Environmental Chemistry for a Sustainable World 73

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Microplastic Occurrence, Fate, Impact, and Remediation

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Environmental Chemistry for a Sustainable World

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Preface

Plastics are basically polymers of natural and anthropogenic origin. Most natural polymers are not of concern because they are usually highly biodegradable and thus safely recycled into the global carbon cycle; only a small fraction, about 0.1%, is preserved in sediments and will form coal and petroleum over millions of years. Nonetheless, the excessive production of polymers derived from fossil fuels during the last decades has induced a global pollution by plastics and their fragments, microplastics and nanoplastics. There are several concerns about these pollutants: first, fossil-fuel-derived plastics contribute to the exhaustion of already depleted fossil-fuel resources, and they are carbon positive because their degradation increases atmospheric levels of carbon dioxide. This issue may be solved by bioplastics synthesized with modern biomass. Second, some synthetic plastics and their fragments are toxic because they are made from toxic monomers that are released in the environment by aging, and because they contain toxic additives and plasticizers. Third, some synthetic plastics are chemically very stable and hardly decompose in the environment and inside living organisms; they can thus induce diseases many years after their introduction in environmental media and living organisms. Fourth, once fragmented and degraded in the environment, microplastics act as both 'sponges' and 'vehicles' that can carry other pollutants such as metals, pesticides, and pathogenic microorganisms to remote locations (Fig. 1). The recent discovery of nanoplastics is of high concern because these pollutants are potentially more toxic due to their smaller size and reactivity, and they can easily penetrate the human body.

This book summarizes recent research on microplastic pollution and remediation methods. The first chapter by Wang et al. details research trends in microplastic research from 1991 to 2020 using bibliometic analysis. Characterization of microplastics in soils, water and air is presented in Chap. 2 by Mehmood et al. Then Tahsin et al. discuss the unexpected behavior of corals in the presence of microplastics, in Chap 3. Methods for the removal and degradation of microplastics are detailed in Chapters 4, 5, 6, 7, and 8 by Liu et al., Jadoun et al., Subair et al., Tadsuwan and Babel, and Yadav et al. Chap. 9 by Dahal and Babel focuses on microplastics in outdoor and indoor environments. Finally, the fate of microplastics in soil-plant systems is discussed in the last chapter by Lepcha et al.

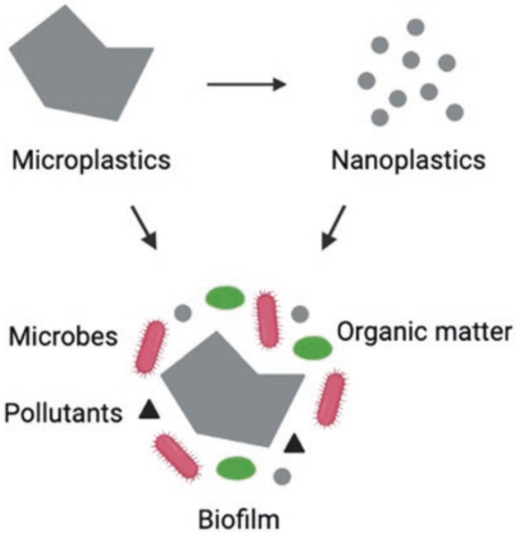

Fig. 1 Microplastics carry other pollutants and microbes. (Reprinted with permission from Sharma et al. (2023). Nanoplastics are potentially more dangerous than microplastics. 10.1007/s10311-022-01539-1)

The editors of this book would like to thank all the authors for contributing high-quality chapters. We also extend our thanks to the reviewers for their critical comments on the manuscripts. We express our sincere thanks to production team at Springer Nature for the efficient publication of this book.

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Contents

Microplastic Research Publications from 1991 to 2020

Chongqing Wang, Hongru Jiang, and Yuh-Shan Ho

Abstract Microplastics as emerging pollutants receive global attention and growing research interests. We report a bibliometric analysis of microplastics-related research from 1991 to 2020. 4026 documents were collected and analyzed for occurrence and types of microplastics, and research fields. We found that number of articles increased sharply from 2015, and microplastics. Environmental science is the leading subject category, followed by marine and freshwater biology, environmental engineering, materials science, toxicology water resources, multidisciplinary sciences, metallurgy and metallurgical engineering, and analytical chemistry. Marine Pollution Bulletin was the most productive journal, followed by Environmental Pollution, Science of the Total Environment, Environmental Science & Technology, and Chemosphere. The 3536 articles on microplastics were from 107 different countries, and China was the most productive country.

Keywords Microplastics · Environment · Bibliometric · Citations · Research trends

1 Introduction

Plastics have been widely used in various fields and applications due to especially their unique properties of low-cost, durability, lightness, hygiene, and corrosion resistance. The global production of plastic products exceeds 3.48×10^8 tons per

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year, resulting in a considerable amount of plastic waste (Li et al. 2020). Inevitably, plastic waste enters the aquatic environment, and it is estimated that more than 2.5×10^5 tons of plastics are floating on the global ocean surface (Eriksen et al. 2014). Large plastic debris can be easily removed from the environment, whereas plastic debris with small size is prone to be ignored and difficult to remove from environmental matrices.

Microplastics, commonly defined plastic particles less than 5 mm, receive increasing public attention and research interests all over the world (Zhang et al. 2021). Microplastics are derived from primary microplastics and secondary microplastics (Hamidian et al. 2021). The former was originally made of small-sized polymers for special purposes such as pharmaceuticals and personal care products. The latter is mainly created by fragmentation and degradation of large particles of plastics. Microplastics have been found in a wide range of ecosystems, including aquatic systems (oceans, rivers, and lakes), soils and sediments, and atmospheric air (Wang et al. 2021a). Initially, the majority of research was focused on the maritime environment. As a result of the interest in the sources and transfer channels of microplastics, more attention is being directed to additional environmental compartments.

Microplastics induce significant public attention owing to the persistence and ubiquity in water environment and the threats to ecosystems. Because of their small size, microplastics can be ingested by organisms and aquatic creatures, potentially accumulating in the food chain (Ribeiro et al. 2019). The negative consequences of microplastics involve physical injury to the gastrointestinal tract of organisms, and toxic impacts resulting from polymers and additives in the microplastics (Barboza et al. 2020). Additionally, microplastics can be carriers to concentrate and transfer pollutants. Therefore, the interaction between microplastics and pollutants and the removal of microplastics have attracted much attention (Jiang et al. 2022a, b; Bian et al. 2022). With increasing awareness of the worldwide distribution and potential risk of microplastics, more study is being conducted on identifying the origins and transfer pathways, disclosing the threats to ecosystems, attempting to regulate microplastics discharges, and removing microplastics from the environment.

Bibliometric analysis is an important method to reveal the past research evolution of microplastics, providing a better understanding of the emerging research areas. Mathematical techniques are employed to examine the published documents based on macro-perspective. The bibliometric method is related to informetrics and scien-tometrics, which provide fundamental theory and methodology for bibliometric analysis (Hood and Wilson 2001). A bibliometric analysis of the literature on a certain issue provides vital information for the topic and research progress (Ertz and Leblanc-Proulx 2018). Currently, numerous review papers (Andrady 2011; Cole et al. 2011) and bibliometric studies (Pauna et al. 2019; Palmas et al. 2021) on microplastics have been carried out.

Publication performance on microplastics and the main focuses and their development trends were studied by using the Science Citation Index Expanded (SCI-EXPANDED). This study addresses the data analysis of microplastics documents in terms of different criteria, identifying the occurrence and types of microplastics, emerging interests of the research fields, the research gap in the current state, and future perspective.

2 Materials and Methods

This work conducts a data-driven bibliometric study based on a literature review, aiming to explore indicators for further research on microplastics. The literature data were obtained from the SCI-EXPANDED database in Web of Science, which is one of the most important databases for scientific research. The database of the Web of Science is listed in Supporting Material (Text S1). The journal impact factor in 2020 was based on Journal Citation Reports in 2020. The published literature was collected after June 30, 2021. It was pointed out that the SCI-EXPANDED was useful to search published literature but not employed for bibliometric studies (Ho 2020a). Therefore, it is essential to have a data treatment but have data directly from the database of SCI-EXPANDED for bibliometric studies. It was reported that "front page" containing paper title, abstract, and author keywords could be used as a filter for bibliometric studies (Ho 2020b; Fu et al. 2012). *KeyWords Plus* supplied supplementary search items extracted from paper titles cited by authors and amplified author-keyword and title-word indexing (Garfield 1990). The documents searched by *KeyWords Plus* were not closely relevant to the target topic (Fu and Ho 2015). The search keywords "microplastics," "microplastic," "micro-plastics," and "micro-plastics" were searched by topic in the database. It resulted in 4972 documents from 1991 to 2020, which may be relevant to the topic. 4026 documents were used as microplastics publications for a bibliometric study because no search keywords were found on the 'front page' of 946 documents. The document records were downloaded and manually coded for analysis using Microsoft Excel 2016 (Li and Ho 2008; Ho 2021).

For one corresponding author, it was used as corresponding author (Ho 2012), while the last one of multiple corresponding authors was used as corresponding author (Ho 2019). As to single-author articles, the author was designated as the first and corresponding author (Ho 2014a). For affiliations, England, Scotland, Northern Ireland, Wales, and the Falkland Islands were assigned to the United Kingdom. Greenland was assigned to Denmark (Tchuifon Tchuifon et al. 2017). Additionally, affiliations from the USSR were assigned to Russia or Ukraine (Wambu et al. 2017). Four citation indicators were defined in this work: (1) C_0, (2) C_{year}, (3) TC_{2020}, and (4) CPP_{year} (Ho 2013, 2014b; Wang and Ho 2011). The citation indicators were used for bibliometric analysis.

3 Results and Discussion

3.1 Documents Summary

The documents used for bibliometric analysis were collected for the period 1991–2020. The total number of filtered documents relevant to microplastics is 4026. The citation indicator of CPPyear can be employed to describe the citations per publication more accurately (Ho and Ho 2015). Recently, the author number of each publication was also applied to analyze the types of documents related to specific topic (Monge-Nájera and El Ho 2017). As listed in Table 1, 14 types of documents were involved, and the type of article was the top one with an APP of 5.3, accounting for 84% of 4204 documents. Since some documents could be assigned to different document types, the total percentage was higher than 100% (Usman and Ho 2020). For example, 83 documents were assigned to proceedings papers and articles. The document type of retracted publications had the highest CPP_{2020} of 124 which is due to the highly cited retracted publication with a TC_{2020} of 100 or more by Lönnstedt and Eklöv (Lönnstedt and Eklöv 2016). Document type corrections had the highest APP of 6.1. In addition, each microplastics-related article had an average of 5.3 authors. The study reported by Gorsky et al. had a maximum author count of 145 (Gorsky et al. 2019). The 3546 articles were employed for bibliometric study, and this is due to the complete structure of article-type research.

Table 1 Citations and authors according to document type

Document type	TP	TP*	%	AU	APP	TC_{2020}	CPP_{2020}
Article	3546	3544	84	18,750	5.3	113,771	32
Review	411	411	10	2008	4.9	24,725	60
Proceedings paper	83	83	2.0	338	4.1	2122	26
Editorial material	82	76	2.0	205	2.7	2288	28
Meeting abstract	72	72	1.7	261	3.6	16	0.22
News item	40	17	1.0	17	1.0	7	0.18
Letter	27	27	0.64	77	2.9	914	34
Correction	25	25	0.59	152	6.1	17	0.68
Book chapter	4	4	0.10	17	4.3	169	42
Book review	1	1	0.024	1	1.0	0	0
Data paper	1	1	0.024	2	2.0	4	4.0
Note	1	1	0.024	2	2.0	8	8.0
Retracted publication	1	1	0.024	2	2.0	124	124
Retraction	1	1	0.024	3	3.0	2	2.0

TP number of publications, *AU* number of authors, *APP* number of authors per publication; TC_{2020}: the total number of citations from Web of Science Core Collection since publication year to the end of 2020; CPP_{2020}: number of citations (TC_{2020}) per publication (*TP*)

3.2 Language of Publications

Many bibliometric studies regard publication languages as one basic content (Wang and Ho 2011). There were nine languages in use, and English accounted for 99% of the 3546 articles. Some other languages were as follows: Russian (11 articles), German (9 articles), Japanese (6), Chinese (5), French (5), Ukrainian (4), Korean (1), and Spanish (1). The CPP_{2020} of articles in English was 32, remarkably higher than that of non-English articles (2.5). Moreover, the *APP* of articles written in English was 5.3, higher than that of non-English articles (3.0). It should be noted that most of the journals in the Clarivate Analytics database are published in English.

3.3 The Variation of Publications

Figure 1 presents the variation of *TP* and CPP_{2020}. A significant increase in the number of articles was observed from 109 in 2015 to 1372 in 2020, indicating that microplastics receive increasing attention in the research field. The increase in the number of articles can be attributed to researchers' finding a new topic or developing research interests in microplastics. In 2014, with 70 articles, we had the highest CPP_{2020} of 190. Three of the top ten cited articles were published in 2014, including articles by Eriksen et al. (2014), Cozar et al. (2014), and Van Cauwenberghe and Janssen (2014), which ranked third, fourth, and tenth, respectively. A total of 1650 microplastics articles (47% of 3546 articles) were not cited by published studies in the publication year ($C_0 = 0$) (Ho and Kahn 2014).

3.4 The Subject Category of Web of Science

A total of 9531 journals were indexed Journal Citation Reports in 2020, and 178 subject categories were involved. The relationship between article number in a specific subject category and publication year provides some information about research trends and the interactions (Ho et al. 2010). Table 2 shows the top ten subject categories. In 2020, the environmental sciences category was the most productive category with 2449 articles (69% of 3546 articles), followed distantly by other categories. This implies that microplastics become emerging pollutants and gain great attention due to potential environmental threats. Compared to the top ten categories, microplastics articles in the multidisciplinary sciences category had the highest CPP_{2020} (55), and it was followed by the environmental engineering category (CPP_{2020} of 50). The *APP* in the environmental engineering

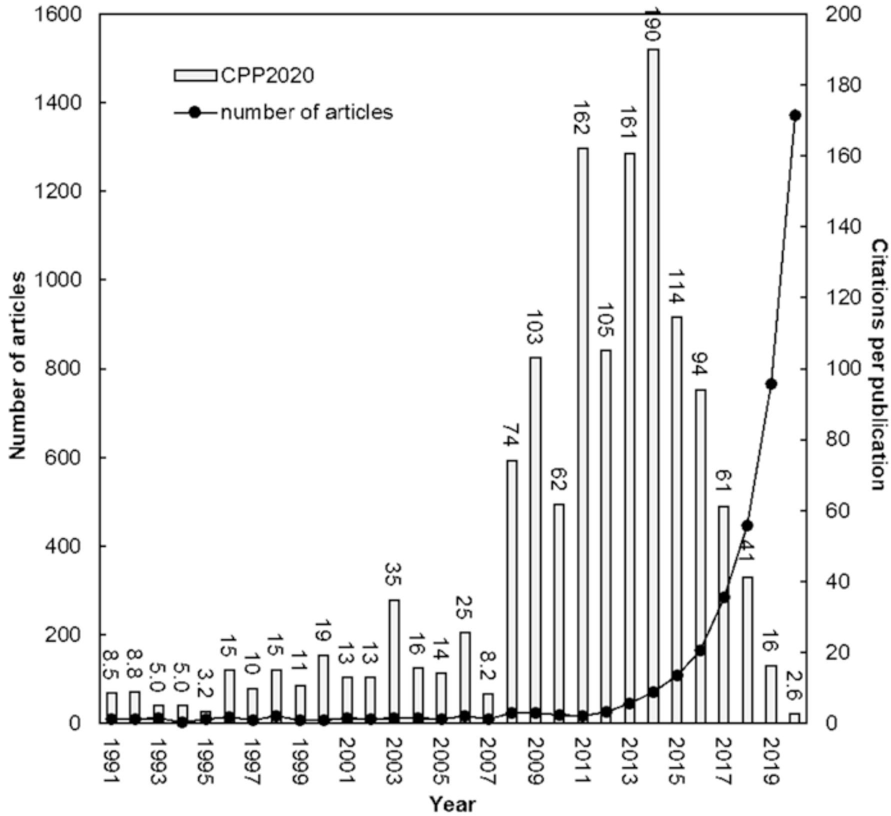

Fig. 1 The number of articles and citations per publication by year. CPP_{2020}: number of citations (TC_{2020}) per publication

category was 5.7, and the metallurgy and metallurgical engineering category had an *APP* of 3.8. Figure 2 shows the variation trend of the top five subject categories. Microplastics-related studies were reported chiefly in the category of environmental sciences. The category of environmental sciences has been the most popular since 2011. The first microplastics article in the category of environmental sciences was published in 2006 by Ng and Obbard in *Marine Pollution Bulletin* (Ng and Obbard 2006). Furthermore, the category of multidisciplinary chemistry become popular in recent years, ranking tenth in 2020. The of multidisciplinary materials science category published 217 microplastics-related articles and ranked fourth, but ranked 11th in 2020 since only 27 articles were reported. Journals could be assigned to different subject categories, and hence the total percentage was larger than 100%. For example, *Water Research* journal was assigned to the environmental engineering category, the environmental sciences category, and the water resources category.

Table 2 The top ten productive Web of Science category

Web of Science category	*TP* (%)	TC_{2020}	CPP_{2020}	AU	APP
Environmental sciences	2449 (69)	88,547	36	13,642	5.6
Marine and freshwater biology	756 (21)	28,503	38	4095	5.4
Environmental engineering	406 (11)	20,485	50	2315	5.7
Multidisciplinary materials science	217 (6.1)	2948	14	885	4.1
Toxicology	215 (6.1)	7419	35	1123	5.2
Water resources	178 (5.0)	4218	24	964	5.4
Multidisciplinary sciences	155 (4.4)	8524	55	857	5.5
Metallurgy and metallurgical engineering	131 (3.7)	1721	13	503	3.8
Analytical chemistry	106 (3.0)	3015	28	522	4.9
Multidisciplinary chemistry	80 (2.3)	1186	15	395	4.9

TP number of publications, % percentage of 3546 articles, TC_{2020} the total number of citations from Web of Science Core Collection since publication year to the end of 2020, CPP_{2020} number of citations (TC_{2020}) per publication (*TP*), *AU* the total number of authors, *APP* number of authors per publication

3.5 Analysis Based on Journals

A total of 3546 articles related to microplastic researches were reported in 566 journals. These journals covered 112 subject categories of Web of Science. The top five journals publishing more than 100 microplastics-related articles included: *Marine Pollution Bulletin* (IF_{2020} = 5.553) with 573 articles (16% of 3546 articles), *Environmental Pollution* (IF_{2020} = 8.071) with 426 articles (12%), *Science of the Total Environment* (IF_{2020} = 7.963) with 361 articles (10%), *Environmental Science & Technology* (IF_{2020} = 9.028) with 172 articles (4.9%), and *Chemosphere* (IF_{2020} = 7.086) with 135 articles (3.8%). All above journals were related to the field of environment, suggesting microplastics gained great growing attention and research interests due to environmental problems. *Science* with three articles, places first with the highest IF_{2020} of 47.728, followed by *Nature Nanotechnology* with one article (IF_{2020} = 39.213), and *Advanced Materials* with one article (IF_{2020} = 30.849). Microplastics-related studies were preferred by top journals, such as *Science* and *Nature Nanotechnology*, indicating the importance and popularity of the microplastics topic.

3.6 Analysis Based on Countries

The articles (0.28% of 3546 articles) without affiliation information were excluded from the analysis. The 3536 articles related to microplastic studies were from 107 countries. Among them, a total of 2539 single-country articles were from 55 countries, while 997 articles with international collaborations were from 101 countries.

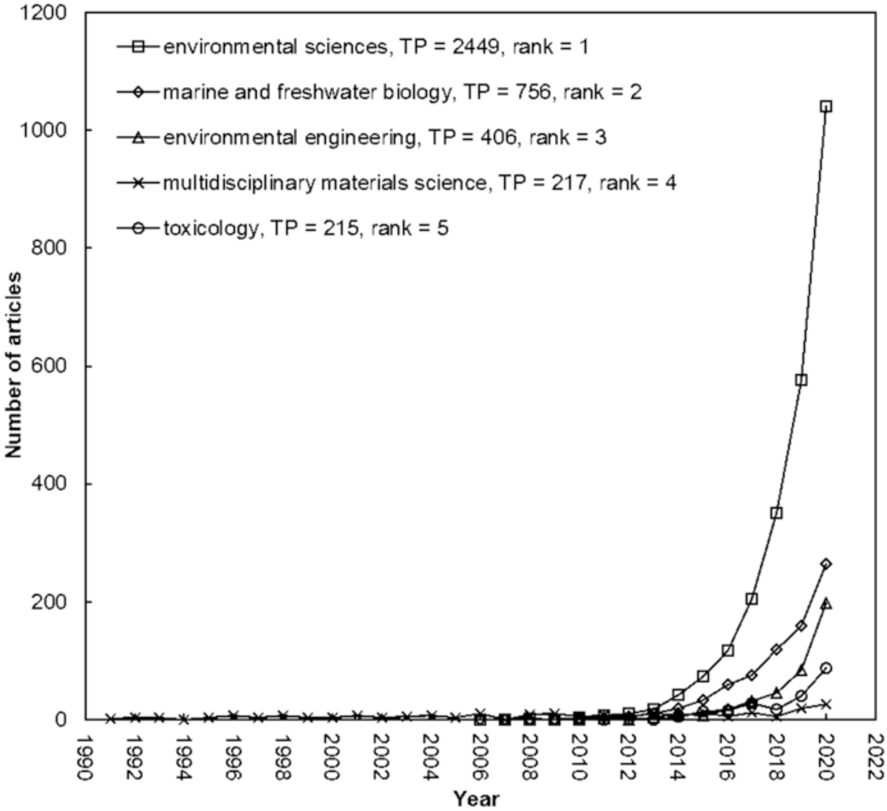

Fig. 2 Microplastic articles in the Web of Science categories

The top 13 productive countries, publishing over 100 articles, are displayed in Table 3. These countries included seven European countries (Germany, UK, Italy, France, Spain, Netherlands, and Portugal), three American countries (USA, Canada, and Brazil), two Asiatic countries (China and Russia), and one Oceanian country (Australia). Additionally, South Africa published 52 articles, ranking first in Africa. The indicators, including *TP*, *IP*, *CP*, *FP*, *RP*, and *SP* were applied to compare publication performance (Hsu and Ho 2014). China had the highest publication indicators, with a *TP* of 25%, an *IP* of 6%, a *FP* of 23%, and a *RP* of 23%. USA was the most collaborative country, with 230 collaborative articles and a *CP* of 23%. Russia was poor in collaborative studies due to the most single-author articles with *SP* of 22%. The variation of published articles for the top five countries is shown in Fig. 3. The annual number of microplastics-related publications was no more than 10 before 2014, primarily reported by Russia. A sharp increase was found in China after 2017. China, the USA, Germany, the UK, and Italy were also the top five countries on the total number of articles in 2020.

Table 3 Top 13 productive countries with *TP* > 100

Country	TP	*TPR* (%)	*IPR* (%)	*CPR* (%)	*FPR* (%)	*RPR* (%)	*SPR* (%)
China	869	1 (25)	1 (16)	2 (20)	1 (23)	1 (23)	7 (3.4)
USA	460	2 (13)	3 (5.5)	1 (23)	2 (8.7)	2 (8.9)	2 (13)
Germany	403	3 (11)	2 (5.5)	3 (17)	3 (8.5)	3 (8.5)	4 (7.9)
UK	320	4 (9.0)	4 (3.6)	4 (17)	4 (6.1)	4 (6.2)	3 (11)
Italy	250	5 (7.1)	5 (2.9)	5 (13)	5 (5.3)	5 (5.4)	10 (2.2)
France	199	6 (5.6)	8 (1.8)	6 (12)	8 (3.3)	8 (3.4)	7 (3.4)
Spain	198	7 (5.6)	7 (2.1)	7 (11)	6 (3.5)	6 (3.5)	N/A
Australia	149	8 (4.2)	15 (1.1)	8 (10)	10 (2.4)	10 (2.4)	15 (1.1)
Netherlands	144	9 (4.1)	16 (1.0)	8 (10)	11 (2.2)	11 (2.3)	10 (2.2)
Canada	133	10 (3.8)	11 (1.3)	11 (7.8)	12 (2.2)	13 (2.2)	5 (6.7)
Russia	129	11 (3.6)	6 (2.3)	18 (3.2)	7 (3.5)	7 (3.5)	1 (22)
Portugal	109	12 (3.1)	14 (1.2)	12 (6.0)	14 (2.1)	14 (2.1)	15 (1.1)
Brazil	101	13 (2.9)	12 (1.3)	15 (4.7)	12 (2.2)	12 (2.2)	N/A

TP total number of articles, *TPR* (%) rank of total number of articles and percentage, *IPR* (%) rank of single country articles and percentage in all single country articles, *CPR* (%): rank of internationally collaborative articles and percentage in all internationally collaborative articles, *FPR* (%) rank of first-author articles and percentage in all first-author articles, *RPR* (%) rank of corresponding-author articles and percentage in all corresponding-author articles, *SPR* (%) rank of single-author articles and percentage in all single-author articles, N/A not available

3.7 Analysis Based on Institutions

Table 4 demonstrates the top ten institutions as characterized by six indicators (Hsu and Ho 2014). Single-institution articles accounted for 33% of 3536 articles, while inter-institutionally collaborative articles accounted for 67%, suggesting that many researchers conducted collaborative studies on microplastics. It is worthwhile that the Chinese Academy of Sciences in China, the Russian Academy of Sciences in Russia, the National Research Council (CNR) in Italy, and the French Research Institute for Exploitation of the Sea (IFREMER) in France are national government institutions, rather than universities. The Chinese Academy of Sciences was ranked first and had the highest publication indicators, with a *TP* of 4.1%, a *CP* of 5.9%, a *FP* of 2.7%, and a *RP* of 2.5%. University of Chinese Academy of Sciences in China took the second position with *TP* of 2.4% and *CP* of 3.6%. Russian Academy of Sciences had the maximum publication indicators with *IP* of 3.1% and *SP* of 11%. All these 86 articles collaborated with the Chinese Academy of Sciences in China. However, the university had no institution-specific articles or single-author articles, respectively, and three first-author articles and corresponding-author articles. Chinese Academy of Sciences and the Russian Academy of Sciences was the most productive institutions, probably because they have a number of departments or branches (Li et al. 2009).

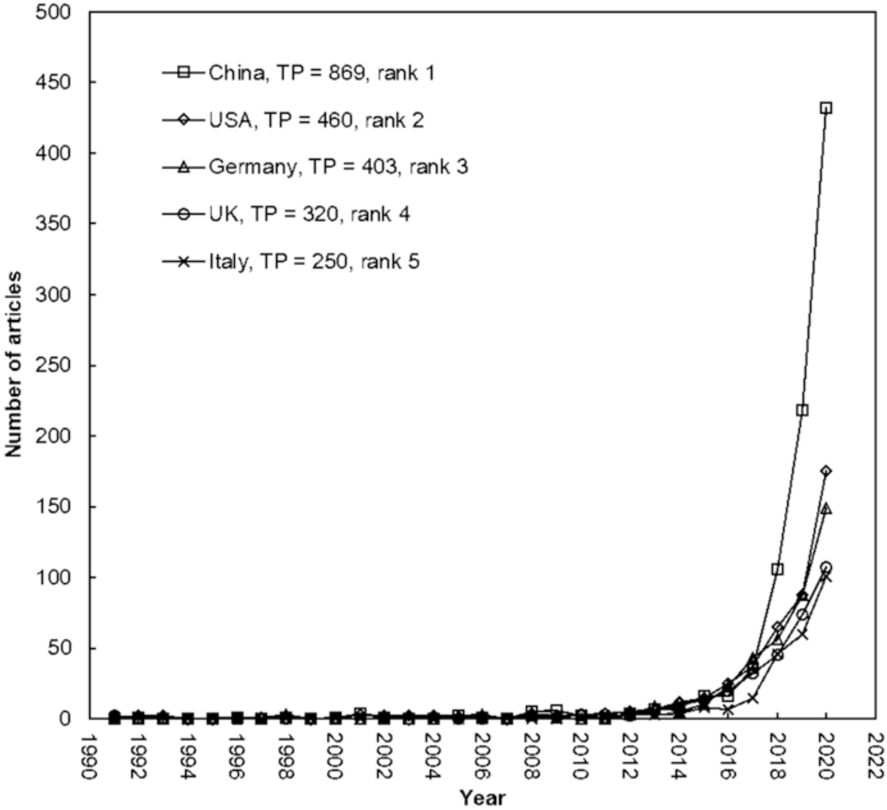

Fig. 3 Comparison of development trends among the top five productive countries

3.8 The Important Articles in 2020

The publication indicator, C_{2020}, could offer supplementary insights into understanding the influence of highly cited articles (Ho 2012). The ranking of 3546 microplastics-related articles differed significantly for sorting by TC_{2020} or sorting by C_{2020}. Among these publications, 22% articles exhibited $C_{2020} = 0$ and 17% articles had $TC_{2020} = 0$. In addition, 73% of the top 100 C_{2020} publications were among the top 100 TC_{2020} papers. A total of 2508 articles (71% of 3546 articles) contained microplastics-related keywords in the Title. 3296 articles (94% of 3507 articles with abstracts) had search keywords in the Abstract. 2106 articles (74% of 2854 articles with author keywords) had microplastics-related keywords in author keywords. Seven of the top 20 articles on TC_{2020} had microplastics-related keywords in all Title, Abstract, and author keywords. For example, publications reported by Eriksen et al. (. 2013), Van Cauwenberghe and Janssen (2014), Claessens et al. (2011), Woodall et al. (2014), Van Cauwenberghe et al. (2013), Farrell and Nelson (2013), and Fendall and Sewell (2009) ranked ninth with TC_{2020} of 589, tenth with TC_{2020} of

Table 4 Top ten productive institutions

Institute (country)	TP	*TPR* (%)	*IPR* (%)	*CPR* (%)	*FPR* (%)	*RPR* (%)	*SPR* (%)
Chinese Academy of Sciences (China)	145	1 (4.1)	34 (0.43)	1 (5.9)	1 (2.7)	1 (2.5)	10 (1.1)
University of Chinese Academy of Sciences (China)	86	2 (2.4)	N/A	2 (3.6)	230 (0.085)	228 (0.085)	N/A
East China Normal University (China)	83	3 (2.3)	4 (1.1)	3 (3.0)	3 (1.7)	3 (1.6)	N/A
Russian Academy of Sciences (Russia)	70	4 (2.0)	1 (3.1)	10 (1.4)	2 (1.8)	2 (1.8)	1 (11)
University of Plymouth (UK)	53	5 (1.5)	3 (1.2)	5 (1.6)	5 (0.74)	5 (0.68)	N/A
University of Exeter (UK)	50	6 (1.4)	34 (0.43)	4 (1.9)	26 (0.40)	21 (0.42)	N/A
National Research Council (CNR) (Italy)	41	7 (1.2)	34 (0.43)	6 (1.5)	15 (0.51)	11 (0.51)	10 (1.1)
French Research Institute for Exploitation of the Sea (IFREMER) (France)	38	8 (1.1)	70 (0.26)	7 (1.5)	98 (0.17)	65 (0.23)	N/A
Nanjing University (China)	37	9 (1.0)	9 (0.69)	15 (1.2)	4 (0.85)	4 (0.82)	N/A
University of Toronto (Canada)	37	9 (1.0)	45 (0.34)	11 (1.4)	15 (0.51)	16 (0.45)	3 (2.2)

TP total number of articles, *TPR* (%) rank of total number of articles and percentage, *IPR* (%) rank of single institute articles and percentage in all single institute articles, *CPR* (%) rank of inter-institutionally collaborative articles and percentage in all inter-institutionally collaborative articles, *FPR* (%) rank of first-author articles and percentage in all first-author articles, *RPR* (%) rank of corresponding-author articles and percentage in all corresponding-author articles, *SPR* (%) rank of single-author articles and percentage in all single-author articles, N/A not available

583, 13rd with TC_{2020} of 537, 15th with TC_{2020} of 532, 16th with TC_{2020} of 512, 17th with TC_{2020} of 511, and 19th with TC_{2020} of 465, respectively.

