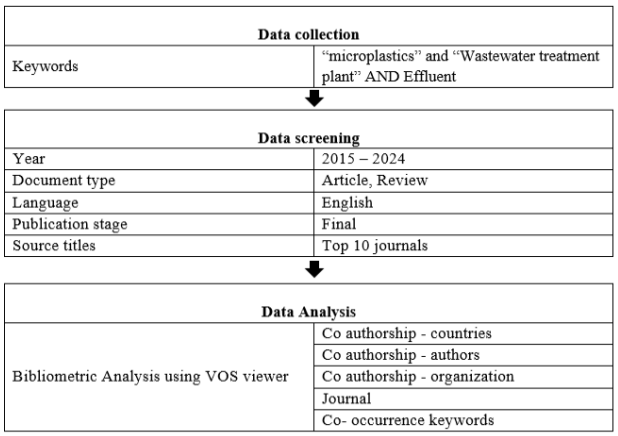


Figure 1 Flowchart of this study

This study focuses on top-tier publications from journals that are highly active and influential in the field. In order to ensure the inclusion of high-impact and widely recognized research, the analysis prioritized journals with at least 10 publications on MPs in WWTPs. This criterion was adopted to focus on journals actively contributing to the relevant research field and to prioritize prominent sources.

2.3 Data Analysis

VOSviewer is a visualization tool that was used for the analyses and publishing data to produce web maps. Distance-based visualization is created in this software in which more closely related terms are located closer [46]. Co-occurrence maps of all keywords can be produced using this software. However, the keyword should have appeared at least ten times in a

publication to be included in the map [46]. Here, the Items with higher weight have larger labels and circles [47]. Furthermore, Microsoft Excel 2020 was also used for data organization and analysis.

3.0 RESULTS AND DISCUSSION

3.1 Chronological and subject analysis of MPs in WWTPs

There were around 10,879 publications related to the existence of MPs in the environment from 2006 to 2024. However, the number of studies on the existence of MPs in WWTPs has received attention since 2015. There are around 397 research papers published related to MPs in WWTPs from 2015 to 2024. However, only 205 publications were found eligible for the analysis after screening.

3.1.1 Publication trends and regional contributions

Figure 2 (a) shows the temporal trend of articles published from 2015 to 2024. The number of publications related to MPs in WWTPs grew slowly from 2015 to 2018. It can be seen that the number of publications remained low, with fewer than 10 papers per year until 2018. There was a gradual increase in 2019, followed by a significant acceleration from 2020 onward. Around 84.4% of articles were published between 2020 and 2024. This reflects the growing scientific interest in MPs due to their inherent potential to generate environmental toxicity and adverse health effects on humans and aquatic life [48].

Figure 2 (b) shows that Finland emerged as the initial contributor, publishing the first article in 2015 on MPs in WWTP due to its strong environmental commitment [49], and the vulnerability of the Baltic sea to MPs pollution [50]. Early investigations showed that WWTPs act as a potential point source of MPs in the Baltic Sea [51]. Finland's active participation in European Union environmental programs further supported its pioneering role in microplastic research [52]. Only three countries published articles on the following year 2016. Only Europe, America and Australia were publishing articles until 2017. From 2018 Asian and African countries also started contributing to the field. This shows a gradual increase in the publication of articles by different countries.

China leads in the number of published articles from 2015 to 2024, with approximately 55 publications, followed by Spain and United states with 23 articles each. China began to publish the articles from 2018. Average publication from China is 22.2% from 2018 to 2024, while Spain and the United States each contributed 9.3%. This shows the growing interest of Chinese researchers in the field in recent years. Recent studies highlight China's leading role in wastewater management research, particularly regarding MPs, contaminants, and treatment technologies [53].

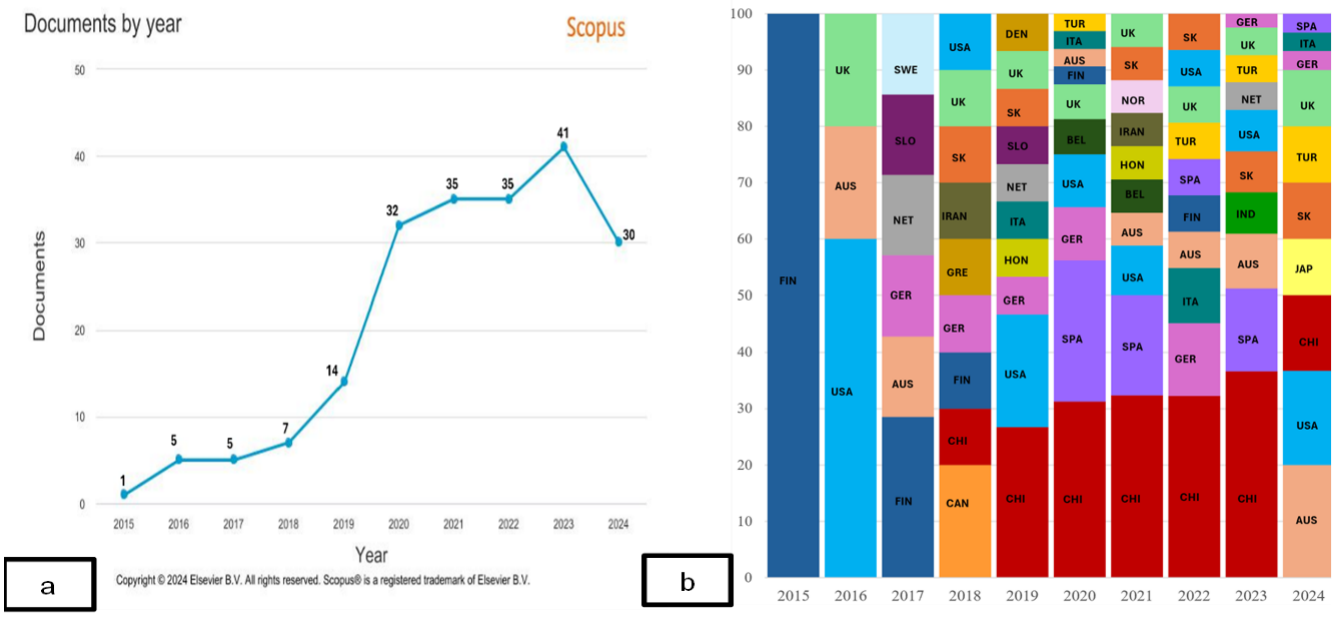


Figure 2 (a) Annual publications in MPs in wastewater treatment plants, (b) The top 10 most countries based on the articles published each year. FIN= Finland, USA = America, AUS=Australia, UK=United Kingdom, GER=Germany, NET=Netherlands, SLO=Slovakia, SWE=Sweden, CAN=Canada, CHI=China, GRE=Greece, SK=South Korea, HON= Hong Kong, ITA=Italy, DEN=Denmark, SPA=Spain, BEL=Belgium, TUR=Turkey, NOR=Norway, IND=India, JAP=Japan

Figure 3 shows the overall number of publications from top 10 countries from 2015 to 2024.

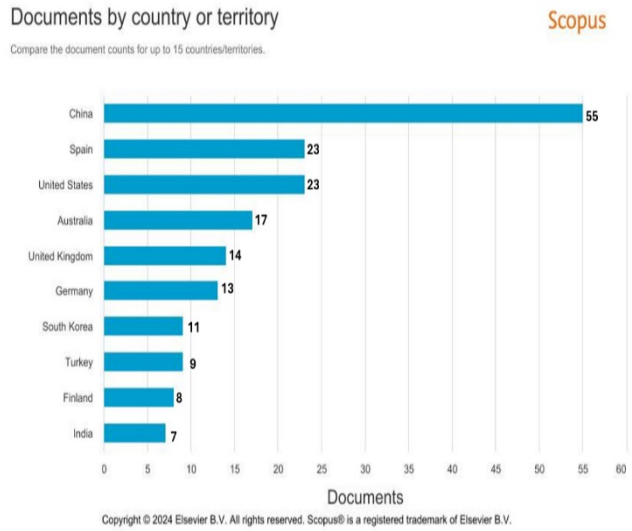


Figure 3 Number of articles published by different countries from 2015 to 2024

International collaboration has also increased among countries from 2019 to 2023. As shown in Figure 4, China, Spain, and the United States are the most active in partnerships, reflecting the increasing global cooperation on MP-related challenges.

3.1.2 *Subject area*

Table 2 shows the distribution of publications by subject areas. It could be seen that the related research field is dominated by the field of Environmental Science (56.2%), and it is followed by the field of Engineering (10.1%). Environmental Science has a significantly higher number of publications compared to other fields, indicating it as a prioritized research field. The topmost fields that have contributed to the publications in the related study are "Environmental Science", "Engineering", "Chemistry", "Pharmacology, Toxicology and Pharmaceutics", "Medicine", "Agricultural and Biological Sciences", "Earth and Planetary Sciences" and "Chemical Engineering". However, Chemical Engineering has the fewest publications which indicates less research activity in this field.

3.2 Citations

Table 3 is derived from VOSviewer, based on citation analysis by country, and it shows the top ten countries based on the number of citations. Citations are often used to determine the impact factor of a journal [54]. The minimum number of citations per country was selected as fifty. 39 countries out of 52 met the threshold. Figure 5 shows the citation analysis by country using VOSviewer. Although China leads in the number of publications, the United States surpasses China in terms of citation impact. The Unites states has around 4038 citations, while China has 3099 citations. This shows the high impact of research publications in the United States indicating that publications from United States receive considerable attention and influence in the related field. It can be seen that the Finland ranks third with 2961 citations, despite having only 8 publications. Netherlands, Finland and Mexico rank the top three places in terms of the average citations per publication having the values of 388.4, 370.1 and 327.0 respectively. This shows the significant influence of countries in the research field regardless of the number of publications. However, China has the lowest average citation per publication (56.3) in the top ten countries. This indicates the lowest impact per publication despite having the highest number of publications.