Figure 4 manifested the citation variation of the top ten highly cited articles with microplastics-related keywords in the Title or author keywords. A study conducted by Barnes et al. (2009) ranked first on annual citations between 2012 and 2020 in the field of microplastics. An article by Browne et al. (Browne et al. 2011) had a similar trend of increasing citations. Table 5 shows the top ten highly cited papers with microplastics-related keywords in the Title or author keywords. The top 10 publications were reported by 20 institutes derived from 11 countries. The UK reported five of the top ten highly cited publications, followed by the USA (3 articles), Finland (2), and one each by Australia, Belgium, Canada, France, Germany, Ireland, Norway, and Switzerland. It can be deduced that microplastics receive great attention in most developed countries, and this can be ascribed to the massive production and consumption of plastic products and increasing environmental awareness. The University of Plymouth in the UK reported four articles among the top ten highly cited papers, and it was followed by the Algalita Marine Research Foundation

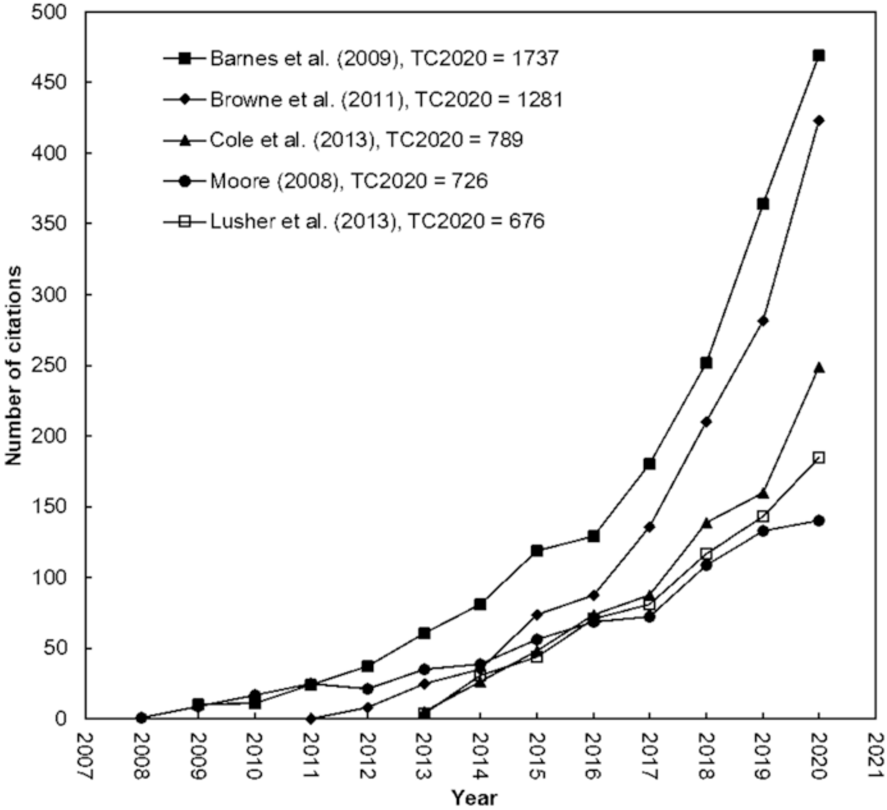

Fig. 4 Citations of the top five most frequently cited articles with search keywords in their title or author keywords

in the USA and the University of Exeter in the UK, which published two of the top ten articles, respectively.

Among 3546 microplastics-related articles, four articles ranked in the top ten TC_{2020} and C_{2020}, indicating the most frequently cited and most impactful articles. The four important articles in 2020, considering high citations and impacts, were discussed as below:

1. Accumulation and fragmentation of plastic debris in global environments (Barnes et al. 2009)

$$TC_{2020} = 1737, \text{ rank first and } C_{2020} = 469, \text{ rank first.}$$

In this work, the global plastics production and the accumulation of plastic waste were briefly surveyed. The presence of plastic debris in global environments was discussed in detail, as was the accumulation trend. It was found that the particle size of plastics in the environment decreased and the abundance and worldwide distribution of microplastics increased in the past decades. Many studies on

Table 5 The top ten most frequently cited articles with search keywords in their title or author keywords

R (TC_{2020})	*R* (C_{2020})	Title	Country	References
1 (1737)	1 (469)	Accumulation and fragmentation of plastic debris in global environments	UK, France, USA	Barnes et al. (2009)
2 (1281)	2 (423)	Accumulation of microplastic on shorelines woldwide: Sources and sinks	Ireland, Australia, UK, Canada	Browne et al. (2011)
6 (789)	5 (249)	Microplastic ingestion by zooplankton	UK, Norway	Cole et al. (2013)
7 (726)	30 (140)	Synthetic polymers in the marine environment: A rapidly increasing, long-term threat	USA	Moore (2008)
8 (676)	8 (185)	Occurrence of microplastics in the gastrointestinal tract of pelagic and demersal fish from the English Channel	UK	Lusher et al. (2013)
9 (589)	11 (178)	Microplastic pollution in the surface waters of the Laurentian Great Lakes	USA	Eriksen et al. (2013)
10 (583)	14 (174)	Microplastics in bivalves cultured for human consumption	Belgium	Van Cauwenberghe and Janssen (2014)
11 (578)	7 (200)	The impact of debris on marine life	UK	Gall and Thompson (2015)
12 (544)	12 (177)	Uptake and effects of microplastics on cells and tissue of the blue mussel *Mytilus edulis* L. after an experimental exposure	Switzerland, Germany	Von Moos et al. (2012)
13 (537)	13 (176)	Ingestion and transfer of microplastics in the planktonic food web	Finland	Setälä et al. (2014)

TC_{2020} the total number of citations from Web of Science Core Collection since publication year to the end of 2020, C_{2020} the number of citations of an article in 2020 only, *R* ranking in 3546 microplastics articles

microplastics reported the occurrence and abundance of microplastics in different regions, providing better knowledge of the sources, quantities, and distribution. More valuable and comparable data were still required due to the variation in sampling methodology. In addition, it was pointed out that the environmental consequences of microplastics were still poorly understood.

2. Accumulation of microplastic on shorelines worldwide: sources and sinks (Browne et al. 2011)

$$TC_{2020} = 1281\text{, rank second and } C_{2020} = 423\text{, rank second.}$$

Browne et al. (2011) reported a worldwide study on the sources and transfer pathways of microplastics. It was found that fibers from washing clothes were an important source of microplastics. A large amount of microplastic fibers were identified in marine environments, and most of them originated from sewage effluent because of the washing of clothes. This study offered novel insights into the sources, abundance, sinks, and pathways of microplastic into the environment. Subsequently, more research interests are paid on microplastics in the freshwater environment.

3. Microplastic ingestion by zooplankton (Cole et al. 2013)

$$TC_{2020} = 789\text{, rank sixth and } C_{2020} = 249\text{, rank fifth.}$$

Intake of microplastics by various marine biota has been widely reported by researchers, such as mussels, fish, and seabirds. Cole et al. conducted research on microplastic ingestion by zooplankton due to their important ecological role in marine food webs (Cole et al. 2013). Bioimaging techniques were employed to examine the microplastics in zooplankton in different stages, such as ingestion, egestion, and adherence. Ingestion of microplastics by zooplankton in the ocean was verified, and negative impacts included reduced function and health, transferring pollutants to predators, and the ingesting of fecal pellets. This study not only provides insights into the knowledge of microplastic contamination in aquatic environments but also induces significant attention to the problems of microplastic pollution.

4. Occurrence of microplastics in the gastrointestinal tract of pelagic and demersal fish from the English Channel (Lusher et al. 2013)

$$TC_{2020} = 676\text{, rank eighth and } C_{2020} = 185\text{, rank eighth.}$$

In this work, the abundance of microplastics in natural environments was investigated through the fish samples from the English Channel. It was reported that the studied pelagic species and demersal species had ingested microplastics. Polyamide (36%) and rayon (58%) were the most common types of ingested plastics. The potential consequences of ingesting microplastics were not studied. The widespread occurrence of microplastics and their ingestion by fish suggest that revealing the potential risks of microplastics in the marine environment is imperative.

3.9 Research Focuses and Their Trends

To better understand the research topic, the keywords in microplastics-related publications were examined. A total of 3257 articles (92% of 3546 articles from 1991 to 2020) published in the active period from 2013 to 2020 were further analyzed for research focuses and their trends. The words in article Title, Abstracts, author keywords, and *KeyWords Plus* were explored, and microplastics-related articles were ranked based on the study period, which was exhibited in Supplementary Material A, B, and C. The top 20 author keywords commonly mentioned in articles were listed in Table 6. Besides the keywords, including microplastic, microplastics, micro-plastic, and micro-plastics, plastic pollution

Table 6 Top 20 author keywords in publications related to microplastics

Author keywords	TP	2013–2020 Rank (%)	2013–2014 Rank (%)	2015–2016 Rank (%)	2017–2018 Rank (%)	2019–2020 Rank (%)
Microplastics	1234	1 (45)	1 (27)	1 (44)	1 (46)	1 (46)
Microplastic	511	2 (19)	2 (15)	2 (19)	2 (21)	2 (18)
Plastic pollution	139	3 (5.1)	7 (3.8)	7 (4.3)	4 (4.7)	3 (5.4)
Pollution	129	4 (4.8)	5 (5.1)	5 (5.3)	3 (5.9)	5 (4.3)
Marine debris	110	5 (4.1)	3 (13)	3 (10)	7 (4.0)	8 (3.1)
Sediment	109	6 (4.0)	7 (3.8)	54 (1.0)	9 (3.5)	4 (4.5)
Marine litter	90	7 (3.3)	7 (3.8)	4 (6.2)	6 (4.5)	13 (2.6)
Plastic	87	8 (3.2)	4 (11)	8 (3.3)	7 (4.0)	13 (2.6)
Ingestion	79	9 (2.9)	7 (3.8)	6 (4.8)	4 (4.7)	17 (2.1)
Polystyrene	79	9 (2.9)	40 (1.3)	11 (2.4)	14 (2.5)	6 (3.2)
Polyethylene	74	11 (2.7)	N/A	8 (3.3)	10 (3.2)	11 (2.6)
Nanoplastics	73	12 (2.7)	N/A	17 (1.9)	17 (1.8)	6 (3.2)
Freshwater	70	13 (2.6)	N/A	17 (1.9)	11 (2.7)	10 (2.7)
Adsorption	67	14 (2.5)	40 (1.3)	122 (0.48)	22 (1.5)	8 (3.1)
Fish	61	15 (2.2)	12 (2.5)	27 (1.4)	15 (2.3)	15 (2.3)
Oxidative stress	53	16 (2.0)	N/A	N/A	60 (0.84)	11 (2.6)
Sorption	52	17 (1.9)	40 (1.3)	17 (1.9)	19 (1.7)	18 (2.0)
Marine pollution	51	18 (1.9)	12 (2.5)	11 (2.4)	11 (2.7)	22 (1.5)
Plastic debris	48	19 (1.8)	40 (1.3)	11 (2.4)	11 (2.7)	25 (1.4)
Surface water	47	20 (1.7)	N/A	122 (0.48)	40 (1.0)	16 (2.2)

TP total number of articles, N/A not available

was the most commonly employed author keyword in 2013–2020 (in 139 articles; 5.1%), followed by pollution (129; 4.8%), marine debris (110; 4.1%), and sediment (109; 4.0%). Based on the results of keywords, it can be deduced that microplastics gain great attention due to environmental problems. The potential pollution from microplastics becomes the key concern. Reports on microplastics date back to the 1970s, and less attention was received until the beginning of the twenty-first century (Shim et al. 2018). Motivated by the report of Thompson et al. (2004), renewed interest over the last decade has made microplastics an emerging research area with an emphasis on environmental pollution. Numerous studies have been reported on microplastics in marine environment, and this is in agreement with the keywords of marine debris. Three keywords "marine debris", "marine litter", and "marine pollution" suggest that great attention is paid to microplastics in the marine environment and the potential environmental pollution. The sources, fate, and potential impacts of microplastics are extensively investigated in marine environments (Auta et al. 2017). Subsequently, researchers expanded the focus to freshwater and terrestrial environments since an estimated 80% of microplastics in the marine environment derive from land (Rochman

2018). This meets the top keywords of "sediment," "freshwater," and "surface water." "Freshwater" and "surface water" are used as author keywords since the period of 2015–2016, and the rank of them has increased constantly, especially for "surface water", implying that microplastics in freshwater environment gain increasing attention in the past several years.

With the increasing occurrence and abundance of microplastics, the potential threats to marine life gain more interest. Microplastics are of special concern due to their accessibility to many organisms and their potential for physical and toxicological injury (Habibi et al. 2022). Microplastics are of special concern due to the accessible size to many organisms with potential physical and toxicological injury (Habibi et al. 2022). The keywords "ingestion," "fish," and "oxidative stress" reveal great interest in the consequences of microplastics on aquatic organisms and animals. The emerging keyword "oxidative stress" since 2017 and its elevated rank suggest in-depth research on the potential threat of microplastics. "Nanoplastics" as an emerging keyword since 2015, and nanoplastics receive special interests owing to the nano-specific features, such as larger surface area, more accessible size for organisms, and difficulty in detection (Koelmans et al. 2015). "Adsorption" and "sorption" refer to the interaction of toxic chemicals with microplastics (Wang et al. 2018), and this is a hot topic relating to the toxicity of microplastics in environments.

The keywords "polyethylene" and "polystyrene" are related to the types of microplastics. The existence of different microplastics has been reported in various environments. The major polymer types of microplastics involve (1) polyethylene, (2) polystyrene, (3) polypropylene, (4) polyethylene terephthalate, (5) polyester, (6) polyvinyl chloride, and (7) polyamide. Fig. S1 shows the development of research trends of the eight polymers and microplastics. Polyethylene is the most-frequently-mentioned microplastics followed by polystyrene and polypropylene, and this agrees well with the composition of microplastics in real environment. The number of articles mentioning polyethylene, polystyrene, and polypropylene increased sharply after 2016.

Microplastics in the marine environment are mainly derived from the transport of terrestrial microplastics in the waterbody. Wastewater treat plant is a vital source of microplastics in the waterbody, and atmosphere is also a migration pathway for microplastics (Jiang et al. 2022c). The previous research on the microplastics abundance focused on the natural environments, including marine, freshwater, soil, and atmosphere environments. However, with the microplastics transportation in the food chain, current research about the abundance of microplastics in human blood, feces, and fetuses attracts more attention. The relationship between health and microplastics has been emphasized. The threat of microplastics could be divided into the direct and indirect hazards to ecosystems. In addition to the adsorption of heavy metals, metalloids, and organic pollutants on microplastics surfaces (Wang et al. 2021b), researchers are more interested in the combined toxicity of microplastics and pollutants and the migration of microplastics into organisms. Besides, the focus of research has gradually shifted from microplastic toxicity to aquatic organisms and mice to the effects of microplastics on human health (Prata et al. 2020).

Research on microplastics includes several topics: (1) the occurrence and distribution of microplastics in the marine environment and global regions; (2) the ingestion and potential threat of microplastics to marine life and the ecological environment; (3) the sources and transfer of microplastics from human habits; (4) the interactions between microplastics and other toxic substances for identifying the potential threat of microplastics; and (5) the occurrence and abundance of microplastics in soil, sediments, and the atmosphere. It should be pointed out that the identification of microplastics is highly dependent on the sampling methodology. Research data in the initial stage may be misleading due to inappropriate sampling. With significant advances in sampling technologies, more valuable and comparable data can be reported (Barnes et al. 2009). With better knowledge and an in-depth understanding of the wide existence and penitential threats of microplastics, the control of microplastics discharge and the removal of microplastics from the environment are becoming imperative (Wang et al. 2022; Jiang et al. 2022d).

4 Conclusion

1. A total of 4026 documents of microplastics-related studies were collected; 14 document types were involved, and articles accounting for 84% were used for bibliometric analysis. English was the most widely used language among nine languages.
2. The number of articles increased sharply since 2015, indicating that microplastics received increasing attention in the research field. This can be ascribed to finding a new topic or research interests about microplastics. Web of Science category of environmental sciences was the leading category (69% of 3546 articles). This implies that microplastics become emerging pollutants and gain great attention due to potential environmental threats. Microplastics-related research was published in 566 journals, and the top three most productive journals included *Marine Pollution Bulletin*, *Environmental Pollution*, and *Science of the Total Environment*.
3. Of the 3536 articles on microplastics from 107 different countries, articles from single country accounted for 72%, while the percentage of articles with international collaborations was 28%. China was the most productive country, followed by USA, Germany, UK, and Italy. In additional, single-institution and inter-institutionally collaborative articles were 33% and 67% of these microplastics-related papers. The top 3 institutes were from China, including Chinese Academy of Sciences, University of Chinese Academy of Sciences, and East China Normal University.
4. The most impactful articles in 2020 were discussed. With the increasing occurrence and abundance of microplastics, the potential threats to marine life gain more interest. The major polymer types of microplastics involve polyethylene, polystyrene, polypropylene, polyethylene terephthalate, polyester, polyvinyl chloride, and polyamide. The research focus and perspectives were briefly summarized. This work provides insights into a better understanding of microplastics-related research.

Conflicts of Interest The authors declare no conflict of interest.

Data Availability Statement Data available on request from the authors.

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Characterization and Toxicology of Microplastics in Soils, Water and Air

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Abstract Pollution of air, water, and soil by microplastics is a recent issue of health concern, yet methods for microplactic characterisation are actually limited. Recent reseach shows that microplastics in soil, water, and air all have their own unique sampling, detection, characterization and behavior. Here we review microplastics in soils, waters, drinking water, and air, with focus on microplastic characterization, types of microplastics, sampling methods, extraction methods, environmental implications, toxicology and human exposure.

Keywords Soil · Water · Air · Microplastics · Identification · Extraction · Toxicity and implications

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1 Introduction

Microplastics have a diameter lower than 5 mm. Microplastic pollution has become a global environmental problem, and its accumulation in the environment is increasing, with Sharma et al. (2021) reporting that the worldwide share of microplastics in plastic pollutants will reach 13.2% by 2060. In recent years, scholars have shown that microplastics are abundant in water, soil, and atmospheric environments. Microplastic accumulation has been observed in human embryos (Ragusa et al. 2021; Wang et al. 2021), and there is now widespread interest in microplastic pollution.

Microplastics are self-toxic, and their ingestion by animals has negative effects on growth, intestinal tissues, etc. (Rodriguez-Seijo et al. 2017; Wang et al. 2019a), and a variety of additives often accompanies the manufacturing process of plastics, e.g., antioxidants, pigments, and plasticizers, and their exposure to external factors, e.g., shear, UV irradiation, and weathering, are easily released into the environment (Lambert et al. 2014; Paluselli et al. 2018; Wang et al. 2020b), thus endangering the health of organisms. In addition, microplastics are also loaded toxic, and their smaller particle size and larger surface area lead to their strong adsorption properties, which can easily adsorb various toxic substances in the environment, e.g., polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), and antibiotics, thus indirectly exerting toxic effects on biological processes (Wang et al. 2020a, 2021).

Given microplastics' direct and indirect hazards, searching for an efficient and environmentally friendly degradation method is imminent. There have been many studies on the degradation of microplastics, which are divided into two main categories: biotic and abiotic interventions, including four pathways of biological, photo, chemical and thermal degradation (Lambert et al. 2014). The latest research showed that microorganisms can mineralize microplastics, disrupt their skeletal structure, and depolymerize polymers into oligomers or monomers, where enzyme specificity and temperature are the main factors affecting the biodegradation process (Anjana et al. 2020) and that the combined action of multiple enzymes and microorganisms degrade better compared to a single enzyme or microorganism (Singh and Wahid 2015; Taniguchi et al. 2019).

Numerous studies have shown that microplastics have polluted soils, water (including rivers, lakes and oceans), and air (Chia et al. 2021; Fischer et al. 2016; Mehmood and Peng 2022). The distribution of microplastics is ubiquitous, and its distribution involves all latitudes of the Earth, even the Antarctic and the Arctic. Currently, the emission inventories (Bradney et al. 2019), distribution (Fu et al. 2020), transport (Guo et al. 2020), toxicity (Chen et al. 2020a), accumulation (Xu et al. 2020a), and risk (Ma et al. 2020) of microplastics are of general concern.

The range of problems resulting from inadvertent uptake of microplastics by organisms (including reduced foraging ability, digestive tract blockage, and nutrient loss) is a major severe environmental challenge (Bakir et al. 2012; Graham and Thompson 2009), and it has been shown that microplastics have a wide range of biological effects, with filter-feeding and deposit-feeding invertebrates (Xu et al. 2020b), seabirds (van Franeker 1985), crustaceans (Murray and Cowie 2011) and commercially (Lusher et al. 2013) have been shown to ingest microplastics that will eventually enter humans body through the food chain (Habib et al. 2020), and traces of microplastics have been shown to be present in human feces (Schwabl et al. 2019). Although there are various regulations for marine litter pollution, there are fewer regulations for microplastics. Since 2014, when the Netherlands prohibited the use of microbeads in cosmetics, regulations have been enacted in a number of countries, including Sweden, Australia, New Zealand, Italy, Canada, the United Kingdom, and the United States (OECD 2021).

Understanding the shared and distinct properties of soil, water, and the air is a key barrier to the control, monitoring, and treatment of microplastics. Numerous factors, such as the plastic product's type, content, uses, and persistence, are known to influence microplastics production and their eventual fate in their respective environments. To the best of our knowledge, a unified assessment of microplastics from identification to environmental implications in soil, water, and air has not been reviewed so far. This chapter combined current perspectivess and trends in microplastics contamination, including sampling, characterization, and environmental consequences. A high-level overview of microplastics in the soil, water, and air ecosystems. By integrating and critically analyzing current advances in microplastics research in many environmental components, this chapter provides both specialists and newcomers with broad concepts and suggestions for future investigation.

2 Characterization and Quantification

Methods for the analysis of microplastics in the environment have been reviewed (Huang et al. 2023). Instrumental analysis is required to obtain the physical (shape, size, color) and chemical (polymer type) characteristics of airborne particulate matter. Among these physical characteristics are mainly observed with scanning electron microscopy (SEM), with a stereomicroscope and digital microscopy being the most commonly used (Dris et al. 2016; Liu et al. 2019b), while fluorescence microscopy needs to be combined with optical microscopy to be practical (Abbasi et al. 2019; Dehghani et al. 2017).

There have also been studies using SEM in combination with energy distribution X-ray spectroscopy (EDS) to analyze the surface morphology and composition of particulate matter (Abbasi et al. 2019; Dehghani et al. 2017), but this technique is costly and time-consuming, so it is only suitable for selecting representative particles for reanalysis after preliminary physical characterization. The most commonly used technique for the identification of the chemical composition of particles is Fourier transform infrared micro-spectroscopy (m-FTIR) (Dris et al. 2016, 2017), although Fourier transforms infrared spectroscopy (FTIR) has also been employed to detect the chemical composition of microplastics in water, sediment, and soil.

Still, due to its lower sensitivity compared to m-FTIR, it is not significant for the identification of small-scale microplastics in the air. Therefore, there is no use for it for airborne microplastics identification cases.

In addition, given the advantages of hyperspectral imaging in recent years for identifying microplastics in seawater and soil (simple, fast, no digestion required), the possibility of its application for the identification of particulate matter in the air can be further investigated. The determination of the mass concentration of microplastics polymers in the atmosphere has also been reported recently, where two major polymers, PET and PC, have been quantified by pyrolytic polymerization, and other methods include pyrolytic gas chromatography-mass spectrometry (Pyr-GC-MS) (Fischer and Scholz-Bottcher 2017) and gas desorption chromatography-mass spectrometry (TDSGC-MS) (Dumichen et al. 2015).

2.1 Identification of Microplastics

2.1.1 Visual Identification

Visual identification relies mainly on microscopy for observation, which is a simpler and less expensive method and is more effective in identifying larger microplastics (Hidalgo-Ruz et al. 2012). Visual identification initially identifies microplastics types by shape and color (Crawford and Quinn 2017). Ensuring that the sample is free of organic matter and that the particles are uniform in color and gloss can effectively improve the accuracy of visual identification, which can be combined with magnification and fluorescence microscopy for white particles (Crawford and Quinn 2017; Zhang et al. 2016).

Furthermore, visual identification has a number of drawbacks, primarily because the accuracy of identification mostly depends on the experimenter and the particle size and microscope type can interfere with the researcher's identification process. (Li et al. 2018; Löder and Gerdts 2015). In addition, minor variations in the morphology of different microplastics will increase the difficulty of visual identification, and the error rate of identification will increase significantly as the particle size of microplastics decreases (Crawford and Quinn 2017) . Combined with these effects, the results of visual identification are often highly inaccurate (Löder and Gerdts 2015). Given these visual identification shortcomings, identification can be combined with other analytical methods.

2.1.2 Thermochemical Techniques

The most widely used method is pyrolysis gas chromatography-mass spectrometry (Pyr-GC-MS), which is primarily based on the fact that the pyrolysis chromatogram of each substance has its own characteristics and is identified by comparing it with known polymers to find the same properties. This method uses pyrolysis to detect microplastics' chemical properties (Löder and Gerdts 2015). It is also possible to analyze the chemical composition in polymers qualitatively and quantitatively using characteristic fragments of the pyrolysis spectra that reflect the structure and composition of the substance (Käppler et al. 2018).

Although some studies have used this method to analyze atmospheric microplastics (Fabbri 2001), it has not been widely used. This is mainly because some substances are destructive to the MS detector, and in addition, the method does not reflect the structure of the particles, such as shape and size. With the continuous technical improvements in GC-MS, the method can analyze particles of smaller sizes and estimate the number of particles. Overall, thermochemical techniques are still in the exploratory stage and may become the primary method for microplastics identification in the future (Dumichen et al. 2017).

2.1.3 Fourier Transform Infrared Spectroscopy

Fourier transform infrared spectroscopy (FTIR) can acquire detailed polymer data from the distinctive spectra of particles, which is most frequently used technique in microplastics identification, with two modes, reflection and transmission. The transmission mode can provide high-quality spectra but involves infrared filters, while the reflection mode can quickly analyze samples of specific thickness and opacity and is more appropriate for perceiving microplastics in samples, so the operation mode can be flexibly selected to analyze specific samples according to different needs, advantages, and is commonly used for qualitative analysis and compositional assessment of microplastics (Shim et al. 2017; Silva et al. 2018). However, it is not currently possible to identify smaller plastic particles in the air, and it is difficult to analyze black or opaque plastic particles. In addition, the moisture content in the sample can affect the identification, and samples to be thrown for observation must be thoroughly dried and processed. Currently, the method has been used to identify microplastics in the environment (Cai et al. 2017).

2.1.4 Raman Spectroscopy

Raman spectroscopy is also one of the reliable tools for microplastics identification (Araujo et al. 2018), which is a vibrational spectroscopy method grounded on the inelastic scattering of light, where the excitation light is inelastically scattered and generates Raman shifts due to the vibration of molecules when the excitation light is irradiated onto the sample, resulting in a characteristic Raman spectrum of the substance. It is rapidly gaining popularity among researchers because of its substantial advantages in identifying microplastics, such as high throughput screening, low volume sample testing, non-destructive, and environmental friendliness.

Meanwhile, compared to the FTIR method, Raman method shows better spatial resolution to analyze particles of 10 μm and is also moving towards analyzing smaller particles (2 μm), which is superior in detecting microplastics of smaller sizes (Allen et al. 2019; Araujo et al. 2018). Also, with a wider spectral coverage, better responsiveness to non-polar functional groups, freedom from water molecules, and a narrower spectral band. In contrast, μRaman and μFTIR are applied to the analysis of small particles due to their higher resolution, allowing the analysis of particles as small as 250 nm and 10 μm, respectively (Araujo et al. 2018; Renner et al. 2018).

In practice, the limit of particle size that can be identified by μFTIR is about 20 μm, and a study showed that μFTIR could identify only about 35 particles below 20 μm compared to the μRaman method (Käppler et al. 2016). It is desired to add to the μRaman method a library of polymer-type resources similar to the μFTIR method, which would also undoubtedly reduce the cost of smaller particle analysis (Zhang et al. 2020d). The development of μRaman spectrometers is also an important future research direction.

2.1.5 Quality Control and Quality Assurance

To ensure the reliability of the results of microplastics determination, it is necessary to prevent plastic contamination during all sample collection, pretreatment, and metal analysis. Lab coats, masks and gloves should be worn throughout the experiment (Abbasi et al. 2019; Allen et al. 2019), plastic equipment should be avoided, and if it must be used, it should be washed at least three times with ultrapure water (Dris et al. 2016; Liu et al. 2019b), and all glassware and fiber filters should be thoroughly cleaned and treated at high temperatures (500 °C) during the experimental study (Dris et al. 2016).

The samples used were handled in a clean room with closed doors and windows (Abbasi et al. 2019). During testing, empty containers or containers with ultrapure water were set up as controls, and the procedure was kept consistent with other samples to eliminate interference caused by microplastics input from laboratory air in later analyses (Abbasi et al. 2019; Dehghani et al. 2017). Also, microplastics in laboratory air can be collected according to the method of Allen et al. (2019) to estimate their contamination of the experimental sample assay. Also, repeat sampling is needed to eliminate chance errors.

Dris et al. (2017) calculated the abundance of atmospheric microplastics by three investigators simultaneously with differences of less than 5%. Moreover, Abbasi et al. (2019) investigated dust samples from five neighborhoods on two separate occasions with differences in abundance ranging from 5% to 17%.

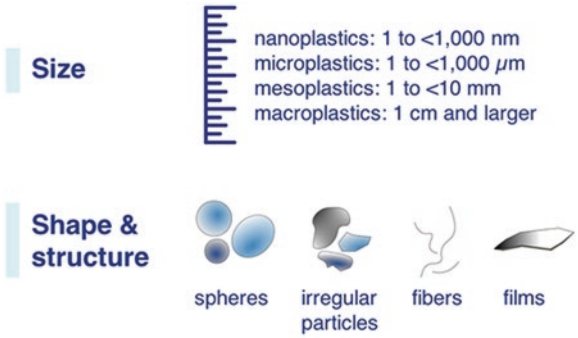

Fig. 1 Various sizes and shapes of dominant microplastics in soil,water and air. (Adapted with permission from Hartmann et al. (2017) copyright American Chemical Society, 2019)

3 Types of Microplastics

Microplastics vary in chemical composition, size, form, specific density, and color. The majority of investigations concentrated on the form and chemical composition of microplastics. Herein the major form of microplastics on the bases of shapes found in soil, water and air are discussed. Figure 1 shows the shapes and sizes of microplastics.

3.1 Microbeads

Microbeads were first found in personal products, whose main purpose was to replace natural chemicals in cosmetics; their particle size is so small that they can even pass directly through water filters and thus into lakes and oceans, and these microbeads can impede the function of the digestive tract of fish when they are accidentally ingested (Kershaw 2015). One study counted that about 94,000 microbeads enter the sewer with the water flow due to personal toiletries containing microbeads, which in turn have a strong adsorption capacity and may adsorb some organic pollutants. The phenomenon of PE adsorption by microbeads was reported by (Napper et al. 2015).

3.2 Fragments

Fragments are the most common form of microplastics, which are mainly formed by the decomposition of larger plastics (polyethylene tableware, disposable products, etc.) (Eriksen et al. 2014). Few studies have been able to precisely describe the process of debris formation, but it is generally influenced by weathering and UV light, with Kalogerakis et al. (2017) reporting that under aerobic conditions, UV light exposure is the most important cause of plastic decomposition, followed by weathering and other processes. Fragments are often mistakenly identified as food and consumed by fish due to their small size and specific morphological characteristics (Lusher et al. 2013), for example, they found that most of the debris present in the digestive tract of fish existed in the form of fragments.

3.3 Nurdles

Nurdles are microplastics in the particulate form that are second only to debris in freshwater (Mason et al. 2020), and they are the basic building blocks of practically every plastic product. Nurdles are made from synthetic polymers such as polystyrene, polypropylene, polyethylene, and polyvinylchloride. They enter the aquatic environment primarily due to erosion during transport and, in turn, coastal and waterfront soils by the action of water waves. Nurdles were identified as a life-threatening product to fish and wildlife by the USEPA in the early 1990s. Nurdles can adsorb toxic contaminants such as PCBs (polychlorinated biphenyls) and DDT (dichloro-diphenyl trichloromethane) due to their soft, less dense, sponge-like texture, which can cause severe damage to fish when consumed.

3.4 Foams

Foams are lightweight microplastics that are widely utilized in containers and packaging materials. Polystyrene is the principal polymer found in foams. These toxic polymers in foam can be released into food when in contact with food for a long time and are more pronounced under high cooking temperatures, thus indirectly threatening human health. In addition, foams, like other types of microplastics, are porous and capable of adsorbing toxic contaminants. It has been shown that foams can adsorb hydrophilic pollutants such as antibiotics and phthalates and transport them over long distances (Atugoda et al. 2021).

4 Microplastics in Soils

4.1 Sampling of Microplastics in Soils

Numerous sampling procedures have been used to endorse the abundance and existence of microplastics in the environment of soil, but still, no regular approach is accessible (Akdogan and Guven 2019). Hurley and Nizzetto (2018) addressed that due to the complexity of the ecosystem of the soil and microplastics characteristics, microplastics removal from the soil is more difficult than in aquatic settings. Liu et al. (2018) collected 20x site soil samples from the study region (vegetable farmlands in Shanghai, China), where an intensive operation was conducted by plastic film mulching. A GPS gadget was used to locate sampling sites, and three samples of soil were obtained in an 0.5 0.5 m^2 area from (0–3 cm) superficial and (3–6 cm) deep layers of the soil.

Following debris removal, the soil samples were kept in Al (aluminum) before being submitted to the research laboratory for further investigation. Another study conducted the sampling process of soil for microplastics in the soil by collecting 24 samples of soil from unoccupied soil areas of shrubs in Wuhan city, also plots of vegetables and woods (Zhou et al. 2019). The mixed soil samples were gathered with a shovel of steel at a 5 cm depth, and each piece was mixed or then separated into 5 subsamples. After eliminating larger than 5 mm debris, samples were collected in Al (aluminum) boxes and then at 4 °C stored for future examination. A sampling of local soils from Shouguang, a City area, their research region, at depths of 0–5 cm, 5–10 cm, and 10–25 cm (Yu et al. 2021). A steel shovel was used to gather samples, and a compound sample was created by uniformly combining 5 obtained samples. Then each compound sample (2 kg) was stored in a box of aluminum, tagged, and for further processing, eventually sent to the laboratory.

4.2 Extraction of Microplastics from Soils

The following methods have been used to extract microplastics from soil: (1) density suspension; (2) air flotation; and (3) heating 3–5 s at 130 °C. Notable problems with these techniques contain: (1) the recovering processes for microplastics are inefficient and slow (ii) difficulties in soil plastic pollution for capturing 3D heterogeneity; (iii) current methodologies are not capable of extracting plastic particles which are nano- as well as pico-plastic in size; and (iv) more or less approaches, such as the heating, are not feasible for larger quantities of soil samples and are incompetent to categorize the quantity as well as. As a result, soil samples from various conditions are not suitable for analysis; (v) the density suspension procedure is a well-known approach for the extraction of microplastics; however, its suitability for the soil has to be determined (Qi et al. 2020).

Several scientific procedures in the literature have been used to extract microplastics from the soil. Liu et al. used a separation density technique using the solution of NaCl (= 1.19 g cm^{-3}) to recover microplastics (Liu et al. 2018). The density separation process was monitored by the addition of (30%) H_2O_2, and after full chemical breakdown (for 72 h at 50 °C), the digestate solution was filtered (using 20-mm nylon net filters). The microplastics were isolated at room temperature, dried, and kept for later investigation. On the other hand, it was expected that the technology would be unable to separate a variety of higher-density polymers such as PVC and PET (Masura et al. 2015). Zhou et al. employed the same density separation process with minor modifications to extract microplastics from soil samples (Zhou et al. 2019).

For the reason that the density of numerous synthetic polymers, such as (PBT, = 1.34–1.39 g cm^{-3}) polyethylene terephthalate, (PLA, = 1.21–1.43 g cm^{-3}) polylactic acid, and (PVC, = 1.38 g cm^{-3}) polyvinyl chloride recorded to be higher than the saturated solution of NaCl, a second density separation step using ZnCl2 (= 1.55 g cm^{-3}) was added. However, it was expected that the technology would be unable to separate a variety of higher-density polymers such as PET and PVC. Zhou et al. extracted microplastics from soil samples using the same density separation approach (Zhou et al. 2019). For low-density polymers such as polyethylene (PE) and polypropylene (PP), several researchers developed an easy and cost-effective extraction procedure using distilled water for microplastics from the soil instead of ZnCl2 or NaCl solution (Zhang and Liu 2018).

Several extractions and ultrasonic treatments are used in the process, lengthening the time of the floatation phase and using brine (NaCl solutions) for extraction. The technique can remove around seven different forms of plastic leftovers from the soil. According to certain study studies, ($CaCl_2$) calcium chloride solution might be employed for extraction since it has higher effectiveness than solutions of NaCl. The difficulty limiting its use is the Ca2+ (divalent) which can assemble the organic material, ultimately disturbing the experimental method (Scheurer and Bigalke 2018). Former authors published oil extraction techniques utilizing microplastics oleophilic characteristics from sediments for the microplastics extraction. For the recovery of microplastics, the protocol proved to be efficient more than 90% (Crichton et al. 2017). A detailed discription of soil microplastics sampling, extraction and identification is given in Fig. 2.

4.3 Environmental Implications of Microplastics in Soils

Appropriate moisture and temperature condition under microplastics can stimulate root exudation of plants, hence encouraging root development (Wang et al. 2016a, b). On a larger scale, however, microplastics restrict the penetration of irrigation water and precipitation into the soil, reducing the soil's ability to produce anoxia and water-holding capacity (Liu et al. 2014a, b). These contaminants also limit evaporation, which can increase the moisture content of the soil (Qin et al. 2015). According to some authors, microplastics limit aeration (the entry of oxygen-rich air into the soil) and water permeability (porousness) (Jiang et al. 2017; Zhang and Liu 2018). According to study, microplastics may eventually modify the physical characteristics of soil and structure by increasing the fraction of water aggregates stable (Siwer et al. 2015). According to research, microplastics change the water permeability and retention of sandy soil, hence disrupting that kind of soil (Souza Machado et al. 2018).

Several investigations have found that microplastics act as carriers of dangerous chemical contaminants in the soil matrix (Jiang et al. 2017; Zhang and Liu 2018).

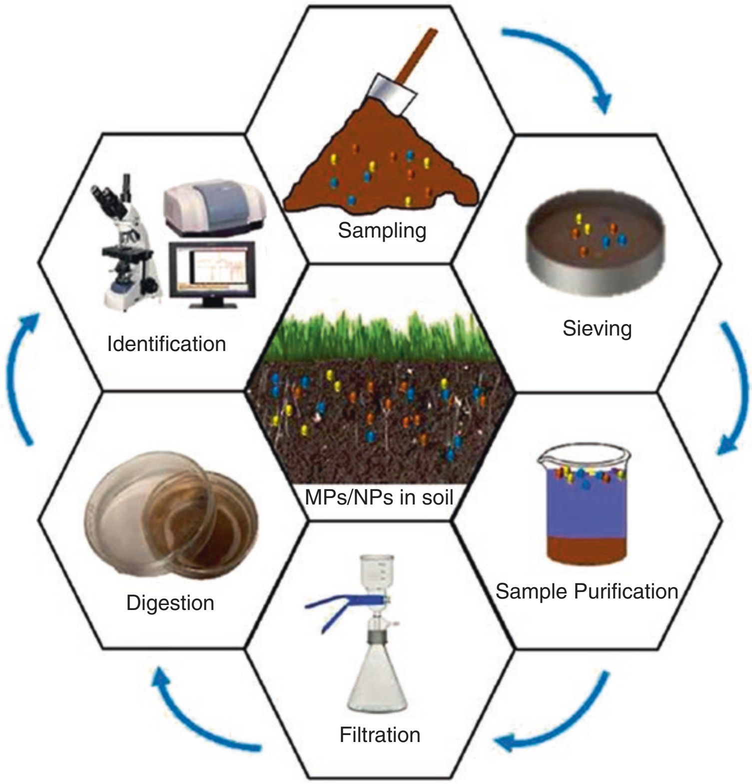

Fig. 2 Extraction of microplastics from soil. (Reproduced with permission (Junhao et al. 2021), copyright Elsevier, 2021). *MP* microplastic, *NP* nanoplastic

MP reservoirs include agricultural and urban soils. Plastic mulching remnants are transformed into microplastics by time and environmental rules. Microplastics diffuse through the soil and interact with heavy metals, herbicides, and persistent organic pollutants, harming soil flora and wildlife. Agricultural runoff can transport microplastics to rivers, oceans, and other bodies of water, causing lake and sea pollution (Mehmood and Peng 2022; Sighicelli et al. 2018). Figure 3 shows how microplastics contaminate the soil.

According to Kirstein et al. (2016), clay soil, in contrast to sandy soil, may be impacted differently; it cracks and shrinks during evaporation. Cracks are intimately related to the transfer of solutes and water in the soil. Previous research has described processes of cracking of soil desiccation (Suits et al. 2009; Wells and Hancock 2014).

As microplastics contaminate soil, its physical characteristics, such as pore structure, bulk density, and water storage capacity, change (de Souza Machado et al. 2018). Microplastics influenced soil water evaporation, cracking, and shrinkage (Wan et al. 2019). Enhanced water loss from the soil top may encourage pollutant leaching into deep soil layers. Microplastics are known to accumulate in the environment and pose a significant global danger to ecosystems (Jang et al. 2020).

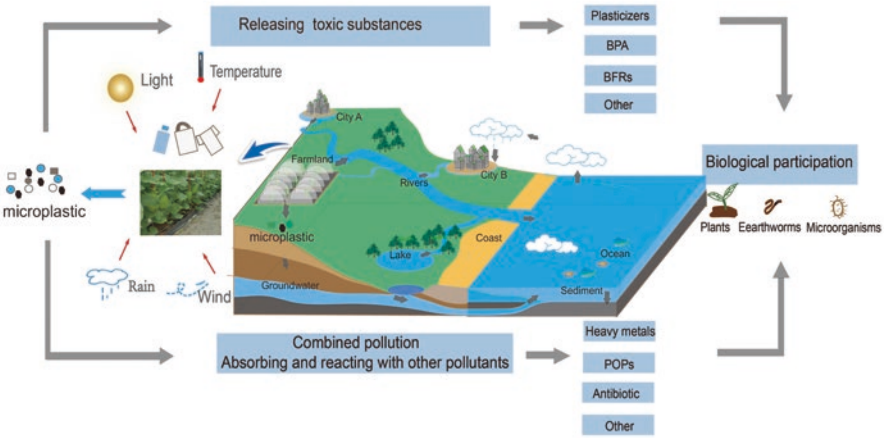

Fig. 3 Microplastic contamination and implications. (Reproduced with permission from (Sajjad et al. 2022). Copyright 2022, Elsevier)

An earlier study on this subject demonstrated that microplastics could change the physical properties of soil, such as the aggregate structure and the number of pores, changing the soil's enzymatic activity (Zhang and Liu 2018). Moreover, high-density polyethylene (HDPE) and polypropylene (PP) microplastics had a considerable impact on bacterial diversity of soil (Cheng et al. 2021).

They revealed that these microplastics were responsible for altering a bacterial community's structure to reduce the bacterial population. In other investigations by Liu et al. (2017), microplastics have also been found to have a detrimental effect on the microbial activity of the soil, organic carbon (C), nutrient transfer, and nitrogen (N) cycling. By providing a medium, microplastics, on the other hand, can increase the likelihood of earthworms and raise zinc bioavailability coming into touch with zinc; nevertheless, nothing is known regarding the potential hazard to earthworms (Hodson et al. 2017).

Microplastics contamination in the terrestrial ecosystem has received less attention than research on the negative impacts of microplastics on the maritime environment. Microplastic concentrations in soil are rapidly increasing and are extensively scattered over the world (Fig. 4). According to Kim and Lee (2020), Korea had the greatest yearly plastic use in the world in 2016.

5 Microplastics in Water

5.1 Sampling of Microplastics in Water

Microplastics' distribution in the water column depends on their density, size, shape, biofouling, chemical absorption, and metrological factors such as waves, currents and wind. Moreover, microplastics amount and property depend on

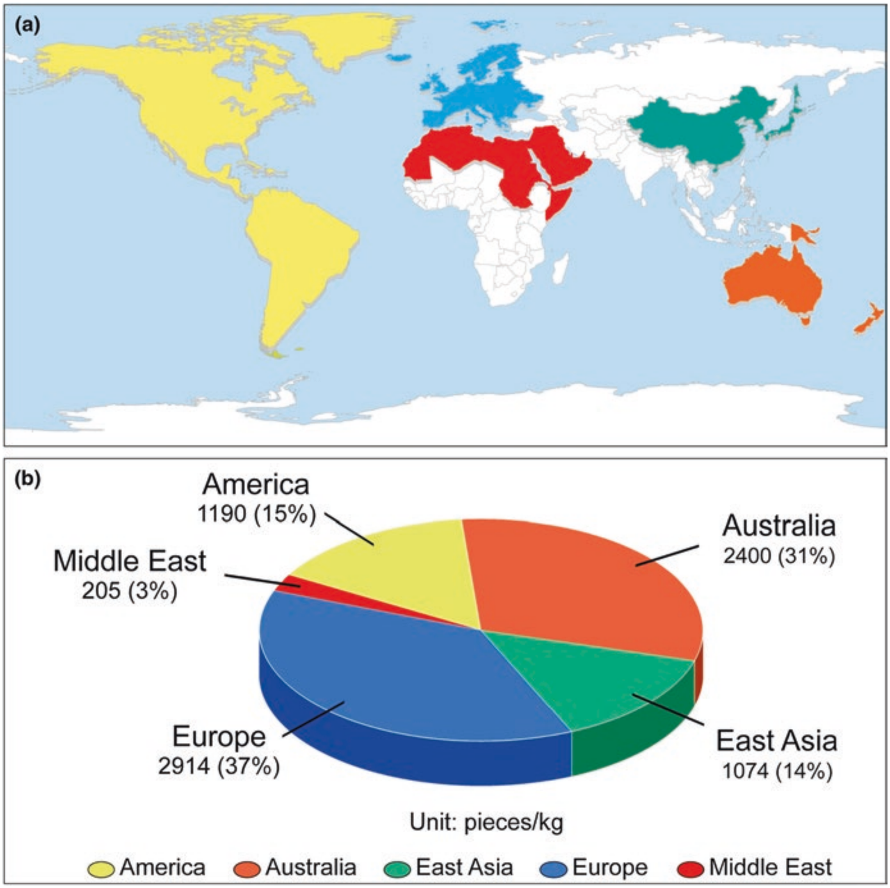

Fig. 4 Average global soil microplastics, (**a**) geographical distribution of soil microplastic concentrations and (**b**) global percentage. (Adapted from (Büks and Kaupenjohann 2020))

sampling depth and location. Both fresh and saltwater sampling and handling procedures are identical, allowing future standardization. The major steps in sampling and extraction of microplastics from water is depicted in Fig. 5. Spreading of microplastics in every system is affected by hydrodynamic profiles and density. Salt and freshwater densities of 1.03 g/cm^3 and 1.00 g/cm^3 can lead to different microplastics distributions in each system and usually, microplastics accumulate deeper in freshwater systems. Representativeness may require enormous sampling volumes of water, often with pumps, sieves, or nets.

Bongo nets collect water column samples in pairs, while plankton nets are frequently dragged or towed slowly because to their small mesh size (100 mm). These nets can be towed horizontally or hauled vertically or obliquely. All nets should have a flow meter attached to estimate sampled water volume and express the results in m^3 units. Alternatives to nets include water pumps from deck pumps, coastal

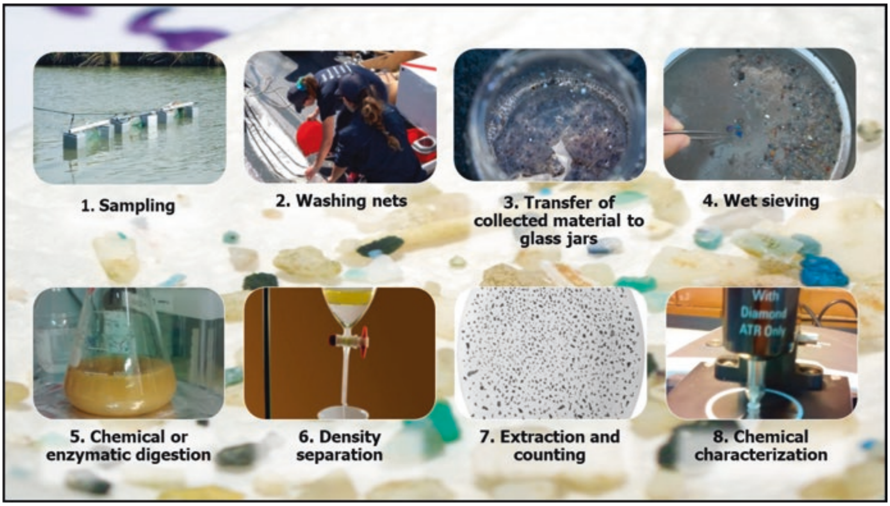

Fig. 5 Sampling and extraction of microplastics from water. (Reproduces from (Campanale et al. 2020). Copyright MDPI, 2022)

areas, or vessel intakes. Mesh size affects reported values, for example, a 100-mm nylon net revealed approximately 100 times higher concentrations than a 333-mm manta net (Vermaire et al. 2017). Manta nets offer large-volume water sampling and are widely utilized, standardizing processes. Plankton nets' smaller mesh diameters (100 mm) allow sampling in under a minute and 30 fold higher values than manta nets (Dris et al. 2015). Plankton nets can clog with suspended organic or mineral particles, reducing the volume of collected water.

Moreover, 80 mm mesh filters 250 times more fibers than 330 mm (Dris et al. 2018). On-shore bucket filtering or sifting is a viable method but is considered a time-spending approach. Labs can process the collected water samples from glass bottles. In a recent study, authors collected surface water having volumes of 100 mL and stated considerable variability (Dubaish and Liebezeit 2013). Representativeness may necessitate collecting more water. Pre-treatment using decreasing-size steel meshes can reduce sample size in the lab (Ziajahromi et al. 2017). Pumping systems and nylon nets may contain microplastics, whereas metallic sieves and glass bottles are considered safe. Plastic-free materials normally process restricted water volumes. Thus, choosing between avoiding contamination and representativeness may be challenging task. Specifying a minimal sample volume to attain representativeness could ease decision-making and sampling.

Generally, in 20 water sample experiments, nets (11), pumps (5), and sieves (3) were most commonly used. One study collected water samples using bottles and buckets. Only 8 studies reported sampling volume (10–2000 L). The information about volume and nets must be provided because it determines outcomes representativeness. NOAA suggests manta nets having 0.3 mm sieving and filtering (Masura et al. 2015).

5.2 Extraction of Microplastics from Water

Usually samples are taken from lakes and calm waterbodies; however, Shruti et al. studied microplastics in stormwater (Shruti et al. 2021), and optimal sampling depth is still unknown (Hamm et al. 2018; Lattin et al. 2004). First, marine remains are gathered using Bongo or Manta trawls (Rist et al. 2020), filtering pumps (Lusher et al. 2014), or epibenthic sled (Barnes et al. 2010). Some of the pre-handling can be accomplished on-site, but a comprehensive evaluation must be completed in a lab (Karlsson et al. 2020).

Microplastics are developing automatic collection and analysis methods, and such devices can quickly evaluate probes in situ. "Albatross" was constructed to minimize specimen gathering time up to 3 minutes or less (Abeynayaka et al. 2020). The MantaRay gadget incorporates a water pump with a separate sensor for microplastics value estimate (Edson and Patterson 2015). The PLEX (PLastic EXplorer) is a self-priming pump for a bulk sampling water and microplastics filtering (Zobkov et al. 2019).

Microplastics demand precise sampling and lab organization regulations to avoid plastic contamination during sample processing and also avoid wearing synthetic garments and clean plastic instruments via ultrasonic cleaners. Yu et al. (2019) recommend cotton fabric, masks, and nitrile gloves for lab workers. Glassware should be soaked in 10% nitric-acid and air-drying may be done after ultrapure water and 70% ethanol cleaning. The NOAA Marine Debris Program created the most widely used approach for removing microplastics (Masura et al. 2015).

The NOAA process involves sieving, digesting organic matter (without harming microplastics), filtration, and density separation (Masura et al. 2015). Sieving (also termed as filtration) is the most frequent way to remove solids from water probes. Filter pores or mesh size defines microplastics size, but organic mineral debris can clog smaller pores faster (Prata et al. 2019a). Filtered samples need additional refining to remove organic and inorganic impurities, neat microplastics' organic surfaces, and release microplastics stuck in the filter's pores. Therefore, filtration and purification of microplastics is recommended and considered an inexpensive method (Loder et al. 2017).

Density separation can eliminate inorganic impurities from the probe. This approach doesn't help separate biological stuff due to density similarities with PET and Nylon (Blasing and Amelung 2018). Wet chemistry requires an oxidizing agent to remove organic materials. Strong acidic or alkaline chemicals can damage delicate synthetic polymers. Centrifugation and microwave digestion can distort, break down, or decompose microplastics (Dyachenko et al. 2017). Wet peroxide oxidation (WPO) digests organic materials well. Fenton's reagent is a combination of Fe^{2+} and H_2O_2 and is used for the rapid isolation of microplastics (Tagg et al. 2017). The NOAA method uses 30% H_2O_2 and 75 °C sample solution temperature. Ferrous ions catalyze the breakdown of H_2O_2 and the production of radicals, which play a role as powerful oxidation agents (Rodrigues et al. 2018).

Peroxide oxidizes plastics, whereas organic stuff degrades at 75 °C (Masura et al. 2015). WPO is a popular oxidative treatment because it can decompose grease, cellulose, and chitin. It's also good for creatures with chitin exoskeletons and fat-rich organs (Zhu and Wang 2020). Other oxidizing agents besides Fenton's reagent include NaOCl, H_2O_2, KOH, and sodium dodecyl sulfate (Nguyen et al. 2019; Poulain et al. 2018). Aggressive oxidizing chemicals can eliminate organic materials more quickly and effectively, but they risk degrading microplastics.

Enzymatic purification may remove shells, grass, or leaves from microplastics detritus. Mani et al. (2015) treated the samples with numerous incubation phases with different agents: (1) for 12 h sodium dodecyl sulfate at 70 °C, (2) for 3 days 0.5% *Lipase* and *Protease* or *Amylase* at 37 °C, (3) for 24 h 30% H_2O_2 at 37 °C, (4) for 5 days 10% chitinase in phosphate buffer (having 5.6 pH), and (5) for 24 h 10% cellulase at 50 °C. The density separation method is based on plastic particles' flexibility in high-density solutions (Thomas et al. 2020). Common polymers have densities between 0.8 and 1.7 g/cm^3. Expanded PS is 0.05 g/cm^3, polytetrafluoroethylene/Teflon is 2.1–2.3 g/cm^3 (Chubarenko et al. 2016), and sand's density is 2.65 g/cm^3 (Zobkov and Esiukova 2018). Density separation uses seawater, tap water or freshwater, sodium chloride solution, zinc chloride, lithium metatungstate, sodium polytungstate (SPT), and sodium iodide (NaI).

A saturated NaCl solution can separate plastics having a density below 1.2 g/cm^3. While PET and PVC have a density of 1.32–1.41 g/cm^3 and 1.14–1.56 g/cm^3 are inappropriate (Claessens et al. 2013). Large-volume NaI or SPT treatment is too expensive, but fresh water can gather floating plastic foams (Tagg et al. 2015). A dedicated instrument like Munich plastic sediment separators can improve the technique (Imhof et al. 2012) (Table 1).

5.3 *Microplastics in Drinking Water*

Table 2 lists 10 studies on microplastics in drinking water, where microplastics larger than 50 μm could be removed during water treatment, with removal rates ranging from 25% to 90% due to differences in water treatment methods. No microplastics were detected in tap water in Italy and Denmark, and the highest concentration of microplastics in tap water was 9.2 items-L^{-1} in the U.S. The maximum concentration of microplastics in bottled water was 5.4107 items-L^{-1}, compared to water in reusable bottles, which contained substantially more microplastics than water in single-use bottles. In comparison, water in reusable bottles contains more microplastics than water in single-use bottles (Table 3).

A direct comparison of microplastics abundance in different studies is difficult due to differences in the type of filter membrane and microplastics identification methods in the water treatment process. It is generally believed that contaminated surface water and groundwater are the main sources of microplastics in drinking water, but Koelmans et al. (2019) found that the abundance of microplastics in some water bodies was lower than that of tap water and bottled water, with the lowest

Table 1 Microplastics in soils

Area	Soil use	Soil depth (cm)	Concentration (microplastics particles/kg)	Source	References
Shanghai, China	Paddy rice cultivation	0–10	10.3 ± 2.2	Irrigation	Lv et al. (2019)
Cienaga Grande de Santa Marta, Colombia	Urbanization (mangrove forest)	0–5	2863	Littering (either voluntarily or not)	Garcés-Ordóñez et al. (2019)
Hangzhou Bay, east, China	Crop cultivation	0–10	571	Plastic mulching	Zhou et al. (2020)
Spain	Agriculture field	0–30	5190	Sewage sludge	van den Berg et al. (2020)
Lahore, Pakistan	Urbanization (parks)	0–10	6250 ± 3776	Littering in park	Rafique et al. (2020)
Gold Coast, Australia	Urbanization	0–5	320 ± 42	Abrasion from tires	Ziajahromi et al. (2020)
Ontario, Canada	Industrial waste managemen	0–15	1.4 × 104	Waste dumping (biosolids)	Crossman et al. (2020)
Ghana	Mangrove forest	0–30	467	Littering (runoff)	Chico-Ortiz et al. (2020)
Hokuriku, Japan	Paddy rice	0–15	48 ± 26	Coated fertilizer	Katsumi et al. (2021)
Yangtze, China	Urbanization	0–15	3748 ± 2301	Littering	Zhou et al. (2021)
Oaxaca, Mexico	Natural forest	0–20	1.49–1.53	Atmospheric disposal	Álvarez-Lopeztello et al. (2021)
Hokuriku, Japan	Paddy rice	0–15	48 ± 26	Coated fertilizer	Katsumi et al. (2021)
Chile	Cropland	0–25	306 ± 360	Unidentified origin	Corradini et al. (2021)
Yongin	Paddy rice	0–5	160 ± 93	Irrigation	Kim et al. (2021)
Yongin	Vegetable cultivation	0–5	81 ± 77	Plastic mulching	Kim et al. (2021)
Yeoju	Urbanization (traffic)	0–5	1108	Roadside (traffic)	Choi et al. (2021)
Yongin	Cropland (vegetables)	0–5	1880 ± 1563	Greenhouse	Kim et al. (2021)
Yeoju	Agriculture soil	0–5	664	Orchard	Choi et al. (2021)

abundance of microplastics in groundwater (1×10^{-2} items-L^{-1}), which shows that the source of microplastics in drinking water is also influenced by other factors, such as the supply process of tap water or the packaging process. Another research identified bottle components as a possible major cause of microplastics generation

Table 2 Microplastics in water

Medium	Type	Country	Size (μm)	Abundances (item/L)	Pore size (μm)	References
Tap water		Cuba	100–5000	7.2	2.5	Kosuth et al. (2018)
		Denmark	–	0	0.2	Strand et al. (2018)
		Ecuador	100–5000	4.0	2.5	Kosuth et al. (2018)
		Germany	100–5000	0.9	2.5	Kosuth et al. (2018)
		India	100–5000	6.2	2.5	Kosuth et al. (2018)
		Indonesia	100–5000	3.2	2.5	Kosuth et al. (2018)
		Ireland	100–5000	1.8	2.5	Kosuth et al. (2018)
		Italy	100–5000	0	2.5	Kosuth et al. (2018)
		Lebanon	100–5000	6.6	2.5	Kosuth et al. (2018)
		Slovakia	100–5000	3.8	2.5	Kosuth et al. (2018)
		Switzerland	100–5000	2.7	2.5	Kosuth et al. (2018)
		U.K.	100–5000	7.7	2.5	Kosuth et al. (2018)
		U.S.A.	100–5000	9.2	2.5	Kosuth et al. (2018)
		Uganda	100–5000	3.9	2.5	Kosuth et al. (2018)
Treatment plants	Raw	China	1–100	6.7×10^3	0.2	Wang et al. (2020c)
	Drinking		1–100	9.3×10^2	0.2	Wang et al. (2020c)
	Raw	Czech	1–10	$1.5–3.6 \times 10^3$	0.2	Pivokonsky et al. (2018)
	Drinking		1–10	$3.4–6.3 \times 10^2$	0.2	Pivokonsky et al. (2018)
	Raw	Germany	50–150	$0–7 \times 10^{-3}$	3.0	Mintenig et al. (2019)
	Drinking		50–150	7×10^{-4}	3.0	Mintenig et al. (2019)

(continued)

Table 2 (continued)

Medium	Type	Country	Size (μm)	Abundances (item/L)	Pore size (μm)	References
Bottle water		Brazil	6.5–5000	$0.1–1.5 \times 10^2$	1.5	Mason et al. (2018)
		China	6.5–5000	$0.7–1.6 \times 10^2$	1.5	Mason et al. (2018)
	PET bottle	Germany	0–5	2.6×10^3	0.4	Ossmann et al. (2018)
	Reusable PET bottle		0–5	4.9×10^3	0.4	Ossmann et al. (2018)
	Glass bottle		0–10	6.3×10^3	0.4	Ossmann et al. (2018)
	Beverage Carton	Germany	5–100	11	3.0	Schymanski et al. (2018)
	Glass bottle		5–100	50	3.0	Schymanski et al. (2018)
	Returnable plastic bottle		5–100	118	3.0	Schymanski et al. (2018)
	Single-use plastic bottle		5–100	14	3.0	Schymanski et al. (2018)
		India	6.5–5000	0–39	1.5	Mason et al. (2018)
		Indonesia	6.5–5000	$0.4–7.1 \times 10^2$	1.5	Mason et al. (2018)
		Italy	0–10	5.4×10^7	–	Zuccarello et al. (2019)
		Kenya	6.5–5000	74.6	1.5	Mason et al. (2018)
		Lebanon	6.5–5000	49.3	1.5	Mason et al. (2018)
		Mexico	6.5–5000	$0.2–6.9 \times 10^2$	1.5	Mason et al. (2018)
		Thailand	6.5–5000	4.7×10^2	1.5	Mason et al. (2018)
		U.S.A.	6.5–5000	$58–1.4 \times 10^3$	1.5	Mason et al. (2018)

based on the chemical type of microplastics in bottled water (polyethylene terephthalate and polyester) (Schymanski et al. 2018).