Table 2 Distribution of publication by subject areas

Subject area	Distribution of publication
Environmental Science	56.2%
Engineering	10.1%
Chemistry	9.6%
Pharmacology, Toxicology and Pharmaceutics	7.4%
Medicine	5.5%
Agricultural and Biological Sciences	4.4%
Earth and Planetary Sciences	4.4%
Chemical Engineering	2.5%

Table 3 Top ten countries based on the number of citations

Country	No. of publications	Citation	Citations per Publication
United States	23	4038	175.6
China	55	3096	56.3
Finland	8	2961	370.1
United Kingdom	14	2151	153.6
Netherlands	5	1942	388.4
Spain	23	1798	78.2
Australia	17	1749	102.9
Germany	13	1611	123.9
Canada	5	998	199.6
Mexico	3	981	327.0

The contribution of Southeast Asian countries to the field of MPs in the environment has been significant in recent years, with Thailand (49 studies), Indonesia (45), Malaysia (27), Vietnam (21), and the Philippines (15) leading in publication output. Most of these studies focus on MPs in freshwater, biota, and sediments [55]. However, research on MPs from WWTPs remains limited across the region when compared to countries such as the United States, China, and European countries.

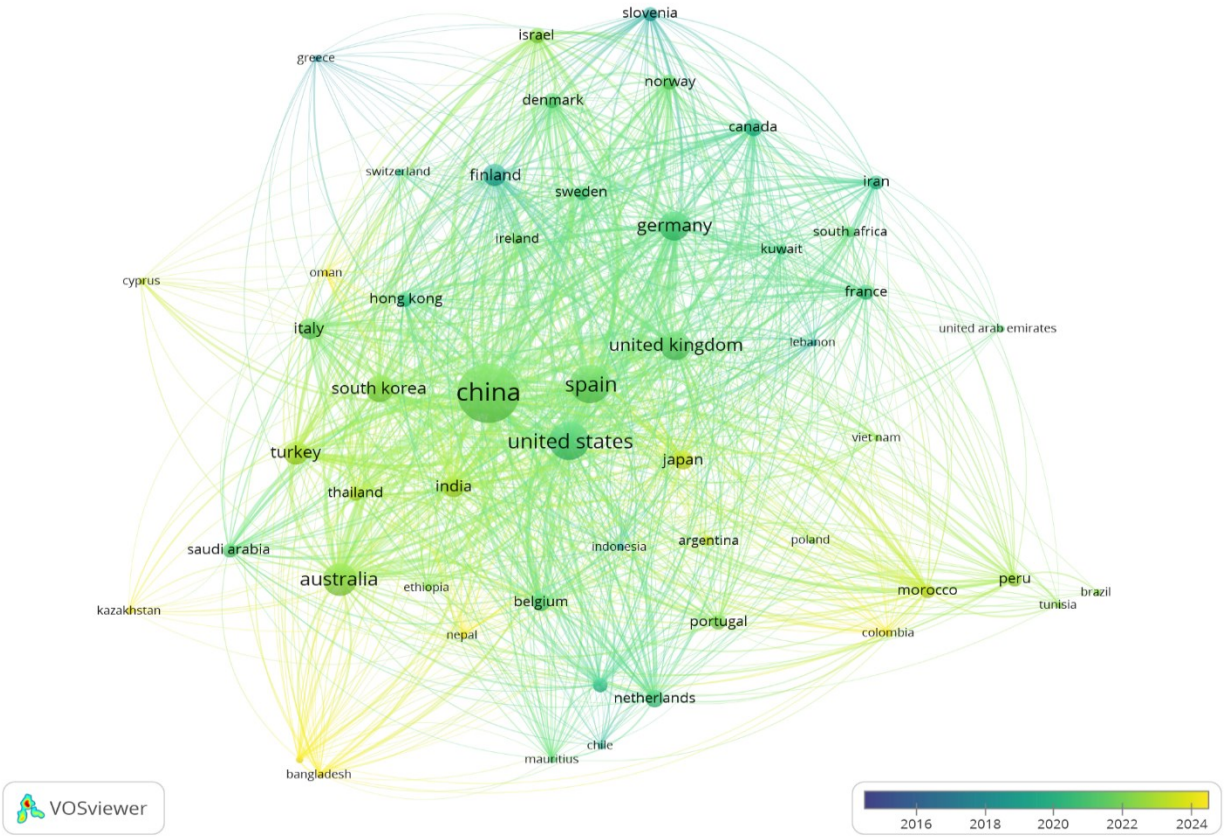


Figure 4 Overlay visualization map of countries published articles

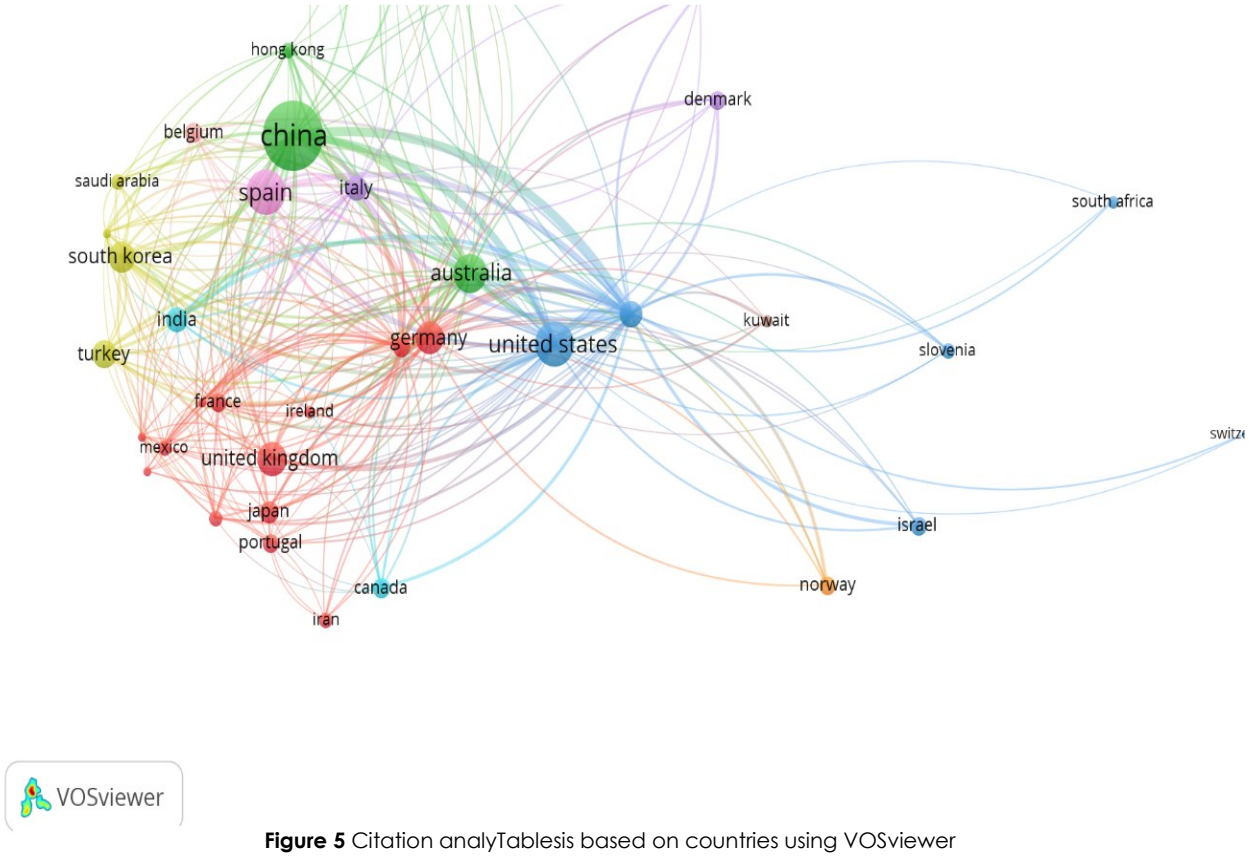


Figure 5 Citation analyTablesis based on countries using VOSviewer

3.3 Publication distribution Co-Citation relationship among the publications

Only journals with more than 10 articles on MPs in WWTPs were considered during screening to ensure data accuracy. This approach facilitates the identification of relevant journals and enhances scholarly understanding by examining current literature. Figure 6 shows that the screening resulted in 205 publications, comprising 180 articles (87.8%) and 25 review articles (12.2%).

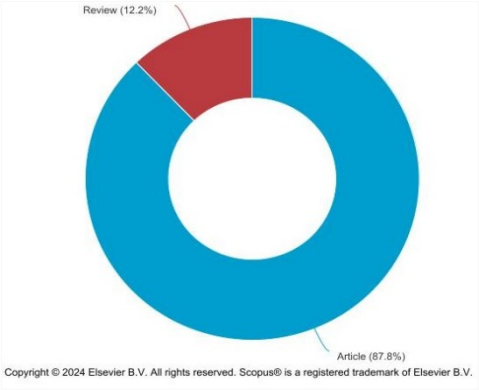


Figure 6 Published documents by type

The dominance of research articles highlights a strong emphasis on peer-reviewed work, while the presence of review articles reflects the depth of research and understanding in the field. Table 4 shows the top ten journals selected for this study, including the number of publications, cite score, citation and citation strength per article. The journal titled *Science of the total environment* ranks first, contributing around 30.2% of the total publications and having a cite score of 17.6. The cite score was sourced from Scopus database, while the number of citations was obtained from VOSviewer, in order to calculate the citation strength per article. Although Water Research published 28 articles, it has the highest citation strength per article (260.8). The *Journal of Hazardous Materials* holds the highest cite score among the listed journals.

The co-citation analysis was done using VOSviewer, and the result is shown in Figure 7, which helps to identify influential publications and authors, and the connections between different research topics [56]. Co-citation refers to the practice of journals, authors, or references being cited together by researchers [57]. Journals with a minimum number of citations per journal were limited to 20 in this analysis. 66 journals out of 2486 met the threshold. Each circle represents a journal, and the size of the circle shows the total link strength of the journal. The connecting lines show the co-citation relationship, and the thickness of the lines shows the strength of co-citation between the journals. Science of the total environment, Water research, Marine pollution bulletin, Environmental science and pollution research, and Environmental pollution are the top five journals in terms of the number of co- citations and the total link strength.

Table 4 Top 10 journals published articles in the related field

Journals	No. of Articles	cite score	citations	Citation strength
Science of the total environment	62	17.6	3788	61.1
Water research	28	20.8	7303	260.8
Environmental pollution	27	16.0	2185	80.9
Chemosphere	26	15.8	1747	67.2
Marine pollution bulletin	16	10.2	2706	169.1
Environmental science and pollution research	11	8.7	622	56.5
Chemical engineering journal	9	21.7	897	99.7
Journal of environmental management	9	13.7	542	60.2
Journal of hazardous materials	9	25.4	187	20.8
Water science and technology	8	4.9	769	96.1

3.4 Keywords analysis

Figure 8 shows the most frequently keyword analysed using VOSviewer. The most frequent keywords were "wastewater treatment, Microplastics, Microplastic, effluent and article" which occurred around 194,186,184,171 and 159 times respectively. The keyword "Microplastics" and "wastewater treatment" appear to be a central focus, having connections to keyword such as "water pollutants" and "plastic pollution." This shows the current research trend on the interaction of MPs with the environment and the removal of MPs in WWTPs. Cluster 1 has 55 items, which focuses mainly on the MP and plastics pollution in wastewater treatment and environmental monitoring, which includes the main keywords such as "wastewater treatment", "microplastics" and "plastics". Cluster 2 has 38 items, which describes the types types of MPs and detection methods, includes main keywords such as "article", "polymer" and "mass spectrometry". Cluster 3 has 31 items, which mainly deals with fate of MPs in the WWTP effluent, and it includes the main keywords such as "sludge", "sewage sludge" and "suspended particulate matter". Cluster 4 has 23 items, which delves into the role of the WWTPs in the removal of MPs and includes the main keywords such as "adsorption", "filtration", and "effluent treatment". Generally, a shorter distance between the keyword shows a stronger connection.

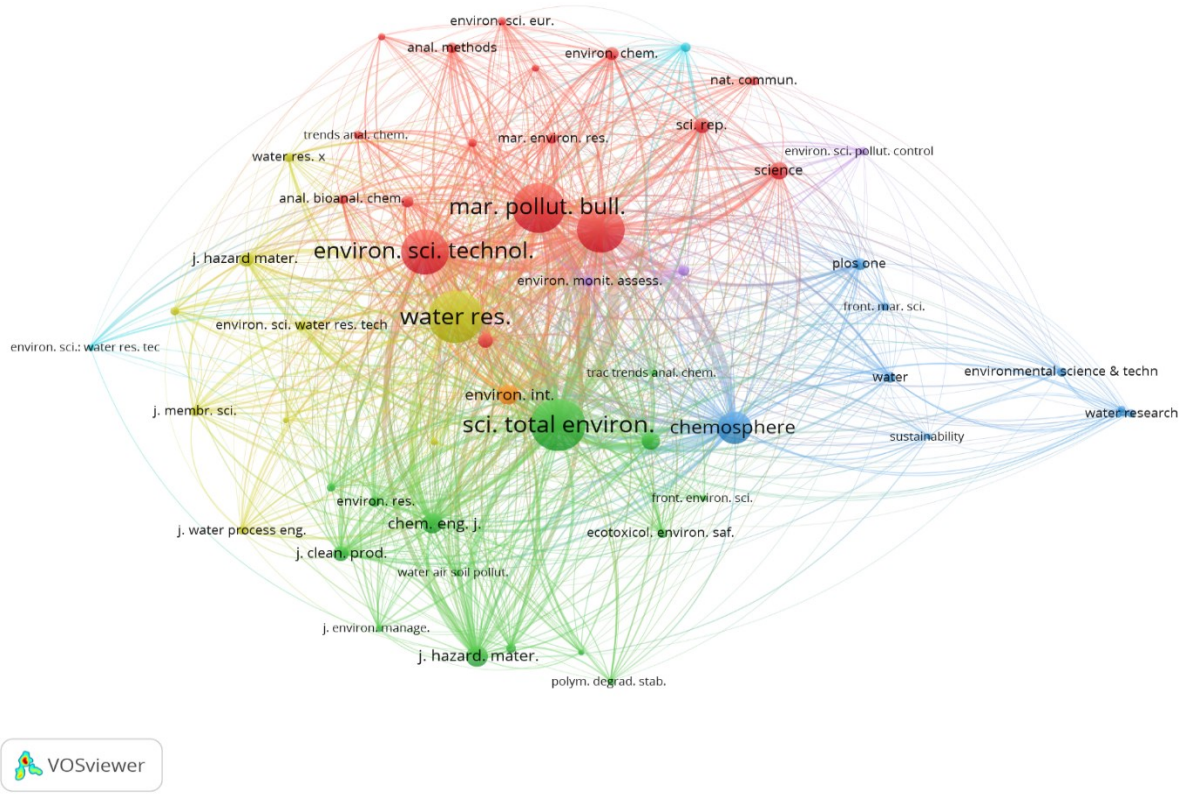


Figure 7 Co- citation analysis using cited sources as unit of analysis

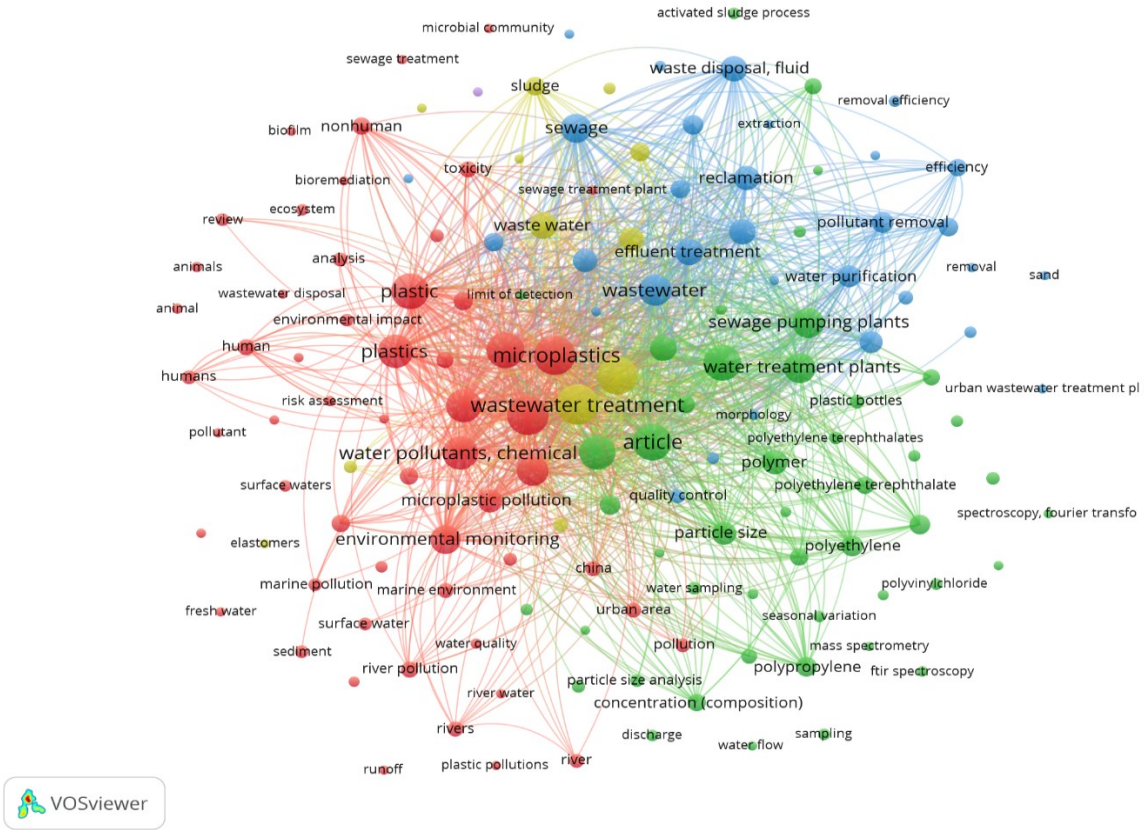


Figure 8 Most occurred keywords

3.5 Research hotspots and future directions

This bibliometric study of MPs in WWTPs has revealed several key research hotspots that need further exploration. These include understanding the fate and transport of MPs within WWTPs and their subsequent release into the environment, evaluating the removal efficiency of various treatment technologies, investigating the interactions between MPs and other environmental contaminants, and improving detection methods for accurate monitoring.

3.6 Fate of MPs in WWTP and the effluent

Researchers have increasingly focused on the transport, release, and fate of MPs in WWTPs in recent years [58][59][60]. However, literature has reported significant removal of MPs in the treatment undertaken in WWTPs [61][62][63]. MPs are removed when they are adsorbed onto suspended solids during both primary and secondary treatment stages of wastewater treatment [64]. Sun *et al.* [65] have reported that around 35%-59% of MPs were removed during the preliminary treatment, while the 50% -98% were treated after the primary treatment. Any MPs that are not removed by WWTPs will end up in rivers and ultimately flow into the oceans [66]. Conley *et al.* [67] have found that 100 million to 500 million MPs were released from three WWTPs in the USA.