High levels of microplastics were also detected in water packaged in glass bottles. This may be because the plastic bottle top causes the glass bottle to deteriorate. Therefore, we believe the packaging process is a major reason bottled water contains so many microplastics. Comparing samples showed that microplastics' concentration varied by up to 11 orders of magnitude (Table 2). During the water treatment process, a change in the pore size of the filter membrane may be one of

Table 3 Microplastics in the air

Sampling method	Location	Points/ Unit	Sample type	Size (μm)	Abundance	Pore size (μm)	References
Air sampler (item/m^3)	Aarhus, Denmark	Point 1	Indoor	11–105	14.0 ± 2.2	0.8	Vianello et al. (2019)
	Aarhus, Denmark	Point 2	Indoor	11–105	10.6 ± 5.9	0.8	Vianello et al. (2019)
	Aarhus, Denmark	Point 3	Indoor	11–105	3.4 ± 2.6	0.8	Vianello et al. (2019)
	Asaluyeh, Iran		Outdoor	2–100	1 (0.3–1.1)	2	Abbasi et al. (2019)
	Beijing, China		Outdoor	5–200	5.7×10^3	0.8	Li et al. (2020)
	East Indian Ocean		Outdoor	59–2252	$4–6 \times 10^{-3}$	1.6	Wang et al. (2020a)
	Paris, France	Point 1	Indoor	0–3250	0.8–6.0	1.6	Dris et al. (2017)
	Paris, France	Point 2	Indoor	0–3250	1.3–19.6	1.6	Dris et al. (2017)
	Paris, France	Point 3	Indoor	0–3250	0.4–5.4	1.6	Dris et al. (2017)
	Paris, France		Outdoor	0–1650	0.01–0.5	1.6	Dris et al. (2017)
	Pearl River Estuary		Outdoor	59–2252	4.2×10^{-2}	1.6	Wang et al. (2020a)
	Sakarya, Turkey		Outdoor	50–500	0.3–12.9	50	Kaya et al. (2018)
	Shanghai, China		Outdoor	12–2191	0.4 (0–2)	1.6	Liu et al. (2019c)
	Shanghai, China		Outdoor	23–9955	1.42 (0–4.18)	1.6	Liu et al. (2019b)
	South China Sea		Outdoor	59–2252	0.8–1.3×10^{-2}	1.6	Wang et al. (2020a)
	Surabaya, Indonesia		Outdoor	0–5000	1.3–1.8×10^4	1.6	Asrin and Dipareza (2019)
	West Pacific Ocean		Outdoor	16.14–2086	0.06 (0–1.4)	1.6	Liu et al. (2019d)

(continued)

Table 3 (continued)

Sampling method	Location	Points/ Unit	Sample type	Size (μm)	Abundance	Pore size (μm)	References
Sweeping operation	12 countries	(PET) mg/g	Indoor dust	–	2.9×10^{-2}–1.1×10^{2}	N/A	Zhang et al. (2020a)
	12 countries	(PC) mg/g	Indoor dust	–	1.1×10^{-4} – 0.8	N/A	Zhang et al. (2020a)
	Arctic Fram Strait	(Arctic snow) item/L	Snow	11–475	0–1.4×10^{4}	N/A	Bergmann et al. (2019)
	Arctic Fram Strait	(European snow) item/L	Snow	11–475	1.9×10^{2}–1.5×10^{5}	N/A	Bergmann et al. (2019)
	Asaluyeh, Iran		Outdoor dust	1000–5000	60 (3.3–67)	2	Abbasi et al. (2019)
	China – 39 cities		Indoor dust	50–2000	27 (PET); 4.6×10^{-3} (PC)	N/A	Liu et al. (2019a)
	China – 39 cities		Outdoor dust	50–2000	2.8 (PET); 2.0×10^{-3} (PC)	N/A	Liu et al. (2019a)
	Forni Glacier	mg/g	Cryoconite	100–5000	7.1×10^{-2}	0.45	Ambrosini et al. (2019)
	Japan	item/m^2	Outdoor dust	100–5000	2.0 ± 1.6	100	Yukioka et al. (2020)
	Nepal	item/m^2	Outdoor dust	100–5000	12.5 ± 10.1	100	Yukioka et al. (2020)
	Tehran, Iran		Outdoor dust	0–5000	2.7–20	2	Dehghani et al. (2017)
	Turkey	item/g	Outdoor dust	50–500	18–29	50	Kaya et al. (2018)
	Vietnam	item/m^2	Outdoor dust	100–5000	19.7 ± 13.7	100	Yukioka et al. (2020)

(continued)

Table 3 (continued)

Sampling method	Location	Points/ Unit	Sample type	Size (μm)	Abundance	Pore size (μm)	References
Wet and dry deposition (item/ day-m^2)	Dongguan, China		Outdoor	0–5000	36	1	Cai et al. (2017)
	Hamburg, Germany		Outdoor	0–5000	2.8×10^2	5–13	Klein and Fischer (2019)
	London, U.K.		Outdoor	0–3000	7.7×10^2	0.2	Wright et al. (2020)
	Paris, France		Outdoor	100–5000	1.2×10^2	1.6	Dris et al. (2015)
	Paris, France		Urban	0–5000	1.1×10^2	1.6	Dris et al. (2016)
	Paris, France		Suburban	0–5000	53	1.6	Dris et al. (2016)
	Paris, France		Indoor	0–5000	0.2–1.1×10^4	1.6	Dris et al. (2017)
	Pyrenees mountains, France		Outdoor	0–750	3.7×10^2	0.45	Allen et al. (2019)
	Yantai, China		outdoor	50–1000	4.0×10^2	5	Qian et al. (2017)

the causes of this phenomenon. Aside from the pore size of the filter membrane, another important factor influencing microplastics abundance detection is the difference in identification procedures, such as the FTIR method commonly used for microplastics detection in tap water, the Raman method commonly used for microplastics detection in bottled water, or other detection techniques, which can lead to varying microplastics abundance detection results.

Moreover, there is a phenomenon in which the concentration of microplastics in tap water is greater than that in bottled water, but the abundance is lower; this is likely owing to the lower detection limit of microplastics detection methods in bottled water. In other words, the widely used FTIR detection method for tap water cannot identify microplastics smaller than 10 m, possibly resulting in an underestimation of microplastics abundance.

5.4 *Environmental Implication of Microplastics in Water*

Previous research has identified the sources of plastic trash and other pollutants in the lagoon, lakes, rivers, and other water bodies. Besides various demodectic and economic activities, such as domestic trash dumping, aquaculture, fishing, river discharge, and trade, microplastics pollution in water (Garcés-Ordóñez et al. 2019; Jiang et al. 2022). This suggests a vicious circle in which the same community that lives in and around the water bodies and is critically dependent on them is also responsible for destroying the natural environment from which they derive a significant percentage of their income (Fig. 6).

Aquatic and terrestrial ecosystems are threatened by microplastics pollution since microplastics are absorbed by aquatic microbiota, e.g. microalgae; and fishes (Galloway et al. 2020). Humans consume a lot of fisheries since it's a high-quality protein source. Microplastic-contaminated fish and other seafood can cause human illnesses (Gündogdu et al. 2022). Microplastics, associated metals, and organic compounds can affect human health by interfering with metabolism. Microplastics polymerization process absorbs metal contaminants. In this way, it can carry organic contaminants and aid bioaccumulation in exposed organisms (Mehmood and Peng 2022).

Microplastics can disrupt the food chain by causing physiological stress in living bodies, altering the balance and health of the ecosystem (Gündogdu et al. 2022). Microplastics combined with harmful metals and organic species can disturb low trophic species, especially micro algae like *Chlorella vulgaris* and *Chlorella pyrenoidosa*. It can slow algae development procedure by boosting oxidative stress and affecting Superoxide dismutase, catalase, etc. (Yu et al. 2022). Due to oxidative

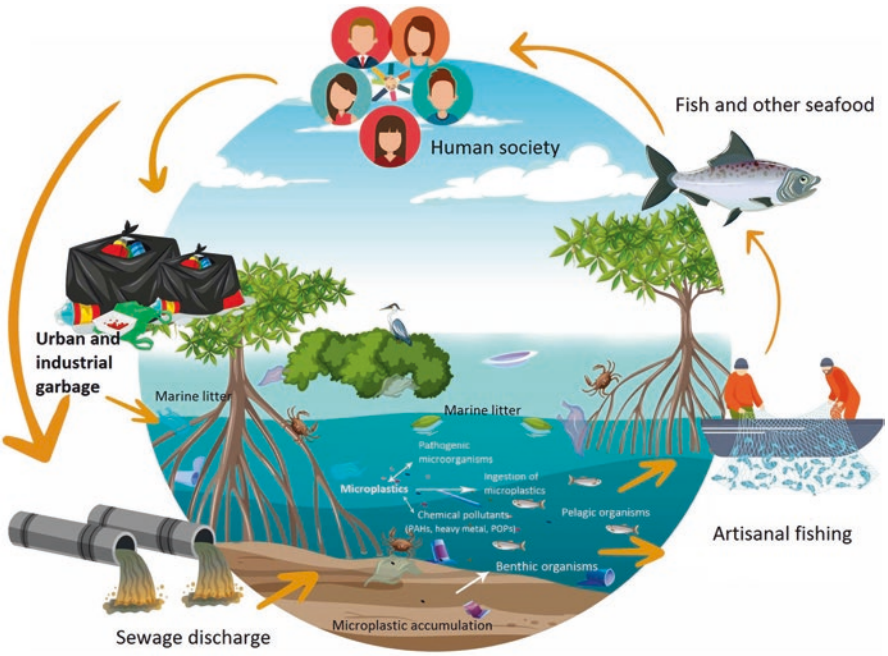

Fig. 6 Sources, transportation and consumers of microplastics pollution in water. (Reproduced with permission from (Garcés-Ordóñez et al. 2022) Copyright 2022, Elsevier)

stress, reactive oxygen species develop and accumulate in algal cells. Increased ROS and stress oxidation drive lipid peroxidation by creating more malondialdehyde (MDA), a peroxidation byproduct. Higher microplastics concentrations and metal-absorbed microplastics affect algae growth and chlorophyll production (Wu et al. 2019; Yu et al. 2022). Fish are also particularly sensitive to microplastics exposure and ingestion.

Microplastics penetrate water bodies globally, and their sources and effects threaten aquatic life by making them fish food (Dai et al. 2018; Wang et al. 2019b). Pathogenic microorganisms, plastic additives, and organic and metal pollutants on bond on microplastics surface can concentrate in exposed fish. Several investigations found microplastics polymers in fish digestive tracts. Because of their dimensions and shape, microscopic microplastics particles are able to penetrate the epidermis, lymphatic systems, and gills of sea species (Calderon et al. 2019). Ingesting microplastics particles can cause fish digestive tract damage and obstruction. It affects fish eating, growth, and nutritional absorption (Jabeen et al. 2018). Microplastics can cause allergic reactions and affect fish's natural immunity (Wen et al. 2018). Microplastics can pass through fish's circulatory system and injure organs, i.e., the liver (Barboza et al. 2018).

The study reveals that microplastics chemical additives, including PAH, PCB, and PBD can be kept in fish intestines and transported between trophic levels. Biofilms adhering to microplastics can cause bacterial infections in fish (Wang et al. 2019b). Microplastics can affect fish's metabolic, oxidative stress, enzyme activity, and reproductive and endocrine systems (Law 2017). Microplastics are more likely to affect young fish (Duran and Beiras 2017). Microplastics can impair fish larval development, motility, head-to-body length, and hatching time. Along with these, microplastics and chemical additives cause cardiovascular irregularities, DNA breakdown, and larval death (Kogel et al. 2020).

6 Microplastics in Air

6.1 Sampling and Analysis of Microplastics in Air

Quantitative analytical methodologies and standardized sampling for atmospheric microplastics are still not authenticated; thus, sampling is crucial (Chen et al. 2020b). Passive atmospheric deposition and active pumping samplers are utilized to sample airborne microplastics. Passive sampling estimates airborne microplastics using gravitational, inertial, or diffusive fallout (Chen et al. 2020b).

Fallout is gathered in a glass funnel and flask, and this technique is suited for rural places without power or long-term continuous sampling. Actively pumped samplers efficiently collect microplastics from outdoor and interior air (Wright et al. 2021). The pump's input flow rate may be changed, and microplastics concentration can be stated in microplastics/m^3 (Torres-Agullo et al. 2021). Cellulose, glass fiber, quartz, silver membranes, and alumina are employed in functional air samplers to collect microplastics (Fig. 7a).

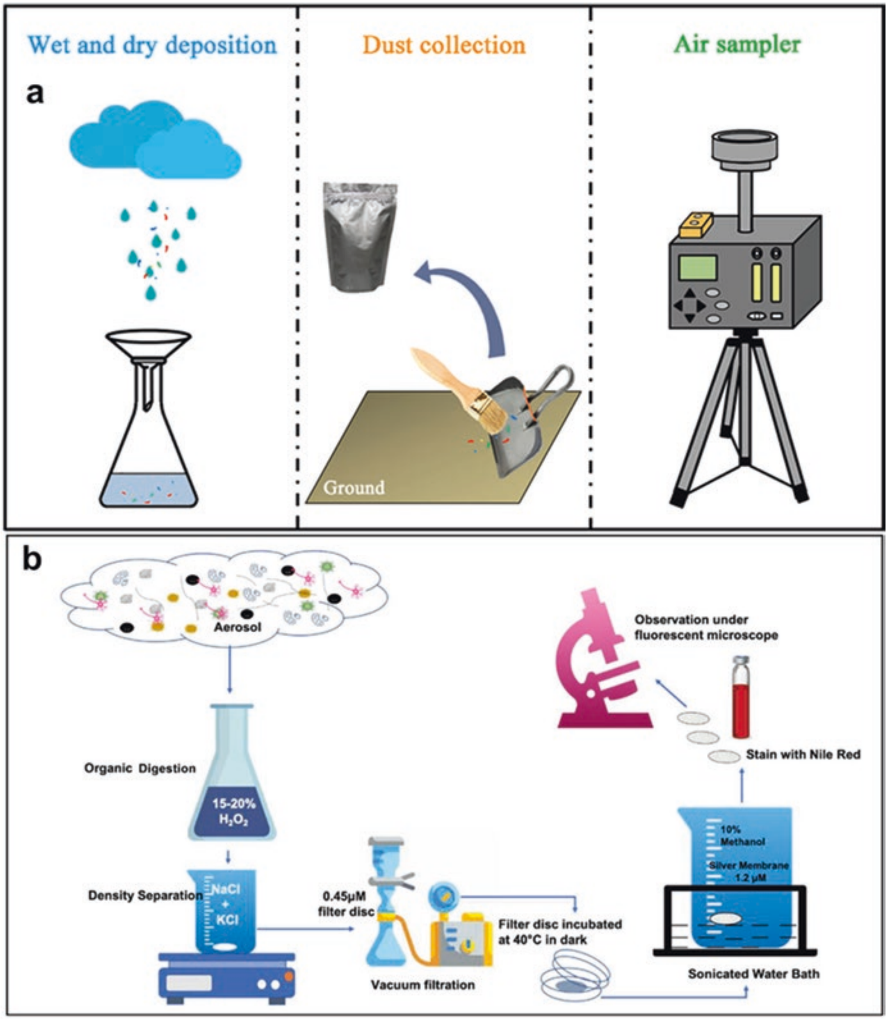

Fig. 7 (**a**) Sampling of microplastics from air. (Reproduced with permission from (Zhang et al. 2020b). Copyright 2020, American Chemical Society), (**b**) extraction of atmospheric microplastics. (Reproduce with permission from (Junhao et al. 2021) Copyright Author(s) 2022)

6.2 Extraction of Microplastics from Air

Several pre-treatment methods are being used; however, there is no standardization (Fig.7b). Visual methods were used to identify microplastics in the past, but only for big fragments. 500 μm microplastics require sample pretreatment because organic matter increases background noise (Zhang et al. 2020d). To eliminate organic waste, samples are handled with 30% H_2O_2 solution or sodium hypochlorite (Chen et al. 2020b). However, a recent study has revealed Fenton's reagents are effective tools for digesting organic matter (Prata et al. 2019b). Most polymers resist H_2O_2, but still lack research concerning chemical cures for worn plastics (Xu et al. 2019). After eliminating biological debris, microplastics should be removed from other particles, and the best method is density separation for this (Chen et al. 2020b). Moreover, ZnCl solutions having a density of 1.6–1.7 g/cm^3 are the most successful approach for separating microplastics particles (Chen et al. 2020b; Dris et al. 2017).

6.3 Environmental Implication of Microplastics in Air

Current research on microplastics has focused on terrestrial and aquatic ecosystems, while less research has been conducted on airborne microplastics (Enyoh et al. 2019). Atmospheric microplastics are a type of atmospheric particulate matter, and many collection methods have been described for atmospheric particulate matter, including direct collection(Zhang et al. 2020c), vacuum cleaner collection (Soltani et al. 2021), wet and dry sampler collection (Finnegan et al. 2022), collection of leaves with particulate matter deposition (Huang et al. 2022), and air filtration (Li et al. 2020) to investigate the concentration of respirable particles and their human health response (Vianello et al. 2019). However, many data are not comparable due to differences in sampling techniques and measurement units (Mehmood and Peng 2022).

Preliminary monitoring of atmospheric microplastics has been performed based on studies of atmospheric particulate matter. The presence of plastics, including debris, fibers, and films, has been observed in different locations. Many studies have shown that there are more types of microplastics in street dust, while fibers are the dominant form type in atmospheric samples. The number of atmospheric microplastics is significantly higher indoors than outdoors (Choi et al. 2022; Fang et al. 2022).

In addition, microplastics have been found in remote areas; authors of a study found the presence of microplastics in atmospheric precipitation samples from the Pyrenees and mostly as small particles smaller than 50 μm (Allen et al. 2019). Microplastics have also been noticed in the air of the Atlantic Ocean, the South China Sea, and the East Indian Ocean, suggesting that microplastics can be transported over long distances in the atmosphere and can contaminate water, soil, and glaciers with dry and wet deposition (Fig. 8).

Currently, the quantification of microplastics of smaller sizes remains challenging due to limitations in sampling and detection techniques (Zhang et al. 2020d). The size of microplastics found in some studies varied between 5 μm and 750 μm in the form of fragments and between 10 μm and 1520 μm in the form of thin films (Szewc et al. 2021). Therefore, improved sampling tools and detection techniques are needed to quantify more minor microplastics (Vethaak and Legler 2021).

Studies have shown atmospheric microplastics deposition in Paris is about 118 pm/m^2/d (Dris et al. 2015), and urban areas in China have microplastics deposition between 175 and 313 pm/m^2/d (Cai et al. 2017). Also, a large amount of

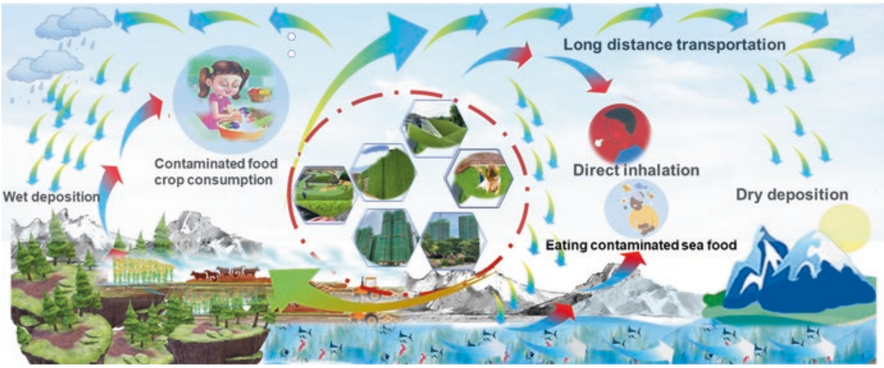

Fig. 8 Atmospheric microplastics pollution, transportation and deposition. (Reproduced with permission from (Mehmood and Peng 2022), Copyright 2022, Elsevier)

microplastics is present in the air at human breathing heights, where indoor concentrations (0.3–20/m^2/d) are more significant than outdoor concentrations (0.1–0.5/m^2/d) (Dris et al. 2017). There are large differences in the atmospheric concentration of microplastics in different regions, which may be closely related to climatic, geographical and human conditions (Mehmood and Peng 2022).

7 Toxicology of Microplastics

Microplastics can enter the human body by drinking contaminated water, eating contaminated food, and inhaling (Fig. 9a). The risk of human inhalation grows as the particle size falls. Studies have shown that microplastics smaller than 2.5 μm are more likely to be deposited in the lungs and may penetrate the respiratory tract to reach the circulatory system. Akhbarizadeh et al. (2021) showed that adults inhaled 32.5 and 161.2 microplastics/day in normal and dusty weather, respectively. Another study explored the distribution and potential health effects of microplastics from Asalouye County, Iran, showing that construction workers and children inhaled 515 and 27 microplastics per day, respectively (Abbasi et al. 2019). Both studies highlight the importance of atmospheric suspended microplastics and their possible impact on human health.

As shown in Fig. 9b, the toxicity due to microplastics exposure is related to oxidative stress and inflammation in the human body. For instance, the response of the body to foreign species and the merging of the granulation tissue are both attributable to microplastic exposure (Ding et al. 2019). As a result, granuloma prone to necrosis is formed which leads to fibrosis and scar tissue (Wright and Kelly 2017). After exposure to polystyrene, there was an increase in IL-8 and IL-6 generation. The synthesis of cytokines is responsible for regulating and driving inflammatory feedback. Oxidative bursts and inflammation were observed in mouse and human

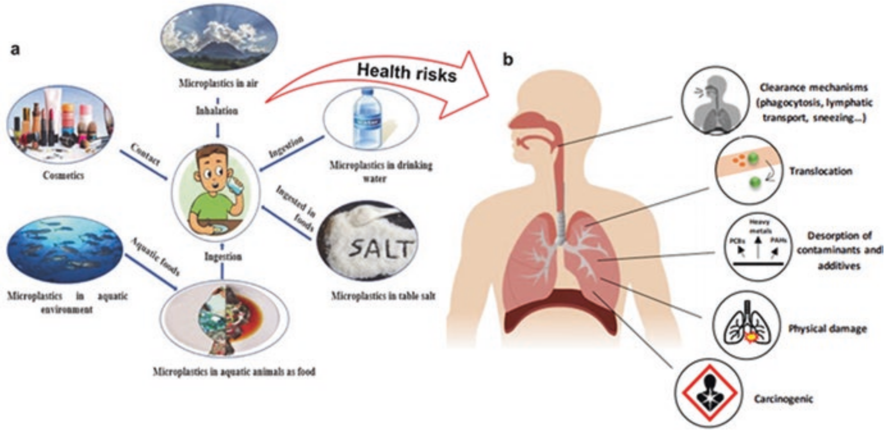

Fig. 9 (**a**) Microplastic exposure routes. (Reproduced from (Usman et al. 2020) Copyright 2020, MDPI), (**b**) risk from exposure to microplastics. (Reproduced with permission from (Torres-Agullo et al. 2021), Copyright 2021, Elsevier)

monocyte and macrophages of several strains(Evereklioglu et al. 2002). Increased cytokine levels can induce macrophages and increase the inflammatory response in exposed tissues (Evereklioglu et al. 2002). Furthermore, microplastics are responsible for surface oxidation caused by weathering, and exposure it induces oxidative stress in cells (Gewert et al. 2015).

The release of absorbed oxidizing substances, like metals, might mitigate oxidative stress (Mehmood and Peng 2022). Mahadevan and Valiyaveettil reposted that in hamster cells exposure of PMMA (polymethyl methacrylate) and BHK-21 PVC microplastics with sizes of 0.14 μm and 0.12 μm cause inflammatory reactions, and oxidative stress can cause cytotoxicity. In consequence, ROS levels increased and increased cell death (Mahadevan and Valiyaveettil 2021). Decreased viability and distinctive morphological modifications were detected in A459 human lung cells after PS microplastics reaction.

In addition, microplastics exposure can cause genetic damage due to stress, monomer leaching, and carcinogenic chemicals (Mueller et al. 2020). Moreover, microplastics can play a role as a transporter of contaminated substances into the body. Studies have shown that the leaching of monomers and microplastics additives contributes to toxicity (Martínez-Gómez et al. 2017). In addition, contaminated chemicals, including heavy metals and residual organic pollutants, can absorb microplastics and be discharged into the body after ingestion (Liao and Yang 2020). microplastics may not only be carcinogenic but also act as an endocrine disruptor in organisms (Sun et al. 2021). Endocrine-disrupting chemicals can also threaten reproductive health and fertility and affects the control of several important functions (D'Angelo and Meccariello 2021).

8 Conclusion

A literature review on microplastics pollution in different environmental components was conducted. We propose to provide a fundamental assessment of microplastics by using international research that conforms to the most recent recommended methodologies for evaluating PMs abundance, sampling, extraction, and effects in the soil, water, and air worldwide. The main conclusions, information gaps, and research recommendations are mentioned below.

1. Standardization is needed for microplastic analysis in soil, water, and air due to a dearth of high-quality studies. Sample handling, polymer identification, laboratory setup, clean air, and positive controls are the areas that need improvement the most. Standardized procedures will facilitate reproducibility and comparability of results and ensure that individual studies are of a higher caliber. It will also help to produce the high-quality data needed for risk assessments. It is crucial to carry out investigations using statistical techniques and tools, including analysis of variance (ANOVA), correlation, and regression, to ascertain whether there is a connection between soil, water, and air microplastics.
2. Automatic microplastics collection and analysis are now possible. Vibrational spectroscopy is necessary to locate microplastics in probes, requiring remote sensing methods. Leading scientific instrument makers to advocate complicated laboratory instruments combining optical microscopy with FTIR or Raman for microplastics analysis. Monitoring and recognizing microplastics will soon be routine, even though pre-treatment norms remain disputed. The eradication strategy used microplastics and a global contamination map. Filtering and separating microplastics is prevalent in water treatment and potable water systems (using membranes, sieves, filters, etc.).
3. Because sampling methods lack uniformity and simplicity, their spatial and geographical prevalence in ecosystems, which is necessary for estimating organism susceptibility, is little understood. All sampling steps have group differences. No consistent net, pore, or mesh size means each investigation samples different-sized microplastics. Inaccurate methodological descriptions, like bulk sample volume, impair predictive ability and reproducibility. A verified, quick, and simple process is warranted. This approach should include: I assessments to decrease cross-contamination; (ii) bulk sampling protocol; (iii) how to detach microplastics from bulk samples feasibly via precise filtration, establishing a filter's pore dimensions, or with a better adaptation to a salt-saturated solution, such as NaI; (iv) a digestion framework that is fast and has limited impact on polymer stability, such as H2O2 or enzymes; and (v) standards for verification using staining colors and suggested chemical analysis techniques.
4. Particles, fibers, films, foam, and pellets are the most common microplastics types in most samples. Research has led to the discovery of several polymers reflective of plastics' density and manufacturing. However, additional research is needed to better understand plastic particles' size, shape, polymer type, and preponderance.

5. Topsoil is typically sampled. It would be fascinating to study microplastics in deeper soil layers. Microplastics in the soil carry heavy metals and microbes. Further studies are required to determine how much microplastics can transport in soil and if this changes by plant type, region, or season. Microplastics from the soil, water, and air entering groundwater or the food chain needs additional research. Nematodes that ate microplastics died. No research has determined how much microplastic can treat soil diseases without entering the food chain.
6. Although research primarily focuses on discrete size classes, the levels of microplastics in various types of water vary considerably; the literature review revealed microplastics in freshwaters and drinking water. Microplastics are also present in groundwater. Recent studies have found that microplastics are pervasive in terrestrial ecosystems and that some of them may seep into deeper soil layers and groundwater. Even though microplastics in groundwater may come from the terrestrial environment, research on them is still important. Improved examination and detection of microplastics in water samples are required.
7. Recent studies reported variable microplastics air concentrations. Standardizing sampling and analytical methodologies for microplastics is urgently needed to compare results and present a full picture of microplastics today. Statistics would be more accurate. Ambient air microplastics are an important but understudied source of human plastic exposure. Because microplastics are more ubiquitous in the environment, future studies should examine the short- and long-term health consequences of inhaling them.
8. Microplastics could get into the food chain and build up natural systems. Since humans are the final consumers, it can harm them in a number of ways. Besides, hydrophobic surfaces can take in heavy metals, colorants, solvents, and plasticizers. Biological systems bond microplastics early due to their size and surface area.
9. Even though biological pre-treatment and photocatalytic methods could be used together, it is still hard to figure out what to do with leftover plastic particles in the environment. The current studies focus on induced degeneration of microplastics, which are (in their native condition) extremely resilient. Likewise, insufficient literature exists on microplastics' biological and chemical disintegration. Due to biological decline, microplastics disintegrate and become less common in the ecosystem; more studies on microplastics control are needed.

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Coral Feeding Behavior on Microplastics

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Abstract Microplastics travel along food chain, bio-accumulates in organisms, and interferes with natural feeding habits of marine organisms, yet effect of microplastics on marine invertebrates such as corals are poorly known. Here we first review microplastics with focus on sources and formation in Thailand. Then we studied the feeding behavior of two species of corals, *Galaxea Fascicularis* and *Dipsastraea specios,* on microplastics in presence of natural prey, *Artemia nauplii. C*orals were fed with polyethylene, polyethylene terephthalate, and polypropylene (PP) microplastics ranging from 500 to 2000 μm for 3 hours. Results show that corals ingested microplastics even at the presence of natural prey, and that corals egest most of the ingested microplastics and thus retain only small percentage.

Keywords Corals feeding · Microplastics · *Galaxea Fascicularis* · *Dipsastraea speciosa* · Gulf of Thailand

1 Introduction

Plastic production rate has increased in the last few decades. The global plastic production which was 270 million tons (Mt) in 2015, escalated to 348 Mt. in 2017, reached 359 Mt. in 2018, and to 367 Mt. in 2020 (Jambeck et al. 2015; Wang et al. 2020). According to the Global Plastic Industry statistics, plastic production is likely to exceed 500 Mt. by 2050 with the current rate of production (Tiseo 2022).

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This had led to 300 million tons of plastic waste generation per year (Vuleta 2020). The problem intensifies as these large plastic wastes breaks down into smaller fragments/particles which are less than 5 mm in size and are called microplastics (Wu et al. 2018). Microplastics also tend to float on ocean surface due to their lower-density and hydrophobicity. They can release their intrinsic toxic chemicals as they break down into smaller particles; residing in the marine environment for decades (Allen et al. 2017). Microplastics are considered even more dangerous as they travel long distances by wind driven ocean circulation.

Recent research have highlighted microplastic ingestion by corals and the associated health impacts with leaching pollutants (Aminot et al. 2020; Chapron et al. 2018; Lamb et al. 2018; Okubo et al. 2018). Coral reefs, comprising only 0.1% of the total ocean area of the Earth are habitat, breeding, and nursery ground of about 25% of the marine organism (Huang et al. 2021; Huang et al. 2019). However, it is often threatened by multiple anthropogenic and environmental problems, such as global temperature changes, ocean acidification, marine pollution, disease outbreak. Microplastic pollution just exacerbates the situation. Given its importance in marine ecosystem, handful research has been carried out in the context of microplastics ingestion in corals. Studies suggest that corals are particularly more susceptible as plastics tend to release phagostimulants which makes them act similar to corals natural prey (Allen et al. 2017). Microplastic consumption by corals leads to reduced feeding habits, leaching of additives in the digestive tracts of corals, and trophic transfer of additives and other pollutants (Allen et al. 2017; Axworthy and Padilla-Gamiño 2019). Hall et al. (2015) also suggested that corals mistake microplastics for prey and can consume up to 50 μg plastic cm^{-2} h^{-1}, which is similar to their consumption of plankton and *Artemia nauplii*.