The keyword analysis has shown the main hotspots in this research field. The central and frequently co-occurring keywords such as "microplastics," "wastewater treatment," and "plastics," reveal a strong emphasis on the occurrence, monitoring, and treatment of MPs within WWTPs. Distinct clusters further indicate focused research on analytical methods, polymer identification, and environmental monitoring. However, the keywords like "removal efficiency," "adsorption," "filtration," "river pollution," and "sediment" appear less frequently. This suggests that the presence and treatment of MPs in WWTPs are well studied, while the detailed mechanisms of removal, transport post-treatment, and environmental impacts are still underexplored. There is limited insight into the processes governing MP interactions within different treatment stages such as adsorption dynamics, aggregation, and fragmentation. Furthermore, the fate of MPs released in treated effluents such as their transport pathways, degradation rates and accumulation in receiving water bodies requires more attention. Additionally, the potential influence of varying operational conditions, seasonal variations, and different types and sizes of MPs on treatment effectiveness remains underexplored.

There are several key areas that require further investigation. One key area is the development of new or enhanced treatment technologies specifically designed to improve MP removal efficiency, as the WWTPs are not designed to treat MP [68]. Although conventional processes can reduce MP loads significantly, optimizing and innovating treatment methods could more effectively limit MP release into the environment. Furthermore, the behaviour of MPs after their release into receiving environments such as rivers, lakes, and oceans needs deeper exploration. This includes investigating transport mechanisms, degradation processes, and accumulation hotspots, which are essential for predicting environmental impacts and designing effective mitigation strategies. Additionally, the influence of operational parameters such as hydraulic retention times, temperature fluctuations, and seasonal variations on MP removal performance remains insufficiently studied. Similarly, the role of MP specific characteristics such particle size, polymer composition, and shape requires further investigation to understand how these factors affect their interaction with treatment processes. Addressing these research priorities will improve scientific understanding of MP dynamics within WWTPs and their receiving environments.

3.7 MP removal efficiency of different types of technologies

Recent studies have emphasized that the type and configuration of the treatment system strongly influence the concentration of MPs in the final effluent from WWTPs [69][70]. The removal efficiency rates of different technologies were compared in the literature.

The conventional activated sludge (AS) process and its alternative configurations are the most widely studied secondary treatment method for MP removal [19]. These systems have shown high removal rates depending on operational parameters and influent characteristics [71], [72]. Biofilters including trickling filters also demonstrate significant efficiency on the removal of MPs [73], [74]. The sequential batch reactor (SBR) is considered one of the most efficient alternative configurations for AS in terms of MP removal [75]. However, these values vary across studies due to differences in sampling methods, MP size categories, and polymer types, which impact removal rates [76]. The membrane bio reactor (MBR) is the most popular tertiary treatment method in terms of MPs [68], [77], [78]. MBR systems combine conventional biological treatment with membrane filtration, which enables the physical retention of MPs. Furthermore, there are also other technologies mentioned in the literature such as rapid sand filtration (RSF), reverse osmosis (RO), disc filter (DF), dissolved air flotation (DAF), and treatments with ozone [79], [80], [81] for the removal of MPs. These technologies are less commonly implemented due to operational costs, complexity, and membrane fouling issues. Ahmed *et al.* [82] have highlighted the effectiveness of various technologies in removing MPs, ranking them from highest to lowest. Table 5 shows the MP removal efficiencies of different types of treatment methods.

Table 5 MP removal efficiencies of different types of treatment methods

Treatment type	MP removal Efficiency (%)	Treatment Stage	References
Activated Sludge (AS)	80–98	Secondary	[19], [71], [72]
Biofilters	50–80	Secondary	[73]
Trickling Filter	88–98	Secondary	[74]
Sequential Batch Reactor (SBR)	~92	Secondary	[75]
Membrane Bioreactor (MBR)	99.4–99.9	Tertiary	[68], [77], [78]
Rapid Sand Filtration (RSF)	~97.1	Tertiary	[82]
Reverse Osmosis (RO)	> 99	Tertiary	[79], [80]
Dissolved Air Flotation (DAF)	~95	Tertiary	[82]
Electrocoagulation	> 90	Tertiary	[82]
Constructed Wetlands	~88	Tertiary	[82]

Future research to improve MP removal should focus on enhancing existing treatment processes by integrating advanced filtration and separation techniques with conventional biological methods and optimizing operational parameters such as hydraulic retention time, sludge age, and aeration rates. Additionally, improving membrane-based systems requires a deeper understanding of how membrane characteristics such as material type, pore size, and operating pressure affect the MP removal performance. Furthermore, addressing operational challenges like membrane fouling and cake layer formation is essential to maintain the long-term efficiency of membrane systems [83]. Standardizing monitoring methods is important for the development of consistent protocols for sampling, identification, and quantification which are essential for reliable comparison across studies. Moreover, evaluating the cost-efficiency and energy use of high-performance technologies like MBR and RO is essential. Finally, it is crucial to focus on managing sludge and associated environmental risks, particularly concerning the fate of MPs retained in sludge that could be released back into the environment through land application or disposal.

3.8 Interaction of MPs with other contaminants

MPs act as carriers for contamination by adsorbing pollutants or releasing plasticizers from the manufacturing process [84][85][86]. The toxic effects of MPs are linked to their ability to adsorb contaminants [87][88] pathogens [89][90], heavy metals [91][92], polychlorinated biphenyls [93] and antibiotics [94][95]. Table 6 shows the factors Influencing the interaction of MPs with other contaminants.

Table 6 Factors influencing the interaction of MPs with other contaminant

Factor	Description	Impact on Interaction	References
Surface area & crystallinity	High surface area and crystalline regions enhance adsorption	Increased contaminant sorption	[84,96,97]
Hydrophobi-city & lipophilicity	MPs' hydrophobic nature facilitates adsorption of organic pollutants	Strong attraction to hydrophobic pollutants	[98,99]
Dissolved Organic Matter	Competes or modifies MP surfaces	Alters adsorption capacity	[100]
MP shape	Fibers, fragments, spheres vary in surface properties	Affects adsorption efficiency	[101]
Salinity and pH	Environmental conditions alter chemical states	Influences contaminant binding	[102]

There are several knowledge gaps that need to be addressed through future research. A deeper understanding is needed to clarify the physicochemical processes that govern how MPs interact with various contaminants. This includes exploring adsorption kinetics, competitive binding, and desorption behaviour under different environmental conditions. Moreover, current studies predominantly focus on short-term toxic effects, while the long-term effects of MPs as vectors are poorly explored. Thorough ecotoxicological studies are essential to examine bioaccumulation, trophic transfer, and potential toxic effects over time. Furthermore, the influence of environmental variability such as temperature, salinity, pH, and dissolved organic matter on the interaction of MPs with contaminants remains underexplored. Additionally, addressing the effect of seasonal and geographic changes would enhance the accuracy of environmental risk assessments.

3.9 Detection methods of MPs in water

Standard analysis method is required to accurately detect the MPs in water and to assess their risks [103]. Accuracy in identification of MPs is limited due to the complex structure and composition of MPs [104]. The primary techniques employed for MP detection in water are microscopy, spectroscopic, and thermal analysis methods [105]. Stereo microscopy methods are widely used in the detection of MPs greater than

100 µm [106], [107]. Scanning Electron Microscopy (SEM) produces clear, highly magnified images [108]. This analysis is limited to morphological structure and surface characteristics, requiring validation through FTIR and Raman spectroscopy [109], However, FTIR struggles to identify MPs smaller than 20µm [110]. Raman spectroscopy provides detailed chemical insights [111], [112], but is limited by interference from laser excitation of fluorescent samples [113]. Thermal analysis, including Pyrolysis-GC-MS, is a destructive method [114], [115] and may not distinguish whether detected molecules originate from MPs or attached contaminants [116]. Table 7 shows the summary of the advantages and limitations of these detection methods.

Table 7 Summary of the advantages, and limitations of the MP detection methods

Method	Advantages	Limitations
Stereo Microscopy	Detects MPs larger than 100µm, simple and widely used method.	Limited to larger MPs, possible misidentification
SEM	high-resolution morphological analysis of MP surfaces	Requires confirmation with chemical analysis, costly equipment
FTIR Spectroscopy	Identifies chemical structure non-destructively	Limited detection below 20µm, potential overlap in spectra
Raman Spectroscopy	Detects chemical structure, including smaller MPs, with high specificity	Fluorescence interference from some samples, complex data interpretation
Thermal Analysis (Pyrolysis-GC-MS)	Sensitive method for identifying polymer types through decomposition	Destructive, may not distinguish MPs from contaminants

Future research should prioritize enhancing the sensitivity and resolution of spectroscopic methods like FTIR and Raman spectroscopy to accurately identify and quantify smaller MPs. Improvements in microscopy, including the use of Transmission Electron Microscopy (TEM), could provide more detailed images of MPs and their surface characteristics. Integrating multiple analytical techniques can overcome the individual limitations of each method, thereby improving the detection accuracy. Additionally, developing chemical labeling approaches such as fluorescent dyes or molecular markers could enhance the visualization and tracking of MPs within environmental matrices, thus enabling more effective monitoring.

4.0 CONCLUSION

A total number 205 research publications were analysed in this study based on the main keywords such as "microplastics" and "WWTP" and "effluent". It can be seen that the scholars did not show great interest in MPs in WWTPs before 2015. Even though the term "microplastics" was introduced in 2004 by Thompson *et al.* [117] to describe small plastic particles in marine environments, studies related to MPs in WWTPs only began to get published from 2015 onwards. However, 84.4% of the articles were published between 2020 and 2024, highlighting a rapid development in the field. China leads in the number of publications, while the United States leads in total citations. Finland was the first country to publish an article in 2015. At present, 52 countries have contributed to this research area. There were around 180 research articles, and 25 review articles included in this study. The journal titled *Science of the Total Environment* has published the highest number of articles, with 30.2% of the total publications. However, the journal *Water Research*, with 7303 citations, has *surpassed Science of the Total Environment*, which has 3788 citations, making it the leading journal in terms of total citations. It can be seen that this research field is dominated by Environmental Science (56.2%), indicating it as a prioritized research area.

The hot spots in the research area were identified through keyword clustering analysis [118]. The four main clusters explain the key research areas in this field. A total of 147 keywords out of 2886 were selected for the analysis. The most frequently occurred keywords were wastewater treatment, microplastics, microplastic, effluent, and article, which occurred 194,186,184,171 and 159 times, respectively. The bibliometric analysis results show that this study provides a thorough examination of the occurrence of MPs in WWTPs. This comprehensive analysis is crucial for enhancing our understanding of the fate and behaviour of MP in WWTPs and their effluent. The findings of this study also support the development of effective management strategies for this significant issue. Bibliometric analysis is widely used to evaluate research productivity and guide funding and policy decisions. However, its limitation lies in the continuous updates of the Scopus database, which may exclude newly added publications from a specific dataset. This issue can be mitigated by clearly defining the study period and incorporating a large number of publications. Despite this limitation, bibliometric analysis remains valuable for establishing a knowledge framework for policymakers and researchers to address MP pollution from WWTPs.

Acknowledgements

We would like to thank Universiti Teknologi Malaysia for providing the necessary resources and facilities for this research.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

References

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

[2] Hammer, J., M. H. Kraak, and J. R. Parsons. 2012. Plastics in the Marine Environment: The Dark Side of a Modern Gift. *Reviews of Environmental Contamination and Toxicology*. 220: 1–44. https://doi.org/10.1007/978-1-4614-3414-6_1.

[3] Wagner, M., C. Scherer, D. Alvarez-Muñoz, N. Brennholt, X. Bourrain, S. Buchinger, E. Fries, *et al.* 2014. Microplastics in Freshwater Ecosystems: What We Know and What We Need to Know. *Environmental Sciences Europe*. 26(1): 12. https://doi.org/10.1186/s12302-014-0012-7.

[4] Ivleva, N. P., A. C. Wiesheu, and R. Niessner. 2017. Microplastic in Aquatic Ecosystems. *Angewandte Chemie International Edition*. 56(7): 1720–1739. https://doi.org/10.1002/anie.201606957.

[5] United Nations Environment Programme. 2021. *Drowning in Plastics: Marine Litter and Plastic Waste Vital Graphics*. https://wedocs.unep.org/xmlui/bitstream/handle/20.500.11822/36964/VITGRAPH.pdf.

[6] Geyer, R., J. R. Jambeck, and K. L. Law. 2017. Production, Use, and Fate of All Plastics Ever Made. *Science Advances* 3 (7): e1700782. https://doi.org/10.1126/sciadv.1700782.

[7] Hidalgo-Ruz, V., L. Gutow, R. C. Thompson, and M. Thiel. 2012. Microplastics in the Marine Environment: A Review of the Methods Used for Identification and Quantification. *Environmental Science & Technology*. 46(6): 3060–3075. https://doi.org/10.1021/es2031505.

[8] Peng, G., P. Xu, B. Zhu, M. Bai, and D. Li. 2018. Microplastics in Freshwater River Sediments in Shanghai, China: A Case Study of Risk Assessment in Mega-Cities. *Environmental Pollution*. 234: 448–456. https://doi.org/10.1016/j.envpol.2017.11.034.

[9] Law, K. L. 2017. Plastics in the Marine Environment. *Annual Review of Marine Science*. 9: 205–229. https://doi.org/10.1146/annurev-marine-010816-060409.

[10] Lambert, S., and M. Wagner. 2017. Microplastics Are Contaminants of Emerging Concern in Freshwater Environments: An Overview. *Handbook of Environmental Chemistry*. 58: 1–23. https://doi.org/10.1007/978-3-319-61615-5_1.

[11] Lozano, Y. M., T. Lehnert, L. T. Linck, A. Lehmann, and M. C. Rillig. 2021. Microplastic Shape, Polymer Type, and Concentration Affect Soil Properties and Plant Biomass. *Frontiers in Plant Science*. 12: 616645. https://doi.org/10.3389/fpls.2021.616645.

[12] Chandra, S., and K. B. Walsh. 2024. Microplastics in Water: Occurrence, Fate and Removal. *Journal of Contaminant Hydrology*. 264: 104360. https://doi.org/10.1016/j.jconhyd.2024.104360.

[13] Eerkes-Medrano, D., R. C. Thompson, and D. C. Aldridge. 2015. Microplastics in Freshwater Systems: A Review of Emerging Threats, Identification of Knowledge Gaps and Prioritisation of Research Needs. *Water Research*. 75: 63–82. https://doi.org/10.1016/j.watres.2015.02.012.

[14] Bergmann, M., L. Gutow, and M. Klages, eds. 2015. *Marine Anthropogenic Litter*. Cham: Springer. https://doi.org/10.1007/978-3-319-16510-3.

[15] Acarer, S. 2023. Microplastics in Wastewater Treatment Plants: Sources, Properties, Removal Efficiency, Removal Mechanisms, and Interactions with Pollutants. *Water Science and Technology*. 87: 685–710. https://doi.org/10.2166/wst.2023.022.

[16] Alvim, C. B., J. A. Mendoza-Roca, and A. Bes-Piá. 2020. Wastewater Treatment Plant as Microplastics Release Source—Quantification and Identification Techniques. *Journal of Environmental Management*. 255: 109739. https://doi.org/10.1016/j.jenvman.2019.109739.

[17] Azizi, N., S. Nasseri, R. N. Nodehi, N. Jaafarzadeh, and M. Pirsaheb. 2022. Evaluation of Conventional Wastewater Treatment Plants Efficiency to Remove Microplastics in Terms of Abundance, Size, Shape, and Type: A Systematic Review and Meta-Analysis. *Marine Pollution Bulletin*. 177: 113462. https://doi.org/10.1016/j.marpolbul.2022.113462.

[18] Wu, X., X. Zhao, R. Chen, P. Liu, W. Liang, J. Wang, M. Teng, X. Wang, and S. Gao. 2022. Wastewater Treatment Plants Act as Essential Sources of Microplastic Formation in Aquatic Environments: A Critical Review. *Water Research*. 221: 118825. https://doi.org/10.1016/j.watres.2022.118825.

[19] Cunsolo, S. 2023. *Transport and Fate of Microplastics through the Wastewater Treatment Process and Beyond*. PhD diss., University of Portsmouth.

[20] Long, Z., Z. Pan, W. Wang, J. Ren, X. Yu, L. Lin, H. Lin, H. Chen, and X. Jin. 2019. Microplastic Abundance, Characteristics, and Removal in Wastewater Treatment Plants in a Coastal City of China. *Water Research*. 155: 255–265. https://doi.org/10.1016/j.watres.2019.02.028.

[21] Koutnik, V. S., S. Alkidim, J. Leonard, F. DePrima, S. Cao, E. M. V. Hoek, and S. K. Mohanty. 2021. Unaccounted Microplastics in Wastewater Sludge: Where Do They Go? *ACS ES&T Water*. 1: 1086–1097. https://doi.org/10.1021/acsestwater.0c00267.

[22] Kong, W., M. Jalalah, S. A. Alsareii, F. A. Harraz, A. A. Almadiy, Y. Zheng, N. Thakur, and E.-S. Salama. 2023. Microplastics (MPs) in Wastewater Treatment Plant Sludges: Substrates, Digestive Properties, Microbial Communities, Mechanisms, and Treatments. *Journal of Environmental Chemical Engineering*. 11: 111408. https://doi.org/10.1016/j.jece.2023.111408.

[23] Malematja, K. C., F. Melato, and N. Mokgalaka. 2023. The Occurrence and Fate of Microplastics in Wastewater Treatment Plants in South Africa and the Degradation of Microplastics in Aquatic Environments—A Critical Review. *Sustainability* 15: 16865. https://doi.org/10.3390/su152416865.

[24] Sol, D., A. Laca, A. Laca, and M. Díaz. 2020. Approaching the Environmental Problem of Microplastics: Importance of WWTP Treatments. *Science of the Total Environment*. 740: 140016. https://doi.org/10.1016/j.scitotenv.2020.140016.

[25] Carbery, M., W. O'Connor, and T. Palanisami. 2018. Trophic Transfer of Microplastics and Mixed Contaminants in the Marine Food Web and Implications for Human Health. *Environment International*. 115: 400–409. https://doi.org/10.1016/j.envint.2018.03.007.

[26] McCormick, A., T. J. Hoellein, S. A. Mason, J. Schluep, and J. J. Kelly. 2014. Microplastic Is an Abundant and Distinct Microbial Habitat in an Urban River. *Environmental Science & Technology*. 48: 11863–11871. https://doi.org/10.1021/es503610r.

[27] Kruglova, A., B. Muñoz-Palazón, A. Gonzalez-Martinez, A. Mikola, R. Vahala, and J. Talvitie. 2022. The Dangerous Transporters: A Study of Microplastic-Associated Bacteria Passing through Municipal Wastewater Treatment. *Environmental Pollution*. 314: 120316. https://doi.org/10.1016/j.envpol.2022.120316.