2 Microplastic Sources and Status

2.1 Sources and Formation of Microplastics

Apart from floating plastic being a major threat, degradation and formation of microplastics in marine environment or even microplastics entering in forms of micro-beads from sewage system are particularly of concern (Dedman 2014). Microplastics are small fragments of plastics, less than 5 mm in diameter and found in variety of sizes and shapes. There are two types of microplastics - primary and secondary. Primary microplastics are commercially manufactured and used mostly for cosmetics, toothpastes, detergents etc. and are discharged from sewage systems to the oceans (Andrady 2011). Secondary microplastics results from degradation of macroplastics and are results of landfill runoff or activities like shipping or fishing (Cheang et al. 2018). Bio-degradation, thermo-degradation, chemical abrasion, oxidation, photo-degradation and hydrolysis are some of the degradation processes via which microplastics are formed in marine environment (Guo and Wang 2019). The mechanism for photo-degradation usually occurs within the oceans. UV-B radiation in the sunlight initiates the breakdown of polymers such as low density polyethylene (LDPE), high density polyethylene (HDPE), polypropylene (PP), and polyamide (PA) (Andrady 2011). This breakdown further initiates thermo-oxidative degradation in presence of oxygen.

Biodegradation is comparably slower than photo-degradation (Andrady 2011). Experiment confirmed that, even after 3 weeks of microbial action on microplastics, zero degradation is noticed, suggesting that biodegradation may be slower than other degradation processes (Lobelle and Cunliffe 2011). Hydrolysis in seawater, like biodegradation, is not considered a substantial mechanism of plastic degradation (Dedman 2014). Further, formation of bio-films alters physiochemical properties of plastic, which makes them more neutrally buoyant and changes their position within the water column (Lobelle and Cunliffe 2011).

2.2 Microplastic Pollution and Research in Southeast Asia

Microplastics have been accumulated in the world ocean for more than five decades (Dedman 2014; Rocha et al. 2020). Asia, leading in mismanaged plastic wastes, still lacks in terms of research and data on microplastic pollution. The greatest level of plastic pollution in the world has been identified in East Asian seas, comprising Association of Southeast Asian Nations (ASEAN) countries (Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Singapore, Thailand and Vietnam) (Curren et al. 2021). Despite such high concentration of microplastic pollution, very limited research has been carried out in ASEAN region. Nevertheless, recently the microplastic pollution in marine ecosystem has been gaining momentum in Southeast Asia. Several researches conducted on the beach and benthic sediments, seawater and marine organisms have confirmed presence of microplastics to alarming levels.

Research conducted in beaches of Malaysia, Philippines, Thailand, Vietnam, and Singapore stated that polypropylene, polystyrene and polyethylene were the most abundant microplastic type (Curren et al. 2021; Curren and Leong 2019; Noik and Tuah 2015; Paler et al. 2019). Conversely, polypropylene fibers dominated in seawater of Indonesia and Malaysia (Khalik et al. 2018; Syakti et al. 2018). Microplastics were also examined in sediments of Singapore, Thailand, Indonesia, and Philippines coasts; almost all types of plastics were identified- polypropylene (PP), polyethylene (PE), polyvinyl chloride (PVC), polyethylene terephthalate (PET), and polystyrene (PS) (Bucol et al. 2020; Firdaus et al. 2020; Wang et al. 2020). Additionally, the amount of microplastics in sediments was much more than the amount on the beach and seawater because of more anthropogenic activities. Studies from Thailand, Indonesia, Vietnam, Philippines also provided evidences of microplastic ingestion in marine organisms (Al Hamra and Patria 2019; Bucol et al. 2020; Sutthacheep et al. 2021). However, there are still gaps in portraying status of microplastic related research in ASEAN countries. Therefore, more research on microplastic and marine invertebrates, particularly on corals, are required.

2.3 Research in Thailand

Thailand currently undergoing rapid economic development with increase in coastal population, and lifestyle alteration, is considered as a hotspot for marine and coastal plastic accumulation (Thushari et al. 2017). Ocean Conservancy report published in 2015 cited Thailand as one of the top five countries responsible for plastic leakage into the ocean (Ocean Conservancy 2015). With 54.82% of Thai citizens living in urban areas, single-use habit of plastics has escalated plastic wastes even more in the country. This practice has contributed to more plastic waste to ocean. Hence, in 2019, Thai government declared to ban the use of three types of plastic, i.e., microbeads, cap seals and oxo-degradable plastics (Royal Thai Embassy, Washington D.C., 2019). This step towards microplastic pollution is remarkable, but still is small compared to the existing problems, as the country's plastic waste alone accounts for 16% of all the garbage in the sea (Sharma et al. 2019). Moreover, Thailand's Roadmap of plastic waste management will also ban the use of plastic bag, foam food container, plastic up and plastic straw in 2022 and move toward 100% of target plastic waste to Circular Economy in 2027.

Given the ubiquitous microplastic pollution in Thailand, number of research on beaches, sediments, benthic community, and marine ecosystem is still scant. However, few studies tried to depict the urgency of taking suitable actions. A study in eastern Gulf of Thailand identified that accumulation of microplastics in beach sand ranged from 420 to >200,000 counts/kg; fibers being most abundant. Such alarming level of microplastics was significantly correlated with population density, urban proximity and anthropogenic activities, such as tourism, aquaculture, fisheries, industries, and recreational activities (Bissen and Chawchai 2020). Apart from beaches, surface sediments have also shown quite a high concentration of microplastic pollution. Microplastics ranged between 150.4 ± 86.2 pieces/kg dry weight in sediments of the Gulf of Thailand, which was a medium level of pollution compared to other areas of the seas (Wang et al. 2020). Such studies pointed out that, fibers were the most common microplastics found, indicating necessity of policies and technologies to filter such pollutant from sewage discharge.

Badon Bay, one of the most important mari-culture areas of Thailand, receives quite a high load of river discharge from Tapi Phumduang River. Green mussels and Asiatic hard clams, the two most commercially abundant bivalve species grown in the bay, were found with high concentration of microplastics (Chinfak et al. 2021). Further, studies conducted at the Chaophraya River mouth in Upper Gulf of Thailand concluded that microplastic particle concentration ranged from 16.74 to 59.06 pieces per 100 m^3 during spring tide and 43.26 to 126.13 pieces per 100 m^3 in neap tide, signifying much higher concentration during neap tide (Sukhsangchan et al. 2020). As the research tries to demonstrate the distribution and abundance of microplastics during tidal cycle in the Gulf of Thailand, it also elucidates that such changes in concentration have impacts on plankton feeders. Therefore, more research is required to support the existing data and to further push policies in reducing microplastic pollution in Gulf of Thailand.

2.4 Microplastic Ingestion by Marine Organisms in Thailand

Regardless of the associated uncertainties, the evidence available at this time suggests that microplastics are wide spread and are prolific contaminants which have a probability to increase in future. Currently microplastics are of great concerns as all the oceans and seas are contaminated by them. Microplastic ingestion has been confirmed in all types of species. The smaller size makes them accessible to wide range of species including but not limited to zooplankton, fish, seabirds, decapod crustaceans, mussels, amphipods, lugworms and barnacles (Dedman 2014). Particularly smaller size species, at the lower trophic level are more susceptible to ingest microplastics (Wright et al. 2013).

Research in Thailand provided evidence of the presence of microplastics in edible seaweeds. Edible red seaweed *Gracilaria fisheri* and green seaweed *Caulerpa lentillifera* of inner Gulf of Thailand, food to both animals and humans, were found to be contaminated with microplastics, ranging between 100–1000 μm (Klomjit et al. 2021). Such abundance of microplastics in shallow water seaweeds can particularly be dangerous as both marine vertebrates and invertebrates depend on them for food. Further, zooplanktons (bottom of energy pyramid) were also detected with microplastics in Koh Sichang of Thailand. Through FTIR analysis, it was identified that fibers were the most abundant microplastics in calanoid copepods, cyclopoid copepods, crustacean *nauplii*, and gastropod larvae (Sutthacheep et al. 2021). As these species are indicators for assessing ecological risk in marine environment, abundance of microplastics in such species expresses concern of bioaccumulation at higher tropic levels of the energy pyramid.

Filter feeders which often filter organic matter are unfortunately unable to screen out microplastics from water column (Thusharia et al. 2017). Such behavior surged accumulation of microplastics in sessile and invertebrates, like barnacles, oysters, and bivalves. All three species mentioned are abundant in the upper Gulf of Thailand and were identified with high concentration of microplastic (0.2–0.6 g/counts) (Thusharia et al. 2017). Fishes from eastern coast of Thailand were also identified with significant amount of microplastics in the gastrointestinal tract and gills as well (Phaksopa et al. 2021), indicating that improving management and protection of coastal environment is much required.

Sutthacheep et al. (2018) examined the gut content of reef fishes from the Eastern Gulf of Thailand, which is one of the hotspots for plastic pollution. This study selected fishes from different trophic guilds (both herbivores and carnivores were considered) and found microplastic in gut content of all types of fishes sampled (Sutthacheep et al. 2018). Azad et al. (2018) also investigated microplastics in stomach of pelagic and demersal fishes at the lower Gulf and concluded that 54.29% of all sampled fishes ingested microplastics (Azad et al. 2018). The fishes sampled by Sutthacheep et al. (2018) and Azad et al. (2018) are readily consumed by locals which means there is a high chance of these microplastics to be passed on to humans.

3 Coral Global Importance

Occupying only 0.1% of the total marine environment, coral reefs harbor one-third of all the marine species. Most of which are barely found anywhere else (Reaka-Kudla 2001). Corals reefs are the most bio-diverse ecosystem of the ocean. Their complex three-dimensional structures promotes adaptation, species interdependencies, and are source of medically active compounds (Veron et al. 2009). More than 100 countries have coastlines with coral reefs and almost 8% of the world population lives within 100 km of a reef (Moberg and Folke 1999). Also, around tens millions of these people depend on reef ecosystems for protein and other services (Veron et al. 2009). This has resulted in exploitation and severe depletion of many reef resources which led to widespread reef degradation specifically in highly populated regions.

Corals also have huge roles to play in commercial fishing and recreation activities. They have high productivity, high diversity and density of marine species, and are associated with other tropical marine ecosystem providing goods and services through functional linkages (Gil-Agudelo et al. 2020). Additionally, they protect shorelines from erosion, hurricanes, and tropical storm. Despite offering major ecosystem service and livelihood to human, coral reefs often receives the least attention. The economic valuation of goods and services offered by coral reefs are undervalued and often remains undetermined. An estimated value of coral ecosystem are worth of $172 billion to $375 billion per year (Veron et al. 2009). However, this value has only considered marketed and tangible services, whilst intangible services remain un-quantified.

3.1 Corals in Thailand

Although there are total 300 major coral reefs in Thailand, barely any research has been conducted to update on their status since 2002. Coral reefs condition in Thailand ranges from very good to very poor, and it has been estimated that around 60% of the reefs are in fair or poor condition. However, corals status differs in different provinces. For instance, severe reef degradation is noticed in Chonburi, Phuket, Rayong, Satun, and Surathani provinces due to increasing human activities (Sutthacheep et al. 2013). Nevertheless, the most unique coral communities are found in the inner Gulf of Thailand, Koh Sichang, Chonburi Province (Suraphol and Yeemin 2002). Around eighty-five species of hermatypic corals are available there with *Porites lutea* being the most abundant. At the inner Gulf of Thailand sediment plastic pollution, fishing activities, and temperature stress are one of the few significant factors that inhibit coral growth.

Compared to the inner Gulf, coral communities were better off in the Eastern Gulf of Thailand. However, over the years, it declined due to increasing illegal dynamite fishing activities and tourism. The Western Coast on the other hand, suffers from frequent cyclonic events and went through severe bleaching. Although certain corals such as *Galaxea fascicularis* remains tolerant to bleaching, other species are extremely vulnerable at the western coast (Sutthacheep et al. 2013). Chumporn province in the southern part of Thailand consisting of several island have quite a good number of coral reefs. Unfortunately, due to tourism and high sedimentation, coral reefs are under serious threat in this part of the country (Suraphol and Yeemin 2002). While there are multiple conservation projects going on in southern part, stricter actions must be taken to reduce the rate of degradation.

This chapter attempts to explain how corals reefs are being threatened by multiple anthropogenic factors at the inner Gulf of Thailand with microplastics being one of the prime pollutants. This chapter tries to explain how microplastics can change the feeding behavior in both long and short tentacle corals and investigate the egestion and retention of microplastics in corals under controlled environment within 24 hours. Further, the inherently difficult behavior of corals towards three different types of microplastics was outlined, and the first evidence of corals ingesting microplastics even in the presence of natural prey in Thailand was provided.

4 Corals Feeding Behavior on Microplastics

4.1 Methodology

4.1.1 Coral Collection and Acclimatization

For this experiment, Koh Si Chang (Sichang Island), Chonburi province, was selected as the study area (Fig. 1). Sichang Island is a group of small islands situated in the innermost part of the eastern seaboard of the Gulf of Thailand (13°09 N, 100°49 E) (Wattayakorn and Rungsupa 2012). This area is comparatively flat, comprising mainly of rock. Koh Sichang was selected as it has the most interesting growth of corals. The *Galaxea fascicularis* and *Dipsastraea speciosa (Favia speciosa)* were selected as the target species for this experiment, due to their abundance in Koh Sichang.

Healthy corals were collected from the coral reefs of Koh Ran Dok Mai (N13° 9′5.89″ E100°50′3.53″) by SCUBA divers (Fig. 1). Each coral fragment was about 3x3 cm in surface area and was collected from a mother colony using a chisel and a hammer. Altogether fourteen fragments were collected for each species to set seven trails for each and use the extra ones for preliminary research. The coral samples were then transported to Koh Sichang Aquatic Resources Research Institute (ARRI)

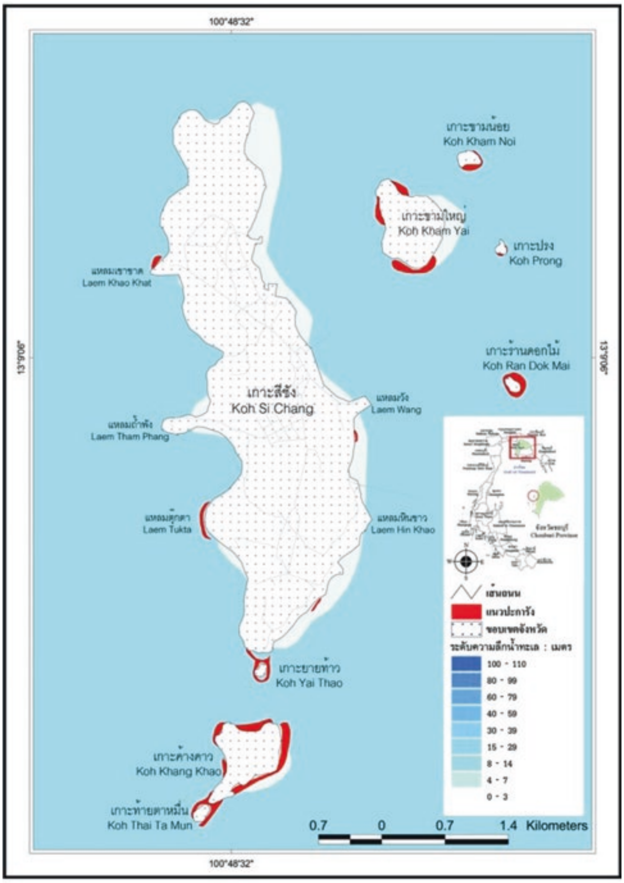

Fig. 1 Map of Koh Si Chang, Koh Ran Dok Mai (N13° 9′5.89″ 18 E100°50′3.53″). Corals were collected by SCUBA divers from Koh Ran Dok Mai

Chulalongkorn University (13°15′49.8”N 100°56′02.9″E) for acclimatization process.

Twenty-eight 700 mL tanks were prepared with oxygen supply for acclimatization process. Tanks were cleaned with tap water and filtered seawater, and then rinsed thoroughly with filtered seawater. Phytoplankton net of mesh size of 60 μm was used to filter the seawater (Fig. 2). Before placing collected corals into the tanks, oxygen level was adjusted and a white cork sheet was used, above which all the tanks were placed to get a clear background and to keep the tanks at same level. Salinity, dissolved oxygen level (DO), temperature and pH were measured using YSI Multi-Parameter Water Quality tester prior to the experiment. Using a clean forceps which was rinsed with filtered seawater, corals were transferred to the tanks. Samples were then kept separately in 28 different tanks of 700 mL (14 for each) to acclimate for 72 hours under starvation with filtered seawater and under natural

Fig. 2 Phytoplankton net of mesh size 60 μm was used to filter seawater, to screen any zooplankton, phytoplankton, or micro-particles present in the seawater used for acclimatization. This was done to ensure no other food particles are available for corals apart from the one provided during experiment. This filtered seawater was then used to wash, rinse and fill tanks for the experiment

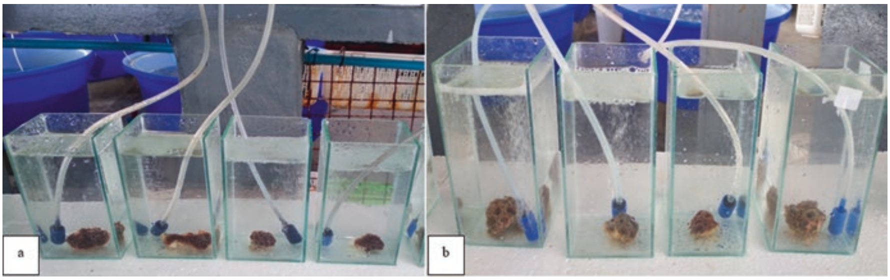

Fig. 3 (**a**) *Galaxea fascicularis*- long tentacles coral species (**b**) *Dipsastraea speciosa*-short tentacle coral species. Both figure a & b shows corals during 24 hours of acclimatization with oxygen supply

illumination at ARRI prior to the experiment (Fig. 3). Corals were kept in an enclosed environment to ensure no other external factors or contaminants affect the experiment.

Corals were kept under natural illumination and the light: dark ratio was 12:12. Six samples from each coral species were randomly selected and used for preliminary work while rest sixteen samples were left for acclimatization. During preliminary test, the volume for water was changed repeatedly to see corals reaction and to identify the most suitable volume for corals to feed on microplastics.

4.1.2 Coral Feed Preparation

Polyethylene (PE), polyethylene terephthalate (PET), and polypropylene (PP) were used for preparing coral feed for this experiment. These three types of plastics were used due to their dominance in marine environment. Virgin white pellets of PET were broken down into smaller pieces to make it suitable for *Galaxea Fascicularis* and *Dipsastraea speciosa*. To get microplastics of 500–2000 μm range, the crushed pellets were then sieved with 2000 μm sieve staked over 5000 μm sieve. These newly crushed microplastics were then kept in a laminar flow cabinet model TC1200 under UVC radiation to disinfect for 2 hours. After 2 hours the microplastics were immediately transferred to cleaned Ziploc bags and kept in an airtight box. For preparing PP, fluorescent (bright red color) nylon fibers were cut into small pieces <2000 μm, sieved and disinfected using the same process. Black PE bags were also cut into smaller pieces (<2000 μm) to be used as coral feed and sterilized and sieved using the same process.

While preparing coral feed, it was realized that due to lower density of plastic particles (0.89–0.98 g cc^{-1} for PE, 0.96–1.45 g cc^{-1} for PET, and 0.83–0.92 g cc^{-1} for PP), microplastics were most likely to float and out of corals reach during experiment. Therefore, PP and PE were soaked in seawater for 2 days to allow them to descend during experiment. PET pellets had higher density compared to other two types and did not float much. So PET was used dry. The microplastics used in this experiment ranged from 500 μm to 2000 μm. This size range of microplastics was also selected in other studies (such as Allen et al. (2017), Hall et al. (2015), Hankins et al. (2018) when exploring the ingestion behavior of microplastics in corals.

For preparing the *Artemia nauplii*, the brine shrimp eggs were cultured for 24 hours prior to the experiment. A tank of 1000 mL was taken and washed thoroughly with tap water and then with filtered seawater. The container was then filled with seawater and half spoon of *Artemia* eggs was added. Oxygen supply was ensured in the container and was left for 24 hours. *Artemia nauplii* size varied between 400–500 μm.

4.2 Experiment Set Up

4.2.1 Tanks Set Up for Ingestion

After the third day of acclimatization, seven tanks per species were randomly selected, and the water was changed in the tanks. The tanks were cleaned and rinsed thoroughly with filtered seawater again and then filled with 500 mL seawater to make it easy for the corals to catch microplastic from the water surface. For 1 mL of seawater, 2 pieces of plastics was suggested by previous studies (Axworthy and Padilla-Gamiño 2019). Therefore, half spatula of each type of plastic was used per tank which contained approximately 1254 ± 100 particles of plastics for 500 mL (approx. 418 pieces of each type of microplastics). *Artemia nauplii* of 2.5 mL was

Fig. 4 Ingestion chamber with inlet flow to keep microplastics in flow and within the reach of corals. This picture shows *Dipsastraea speciosa* in ingestion chamber

then added using a dropper. Total density of *Artemia nauplii* was 400 ± 58 particles for 500 mL.

One portion of *Artemia* was used for three portions of microplastic in the solution. A cylindrical shaped inlet flow was used for oxygen supply to keep the microplastics in flow during the experiment (Fig. 4). The corals were allowed to feed for 3 hours. Two control chambers were set up — one tank for each specie and only 2.5 mL of *Artemia* was given as feed only. Coral feeding behavior was recorded using OLYMPUS TOUGH TG-5 4 k camera.

4.2.2 Egestion Chamber Set Up

After 3 hours of ingestion, the corals were transferred to clean tank, rinsed and filled with 500 mL of filtered seawater. The tanks were closed with a transparent clean plastic cover, and oxygen supply was ensured and left for 24 hours (Fig. 5). After exactly 24 hours of egestion, the water samples were vacuumed using a 2000 mL filtration flask/vacuum pump on a filter paper. Pore size of the filter papers were of 20–25 μm. The tanks were rinsed with filtered seawater repeatedly to collect all the egested materials on the filter papers. The filter papers were then kept in Ziploc bags, labeled, and taken for further analysis (Fig. 6). Corals from the egestion chambers were transferred into clean plastic bags and fixed with 10% formalin for further analysis. For formalin preparation, 45 mL of formalin was diluted with 450 mL of seawater using a measuring cup of 500 mL.

Fig. 5 Egestion chambers showing both species of corals. Plastic cover was used to restrict any microplastic or particles that might enter from outside and affect the results of the experiment

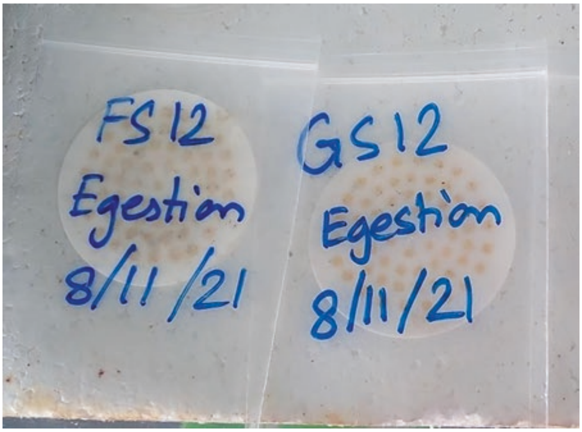

Fig. 6 Samples collected in filter paper of pore size 20–25 μm to assess microplastics egested by each species. FS indicates *Dipsastraea speciosa* and GS indicates *Galaxea Fascicularis*

4.2.3 Coral Dissolution, Egestion and Retention Testing

This study applied the methodology from Axworthy and Padilla-Gamiño (2019) who attempted to identify the retention of microplastics in coral tissues. To measure the amount egested, samples collected on the filter paper were brought to the laboratory. The numbers of microplastics were counted from the filter paper under Leica MZ6 microscope 3.2× magnification. The diameter, type and number of microplastics in each sample were noted and the highest number of microplastic egested was identified.

To count the number of microplastics retained by corals, the coral skeleton and flesh were decalcified, and the amount of plastic retained after 24 hours of egestion was determined (Fig. 7). The samples were decalcified in 3% formic acid over a period of seven days (Hall et al. 2015). To prepare formic acid, 15 mL of formic acid was diluted in 485 mL of water in a 500 mL beaker. Then, the tissues were dissected using forceps and dissecting probes, under OLYMPUS SZ 40 microscope (4×). The

Fig. 7 Corals soaked in 3% formic acid for decalcification for seven days to soften the polyps and dissect it for extracting retained microplastics

coral polyps were then sectioned longitudinally. Retention of microplastics was examined by the presence of microplastics in the mouth and among the polyps. The numbers of microplastics present in the tissues were then counted. To differentiate between organics and MPs in the samples, the following assumption was applied. Organic matter usually breaks when prodded while microplastics have a tendency to bounce off. Additionally, we used colored microplastics (PP-red, PE-black and PET-white) to ensure the microplastics are easily identified.

4.3 Findings

4.3.1 Ingestion of Microplastics by Corals

Both species, *Galaxea Fascicularis* and *Dipsastraea speciosa* ingested microplastics. Figure 8a demonstrates how *Galaxea Fascicularis* polyps become active within first 30 minutes of coral feed transfer, as soon as the microplastic touches the polyps. When microplastics touched the coral polyp, they try to extend their tentacles and catch it (Fig. 8b). To understand the behavior of corals towards each type of plastics, the video recording were played multiple times and identified how corals reacted to each type. It was noted that PET activated coral tentacles, but as it was quite heavy compared to other types of microplastics, corals couldn't ingest it most of the time. Therefore, PET got attached to the tentacles, but it was difficult to take inside the mouth. For PP (Fig. 8c), the responses were quite low compared to other types of plastics added, as most of the PP fibers floated (difficult for corals to catch). However, *Galaxea Fascicularis* did catch some fibers. Corals consumed significantly more PE than any other types of plastic provided in the experiment (Fig. 8d). Responses were particularly visible for *Galaxea Fascicularis* as they have long tentacles which became quite active when came in touch with PE. As PE was light, it was easy for corals to ingest. *Dipsastraea speciosa* having small tentacles ingested

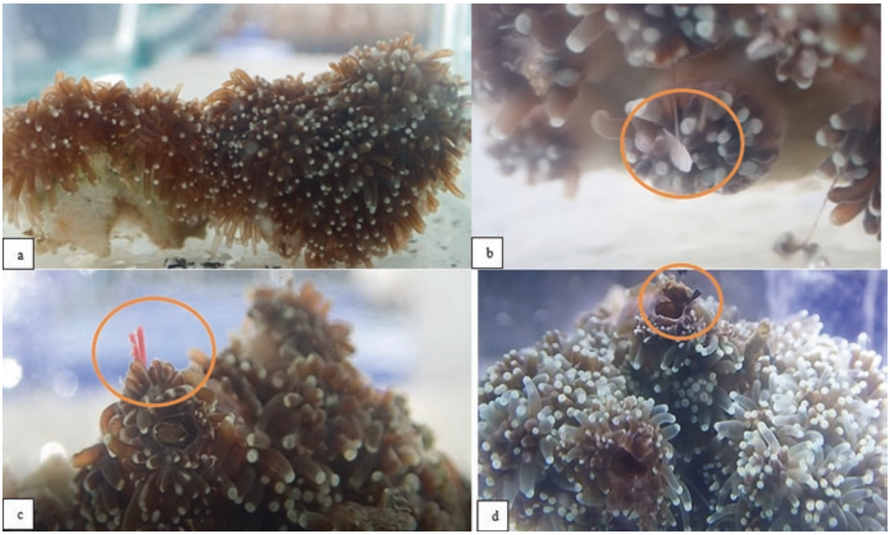

Fig. 8 (**a**) *Galaxea Fascicularis* within the first hour of ingestion process (**b**) Polyps reaction to polyethylene terephthalate (**c**) Polyps reaction towards polypropylene microplastics (**d**) Polyps reaction to polyethylene

Fig. 9 Dipsastraea speciosa within the first hour of adding microplastic to the tanks. As the tentacles were very short the camera could barely catch any movement

fewer microplastics than *Galaxea Fascicularis*. It was also concluded that *Dipsastraea speciosa* was heavier than *Galaxea Fascicularis* and required more time for polyp movement which in turn affects its ability to catch food. Figure 9 illustrates how *Dipsastraea speciosa* responded to microplastics in first 1 hour of ingestion. As the *Dipsastraea speciosa* had short tentacles, the movements were barely visible in the recording.

4.3.2 Number of Microplastics Egested

Average number of microplastics egested by both species was calculated (Fig. 10). *Dipsastraea Speciosa* egested microplastics less than *Galaxea Fascicularis*. Figure 10 also shows that the average egestion by *Galaxea Fascicularis* was 4.71 MPs particles/coral fragment and, for *Dipsastraea Speciosa*, it was 3.57 MPs particles/coral fragment. The variation in data within species exists as each fragment of coral has different energy storage due to differences in photosynthesis rate. The act of egesting microplastics is assumed to be energetically costly and here the only source of energy was photosynthesis for the corals prior the experiment. Zooxanthellae responsible for photosynthesis can be bleached or shrunk in some fragments which resulted in differences in energy storage and impacted egestion in turn. Additionally, corals, when starved, release mucus to catch zooplanktons, and this process also leads to energy loss.

Figure 11 illustrates the size of microplastics detected in coral egestion chambers. It ranged between 248 μm to 1000 μm. During this experiment we found the size of microplastics in the egestion chamber was below 500 μm which was smaller than the size of microplastics provided in the ingestion chamber. From our understanding, we conclude that certain gut activity during the digestion process could result in breaking down the microplastics into a smaller size. However, more research is required to confirm this result . Egestion samples from the control chambers were also analyzed and no microplastics were detected (Fig. 11).

4.3.3 Microplastic Retention in Both Species

After decalcification with 3% formic acid for 7 days, on the eighth day, the coral polyps were dissected under microscope to identify microplastics (Hall et al. 2015). *Galaxea Fascicularis* retained significantly more microplastics from experiment than *Dipsastraea Speciosa.* For retention check, microplastic retained per polyp was calculated and the polyps for both species ranged from 18 to 32. Table 1 shows the number of polyps per fragment from egestion chambers of both species. It also shows the amount retained by each polyp per sample. For *Galaxea Fascicularis*, per polyp retention was about 0.023 MPs particles/coral fragment on average in 24 hours. *Dipsastraea Speciosa* only retained 0.017 MPs particles/coral fragment microplastics on average per polyp for 24 hours. All microplastics identified were PE.

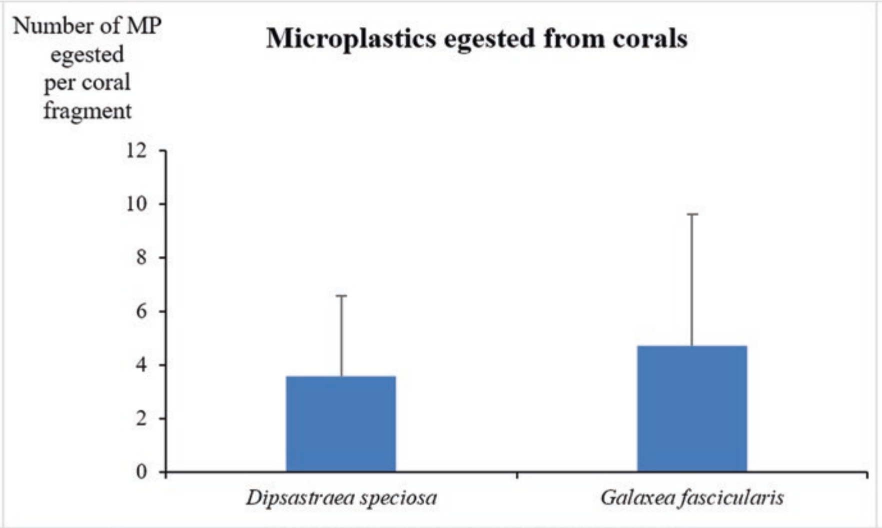

Fig. 10 Average numbers of microplastics egested by *Galaxea Fascicularis* and *Dipsastraea speciosa* within 24 hours. This graph only considered the microplastics which were provided during the experiment. MP: microplastic

The retention in *Dipsastraea Speciosa* was lower due to lower ingestion of microplastics for 3 hours. Figure 12 demonstrates the difference in microplastics retention among species on average. Additionally, differences in size of microplastics retained versus size of microplastics egested were also noticed during analysis. Table 1 shows number of microplastics retained per polyp in each type of corals. Figure 13 shows microplastics retained by corals ranged between 1000 µm to 2000 µm, meaning larger microplastics are hard for corals to egest. Thus, they tend to retain them. Corals from control chambers were also dissected to identify an microplastic present in the corals prior to the study. However, no microplastics were detected in any of the control chambers (Figs. 12 and 13).