[28] Horton, A. A., and D. K. A. Barnes. 2020. Microplastic Pollution in a Rapidly Changing World: Implications for Remote and Vulnerable Marine Ecosystems. *Science of the Total Environment*. 738: 140349. https://doi.org/10.1016/j.scitotenv.2020.140349.

[29] Chen, G., Q. Feng, and J. Wang. 2020. Mini Review of Microplastics in the Atmosphere and Their Risks to Humans. *Science of the Total Environment*. 703: 135504. https://doi.org/10.1016/j.scitotenv.2019.135504.

[30] Sussarellu, R., M. Suquet, Y. Thomas, C. Lambert, C. Fabioux, M. E. J. Pernet, N. Le Goïc, V. Quillien, C. Mingant, Y. Epelboin, *et al.* 2016. Oyster Reproduction Is Affected by Exposure to Polystyrene Microplastics. *Proceedings of the National Academy of Sciences*. 113: 2430–2435. https://doi.org/10.1073/pnas.1519019113.

[31] Gonsilou, A. P., S. Azman, N. I. A. Isharunizam, M. Z. M. Najib, and A. Syafiuddin. 2023. Microplastic Uptake by Mud Creepers (*Cerithidea obtusa*) at Kukup, Johor. *Journal of*

Sustainable Science and Management. 18: 1–23. https://doi.org/10.46754/jssm.2023.03.001.
[32] Kumar, S., M. Rajesh, R. K. M., N. Suyani, A. A. Rasheeq, and P. Ks. 2020. Impact of Microplastics on Aquatic Organisms and Human Health: A Review. *International Journal of Environmental Sciences*. 26: 556184. https://doi.org/10.19080/IJESNR.2020.26.556184.
[33] Sarijan, S., S. Azman, M. I. M. Said, and M. H. Jamal. 2021. Microplastics in Freshwater Ecosystems: A Recent Review of Occurrence, Analysis, Potential Impacts, and Research Needs. *Environmental Science and Pollution Research*. 28 (2): 1341–1356. https://doi.org/10.1007/s11356-020-11171-7.
[34] Huang, Z., Y. Weng, Q. Shen, Y. Zhao, and Y. Jin. 2021. Microplastic: A Potential Threat to Human and Animal Health by Interfering with the Intestinal Barrier Function and Changing the Intestinal Microenvironment. *Science of the Total Environment*. 785: 147365. https://doi.org/10.1016/j.scitotenv.2021.147365.
[35] Solleiro-Villavicencio, H., C. T. Gomez-De León, V. H. Del Río-Araiza, and J. Morales-Montor. 2020. The Detrimental Effect of Microplastics on Critical Periods of Development in the Neuroendocrine System. *Birth Defects Research*. 112(17): 1326–1340. https://doi.org/10.1002/bdr2.1776.
[36] Desforges, J.-P. W., M. Galbraith, and P. S. Ross. 2015. Ingestion of Microplastics by Zooplankton in the Northeast Pacific Ocean. *Archives of Environmental Contamination and Toxicology*. 69(3): 320–330. https://doi.org/10.1007/s00244-015-0172-5.
[37] Schwabl, P., S. Köppel, P. Königshofer, T. Bucsics, M. Trauner, T. Reiberger, and B. Liebmann. 2019. Detection of Various Microplastics in Human Stool. *Annals of Internal Medicine*. 171(6): 453–457. https://doi.org/10.7326/M19-0618.
[38] Sun, J., X. Dai, Q. Wang, M. C. M. van Loosdrecht, and B.-J. Ni. 2019. Microplastics in Wastewater Treatment Plants: Detection, Occurrence and Removal. *Water Research*. 152: 21–37. https://doi.org/10.1016/j.watres.2018.12.050.
[39] Glänzel, W. 2003. *Bibliometrics as a Research Field: A Course on Theory and Application of Bibliometric Indicators*. Leuven: Katholieke Universiteit Leuven.
[40] Zhou, P., and X. Lv. 2015. Academic Publishing and Collaboration between China and Germany in Physics. *Scientometrics*. 105(3): 1875–1887. https://doi.org/10.1007/s11192-015-1643-1.
[41] Alryalat, S. A., L. Malkawi, and S. Momani. 2019. Comparing Bibliometric Analysis Using PubMed, Scopus, and Web of Science Databases. *Journal of Visualized Experiments*. 152: e58494. https://doi.org/10.3791/58494.
[42] Liu, W., J. Zhang, H. Liu, X. Guo, X. Zhang, X. Yao, Z. Cao, and T. Zhang. 2021. A Review of the Removal of Microplastics in Global Wastewater Treatment Plants: Characteristics and Mechanisms. *Environment International*. 146: 106277. https://doi.org/10.1016/j.envint.2020.106277.
[43] Pickering, C., and J. Byrne. 2014. The Benefits of Publishing Systematic Quantitative Literature Reviews for PhD Candidates and Other Early-Career Researchers. *Higher Education Research & Development*. 33(3): 534–548. https://doi.org/10.1080/07294360.2013.841651.
[44] Bornmann, L., and R. Mutz. 2015. Growth Rates of Modern Science: A Bibliometric Analysis Based on the Number of Publications and Cited References. *Journal of the Association for Information Science and Technology*. 66 (11): 2215–2222. https://doi.org/10.1002/asi.23329.
[45] Moed, H. F. 2005. *Citation Analysis in Research Evaluation*. Dordrecht: Springer. https://doi.org/10.1007/1-4020-3714-7.
[46] Van Eck, N. J., and L. Waltman. 2010. Software Survey: VOSviewer, a Computer Program for Bibliometric Mapping. *Scientometrics*. 84(2): 523–538. https://doi.org/10.1007/s11192-009-0146-3.
[47] Romero, L., and E. Portillo-Salido. 2019. Trends in Sigma-1 Receptor Research: A 25-Year Bibliometric Analysis. *Frontiers in Pharmacology*. 10: 564. https://doi.org/10.3389/fphar.2019.00564.
[48] Narwal, N., D. Katyal, N. Kataria, P. K. Rose, S. G. Warkar, A. Pugazhendhi, S. Ghotekar, and K. S. Khoo. 2023. Emerging Micropollutants in Aquatic Ecosystems and Nanotechnology-Based Removal Alternatives: A Review. *Chemosphere*. 341: 139945. https://doi.org/10.1016/j.chemosphere.2023.139945.
[49] Räsänen, T., and S. Laakkonen. 2007. Cold War and the Environment: The Role of Finland in International Environmental Politics in the Baltic Sea Region. *AMBIO: A Journal of the Human Environment*. 36(2): 229–236. https://doi.org/10.1579/0044-7447(2007)36[229:CWATET]2.0.CO;2.
[50] Teittinen, T. 2017. *Marine Litter and Microplastics*. Helsinki: Finnish Environment Institute. Available at: https://barentscouncil.org/document/Finnishresearchonmarinelitterandmicroplastics.pdf.
[51] Talvitie, J., M. Heinonen, J.-P. Pääkkönen, E. Vahtera, A. Mikola, O. Setälä, and R. Vahala. 2015. Do Wastewater Treatment Plants Act as a Potential Point Source of Microplastics? Preliminary Study in the Coastal Gulf of Finland, Baltic Sea. *Water Science and Technology*. 72(9): 1495–1504. https://doi.org/10.2166/wst.2015.360.
[52] HELCOM. 2025. *HELCOM Annual Report 2024: Baltic Sea Environment Proceedings No. 201*. Helsinki: Helsinki Commission. https://helcom.fi/wp-content/uploads/2025/04/Annual-report-2024.pdf.
[53] Omoregie, A. I., M. Alhassan, H. F. Basri, K. Muda, L. C. Campos, O. O. Ojuri, and T. Ouahbi. 2024. Bibliometric Analysis of Research Trends in Biogranulation Technology for Wastewater Treatment. *Environmental Science and Pollution Research*. 31: 50098–50125. https://doi.org/10.1007/S11356-024-34550-W.
[54] Caon, M., J. Trapp, and C. Baldock. 2020. Citations Are a Good Way to Determine the Quality of Research." *Physical and Engineering Sciences in Medicine*. 43: 1145–1148. https://doi.org/10.1007/S13246-020-00941-9.
[55] Collard, F., K. Galtung, and M. Mosberg. 2024. *Baseline Study on Microplastics in ASEAN*. Bonn: Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ).
[56] Błoński, K. 2023. Analysis of Citations and Co-Citations of the Term 'Word of Mouth' Based on Publications in the Field of Social Sciences. *Marketing of Scientific and Research Organizations*. 48: 111–133. https://doi.org/10.2478/MINIB-2023-0012.
[57] Zhang, Y., S. Pu, X. Lv, Y. Gao, and L. Ge. 2020. Global Trends and Prospects in Microplastics Research: A Bibliometric Analysis. *Journal of Hazardous Materials*. 400: 123110. https://doi.org/10.1016/j.jhazmat.2020.123110.
[58] Blair, R. M., S. Waldron, and C. Gauchotte-Lindsay. 2019. Average Daily Flow of Microplastics through a Tertiary Wastewater Treatment Plant over a Ten-Month Period. *Water Research*. 163: 114909. https://doi.org/10.1016/j.watres.2019.114909.
[59] Magni, S., A. Binelli, L. Pittura, C. G. Avio, C. Della Torre, C. C. Parenti, S. Gorbi, and F. Regoli. 2019. The Fate of Microplastics in an Italian Wastewater Treatment Plant. *Science of the Total Environment*. 652: 602–610. https://doi.org/10.1016/j.scitotenv.2018.10.269.
[60] Gündoğdu, S., C. Çevik, E. Güzel, and S. Kilercioğlu. 2018. Microplastics in Municipal Wastewater Treatment Plants in Turkey: A Comparison of the Influent and Secondary Effluent Concentrations. *Environmental Monitoring and Assessment*. 190: 626. https://doi.org/10.1007/S10661-018-7010-Y.
[61] Carr, S. A., J. Liu, and A. G. Tesoro. 2016. Transport and Fate of Microplastic Particles in Wastewater Treatment Plants. *Water Research*. 91: 174–182. https://doi.org/10.1016/j.watres.2016.01.002.
[62] Mason, S. A., D. Garneau, R. Sutton, Y. Chu, K. Ehmann, J. Barnes, P. Fink, D. Papazissimos, and D. L. Rogers. 2016. Microplastic Pollution Is Widely Detected in US Municipal Wastewater Treatment Plant Effluent. *Environmental Pollution*. 218: 1045–1054. https://doi.org/10.1016/j.envpol.2016.08.056.