5 Limitations of the Study

This study used 72-hr acclimatization period for both species of corals which is the minimum time required for corals to acclimatize. For future works, it is recommended to acclimatize corals at least for 6–9 days for better results. Further, this experiment was limited with 3 hours of feeding trial. Corals usually prefer feeding all night. Thus, it would be better to consider night long feeding trials as this would help in accumulating more plastics in the corals. This experiment lacks data in terms

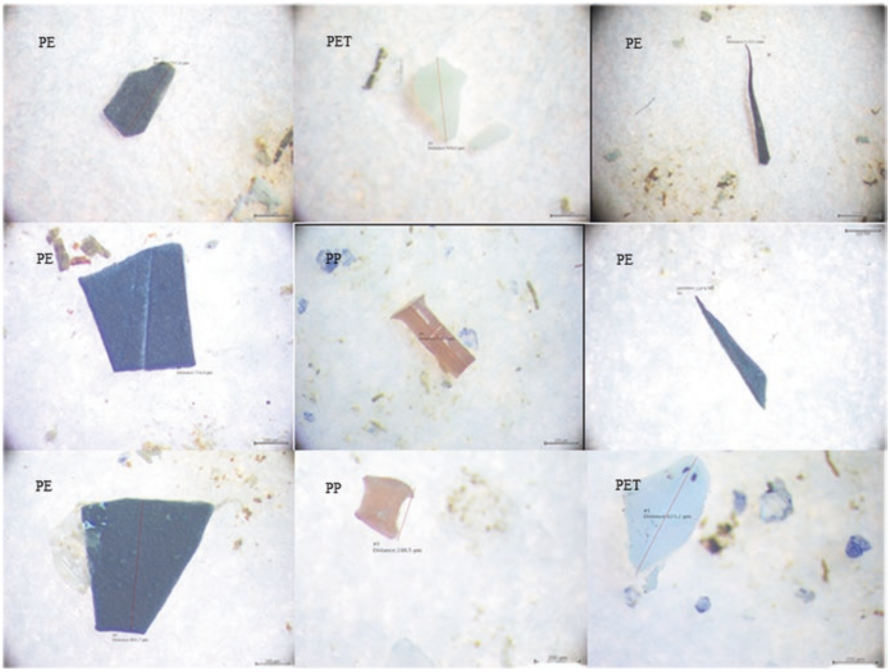

Fig. 11 Scanning Electron Microscopy (SEM) images of microplastics from the egestion samples of both species ranged from 248 μm to 1000 μm. The highest number of microplastic egested was polyethylene (PE) as during experiment this was the most ingested microplastic due to its lighter weight. The identification of microplastics was done based on color as only colored microplastics were feed to the coral. Magnification of 3.2x was used to identify the microplastics in the egestion chamber

of *Artemia* ingestion by corals. A comparison could have been done to measure amount of *Artemia* ingested by corals exposed to microplastics compared with the corals in control chambers. This could have helped to identify if microplastics appeared as a barrier to *Artemia* ingestion. Additionally, no investigation was done to identify the differences of the sizes of microplastics in ingestion and egestion chambers.

6 Conclusion

This study intended to determine whether two different species of corals feed on a variety of microplastics with the presence of *Artemia nauplii*, and whether different types of plastics alters corals feeding behavior. Results show that corals responded differently to each type of microplastics. *Galaxea fascicularis* ingested more microplastics compared to *Dipsastraea speciosa* indicating that corals with long tentacles are at higher risk. From literature review, it was also confirmed that corals have no

Table 1 Number of Microplastics (MPs) Retained per Polyp in both species. GS stands for *Galaxea Fascicularis* while FS represents *Dipsastraea Speciosa*

Coral Samples	No. of polyps	No of MPs (pieces/polyp)
		MPs from experiment
GS 1	46	0.02
GS 2	26	0.04
GS 3	28	0.00
GS 4	27	0.00
GS 5	30	0.03
GS 6	21	0.05
GS 7	43	0.02
AVG	–	**0.023**
SD		**0.02**
FS 1	22	0.00
FS 2	18	0.06
FS 3	16	0.00
FS 4	18	0.00
FS 5	15	0.07
FS 6	28	0.00
FS 7	11	0.00
AVG		**0.017**
SD		**0.03**

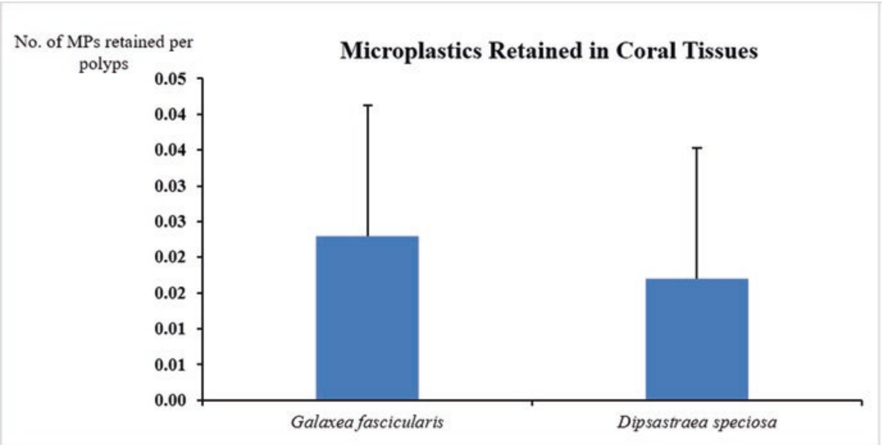

Fig. 12 Number of microplastics (MP) retained in two species of corals *Galaxea fascicularis* and *Dipsastraea speciosa* from our experiment. *Galaxea fascicularis* tends to retain more than *Dipsastraea speciosa* as it ingested more microplastics

visual senses. Therefore, only gustatory receptors are used to discriminate food particles. The color of microplastics did not affect the feeding behavior, however size and density does. This experiment also concludes that both species egested more than they retained within 24 hours of ingestion. However, egestion among species

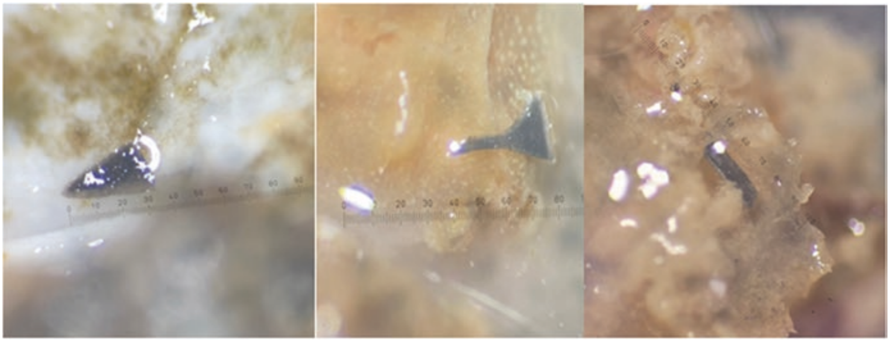

Fig. 13 Shape and size of microplastics retained by both coral species ranged from 1000–2000 μm. Larger particles were difficult to egest, therefore corals tend to retain those

differed as microplastic egestion is energetically costly and, the source of energy for coral fragments in this experiment was dependent on their photosynthesis ability. As coral fragments were not tested for healthy Zooxanthellae prior experiment, their ability to perform photosynthesis differed which affected their energy storage.

Corals usually digest food rapidly (Allen et al. 2017). Nevertheless, for this case, plastic particles were retained beyond 24 hours of ingestion. This was particularly surprising as non-ingested particles are often egested by corals within 50 minutes to 6 hours of ingestion. Therefore, microplastics were stuck in coral polyps as corals lacked the amount of energy required to egest particles which ranged beyond 1000 μm. While little is known about corals feeding behavior towards microplastics, this research can be one of the pioneers. This study can help elucidate and propose act/policies to protect coral ecosystem from microplastic pollution in Thailand. Additionally, more research aiming to scrutinize corals behavior towards other types of microplastics over longer period are required to identify the impacts it might have on corals and on marine ecosystem.

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Microplastics Remediation in the Aqueous Environment

Yuzhi Liu, Shibo Cong, Haiyang Yu, Donglei Zou, and Yu Gao

Abstract Environmental hazards and health risks posed by microplastics is calling for advanced remediation methods. Here we review strategies and methods for microplastic decontamination with focus on physical, chemical, and biological technologies.

Keywords Microplastics · Wastewater treatment plants · Physical remediation · Chemical remediation · Biological remediation

1 Introduction

Microplastics (MPs), defined as plastic fragments with a diameter of less than 5 mm, are considered a burgeoning environmental pollutant and have received considerable attention due to their potential adverse effects on organisms. The lightweight and compact characteristics of microplastics make them easy to transport and flow in wind and water environments. Therefore, microplastics have been found all over the world, both near human settlements and in remote areas far away from human activities (Chen et al. 2022a). In addition, microplatics can have negative effects on organisms by inhibiting growth, development, and reproduction (Lambert et al. 2017). Microplatics can also enter organisms through ingestion, inhalation,

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and digestion (Revel et al. 2018), which in turn bioaccumulates up the food chain and ultimately threatens human health. Therefore, there is an urgent need to develop end-treatment technologies for the remediation of microplastics from the aquatic environment.

The recent review of emerging pollutants removal has begun to pay more and more attention to the end-treatment technology of microplastics. For example, Zhang et al. (Zhang et al. 2021a) systematically expounded on most of the published microplastics' removal technologies, which raised potential challenges and possible improvement plans for microplastics' removal strategies and treatment processes. Reddy et al. (Reddy and Nair 2022) elaborated on the removal technology and efficiency of microplastics in each unit of the wastewater treatment plants (WWTPs), providing a new perspective for wastewater treatment plants to formulate policies to control microplastics pollution. At the same time, Chen et al. (Chen et al. 2022a) paid more attention to the microplastics degradation and plastic recycling strategy, hoping to use new catalytic methods such as photocatalysis, advanced oxidation processes (AOPs,) and biotechnology to transform microplastics and plastic wastes into environment-friendly and valuable products. However, these microplastics' remediation technologies at this stage are not specially designed for the removal of microplastics. The advantages and disadvantages of these technologies in the microplastics' remediation process require a more comprehensive and systematic overview. This chapter summarizes the current physical, chemical, and biological technologies of microplastics' remediation in an aqueous environment analyzes the advantages of various technologies in the field of microplastics' remediation using principal component analysis (PCA), and looks forward to the application ways and development strategies of these technologies in the future.

2 Remediation Technologies and Removal Strategies

2.1 Physical Remediation

2.1.1 Accumulation of Microplastics by the Activated Sludge Process

The wastewater treatment plants are the point source of pollution for microplastics entering surface water bodies through the sewage network (Ziajahromi et al. 2017; Park et al. 2020; Naji et al. 2021). In WWTP, the removal rate of microplastics after only secondary biological treatment is about 88%. The activated sludge processes are wastewater treatment plants' fundamental secondary treatment unit. During the process, a large number of microplastics are captured and enriched in the residual sludge (Xu et al. 2021a). As shown in Fig. 1, the preliminary and primary treatment can remove 35–59% and 50–98% of microplastics by skimming the light floating microplastics, trapping microplastics in solid flocs, and precipitating heavy microplastics. In addition, microplastics larger than 500 μm are easy to remove, while microplastics smaller than 100 μm are difficult to remove in any dimension. The

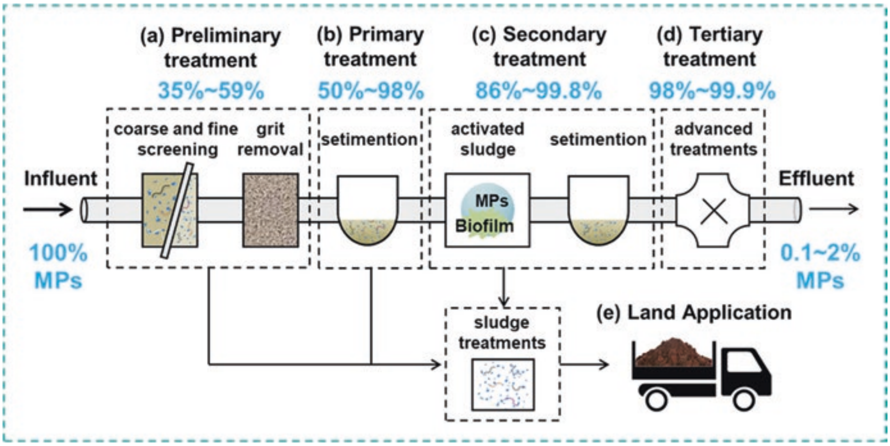

Fig. 1 Estimated microplastics particle flow in wastewater treatmen plants with preliminary, primary, secondary, and tertiary treatment processes. (Chen et al. 2022a)

processing unit that generates mechanical force can decompose microplastics into nano plastics (Menéndez-Manjón et al. 2022; Freeman et al. 2020). After secondary treatment (including biological treatment and clarification), microplastics concentration was 0.2–14%. At this stage, microplastics can accumulate with sludge flocs and extracellular polymers, or be captured by organic matter intake (Freeman et al. 2020). With further treatment, the removal rate of microplastics can increase to more than 97% (Sun et al. 2019). On the one hand, despite the limited data available, most of the microplastics from wastewater treatment plants are transferred to the residual sludge, resulting in sludge being a more serious source of microplastics pollution than wastewater treatment plants discharges (van den Berg et al. 2020). On the other hand, the wastewater treatment plants have high treatment efficiency for microplastics, but the accumulated microplastics pollute the water environment and downstream sediments due to a large amount of water discharge (Zhang et al. 2021a).

2.1.2 Adsorption and Filtration

Adsorption is a conventional pollutant remediation method, which is widely used in the field of water treatment because of its low cost, high efficiency, and simplicity. Activated carbon and molecular sieve are adsorbents widely used in various industries. The shape and size of microplastics have a considerable influence on the adsorption capacity of adsorbents (Goh et al. 2022). Because of its smooth and edge-free surface, the adsorption degree of microbeads is lower than that of microplastics with irregular shapes. Recently, biochar, which can be obtained from agricultural biomass, has attracted more and more attention as a renewable adsorbent (Abuwatfa et al. 2021). Moreover, the adsorption of microplastics on algae in algal microchannels is an interesting idea for the adsorption removal of microplastics (Sundbæk et al. 2018). Furthermore, magnetic adsorbents have received more and more attention in water and wastewater treatment (Shukla et al. 2021). In addition to improving the adsorption performance, the magnetic characteristics can also be easily recovered by using an external magnetic field. This is described in more detail in section "Magnetic Separation".

Filtration is another physical separation technology that can be combined with adsorption to remove microplastics. Filtration can separate solid particles from the fluid (liquid or gas) according to the size of the plastic, usually assisted by a vacuum system (Crawford and Quinn 2017). According to the filter, filtration includes particle filtration and membrane filtration. Particle filtration retains solid particles through transport and attachment steps utilizing particle media that can be provided by quartz sand, glass beads, and activated carbon (Wu et al. 2013). Therefore, particle filtration mainly includes sand filtration (Magni et al. 2019), rapid sand filtration (Hidayaturrahman and Lee 2019), and granular activated carbon filtration (Östman et al. 2019). The transport of microplastics is mainly controlled by Brownian diffusion, while the transport of large particles is mainly controlled by interception and precipitation. The adhesion of plastic particles involves various forces, including the van der Waals force, electrostatic repulsion force, spatial interaction, hydrophobic interact, ion and water resultant force (Magni et al. 2019). Therefore, microplastics particles with similar wettability, reverse surface charge, and non-uniform morphology may be more suitable for particle filtration due to their strong interaction. The initial stage of the waste water treatment plant is the grit chamber and the main sedimentation tank. At this stage, about 50% of microplastics were removed (Hidayaturrahman and Lee 2019; Elgarahy et al. 2021; Bui et al. 2020). Furthermore, Membrane filtration with size exclusion as the main removal mechanism is another important technology for microplastics filtration removal (Poerio et al. 2019). In principle, microplastics with a size larger than the pore size of the membrane separation layer can be rejected by the membrane. Effective membrane filtration technologies include microfiltration (MF), ultrafiltration (UF), nanofiltration, and reverse osmosis membranes. They can effectively remove microplastics particles larger than 0.08–2 μm, 0.005 –, 0.02 μm and 0.002 μm, while reverse osmosis is mainly aimed at desalination (Poerio et al. 2019; Ahmed et al. 2021; Mukherjee et al. 2022). The filtration removal of microplastics is affected by membrane properties, filtration time, flow rate and other factors. Although the operation of membrane filtration is simple and efficient, the rapid decline of filtration effect caused by membrane pollution without pretreatment is the limiting factor (Guo et al. 2020).

2.1.3 Magnetic Separation

Magnetite (Fe_3O_4) nanoparticles can remove microplastics from various surface water environments by magnetizing microplastics of different sizes and shapes (Shi et al. 2022; Zhao et al. 2022). Magnetic separation can be achieved by designing nanomaterial that can be combined with the surface of microplastics (Goh et al. 2022), which has the advantages of large capacity, less waste sludge, and long-distance magnetic enhanced separation (de Vicente et al. 2011). Grbic et al. (Grbic et al. 2019) used hexadecyltrimethoxysilane-modified hydrophobic iron nanoparticles as magnetic seed particles. Due to the hydrophobic interaction, nanoparticles attach to the surface of microplastics, thereby achieving magnetic separation of microplastics. However, the size of microplastics affects their magnetic removal efficiency. Only microplastics >1 mm have a magnetic removal efficiency of more than 90%, and the smaller the size, the lower the magnetic removal efficiency. Consequently, hydrophobic interaction alone cannot effectively remove small-sized microplastics in water.

At the same time, using magnetite to functionalize the surface of carbon nanotubes with high affinity for hydrophobic particles can effectively adsorb non-polar microplastics (such as polyethylene, polypropylene, and polyethylene terephthalate) and other polar microplastics (such as polyamide) (Tang et al. 2021). Hydrophobic interaction, electrostatic interaction, complexation, conjugation, and hydrogen bond interaction make efficient removal of microplastics possible (Patil et al. 2022). Rhein et al. (Rhein et al. 2019) studied the separation of microplastics from aquatic matrix by magnetic seed filtration, which provides an experimental basis for the industrial application of microplastics magnetic removal. In relatively stable industrial wastewater, a rotary drum may be an ideal candidate for magnetic separation equipment (Hu et al. 2014; Wang et al. 2014). At the same time, because it is relatively sensitive to the surface charge, shape, and size of microplastics, the magnetic separation method may not be an ideal choice for the removal of microplastics in natural water. In natural water, due to the existence of organic matter and inorganic ions, the surface functionalized magnetic materials are affinity for most impurities, but not the target microplastics. In addition, microplastics in natural water do not have a specific spherical shape like commercial microbead samples. The non-spherical shape of fibers and films will not contribute to the removal of microplastics in natural water by magnetic separation (Zhang et al. 2021a).

2.1.4 Density Separation

Density separation is a method to separate microplastics from water by using the density difference between microplastics and media. It is a necessary step to separate and detect the types and quantities of microplastics in water or sediment. Microplastics lighter than the medium can float to the upper layer of the suspension after stirring and separate from the sediment sample. Therefore, the density characteristic of the flotation medium is the most critical factor in density separation. For example, common media used for density separation, such as NaCl, NaBr, Nai, $ZnBr_2$, $CaCl_2$, $3Na_2WO_4{\cdot}9WO_3$, and NaH_2PO_4, can distinguish microplastics with different densities from other heavy substances by multiple separations in the range of 1.1–1.8 g cm^{-3} (Zhang et al. 2021a). However, this practice of introducing a large number of foreign media to retain micropollutants in the water body is not suitable for the green and efficient vision of microplastics' remediation in surface water.

2.2 Chemical Remediation

2.2.1 Coagulation, Enhanced Coagulation, and Electrocoagulation

Coagulation is a typical process in wastewater treatment plants. Adding coagulants to wastewater will cause colloidal substances to coagulate, flocculate, and finally separate (Xu et al. 2021a). Although different coagulants have different removal effects on microplastics, their removal mechanism for microplastics in water is to change the floc state of suspended microplastics in water through charge neutralization, adsorption and sweeping flocculation, making them unstable, and promoting their removal through precipitation (Zhang et al. 2021b; Zhou et al. 2021a; Xu et al. 2021b; Lu et al. 2021). Moreover, hydrolytic products are the main factor affecting this process rather than hydrolysis process (Zhou et al. 2021a). Under the same conditions, the hydrolysate of Al^{3+} shows better performance than the hydrolysate of Fe^{3+}, while polyacrylamide (PAM) has better removal effect on large particles (Patil et al. 2022).

As shown in Table 1, the removal effect of traditional coagulants, such as iron-based chemicals, aluminum-based chemicals, and polyacrylamide (PAM), on microplastics fluctuates greatly in aqueous environment due to the differences in

Table 1 Removal performance of microplastics using the coagulation method

Coagulation method	Coagulants	Flocculant	Removal efficiency	Ref.
Coagulation	Iron-based chemicals	/	8.24–99%	(Rajala et al. 2020; Ma et al. 2019)
	Aluminum-based chemicals	/	8.28–100%	(Lu et al. 2021; Ma et al. 2019)
	Polyacrylamide (PAM)	/	29.70–77.83%	(Zhou et al. 2021a)
	Lysozyme amyloid fibrils	/	98.20%	(Peydayesh et al. 2021)
	$CH_3(CH_2)_7SiCl_3$	/	93.3%	(Lee and Jung 2021)
Coagulation + flocculation	Iron-based chemicals	Chitosan and tannic acid	95%	(Park et al. 2021)
	Aluminum based chemicals	PAM	40–96%	(Zhang et al. 2021b; Lapointe et al. 2020)
	$Mg(OH)_2$	PAM	84.9–92.6%	(Li et al. 2022a; Zhang et al. 2021c)
Electrocoagulation	Al anode	/	97.5–100%	(Xu et al. 2022a; Akarsu et al. 2021)
	Fe anode	/	84.6–96.8%	(Shen et al. 2022)

microplastics density, hydrophobicity and surface charge. Increasing their dosage is an effective way to improve the removal efficiency of microplastics, but it will inevitably increase the volume of subsequent microplastics flocs/sludge and the concentration of soluble salt ions (such as SO_4^{2-}) in water. Therefore, new coagulants, adding flocculants, and electrocoagulation are three effective strategies to alleviate this situation (Gao and Liu 2022). The removal effect of new coagulants on microplastics is better than that of traditional coagulants because the surface affinity of new coagulants on microplastics is stronger than that of traditional coagulants (Lee and Jung 2021). In addition, the addition of flocculants can also change the surface affinity of microplastics, thereby enhancing the removal effect of traditional flocculants on microplastics (Park et al. 2021). Although the introduction of these new substances is conducive to the removal of microplastics in water, their subsequent impact on effluent discharge needs further study. Compared with the first two methods to improve the removal effect of microplastics, electrocoagulation (EC) is more suitable for the efficient removal of microplastics because it has the advantages of coagulation, flotation and electrochemistry (Moussa et al. 2017). As shown in Fig. 2, EC uses metal electrodes to generate coagulants under electric field, and achieves efficient removal of microplastics in water through three steps of 'formation- instability-sedimentation', which makes the EC method simpler and more effective (Shen et al. 2020). Among them, the EC method with Al and Fe as electrode anodes is most widely used in the field of microplastics' removal, and the effect of Al electrode is better.

2.2.2 Disinfection

Common wastewater disinfection, including chlorine disinfection, ozone treatment and ultraviolet (UV) disinfection, is the main step to kill or inactivate many pathogenic microorganisms in wastewater (Reddy and Nair 2022). These disinfection processes may cause chemical degradation or physical decomposition of microplastics, but they will only affect the surface properties of microplastics, including roughness, hydrophobicity and chemical bonds (Lin et al. 2022).

First, long-term contact between microplastics and chlorine may lead to microplastics' degradation (Hassinen et al. 2004; Castagnetti et al. 2011; Jung et al. 2022). However, their mineralization efficiency of less than 10% (Liu et al. 2019a; Li et al. 2022b) is not an excellent representative in the field of microplastics removal. And the smaller size microplastics are decomposed will persist in the environment and may adsorb other toxic chemicals in the water body to cause secondary pollution (Reddy and Nair 2022). In addition, ozone oxidation is an advanced oxidation technology in the field of disinfection. It has been fully proved that the presence of ozone in the air, even if the concentration is very low, will accelerate the aging of polymer materials (Kefeli et al. 1971). Through the oxidation process, ozone oxidation can decompose the polymer forming microplastics into functional groups (Chen et al. 2018). Studies have shown that about 90% of microplastics are oxidized by ozone within 1 h of treatment (Hidayaturrahman and Lee 2019; Chen et al.

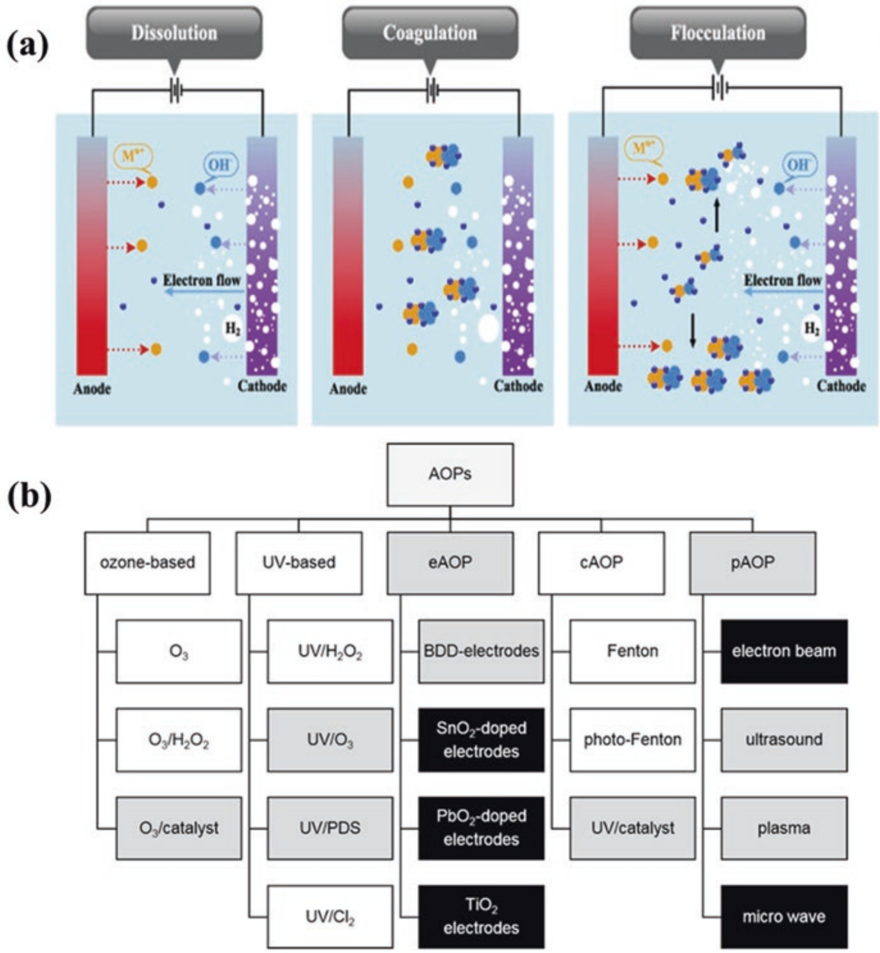

Fig. 2 (**a**) Processes for removing microplastics from water via electrocoagulation (Shen et al. 2020). (**b**) broad overview and classification of different advanced oxidation processes (AOPs). Individual processes are marked as established at full-scale (white), investigated at lab- and pilot-scale (grey), and tested at lab-scale (black) (Miklos et al. 2018)

2018). At the same time, ozone oxidation reduces the particle size, improves the roughness, and increases the hydrophilicity in the presence of carbon-containing groups (Li et al. 2022b). This facilitates the physical removal and biodegradation of subsequent microplastics. Finally, UV irradiation to inactivate microorganisms is an effective disinfection method, which does not affect the chemical composition of wastewater. However, the type of microplastics and the wavelength of UV light can affect the physical, mechanical and optical properties of microplastics exposed to UV light, and even lead to the degradation of some microplastics by UV disinfection (Singh and Sharma 2008). For example, Galafassi et al. (Galafassi et al. 2022) reported that UV disinfection treatment can degrade 9.1% of microplastics in the wastewater treatemt plants. Since the disinfection process is mainly aimed at pathogenic microorganisms in water, although it has a certain repair effect on microplastics in water, it seems that only the ozone process has a certain practical application significance.

2.2.3 Advanced Oxidation Processes

Advanced oxidation process(AOPs) have been used by more and more treatment plants as a tertiary treatment to effectively degrade or mineralize various pollutants including dyes, antibiotics, and persistent organic pollutants due to their strong oxidation capacity (Ganiyu et al. 2016; Arola et al. 2019). Figure 2b summarizes the different established and emerging AOPs, which are divided into ozone-based, ultraviolet-based, electrochemical (e), catalytic (c) and physical (p) AOPs (Miklos et al. 2018). As a kind of unique organic pollutants, microplastics are insoluble in water. Compared with other low molecular weight (MW) organic pollutants mentioned above, its molecular weight is much higher than other low molecular weight organic pollutants (Chen et al. 2022a). Although reactive oxygen species (ROS) generated by AOPs can destroy the surface structure of microplastics particles (Lang et al. 2020), it cannot completely degrade the microplastics body and its subsequent degradation products (Kang et al. 2019). At the same time, it is challenging to elucidate the mechanism involved in AOPs degradation of pollutants. Only a few works in the literature have proposed the degradation mechanism (Tofa et al. 2019; Uheida et al. 2021; Nabi et al. 2020; Jiang et al. 2021). In addition, the chemical conversion of microplastics in AOPs is also of concern due to the possible formation of various toxic by-products. The organic pollutants released by the aging of microplastics have been proven to inhibit the advanced oxidation process (Chen et al. 2022b). How to effectively regulate the parameters of advanced oxidative degradation of microplastics needs further research.

2.3 Biological Remediation

Biotechnological methods to remove microplastics have been reviewed (Anand et al. 2023).

2.3.1 Membrane Bioreactor Technology

At present, membrane bioreactor (MBR), a biofilm system based on the combination of membrane process, mainly membrane or ultra filtration, and biological process (Yi et al. 2020), is one of the most effective treatment technologies for removing microplastics from water (Xiao et al. 2019). The pore size (0.01–5 mm) of the membrane bioreactor filter is usually smaller than other filters commonly used in wastewater treatment (Meng et al. 2017), which can prevent most microplastics from passing through. Membrane bioreactor has been successfully applied to many types of wastewaters, especially wastewater containing emerging toxins, such as antibiotics, pesticides, personal care products, drugs, etc. (Nguyen et al. 2019; Vo et al. 2019). Compared with the traditional activated sludge process, this technology has not only achieved success in wastewater treatment but also saved area and limited sludge production (Elgarahy et al. 2021). As a recognized industrial and urban wastewater treatment technology, the feasibility of membrane bioreactor for microplastics removal has been verified on pilot scale and in actual wastewater treatment plants (Talvitie et al. 2017; Lares et al. 2018). Membrane bioreactor can achieve microplastics retention of up to 99.9%, which shows a better removal effect than fast sand filtration (97%), dissolved air flotation (95%), and disc filter (40–98.5%) (Talvitie et al. 2017). Therefore, as a secondary or tertiary treatment process, membrane bioreactor may be the most effective method to remove microplastics from wastewater among common wastewater treatment technologies.