[63] Murphy, F., C. Ewins, F. Carbonnier, and B. Quinn. 2016. Wastewater Treatment Works (WwTW) as a Source of Microplastics in the Aquatic Environment. *Environmental Science & Technology*. 50(11): 5800–5808. https://doi.org/10.1021/acs.est.5b05416.

[64] Das, S., N. M. Ray, J. Wan, A. Khan, T. Chakraborty, and M. B. Ray. 2017. Micropollutants in Wastewater: Fate and Removal Processes. In *Physico-Chemical Wastewater Treatment and Resource Recovery*. London: IntechOpen. https://doi.org/10.5772/65644.

[65] Sun, J., X. Dai, Q. Wang, M. C. M. van Loosdrecht, and B.-J. Ni. 2019. Microplastics in Wastewater Treatment Plants: Detection, Occurrence and Removal. *Water Research*. 152: 21–37. https://doi.org/10.1016/j.watres.2018.12.050.

[66] Edo, C., M. González-Pleiter, F. Leganés, F. Fernández-Piñas, and R. Rosal. 2020. Fate of Microplastics in Wastewater Treatment Plants and Their Environmental Dispersion with Effluent and Sludge. *Environmental Pollution*. 259: 113837. https://doi.org/10.1016/j.envpol.2019.113837.

[67] Conley, K., A. Clum, J. Deepe, H. Lane, and B. Beckingham. 2019. Wastewater Treatment Plants as a Source of Microplastics to an Urban Estuary: Removal Efficiencies and Loading Per Capita over One Year. *Water Research. X* 3: 100030. https://doi.org/10.1016/j.wroa.2019.100030.

[68] Talvitie, J., A. Mikola, A. Koistinen, and O. Setälä. 2017. Solutions to Microplastic Pollution—Removal of Microplastics from Wastewater Effluent with Advanced Wastewater Treatment Technologies. *Water Research*. 123: 401–407. https://doi.org/10.1016/j.watres.2017.07.005.

[69] Gkika, D. A., A. K. Tolkou, E. Evgenidou, D. N. Bikiaris, D. A. Lambropoulou, A. C. Mitropoulos, I. K. Kalavrouziotis, and G. Z. Kyzas. 2023. Fate and Removal of Microplastics from Industrial Wastewaters. *Sustainability*. 15(8): 6969. https://doi.org/10.3390/su15086969.

[70] Lv, X., Q. Dong, Z. Zuo, Y. Liu, X. Huang, and W.-M. Wu. 2019. Microplastics in a Municipal Wastewater Treatment Plant: Fate, Dynamic Distribution, Removal Efficiencies, and Control Strategies. *Journal of Cleaner Production*. 225: 579–586. https://doi.org/10.1016/j.jclepro.2019.03.321.

[71] Cheng, Y. L., J.-G. Kim, H.-B. Kim, J. H. Choi, Y. F. Tsang, and K. Baek. 2021. Occurrence and Removal of Microplastics in Wastewater Treatment Plants and Drinking Water Purification Facilities: A Review. *Chemical Engineering Journal*. 410: 128381. https://doi.org/10.1016/j.cej.2020.128381.

[72] Liu, F., N. Nord, K. Bester, and J. Vollertsen. 2020. Microplastics Removal from Treated Wastewater by a Biofilter. *Water*. 12(4): 1085. https://doi.org/10.3390/w12041085.

[73] Maw, M. M., S. K. Boontanon, R. Jindal, N. Boontanon, and S. Fujii. 2022. Occurrence and Removal of Microplastics in Activated Sludge Treatment Systems: A Case Study of a Wastewater Treatment Plant in Thailand. *Engineering Access*. 8: 106–111. https://doi.org/10.14456/mijet.2022.15.

[74] Dris, R., J. Gasperi, V. Rocher, M. Saad, N. Renault, and B. Tassin. 2015. Microplastic Contamination in an Urban Area: A Case Study in Greater Paris. *Environmental Chemistry*. 12: 592–599. https://doi.org/10.1071/EN14167.

[75] Ali, I., T. Ding, C. Peng, I. Naz, H. Sun, J. Li, and J. Liu. 2021. Micro- and Nanoplastics in Wastewater Treatment Plants: Occurrence, Removal, Fate, Impacts and Remediation Technologies—A Critical Review. *Chemical Engineering Journal*. 423: 130205. https://doi.org/10.1016/j.cej.2021.130205.

[76] Bui, X.-T., T.-D.-H. Vo, P.-T. Nguyen, V.-T. Nguyen, T.-S. Dao, and P.-D. Nguyen. 2020. Microplastics Pollution in Wastewater: Characteristics, Occurrence and Removal Technologies. *Environmental Technology & Innovation*. 19: 101013. https://doi.org/10.1016/j.eti.2020.101013.

[77] Lares, M., M. C. Ncibi, M. Sillanpää, and M. Sillanpää. 2018. Occurrence, Identification and Removal of Microplastic Particles and Fibers in Conventional Activated Sludge Process and Advanced MBR Technology. *Water Research*. 133: 236–246. https://doi.org/10.1016/j.watres.2018.01.049.

[78] Ngo, P. L., B. K. Pramanik, K. Shah, and R. Roychand. 2019. Pathway, Classification and Removal Efficiency of Microplastics in Wastewater Treatment Plants. *Environmental Pollution*. 255: 113326. https://doi.org/10.1016/j.envpol.2019.113326.

[79] Hidayaturrahman, H., and T.-G. Lee. 2019. A Study on Characteristics of Microplastic in Wastewater of South Korea: Identification, Quantification, and Fate of Microplastics during Treatment Process. *Marine Pollution Bulletin*. 146: 696–702. https://doi.org/10.1016/j.marpolbul.2019.06.071.

[80] Liu, X., W. Yuan, M. Di, Z. Li, and J. Wang. 2019. Transfer and Fate of Microplastics during the Conventional Activated Sludge Process in One Wastewater Treatment Plant of China. *Chemical Engineering Journal*. 362: 176–182. https://doi.org/10.1016/j.cej.2019.01.033.

[81] Tang, K. H. D., and T. Hadibarata. 2021. Microplastics Removal through Water Treatment Plants: Its Feasibility, Efficiency, Future Prospects and Enhancement by Proper Waste Management. *Environmental Challenges*. 5: 100264. https://doi.org/10.1016/j.envc.2021.100264.

[82] Ahmed, M. B., Md. S. Rahman, J. Alom, Md. S. Hasan, M. A. H. Johir, M. I. H. Mondal, D.-Y. Lee, J. Park, J. L. Zhou, and M.-H. Yoon. 2021. Microplastic Particles in the Aquatic Environment: A Systematic Review. *Science of the Total Environment*. 775: 145793. https://doi.org/10.1016/j.scitotenv.2021.145793.

[83] Poerio, T., E. Piacentini, and R. Mazzei. 2019. Membrane Processes for Microplastic Removal. *Molecules*. 24: 4148. https://doi.org/10.3390/molecules24224148.

[84] Bakir, A., I. A. O'Connor, S. J. Rowland, A. J. Hendriks, and R. C. Thompson. 2016. Relative Importance of Microplastics as a Pathway for the Transfer of Hydrophobic Organic Chemicals to Marine Life. *Environmental Pollution*. 219: 56–65. https://doi.org/10.1016/j.envpol.2016.09.046.

[85] Benson, N. U., and O. H. Fred-Ahmadu. 2020. Occurrence and Distribution of Microplastics-Sorbed Phthalic Acid Esters (PAEs) in Coastal Psammitic Sediments of Tropical Atlantic Ocean, Gulf of Guinea. *Science of the Total Environment*. 730: 139013. https://doi.org/10.1016/j.scitotenv.2020.139013.

[86] Catrouillet, C., M. Davranche, I. Khatib, C. Fauny, A. Wahl, and J. Gigault. 2021. Metals in Microplastics: Determining Which Are Additive, Adsorbed, and Bioavailable. *Environmental Science: Processes & Impacts*. 23: 553–558. https://doi.org/10.1039/D1EM00017A.

[87] Li, X., Q. Mei, L. Chen, H. Zhang, B. Dong, X. Dai, C. He, and J. Zhou. 2019. Enhancement in Adsorption Potential of Microplastics in Sewage Sludge for Metal Pollutants after the Wastewater Treatment Process. *Water Research*. 157: 228–237. https://doi.org/10.1016/j.watres.2019.03.069.

[88] Rafa, N., B. Ahmed, F. Zohora, J. Bakya, S. Ahmed, S. F. Ahmed, M. Mofijur, A. A. Chowdhury, and F. Almomani. 2024. Microplastics as Carriers of Toxic Pollutants: Source, Transport, and Toxicological Effects. *Environmental Pollution*. 343: 123190. https://doi.org/10.1016/j.envpol.2023.123190.

[89] Boni, W., K. Parrish, S. Patil, and N. L. Fahrenfeld. 2021. Total Coliform and *Escherichia coli* in Microplastic Biofilms Grown in Wastewater and Inactivation by Peracetic Acid. *Water Environment Research*. 93: 334–342. https://doi.org/10.1002/wer.1434.