2.3.2 Enzyme System for Microplastics

Microbial enzymes system are powerful tools for degrading different toxic and industrial pollutants (Pandey et al. 2021). However, enzymatic treatment of wastewater to remove microplastics is a time-consuming and cumbersome process (Zurier and Goddard 2021). Polymers are difficult to biodegrade, and the factors leading to this behavior include strong C-C bonds, high molecular weight, hydrophobic surface, and crystallinity of polymers. However, few extracellular enzymes have been identified and reported to be able to degrade synthetic polymers (Show et al. 2021). Enzymatic degradation is a two-step process/mechanism. First, the enzyme adsorbs on the polymer surface, which is called the enzyme surface modification mechanism. Secondly, the polymer undergoes enzymatic hydrolysis (Show et al. 2021; Othman et al. 2021). Enzymes involved in surface modification change the polymer surface by increasing the hydrophilicity of the polymer, making it easy to degrade. The enzymes responsible for this modification are hydrolases, such as lipase, keratinase, protease, and carboxylesterase. Polymer hydrolysis involves enzymes that can depolymerize polymers into monomers. The enzymes responsible for depolymerization include esterase, hydrolase, oxidase, peroxidase, laccase, and amidase (Show et al. 2021; Othman et al. 2021). At present, researchers mainly focus on the biodegradation of polyethylene terephthalate (PET). Because PET has an amorphous and low-density structure, it is more easily biodegradable than other polymers with crystalline shapes (Yoshida et al. 2016). However, the enzymatic degradation of other microplastics is rarely reported. Genetic engineering to produce engineering strains with high-efficiency degrading enzymes may provide a new driving force for the development of enzyme system degrading microplastics (Gaur et al. 2022).

2.3.3 Biodegradation

Bioremediation is probably the most widely used technology in the remediation of contaminated waters (Das 2014). Although in most cases, they are not specifically designed to remove and degrade microplastics, such functions have great control and purification prospects for applications in microplastics. The most commonly used bioremediation technologies are bioaugmentation and biostimulation (Das 2014). The organisms for repairing microplastics can be one or more combinations of bacteria, fungi, and algae. Since the 1970s, polyethylene, polypropylene, and polystyrene microplastics have been considered non-biodegradable in the natural environment (Yang et al. 2014; Wu et al. 2016). Until recently, it was reported that *Bacillus* and *Enterobacter* (*Plodia internella*) strains isolated from the worm intestine could biodegrade polyethylene microplastics (Yang et al. 2014). Compared with other non-biological purification methods, biodegradation has the advantages of environmental friendliness, low cost, low energy input, and optimization of carbon footprint. Microorganisms can use plastics as carbon and nitrogen sources to survive and proliferate (Montazer et al. 2020; Hu et al. 2021). The microorganisms used for bioremediation may be non-specific microorganisms isolated from compost, activated sludge or soil, highly specific microorganisms with target pollutant degradation and genetically engineered microorganisms. Genetically engineered microorganisms are developed by inserting or deleting unwanted genes to design genomes. The specific remediation process and mechanism are partially explained in the review by Hu et al. (Hu et al. 2021), and detailed in the review by Miloloža et al. (Miloloža et al. 2022).

2.3.4 Constructed Wetlands

Constructed wetland (CW), a natural wastewater treatment system, is not only simple to operate and convenient to maintain (Xu et al. 2021c), but also possible to eliminate multiple pollutants in wastewater at the same time (Liu et al. 2020). Constructed wetlands shows excellent removal efficiency for common pollutants (i.e., total phosphorus, total nitrogen, chemical oxygen demand, ammonia nitrogen, nitrate, nitrite, heavy metal pollutants), drugs and personal care products, and various emerging environmental pollutants) (Xu et al. 2022b), and shows an optimistic microplastics removal effect (Wang et al. 2021a).

Free water surface flow (FWS) constructed wetlands and subsurface flow constructed wetlands are two common types of constructed wetlands, which are different according to the structure type and flow direction (Li et al. 2018; Headley and Tanner 2012). Physical filtration, retention or adsorption are the main mechanisms of removing microplastics from constructed wetlands. The removal rate of microplastics in constructed wetlands is 30–100% (Xu et al. 2022b). Compared with free water surface flow-constructed wetlands, subsurface flow-constructed wetlands has better removal effect on microplastics. Subsurface flow -constructed wetlands not only has the physical filtering effect of free water surface flow-constructed wetlands on microplastics in wastewater (Pedescoll et al. 2013; Wang et al. 2021b; Wang et al. 2020). Moreover, retention and adsorption are not available in free water surface flow-constructed wetlands because the matrix materials in subsurface flow-constructed wetlands are completely in direct contact with wastewater (Hernández-Crespo et al. 2017). In addition, the development of hybrid constructed wetlands (Hickey et al. 2018) seems to be a more effective strategy to improve the removal efficiency of microplastics in the aqueous environment (Gonzalo et al. 2017). Hybrid constructed wetland combines the advantages of a single constructed wetlands through the combination of two or more constructed wetlands, and can realize the full play of the function of removing microplastics (physical filtration, retention and adsorption) of constructed wetlands (Nguyen et al. 2018).

The physical and chemical properties of microplastics play a key role in the removal of microplastics by constructed wetlands. In the constructed wetlands system, microplastics of smaller size tend to provide a better removal effect (Zhou et al. 2021b). Fiber microplastics is easier to remove than particles or microbeads (Liu et al. 2019b). Compared with shape and size, biodegradable microplastics are easier to be removed by constructed wetlands for microplastics with different chemical structures (Wang et al. 2021b). At the same time, the components of the constructed wetlands system, including matrix materials, plant systems, and biological communities, play an important role in the removal of microplastics by constructed wetlands. The increase of mineral content in constructed wetlands has been proven to greatly enhance the removal process of microplastics (Kniggendorf et al. 2021). Negatively charged microplastics can easily combine with metal cations in minerals to form denser hydroxides, thus promoting the precipitation process (Qian et al. 2021; Jian et al. 2020). Generally speaking, microplastics with smaller particle sizes in constructed wetlands can be effectively retained by biofilms, plant roots, or organisms, and the removal efficiency of microplastics can be as high as 94% (Xu et al. 2022b). microplastics are mainly retained in the constructed wetlands system in the form of interception and adsorption to achieve the effect of purifying water. Unlike traditional pollutants, microplastics cannot be degraded by microorganisms and plants in the water body in a short time, which will lead to the enrichment of microplastics in the subsequent food chain (Merga et al. 2020). Although this 'enrichment' seems to provide constructed wetlands with the potential to remove microplastics, most microplastics are excreted in faeces, which may lead to secondary pollution of the environment (Piarulli et al. 2020).

3 Comparative Analysis of Different Remediation Technologies

The above-mentioned physical, chemical, and biological remediation technologies are relatively mature or promising technologies in the field of sewage treatment. They may not be born specifically to remediate microplastics' pollution, but they

Table 2 Performance of microplastics remediation technologies

Technologies of microplastics' remediation	Running cost	Safety	Flexibility	Sustainability	Separation efficiency	Conversion efficiency	Opportunity
Accumulation of microplastics by the activated sludge process (ASP)	2	5	2	8	8	1	7.5
Adsorption and filtration	6	8	8	6	10	0	8
Magnetic separation	7	6	8	6	7	0	6
Density separation	8	5	7	5	6	0	6.5
Coagulation, enhanced coagulation, and electro-coagulation (Coagulation)	7	6	9	8	9	0	8.5
Disinfection	8	3	9	10	0.5	6.5	2
AOPs	10	4	8	6	3	9	7.5
MBR	6	9	1	9	9.5	2	8.5
Enzyme system for microplastics (Enzyme system)	8	9	3	6	2	7	4.5
Biodegradation	4	9	2	9	1.5	7.5	7
constructed wetland	1	10	1	8	7.5	3.5	7

Note: the score range is 0–10, and the higher the value, the higher the score of this technology in this evaluation part. For example, the score of AOPs in the running cost item is 10, which means that its running cost is the highest among all the microplastics' remediation technologies, while the score of adsorption and filtration in the conversion efficiency item is 0, which means that it can only separate microplastics from water, but cannot degrade or mineralize microplastics

have made great contributions to the removal of microplastics in water. To make their advantages and disadvantages stand out, various technologies are compared from seven aspects: running cost, safety, flexibility, sustainability, separation efficiency, conversion efficiency, and opportunity, as shown in Table 2. This evaluation metric system draws on the description of Chen et al. (Chen et al. 2022a) in their review. Principal component analysis (PCA) is used to analyze the 7 metrics of microplastics removal in each technology to highlight their advantages of them in the field of microplastics' remediation. As shown in Fig. 3a, the first two principal components (PC1 and PC2) can explain 71.54% of the attribute changes in the 7 metrics. Therefore, the first two principal components provide sufficient information for the following analysis.

As shown in Fig. 3b, 7 metrics and 11 technologies are divided into four quadrants. First of all, two technologies (adsorption and filtration, and coagulation) and two metrics (separation efficiency and opportunity) are divided into the first quadrant, which shows that these two technologies have advantages in separation efficiency and brighter development prospects. Secondly, the situation in the second quadrant indicates that although the three technologies of magnetic separation, density separate, on and AOPs have the highest flexibility, they are also limited by operating costs, so their application in specific wastewater is more appropriate or

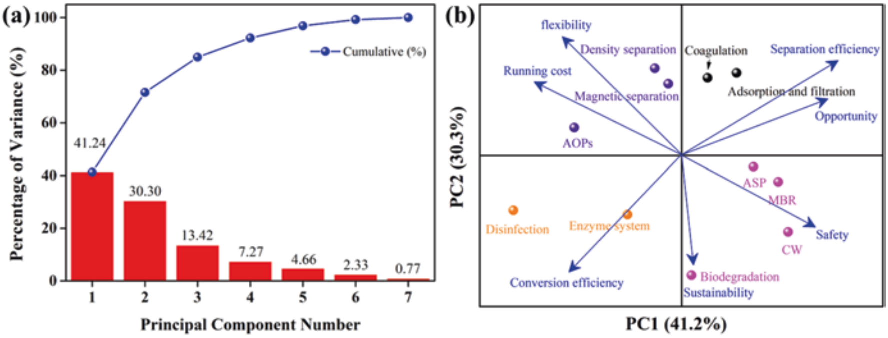

Fig. 3 (**a**) Percentage variance explained by different principal components. (**b**) Principal component analysis (PCA) for the general performance metrics in different technologies of microplastics' remediation

become the choice of pollution remediation emergency technology. Third, only the conversion efficiency is the advantage metric of disinfection and enzyme system. How to further develop their efficiency in other aspects is the focus of future research. Finally, four technologies (ASP, MBR, biodegradation, and constructed wetland) and two metrics (safety and sustainability) are in the fourth quadrant. These four technologies are all related to biological treatment. Among them, ASP, MBR, and constructed wetland are clustered near the eigenvector (safety), indicating that the safety of traditional biological treatment technology is its unique advantage, sustainability reflects the universality of biodegradation technology in the treatment of traditional pollutants and new pollutants (including microplastics). Therefore, the existing remediation technologies have their advantages for the removal of microplastics. A reasonable combination of them may enable them to have broader prospects in practical applications.

4 Perspective

Over the past 50 years, 9.1 billion tons of plastic waste has been discarded into the environment and is expected to continue to grow at an annual rate of 8.7% (Geyer et al. 2017). The production and use of plastics is the main source of microplastics in the aqueous environment. Therefore, reducing the use of plastics or using biodegradable plastics may be the best way to effectively avoid the continuous high content of microplastics in the aquatic environment. The end-treatment of microplastics is also essential as the final remedy for microplastics harming aquatic ecology and human health in the aquatic environment. Among them, coagulation, adsorption and filtration are undoubtedly the fastest and most effective methods to remove microplastics in the water environment. They may have a broader future in the field of drinking water treatment. Traditional waterworks already have these functional units, and only a little improvement is needed to meet the requirements for microplastics removal indicators in the future. ASP, MBR and constructed wetland have good prospects for the removal of microplastics in the field of reclaimed water and landscape water, and their safe and efficient characteristics also determine that they are suitable for the treatment of surface water with large water volume; Although AOPs, disinfection and enzyme system can degrade microplastics in the water environment to a certain extent, they may only be used in slightly polluted water bodies due to high operating costs and secondary pollution problems caused by incomplete degradation. For microplastics' pollution from point sources, such as wastewater treatment plants, the coupling of existing technologies may be the future development trend of better removal of microplastics. For example, the combination of ASP + coagulation + constructed wetland of wastewater treatment plants can basically ensure that most of the microplastics in urban sewage do not enter the aqueous environment through the sewage pipe network. However, for microplastics' pollution from non-point sources, such as surface runoff, we cannot completely collect microplastics, and thus cannot effectively remove them. This may be the pain point of microplastics end-treatment in the future, which needs further research.

5 Conclusion

The existing physical, chemical and biological remediation technologies have shown excellent performance in microplastics' remediation, but they have their boundedness. No one technology is suitable for microplastics' remediation tasks under various conditions. In addition, wastewater treatment plants can efficiently transfer the microplastics in the sewage to the residual sludge. The WWTP itself is a coupling system of physical, chemical, and biological technologies, integrating the advantages of various technologies to achieve this effect. Therefore, appropriate technology selection and an effective multi technology coupling strategy are the keys to solve the current microplastics' remediation in aqueous environment.

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Removal of Environmental Microplastics by Advanced Oxidation Processes

Sapana Jadoun, Juan Pablo Fuentes, Orlando Yepsen, and Jorge Yáñez

Abstract Microplastics are widespread in the environment, which generates high concern worldwide. Microplastics have been found in superficial and ocean waters and soils, and consequently can occur in drinking water, urban wastewaters, and living organisms. Here we review microplastics with emphasis on sources, types, toxicity, analysis and removal techniques. For removal, we focus on advanced oxidation processes for plastic degradation. Thes processes involve highly reactive oxygen species such as hydroxyl, $^{\bullet}OH$, superoxide radical, $^{\bullet}O_2^-$, sulfate radical, $SO_4^{\bullet -}$, and hydrogen peroxide H_2O_2.

Keywords Microplastics · Degradation, removal · Hazardous · Advanced oxidation process · Reactive oxygen species

1 Introduction

Microplastics (MPs) have become a major environmental problem, due to their global dispersal, long lifetimes, small sizes, difficulty for controlling sources and discarded environmental phenomenon. It is leaving a long-term ecological impact globally due to their universal detection and is raising a significant alarm on water security systems (Bellasi et al. 2020). It comes from plastics which are synthetic

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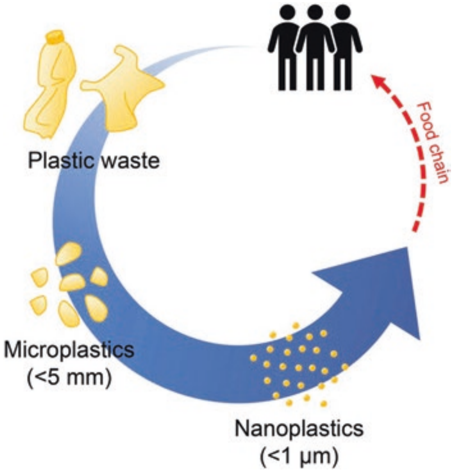

Fig. 1 Plastic waste fragmentation into microplastics and nanoplastics. (Reproduced from Urso and Pumera 2022 with permission)

polymers possessing outstanding properties, and high thermal and chemical stability. They are widely used due to their excellent properties while difficult to remove or degrade from the environment increasing plastic waste (Nawalage and Bellanthudawa 2022). These plastics make microplastics pollution under the action of the sea and weathering in form of continuing fragments into smaller size particles. The fragments less than 5 mm in size are known as microplastics while these can degrade in pieces smaller than 1 μm, known as nanoplastics, Fig. 1 (Urso and Pumera 2022). Microplastics become more toxic when serving as a substrate for the growth of bacterial biofilms or adsorptive material for the pollutants present in wastewater and enter the food chain through seafood and edible aquatic animals ultimately reaching our table or polluting drinking water causing a threat to living beings. Production of plastics and their uses are expected to expand (Okeke et al. 2022). An alarm sound in the north Atlantic Ocean by plastic pellets was first time reported by E.J. Carpenter and it can be assumed that how much plastics are reaching the seas, rivers, oceans, and other water sources to decompose and fragment resulting in microplastics and nanoplastics (NP, Carpenter and Smith Jr 1972).

There are several methods reported for the removal of microplastics from water resources. Advanced oxidation processes (AOP) are a cleaner approach to removing microplastics (Li et al. 2020). This process attracted attention for many decades due to toxic less and safer ways to eliminate numerous types of pollutants from the environment (Jadoun et al. 2022). AOPs involve the production of active reactive oxygen species which are responsible for the degradation of high molecular weight plastics to small intermediates for mineralization (Melin et al. 2021).

2 Plastics and Microplastics

Numerous developments have been done increasing the diversification of plastics, and improvement of plastics, and technologies in plastic industries after the first discovery of polystyrene-based plastics done by Eduard Simon in 1839 (Hu et al. 2021). Plastics possess attractive features and flexibility for various applications. The data for 2022 confirmed that plastic manufacturing is bouncing back after a turbulent period. The global production of plastic shows strong demand for plastic by the rise of 4% to more than 390 million tons (MT) and Europe is top on that challenge. Production of plastic in China is 32% more in 2021 while Europe shares 57.2 million tons in 2021. The COVID pandemic and the Ukraine war have even worsened the scenario (PlasticEurope: Plastics – The Facts 2022). The largest end-use markets of plastics are construction, building, and packing. The most used plastics in these markets are polyvinyl chloride (PVC), polypropylene (PP), and polyethylene (PE). Debris (fragments) of plastics were first coined in 1970s, however, the microplastics term was used by Thomspon in 2004 to define the plastic pollution (Thompson et al. 2004). Microplastics are plastics smaller than 5 mm (upper size limit) while the term nanoplastics could be used for plastics of size less than 1 μm. The various microplastics such as polyamides (PA), polystyrene (PS), PVC, PP and PE. The fate of these microstructures depend on their shapes and morphologies. There are scare studies done on microplastics and nanoplastics (NPs) owing to the new field of research (Caputo et al. 2021). According to literature, there are 42 patents on removal of microplastics and NPs have been published and foreseen to increase significantly soon. From all the patents, 19 patents were only from China while South Korea, United States, and Japan published 10, 7 and 4 patents. Patents published on this topic by year and by country are mentioned in Fig. 2 (Hanif et al. 2022).

3 Sources of and Types of Microplastics

The potential origin of microplastics are the discarded plastics which degrades with time resulting in plastic debris. These materials come by the fate of discard by plastic wastes. Other than these, goes for recycle and thermal destruction (Singh et al. 2017). These microplastics are of two types according to their sources: primary and secondary. Primary source of microplastics includes plastic fibers, plastic pellets, microbeads, etc. from synthetic textiles, industries, and personal care products. The secondary sources are the result of breakdown of large plastics into smaller fragments which happens naturally due to action of water such as exposure to the ultraviolet radiations, air abrasion, wave actions) (An et al. 2020). Both combinedly goes in breakdown resulting in microplastics in the environment and cause of plastic pollution, Fig. 3a (Chellasamy et al. 2022).

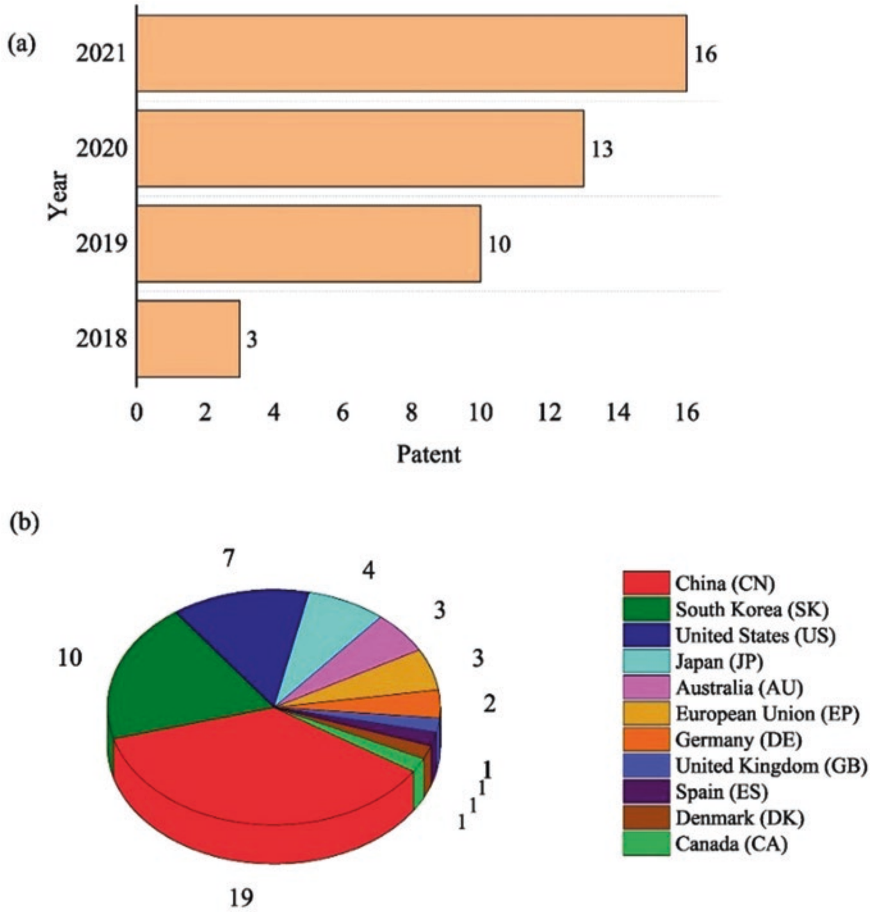

Fig. 2 Number of patents published by (**a**) year and (**b**) granting country or organization. (Reproduced from Hanif et al. (2022) with permission)

Microplastics are generally found in wastewater effluents, beaches, seabed sediments, shorelines, floating and ice surface water. Ocean currents throw these microplastics to Antarctic and Arctic regions. Many sea creatures consume these microplastics scattered in marine environment and was found in more than 114 aquatic species (Szymańska and Obolewski 2020) and they faced numerous issues such as oxidative stress, reduced growth rate, blocked enzyme production, reproductive issues, false satiation, etc. Rivers and lakes were also detected with the abundance of microplastics (Auta et al. 2017). Additionally, in a pilot study, these microplastics were detected in human stool samples. These were also recovered from human organs and tissues. Consequently, microplastics have become known a

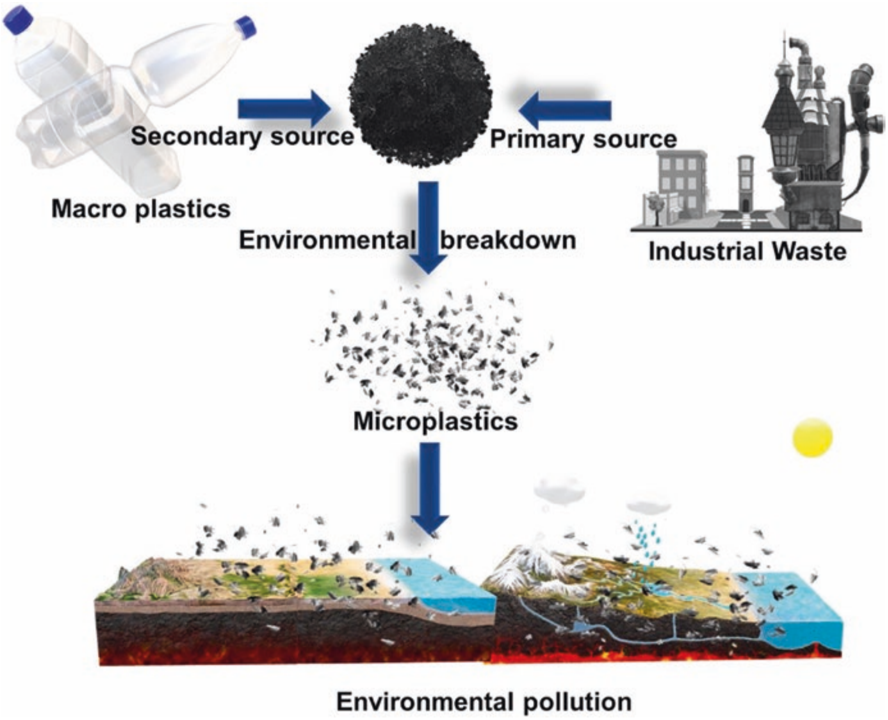

Fig. 3 General sources of microplastics in the environment, including primary and secondary sources. (Reproduced from Chellasamy et al. (2022) with permission)

critical class of materials as use of these are increasing day by day giving threat to living beings (Jiang et al. 2020). The estimation of these given by researchers shows the 12 billion metric tons of plastic waste in environment by 2050 (Borrelle et al. 2017; Geyer et al. 2017). Thus, there is an urgent need to eliminate microplastics from marine environment.

More than 80% plastics include PE, PVC, PET, PS, PP, and PU while recent research shows that polyester (PES), acrylic, and nylon are too much found in the environment. Lesser reported microplastics are polysulfone (PSU) polycarbonate (PC), acrylonitrile-butadiene-styrene copolymer (ABS) and some biodegradable plastics. The primary plastic wastes from polymers are shown in Fig. 4 (Hu et al. 2021). These plastics have been divided in two types according to their stability and degradation possibilities. The first group possess C-C bonded plastics including acrylic, PVC, PS, PP, and PE, while the other group include the plastics with hetero-atom PU, PET, PES, and PA. The first group is prone to photo-initiated degradation while the second group belong to hydrolytic cleavage of ester or amide bond due to high thermal stability of these (Gewert et al. 2015).

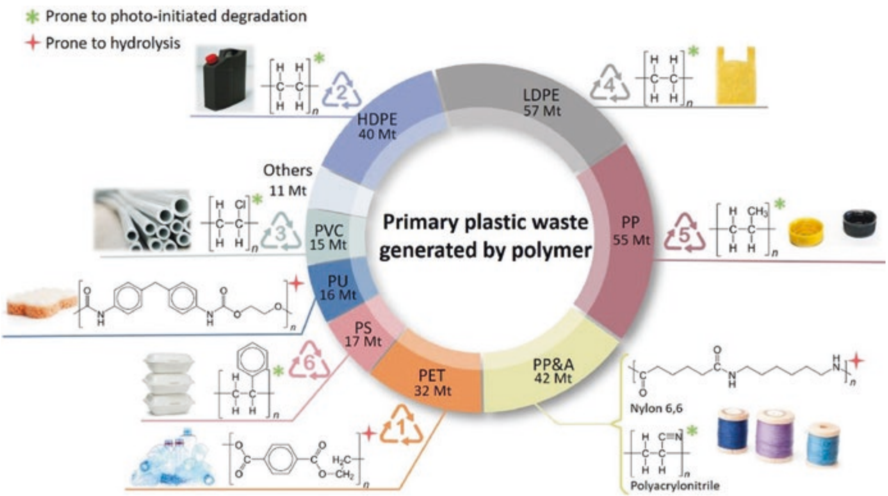

Fig. 4 Polymers that are commonly reported in microplastic research and their contributions to the primary plastic wastes in 2015. Abbreviations: LDPE for low-density polyethylene, HDPE for high-density polyethylene, PP&A for polyester, polyamide and acrylic. (Reproduced from Hu et al. (2021)) with permission)

4 Toxicity of Microplastics and Its Effects on Health

Microplastics can give numerous harmful effects on living beings due to its toxic nature. A fish can be infected with a change of metabolic activity, decrement in essential enzyme activity, oxidative stress, and harmful effects on the endocrine and reproductive system. The early life stage of fish could be hardly affected by microplastics environment which includes growth od larva, reduction in body length, and hatching time. Other than these, fishes face DNA breakdown, cardiovascular anomalies resulting the larval death by harmful effects of microplastics (Jovanović 2017; Kim et al. 2021).

Microplastics swallowed into the human body can be absorbed by intestinal epithelium or can be indirectly absorbed by M cells of the Payer's patch. Microplastics can be easily translocated through the bloodstream finally accumulated in liver. Some small microplastics can be inserted in the respiratory system by nasal cavities and accumulated in the lungs. These can also be absorbed through the mucous membranes and skin by ingredients of prosthetic makeup, surgical gloves, personal care products, and many more (Fournier et al. 2021; Yee et al. 2021). Numerous neurodegenerative diseases such as Alzheimer's disease can be caused by microplastics by increased oxidative stress along with neurotoxicity, cytotoxicity, chronic inflammation. Certain chemicals present in microplastics are carcinogenic and responsible for cancer by excessive cell proliferation (Prata et al. 2020; Watts and Chan 2022). The hormonal imbalances occur frequently nowadays and microplastics are one of the reasons for that as chemical components of microplastics behave

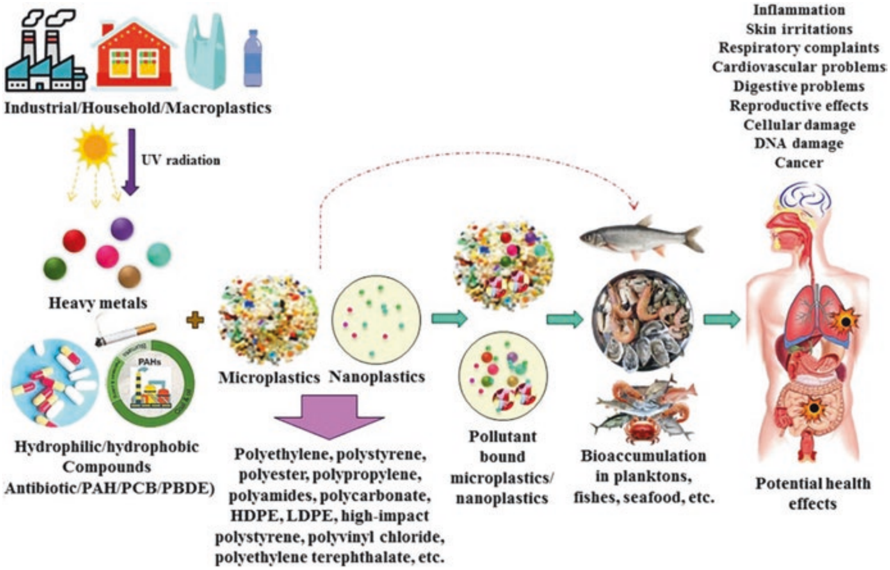

Fig. 5 Bioaccumulation of microplastics and nanoplastics in trophic levels, and harmful effects on human health. (Reproduced from Jaiswal et al. (2022) with permission)

as an endocrine system's modulator. Various infections and tissue damage are also a part of toxicity of microplastics by offering the surface area for colonization of bacteria. Accumulation of microplastics and its effects on human's health are shown in Fig. 5 (Jaiswal et al. 2022).