[90] Nguyen, M.-K., M. R. J. Rakib, C. Lin, N. T. Q. Hung, V.-G. Le, H.-L. Nguyen, G. Malafaia, and A. M. Idris. 2023. A Comprehensive Review on Ecological Effects of Microplastic Pollution: An Interaction with Pollutants in the Ecosystems and Future Perspectives. *TrAC Trends in Analytical Chemistry*. 168: 117294. https://doi.org/10.1016/j.trac.2023.117294.

[91] Li, W.-K., X.-W. Xu, X. Gao, and P.-J. Wang. 2020. Multiple Connection Pattern Combination for Mild Cognitive Impairment Identification from Single Modal Data. *IFAC-*

PapersOnLine. 53: 7–12. https://doi.org/10.1016/j.ifacol.2021.04.077.
[92] Ding, T., L. Wei, Z. Hou, J. Li, C. Zhang, and D. Lin. 2022. Microplastics Altered Contaminant Behavior and Toxicity in Natural Waters. *Journal of Hazardous Materials*. 425: 127908. https://doi.org/10.1016/j.jhazmat.2021.127908.
[93] Wang, F., C. S. Wong, D. Chen, X. Lu, F. Wang, and E. Y. Zeng. 2018. Interaction of Toxic Chemicals with Microplastics: A Critical Review. *Water Research*. 139: 208–219. https://doi.org/10.1016/j.watres.2018.04.003.
[94] Kelly, J. J., M. G. London, A. R. McCormick, M. Rojas, J. W. Scott, and T. J. Hoellein. 2021. Wastewater Treatment Alters Microbial Colonization of Microplastics. *PLOS ONE*. 16: e0244443. https://doi.org/10.1371/journal.pone.0244443.
[95] Prata, J. C., B. R. B. O. Lavorante, B. S. M. Montenegro, and L. Guilhermino. 2018. Influence of Microplastics on the Toxicity of the Pharmaceuticals Procainamide and Doxycycline on the Marine Microalgae *Tetraselmis chuii*. *Aquatic Toxicology*. 197: 143–152. https://doi.org/10.1016/j.aquatox.2018.02.015.
[96] Ashton, K., L. Holmes, and A. Turner. 2010. Association of Metals with Plastic Production Pellets in the Marine Environment. *Marine Pollution Bulletin*. 60(10): 2050–2055. https://doi.org/10.1016/j.marpolbul.2010.07.014.
[97] Browne, M. A., S. J. Niven, T. S. Galloway, S. J. Rowland, and R. C. Thompson. 2013. Microplastic Moves Pollutants and Additives to Worms, Reducing Functions Linked to Health and Biodiversity. *Current Biology*. 23(22): 2388–2392. https://doi.org/10.1016/j.cub.2013.10.012.
[98] Teuten, E. L., J. M. Saquing, D. R. U. Knappe, M. A. Barlaz, S. Jonsson, A. Björn, S. J. Rowland, R. C. Thompson, T. S. Galloway, R. Yamashita, *et al.* 2009. Transport and Release of Chemicals from Plastics to the Environment and to Wildlife. *Philosophical Transactions of the Royal Society B: Biological Sciences*. 364(1526): 2027–2045. https://doi.org/10.1098/rstb.2008.0284.
[99] Guo, X., and J. Wang. 2019. Sorption of Antibiotics onto Aged Microplastics in Freshwater and Seawater. *Marine Pollution Bulletin*. 149(1): 110511. https://doi.org/10.1016/j.marpolbul.2019.110511.
[100] Godoy, V., G. Blázquez, M. Calero, L. Quesada, and M. A. Martín-Lara. 2019. The Potential of Microplastics as Carriers of Metals. *Environmental Pollution*. 255: 113363. https://doi.org/10.1016/j.envpol.2019.113363.
[101] Wang, F., K. M. Shih, and X. Y. Li. 2015. The Partition Behavior of Perfluorooctanesulfonate (PFOS) and Perfluorooctanesulfonamide (FOSA) on Microplastics. *Chemosphere*. 119(1): 841–847. https://doi.org/10.1016/j.chemosphere.2014.08.047.
[102] Guo, X., J. Pang, S. Chen, and H. Jia. 2018. Sorption Properties of Tylosin on Four Different Microplastics. *Chemosphere*. 209(1): 240–245. https://doi.org/10.1016/j.chemosphere.2018.06.100.
[103] Koelmans, A. A., N. H. M. Nor, E. Hermsen, M. Kooi, S. M. Mintenig, and J. De France. 2019. Microplastics in Freshwaters and Drinking Water: Critical Review and Assessment of Data Quality. *Water Research*. 155: 410–422. https://doi.org/10.1016/j.watres.2019.02.054.
[104] Chen, Q., J. Wang, F. Yao, W. Zhang, X. Qi, X. Gao, Y. Liu, J. Wang, M. Zou, and P. Liang. 2023. A Review of Recent Progress in the Application of Raman Spectroscopy and SERS Detection of Microplastics and Derivatives. *Microchimica Acta*. 190(7): 465. https://doi.org/10.1007/s00604-023-06044-y.
[105] Baruah, A., A. Sharma, S. Sharma, and R. Nagraik. 2022. An Insight into Different Microplastic Detection Methods. *International Journal of Environmental Science and Technology*. 19: 5721–5730. https://doi.org/10.1007/s13762-021-03384-1.
[106] Kang, J.-H., O.-Y. Kwon, and W. J. Shim. 2015. Potential Threat of Microplastics to Zooplanktivores in the Surface Waters of the Southern Sea of Korea. *Archives of Environmental Contamination and Toxicology*. 69: 340–351. https://doi.org/10.1007/s00244-015-0210-3.
[107] Song, Y. K., S. H. Hong, M. Jang, G. M. Han, M. Rani, J. Lee, and W. J. Shim. 2015. A Comparison of Microscopic and Spectroscopic Identification Methods for Analysis of Microplastics in Environmental Samples. *Marine Pollution Bulletin*. 93: 202–209. https://doi.org/10.1016/j.marpolbul.2015.01.015.
[108] Cooper, D. A., and P. L. Corcoran. 2010. Effects of Mechanical and Chemical Processes on the Degradation of Plastic Beach Debris on the Island of Kauai, Hawaii. *Marine Pollution Bulletin*. 60: 650–654. https://doi.org/10.1016/j.marpolbul.2009.12.026.
[109] Wagner, J., Z.-M. Wang, S. Ghosal, C. Rochman, M. Gassel, and S. Wall. 2017. Novel Method for the Extraction and Identification of Microplastics in Ocean Trawl and Fish Gut Matrices. *Analytical Methods*. 9: 1479–1490. https://doi.org/10.1039/C6AY02396G.
[110] Andoh, C. N., F. Attiogbe, N. O. Bonsu Ackerson, M. Antwi, and K. Adu-Boahen. 2024. Fourier Transform Infrared Spectroscopy: An Analytical Technique for Microplastic Identification and Quantification. *Infrared Physics & Technology*. 136: 105070. https://doi.org/10.1016/j.infrared.2023.105070.
[111] Cole, M., P. Lindeque, E. Fileman, C. Halsband, R. Goodhead, J. Moger, and T. S. Galloway. 2013. Microplastic Ingestion by Zooplankton. *Environmental Science & Technology*. 47: 6646–6655. https://doi.org/10.1021/es400663f.
[112] Imhof, H. K., J. Schmid, R. Niessner, N. P. Ivleva, and C. Laforsch. 2012. A Novel, Highly Efficient Method for the Separation and Quantification of Plastic Particles in Sediments of Aquatic Environments. *Limnology and Oceanography: Methods*. 10: 524–537. https://doi.org/10.4319/lom.2012.10.524.
[113] Zhang, M., Y. Feng, L. Li, X. Zhang, and F. Xu. 2024. Reducing Fluorescence Interference for Improved Raman Spectroscopic Analysis of Plant Cell Walls. *Wood Science and Technology*. https://doi.org/10.1007/s00226-024-01587-6.
[114] Castañeda, R. A., S. Avlijas, M. A. Simard, and A. Ricciardi. 2014. Microplastic Pollution in St. Lawrence River Sediments. *Canadian Journal of Fisheries and Aquatic Sciences*. 71: 1767–1771. https://doi.org/10.1139/cjfas-2014-0281.
[115] Majewsky, M., H. Bitter, E. Eiche, and H. Horn. 2016. Determination of Microplastic Polyethylene (PE) and Polypropylene (PP) in Environmental Samples Using Thermal Analysis (TGA-DSC). *Science of the Total Environment*. 568: 507–511. https://doi.org/10.1016/j.scitotenv.2016.06.017.
[116] Prata, J. C., J. P. da Costa, A. C. Duarte, and T. Rocha-Santos. 2019. Methods for Sampling and Detection of Microplastics in Water and Sediment: A Critical Review. *TrAC Trends in Analytical Chemistry*. 110: 150–159. https://doi.org/10.1016/j.trac.2018.10.029.
[117] Thompson, R. C., Y. Olsen, R. P. Mitchell, A. Davis, S. J. Rowland, A. W. G. John, D. McGonigle, and A. E. Russell. 2004. Lost at Sea: Where Is All the Plastic? *Science*. 304: 838. https://doi.org/10.1126/science.1094559.
[118] Zhou, C., R. Bi, C. Su, W. Liu, and T. Wang. 2022. The Emerging Issue of Microplastics in Marine Environment: A Bibliometric Analysis from 2004 to 2020. *Marine Pollution Bulletin*. 179: 113712. https://doi.org/10.1016/j.marpolbul.2022.113712.