5 Analysis of Microplastics

For the removal of microplastics from water, suitable analysis is required to access the quantitative and qualitative characteristics. Microplastics are generally analysed for their size, chemical composition, number, and their concentration (Castillo et al. 2020). Quantitative analysis is a crucial information for precis assessment of removal of microplastics. Even though there are some limitation of microscopy based analysis techniques and could be combinedly study with Fourier-transform infrared spectroscopy (FTIR). These techniques can detect the plastic particles (Vermaire et al. 2017). However, FTIR showed non-plastic nature of 90% suspended microparticles in reported works (Ziajahromi et al. 2017; Lares et al. 2018). Sometimes error occurred due to smaller size of microplastics than 100 μm. Consequently, accurate analysis techniques are the key parameter to analyse microplastics (Karimi Estahbanati et al. 2021). Numerous techniques used for analysis can be divided in two parts Fig. 6 (Karimi Estahbanati et al. 2021):

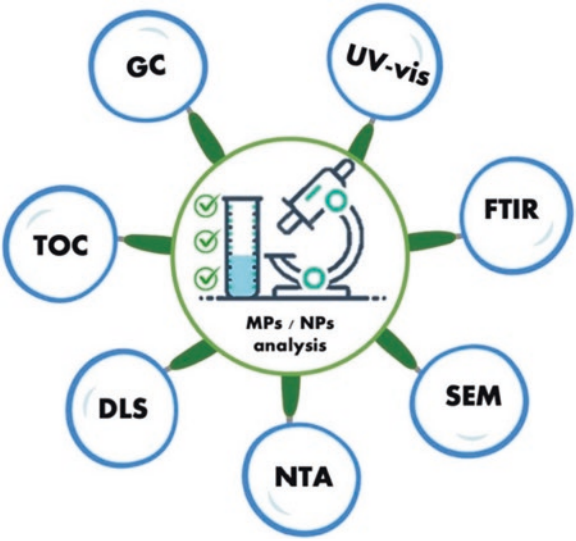

Fig. 6 Most common microplastic (MP) and nanoplastic (NP) analysis techniques in water treatment processes. (Reproduced from. Karimi Estahbanati et al. (2021) with permission)

1. Qualitative analysis: UV-visible spectroscopy, FTIR, SEM (scanning electron microscopy), NTA (nanoparticle tracking analysis), stereo microscopy, and DLS (dynamic light scattering)
2. Quantitative analysis: UV-visible spectroscopy, TOC (total organic carbon), gas chromatography, and weight measurement by scale.

However, the number of MPS could be overestimated by using NTA and DLS due to the impurities present. In addition, these impurities can affect the intensity of the band or the wavelength in FTIR spectra (Caputo et al. 2021). Therefore, the removal of impurities before analysis is mandatory by pre-treating the samples for removal or organic and inorganic matter. Some methods for pre-treatment are: catalytic oxidation, enzymatic maceration, by H_2O_2 (Schrank et al. 2022).

6 Techniques for the Removal of Microplastics from Water

Removal of microplastics pollution has become to the worldwide challenge and very less possible solutions. Some most common techniques for the removal of pollutants are: adsorption, filtration, chemical removal, biological removal, photocatalysis, and others (Padervand et al. 2020; Singh Rathore et al. 2022; Jadoun et al. 2023; Jabin et al. 2023). Drinking water treatment plants (DWTPs) have been set up to remove microplastics from drinking water. Traditional drinking water treatment plants to remove microplastics includes coagulation, sedimentation, filtration, and clarification. Microplastics quantity can be decreased after filtration process (Pivokonský et al. 2020). Rivers and reservoirs of Czech Republic have been treated using DWTPs technique to remove microplastics having size less than 1 µm. The content of microplastics in treated water was found decreased (0–7 particles/m^3) as compared to raw water. A cost-effective tertiary treatment process that is electrocoagulation does not depend on microbes/chemicals. Instead of that, it involved the use of metal electrodes in the electric field to produce cations and coagulants making this process straightforward and robust. This process is called eco-friendly because of no use of oxidant and reductant (Tang et al. 2022).

Magnetic extraction is a recent technique to remove microplastics from water. To improve the speed of separation, this process involved the use of magnetic seeds and acid in external magnetic field (Mateus et al. 2018). For this, Grab et al. (Grbic et al. 2019) have proposed the use of Fe nanoparticle owing to their ferromagnetic properties, high surface area and low cost. To insert the hydrophobic properties, these particles were covered with hexadecyltrimethoxysilane permitting the microplastics isolation using magnetic extraction technique. The other treatment technology is membrane separation technology which is frequently used and has many advantages over other techniques such as easy procedure and stable effluent quality. This technology can be divided in three parts based on the membrane size: ultrafiltration, nanofiltration, and reverse osmosis (Poerio et al. 2019). This technology can eliminate multivalent ions, organic pollutants, and disinfection by-products owing to strong selectivity and separation of membrane (Shi et al. 2022). This technique was used to eliminate microplastics from China's largest water reclamation plant (Yang et al. 2019). During COVID-19, microplastics were treated using biochars which was reviewed by Abufatba and coworkers (Abuwatfa et al. 2021). Tang et al. (2021) used magnetic carbon nanotubes for removal of microplastics from water.

7 Advanced Oxidation Processes for the Removal of Microplastics

AOPs have attracted attention owing to its green approach for the elimination of microplastics from environment safely. Oxidizing free radical generated by AOPs can degrade the high molecular weight microplastics chains to low molecular weight chains promoting the final degradation to CO_2 and H_2O, Fig. 7 (Shen et al. 2022). AOPs can match the efficiency with other conventional water treatment process using the greener way. AOPs includes the production of the strong and most important radicals possessing high redox potentials that are: hydroxyl radical ($^{\bullet}OH$), superoxide radical ($^{\bullet}O_2^-$) and sulfate radical ($SO_4^{\bullet-}$), hydrogen peroxide (H_2O_2). These radicals are responsible for degradation of long chain polymers to small fragments. Microplastics showed fading, embrittlement, cracking, crushing, and eliminating steps in macroscopic manifestations, Fig. 8 (Ranjan and Goel 2019; Shen et al. 2022).

Photocatalysis has been used widely for the removal of numerous types of pollutants from water. It includes the use of UV and visible light from the solar energy (clean energy) and change it to chemical energy to degrade the pollutants in a

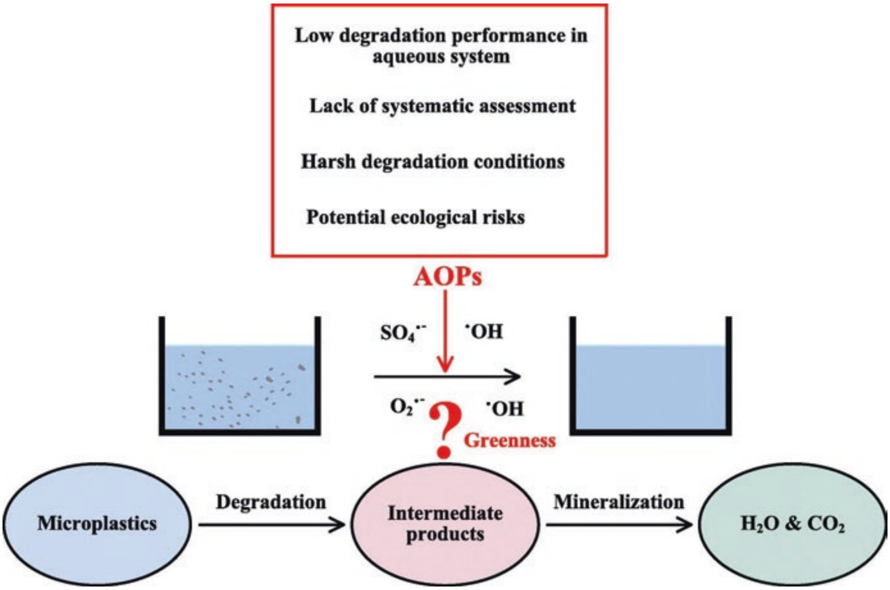

Fig. 7 Advanced oxidation process for the degradation of microplastics for environmental remediation (Reproduced from Shen et al. (2022) with permission. AOP: advanced oxidation processes)

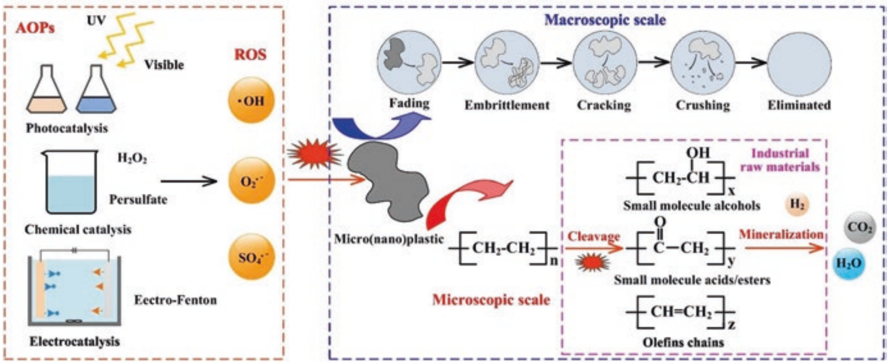

Fig. 8 Processes and mechanisms of removing microplastics by advanced oxidation processes using electro-Fenton . (Reproduced from Shen et al. (2022) with permission)

non-toxic way (Jangid et al. 2021). Semiconductors used in photocatalysis provides electrons and holes responsible for oxidation and reduction reactions, respectively to eliminate the pollutants (Yepsen et al. 2015; Acuña et al. 2017).

The photocatalytic degradation of PS and PE was done under UV light irradiation using TiO_2 as a semiconductor. The results showed the 98.4% degradation of PS in 12 hours while complete degradation of PE was seen in 36 hours. Detection of hydroxyl, hydrocarbon and carbonyl groups, CO_2 as the final product proved the degradation of microplastics (Nabi et al. 2020). Low density LDPE (low density polyethylene) film were degraded using ZnO nanorods by photocatalysis into carbonyl and vinyl, CO_2, and H_2O. This degradation was done in 175 hours of visible light irradiation and the $^{\bullet}OH$ and $O_2^{\bullet -}$ were responsible for the breakage of C-C bond resulting degradation of microplastics (Tofa et al. 2019). ZnO nanorods were also used by Uheida and coworkers (Uheida et al. 2021) for the degradation of PP (polypropylene) and the average particle volume of the microplastics was reduced by 65% in 14 days of irradiation. Nb_2O_5 thin layers were used for the 100% degradation of PE into CO_2 and H_2O in 40 hours. The key mechanism involved was the oxidative C-C fragmentation by $^{\bullet}OH$ and $O_2^{\bullet -}$ while H^+ reacted with CO_2 for the formation of $^{\bullet}COOH$. Mixtures of intermediates $^{\bullet}OCH_2$-COOH, $^{\bullet}$C-COOH, $^{\bullet}$OCH-reduced by CO_2 were responsible for formation of CH_3COOH (Jiao et al. 2020).

Some other authors reported the degradation of numerous types of microplastics by using visible light photocatalysts such as MXene/ZnxCd1-xS for degradation of polyethylene terephthalate (PET) (Cao et al. 2022). For improving the strength of degradation, $SO_4^{\bullet -}$ and some other intermediates were responsible for the degradation of PE in 8 hours at 160 °C by manganese nanoparticles supported magnetic nitrogen doped spring carbon nanotube (Kang et al. 2019).

Fenton and photo Fenton processes are involved as other advanced oxidation processes occurred acidic medium (optimum pH 2.5–3.0) and Fe^{2+} ions for the decomposition of H_2O_2 to generate $^{\bullet}OH$ (Velásquez et al. 2014). While Fenton process have some limitations which can be overcome with electric-Fenton process using electrons as the reactants. Due to electrochemical reduction of O_2 and by providing the regenerated Fe^{2+} ions at the cathode continuously, H_2O_2 is generated to form $^{\bullet}OH$ (Salazar et al. 2017). For the degradation of PVC, TiO_2 was combined with graphite cathode to form a heterogenous electro-Fenton composite. 56% degradation of PVC in small fragments resulting mineralization to CO_2 and H_2O was achieved by the $^{\bullet}OH$ oxidation and cathodic reduction after 6 h of reaction (Miao et al. 2020). A small amount of Na_2SO_4 (sodium sulphate) (0.03 mol L^{-1} increased the efficiency of degradation of PS up to 89% (Kiendrebeogo et al. 2021).

8 Photocatalytic Mechanism for the Degradation of Microplastics

The mechanism of degradation of microplastics using TiO_2 as catalyst possessing the band gap of 3.2 eV for anatase (excitation wavelength 388 nm) while 3.0 eV for rutile (excitation wavelength 410 nm) (Tobaldi et al. 2014). It involves the excitation of electrons (e^-) from valence band (VB) after the irradiation of light onto the surface of TiO_2. Electrons from the VB moves to the conduction band (CB) and leaving a hole (h^+) in the VB and electrons in the CB. The excitation of electrons and movement to the CB has been shown in Fig. 9a. The mechanism for degradation of

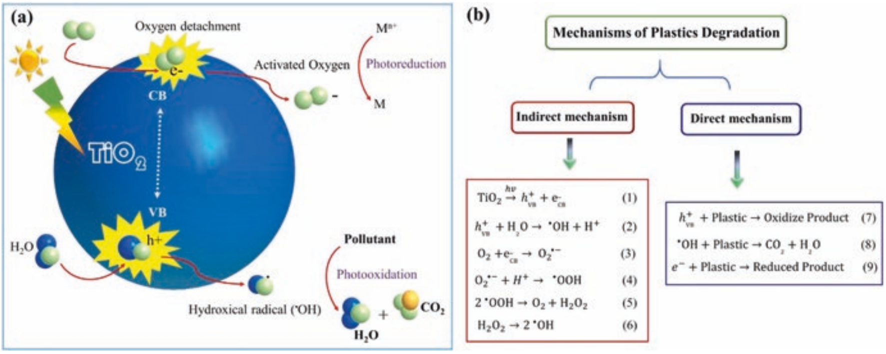

Fig. 9 (**a**) Photocatalytic mechanism of TiO_2 under light irradiation. (**b**) Photocatalytic mechanism of TiO_2 for plastics decomposition under light irradiation. (Reproduced from Nabi et al. (2021) with permission)

plastic includes 2 principles: Direction degradation and indirect degradation which are summarized in Fig. 9b (Nabi et al. 2021).

8.1 Direct Photodegradation

Microplastics can be degraded directly by absorbing the UV-visible light and microplastics gets excited to CB. A semi oxidized radial cation will be formed by this action. Dissolved O_2 will take the e^- to form $O_2^{\bullet-}$ which turns to the $^{\bullet}OH$ responsible for degradation of microplastics (Du et al. 2021). The mechanism is as follows:

$$Microplastic + hv \rightarrow Microplastic^{*}$$

$$Microplastic^{*} + TiO_2 \rightarrow Microplastic^{+} + TiO_2^{-}$$

8.2 Indirect Degradation

Indirect degradation of microplastics involves multiple steps as follows (Dong et al. 2022):

1. Photocatalysis starts with the excitation of e^- in the VB and promotes to the CB leaving a h^+ in the VB upon irradiation of light having energy equal of greater than the band gap of TiO_2 (Ajmal et al. 2014).

$$TiO_2 \rightarrow e_{CB}^{-} + h_{VB}^{+}$$

2. Second step is the water ionization step in which the water molecule reacts with the h^+ present in *VB* forming the HO$^\bullet$ radical which is strong oxidizing agent responsible for photooxidation and mineralization process (Rajput et al. 2021)

$$H_2O + h_{VB}^{+} \rightarrow HO^{\bullet}$$

3. Third step include the use of e^- present in the CB for the formation of superoxide radical ($O_2^{\bullet -}$) for inhibiting the recombination of e^- and h^+ (Liu et al. 2021).

$$e_{CB}^{-} + O_2 \rightarrow O_2^{-\bullet}$$

4. $O_2^{\bullet -}$ produced in step 3 will produce hydroperoxyl radical (HOO$^\bullet$) resulting in the formation of hydrogen peroxide and further dissociate in $^\bullet$OH (Nguyen et al. 2022)

$$O_2^{-\bullet} + H^+ \rightarrow HOO^{\bullet}$$
$$2HOO^{\bullet} \rightarrow O_2 + H_2O_2$$
$$H_2O_2 \rightarrow 2HO^{\bullet}$$

The complete reaction for degradation of microplastics in an indirect way is shown as follows (Zhu et al. 2020):

$$h_{VB}^{+} + microplatics \rightarrow oxidized\ products$$
$$HO^{\bullet} + microplastics \rightarrow CO_2 + H_2O$$
$$e_{CB}^{-} + microplastcis \rightarrow reduced\ products$$

9 Conclusion

AOPs have been attracted attention for the removal of numerous varieties of pollutants from environment by using clean energy. ROS a strong oxidizing and reducing nature play a key role in the degradation of high molecular weight microplastics to small fragments and then mineralization of those. However, some studies claimed that treated microplastics as pollutant carrier by adsorption of contaminants is a threat to living beings. Therefore, the studies are very limited, and no study showed the 100% removal of microplastics from the environment. More studies are needed in this field in near future by designing more advanced materials and experiments from lab to ground scale. There should be the implementation of the application because the process in the lab requires specific conditions of pH, temperature, concentration, and others however, the field conditions are not always feasible and may be some complex environment. Thus, more in-depth, and systematic research is still required in this field. Also, there are two types of plastics: synthetic and biobased.

People should be aware of the use of bio-based plastic in place of plastic as it does not affect significantly to the environment.

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Techniques for Removal and Degradation of Microplastics

Akhila Subair, Meera G., Suchith Chellappan, Sajithkumar K. J., Chinghakham Chinglenthoiba, Priya K. L., and Indu M. S.

Abstract This chapter presents remediation techniques to remove and degrade microplastics. Physical treatments include coagulation, flocculation, flotation, granular filtration, and membrane processes. Targeted removal of microplastics can be done by adsorption on metal-organic frameworks, biochar, biopolymers, and magnetic separation. Microplastics can be degraded by biodegradation, thermal degradation, hydrolytic and mechanical degradation, and advanced oxidation processes such as photodegradation, photocatalytic degradation, electrochemical degradation, Fenton/Fenton-based AOPs, and ozone degradation. About 80% of microplastics can be removed via advanced treatment plants. Advanced oxidation processes are highly efficient in the removal and degradation of microplastics but their implementation on a large scale is challenging.

Keywords Microplastics · Adsorption · Advanced oxidation process · Photodegradation

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1 Introduction

Plastics are ubiquitous synthetic materials mainly produced from a wide range of organic polymers (Rasmussen 2018). Due to their slow degradation and faster accumulation, they are highly persistent in the environment (Vaid et al. 2021; Wang et al. 2021a). Depending upon the properties and environmental conditions, plastics are believed to have a permanence of hundreds or thousands of years (Zhang et al. 2021a). Plastic degradation is a slow process that combines sunlight, heat, air, and moisture (Bajt 2021). These processes eventually lead to the fragmentation of plastics into low molecular weight compounds (Ali et al. 2021), as well as dissolved bioavailable polymeric compounds that can be metabolized into carbon dioxide (CO_2) and water (H_2O). Microplastics are small plastics that have size less than 5 mm (Jung et al. 2021). They are either produced purposefully (primary microplastics) (Zhang et al. 2020; Bian et al., 2022; Ahmed et al., 2022) or formed from large plastic polymers via degradation mechanisms (secondary microplastics) (Karimi Estahbanati et al. 2021).

Microplastics are considered as an emerging pollutant because they are found in almost all ecological components (Debroy et al. 2021), and there are no legal standards to control the occurrence and release of microplastics into the environment (Ricardo et al. 2021). They are highly persistent in air, water, and soil because of their high stability and slower degradation rates (Nanda and Berruti 2021). Wastewater offers a significant route for microplastics into the environment (Shen et al. 2020). Therefore, the removal of these pollutants from water is essential for combating the toxic effects posed by them. Previous studies reports that water and wastewater treatment techniques such as coagulation, flocculation, flotation, granular filtration, and membrane process are capable of removing larger microplastics. Metal organic frameworks, biochar, different biopolymers, and magnetic separation are some of the novel approaches for removing microplastics from water and wastewater and is under research.

Degradation of microplastics differs from the removal, as the former break the chemical bonds of polymer molecules to convert them into valuable products or smaller monomer units (Du et al. 2021). However, these processes take much time for complete mineralization (Corcoran 2022). Research on microplastic degradation prefers chemical photodegradation over physical and biological degradation due to the efficiency and simplicity of the process (Xi et al. 2022). Several methods can also be adopted for microplastics' artificial or simulated degradation (Padervand et al. 2020; Sharma et al. 2021; Anand et al. 2023).

The purpose of the present chapter is to contribute a review of the scientific literature concerning how microplastics are removed and degraded from water and wastewater. The chapter presents the removal of microplastics using various technologies. A summary of microplastic degradation methods and their corresponding mechanisms are also included.

2 Physical Techniques for Microplastic Removal

Microplastics are found in various environmental samples. The appearance of microplastics in drinking water has become a major environmental threat. Microplastics are transported by wastewater to nature in a significant amount. A typical drinking water treatment plant consists of coagulation, sedimentation, sand filtration, and clarification (Shen et al. 2020). Since wastewater has a high organic matter content derived from various sources, it also requires biological treatment (Spellman 2013). The advanced water treatment processes produce better quality effluents which also enhances the removal of microplastics (Wang et al. 2020a). This section describes physical treatment techniques through which microplastic removal is achieved.

2.1 Coagulation and Flocculation

Coagulation is a process that employs coagulants for destabilizing the colloids through various mechanisms. The destabilized particles agglomerate to form micro-flocs, and further micro-flocs coalesce to form large flocs (often called as macro-flocs) in the presence of a flocculant. These flocs can be effortlessly eliminated by sedimentation, filtration, or flotation (Jiang 2015). The appropriate conditions for removing typical oxide colloids and kaolin are also efficacious for microplastic removal (Skaf et al. 2020). Aluminium (Al) and Iron (Fe) salts are extensively used as coagulants in treatment plants. The comparative study of Al-based coagulants and Fe-based coagulants in the removal of polyethylene (PE) microplastics revealed that $AlCl_3.6H_2O$ performed better than $FeCl_3.6H_2O$, and smaller microplastics are more effectively removed than larger ones (Ma et al. 2019b). Polyaluminium chloride (PAC) was found to be a more efficient coagulant than ferric chloride ($FeCl_3$) for the removal of polystyrene (PS) and PE microplastics (Zhou et al. 2021b). The Al-based coagulants form smaller flocs with higher specific areas than the flocs formed by Fe-based coagulants leading to the higher efficiency in microplastic removal (Ma et al. 2019b). PE microplastic spheres are found to be removed by the mechanism of sweep flocculation using alum as a coagulant (Skaf et al. 2020). Alum-based coagulation, flocculation, and sedimentation treatment were also found to be effective in the elimination of a considerable amount of small PS microspheres (<6 μm) from surface waters (Xue et al. 2021).

The process of removal of microplastics by coagulation includes charge neutralization, adsorption bridging, and sweep flocculation (Tang et al. 2022). The negatively charged surface of microplastics adsorbs hydrolysates of coagulants, and the charge on the surface gets neutralized (Zhou et al. 2021b). The electrostatic repulsion between microplastics becomes reduced, and the colloidal stability is lost. The positively charged hydrolysates adsorb many microplastics, forming dense flocs that facilitate sweep flocculation and lead to amorphous precipitation (Sillanpää et al. 2018; Xu et al. 2021; Zhou et al. 2021b). The primary factor affecting the coagulative removal of microplastics is pH. Alkaline conditions are more beneficial for removing PS and PE microplastics (Zhou et al. 2021b). More flocs are produced when PAC is used under alkaline conditions because alkaline pH promotes the hydrolysis of PAC (Sillanpää et al. 2018). Besides that, the flocs formed are larger than that of acidic conditions (Ma et al. 2019a; Ma et al. 2019b), which is more advantageous to sweep flocculation and sedimentation.

2.2 Electrocoagulation

Electrocoagulation offers a less expensive potential tertiary treatment method that is not dependent on chemicals as that conventional coagulation. Sacrificial electrodes release metal cations such as Al^{3+} and Fe^{2+} into a water stream containing hydroxyl anions (Moussa et al. 2017). The hydroxides of aluminium and iron thus produced act as micro-coagulants, and the colloidal impurities lose their stability, resulting in the formation of flocs (Shen et al. 2020). The created flocs can either be removed by sedimentation or flotation. An efficiency of 90% has been achieved in the removal of PE microbead by electrocoagulation using an aluminium electrode in a stirred tank batch reactor (Perren et al. 2018). Removing microplastics with an aluminium electrode is more effective than iron electrodes (Shen et al. 2022b). Microplastics such as PE, polypropylene (PP), polymethyl methacrylate (PMMA), and cellulose acetate can be removed using aluminium anode at efficiencies greater than 90% (Shen et al. 2022b). Microplastics of smaller sizes get easily removed during electrocoagulation; the removal efficiency increases with an increase in ionic strength and natural organic matter (Kim and Park 2021).

2.3 Granular Filtration

Rapid sand filtration and granular activated carbon (GAC) are the most common tertiary treatments adopted in treatment plants. When using granulated media to remove particles, three processes are included: transportation (which includes the Brownian movement process); sedimentation and attraction between particles; sticking ability (which includes mechanical straining, adsorption, and biological processes); and resistance (which includes particle collisions and repelling forces) (Sembiring et al. 2021). Rapid sand filtration alone can remove more than 70% of microplastics in wastewater, and when used as a tertiary treatment, the overall removal efficiency was found to be more than 90% (Hidayaturrahman and Lee 2019). Granular activated carbon (GAC) filtration after coagulation is more effective than sedimentation after coagulation (Wang et al. 2020a). Drinking water treatment plants performing GAC filtration and conventional coagulation-flocculation are found to remove more than 80% of microplastics. Nevertheless, GAC filtration alone is not capable to remove more than 70% of microplastics (Pivokonský et al. 2020).

2.4 Membrane Process

Advanced drinking water treatment plants use various membrane processes to improve the quality of effluents. The membrane processes split the feed stream into concentrate and permeate fractions using a membrane(s) (van der Bruggen et al. 2003). Membrane technology includes membrane filtration, bioreactor, and dynamic membranes (Fig. 1). The filtration process by membranes is classified into microfiltration, ultrafiltration, nanofiltration, and reverse osmosis based on the pore size (Zhang et al. 2021b). Microfiltration, ultrafiltration, and nanofiltration are used for particles larger than 0.082 μm, 0.005–0.02 μm, and 0.002 μm respectively, and reverse osmosis is adopted for desalination (Poerio et al. 2019). The complete removal of polyethylene microplastics by ultrafiltration membrane (pore size 30 μm) is observed and slight membrane fouling is found after coagulation with Al-based salts at a conventional dosage (Ma et al. 2019b).

During the tertiary treatment, reverse osmosis often removes dissolved solids and ions (Trishitman et al. 2020). Microplastic beads and fragments are observed to be removed effectively by the reverse osmosis process (Ziajahromi et al. 2017). The

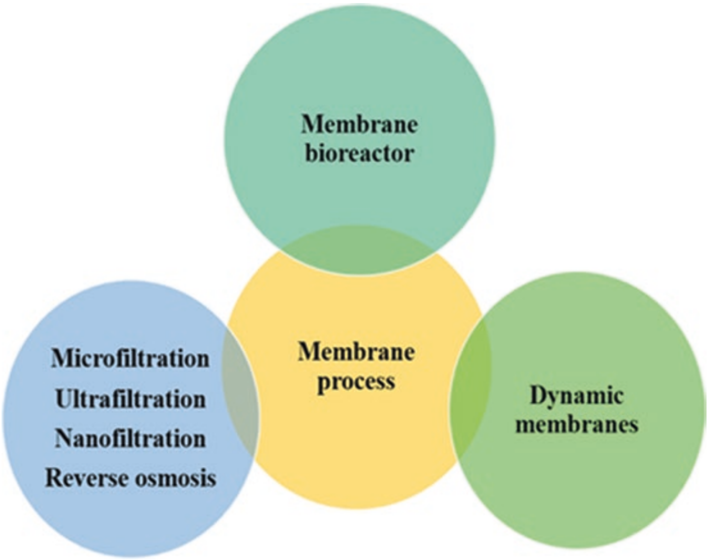

Fig. 1 Membrane technologies to remove microplastics

study of microplastics elimination potential of a drinking water treatment plant in Spain showed that ultrafiltration/reverse osmosis is more beneficial for microplastic removal than the ozonation/carbon filtration stage (Dalmau-Soler et al. 2021). The MP concentration in water may increase after advanced treatment stages such as reverse osmosis and nanofiltration due to the loss of membrane materials (Zhang et al. 2021c). The effluent sample selected from a membrane train consisting of nanofiltration and reverse osmosis had a uniform mix of small, spherical, black PE particles, which was not a part of the influent (Fortin et al. 2019). The dynamic membrane is found to be beneficial for eliminating microplastic from synthetic wastewater (Li et al. 2018). Dynamic membranes are a special type of membrane in which the contaminants form a cake layer and which act as a secondary filter system to remove other microparticles (Saleem et al. 2017)

Several studies have reported the elimination of microplastics by membrane bioreactor (MBR) technology. MBR is a membrane technology that incorporates biological treatment with ultrafiltration or microfiltration (Judd 2008). The comparative study of efficiencies of a rapid sand filter (RSF) and membrane bioreactor in removing the microplastics from a municipal wastewater treatment plant effluent showed that the MBR exhibited higher efficiency (>90%) than RSF (Bayo et al. 2020). The sludge formed in the MBR contains significantly more microplastics than conventional activated sludge (di Bella et al. 2022). The MBR process had a higher retaining rate for microplastics than the secondary conventional activated sludge process (Lares et al. 2018). The major disadvantage of MBR is associated with membrane fouling and clogging.

2.5 Froth Flotation

Froth flotation is the process in which the suspended particulate matter is forced to rise to the surface of the water with the aid of gas bubbles that serves as the transport medium (Shammas and Bennett 2010). Since the use of surfactants offers greater stability to the gas bubbles, higher removal efficiency is obtained for flotation with surface modifiers such as CTAB (cetyltrimethylammonium bromide) and PDADMAC (poly diallyl dimethyl ammonium chloride). The removal efficiencies of microplastics containing hydrophilic groups will be lesser due to water adsorption (Wang et al. 2021c). The efficiency of removal of microplastics by flotation is reduced by the contaminants such as copper ions (Cu2+) and P-benzoquinone, by causing hydrophilization of MP surfaces (Bian et al. 2022). Jiang et al. (2022b) obtained an efficiency greater than 98.5% for the removal of PVC and acrylonitrile butadiene styrene microplastics by froth flotation using terpineol. The coagulation-flocculation process was observed to remove about 60% of PE microplastics from greywater and when dissolved air flotation (DAF) is used after the coagulation-flocculation process, the removal efficiency is found to be increased above 90% (Esfandiari and Mowla 2021). Froth flotation is also found to be sustainable for the removal of microplastics from lake and beach sediments (Jiang et al. 2022a).

2.6 *Adsorption*

Many research studies are committed to the elimination of microplastics during the wastewater treatment processes. The MP removal efficiency of such processes is insufficient (Ahmed et al. 2022). Some recent initiatives developed cost-effective and efficient adsorbents for the removal of microplastics, but the large-scale applicability is not studied.

2.6.1 Removal of Microplastics by Biopolymers

Various studies analysed the ability of biopolymers such as cellulose, chitin, extracellular polymeric substances (EPS) secreted by microbes, and mucous secreted by marine organisms to remove microplastics. Several mechanisms are involved in removing microplastics by biopolymers and is dependent on the type of biopolymer. Chitin is a porous biopolymer that can effectively remove several pollutants by adsorption. Adsorption mechanisms involve hydrogen bonds, electrostatic, and π–π interactions (Sun et al. 2021). The modifications of biopolymers enhance the adsorption by increasing the number of surface functional groups for the interaction of pollutants (Sun et al. 2020). The chitin-graphene oxide sponge with double cross-link can eliminate PS microplastics from water with efficiencies greater than 70% (Sun et al. 2020). The chitin-based sponges fabricated and composed with graphene oxide and oxygen-doped carbon nitride (O-C_3N_4) effectively adsorbed functionalized microplastics (~1 μm) at pH 6–8, including carboxylate-modified PS, amine-modified PS, and PS (Sun et al. 2021). Ultralight chitosan-glutaraldehyde nanofiber sponge effectively adsorbed polyethylene terephthalate microplastics from water (Risch and Adlhart 2021).

The ability of the EPS produced by freshwater algae *Cyanothece* sp. to aggregate nano and microplastics is studied and it is used as a bioflocculant to remove microplastics (Cunha et al. 2020). Bacterial cellulose extracted from *Komagataeibacter saccharivorans* acted as a membrane filter to remove microplastics (Faria et al. 2022).

2.6.2 Removal of Microplastics Using Metal Organic Frameworks

Metal organic frameworks (MOFs) is a class of crystalline compounds designed by employing various metal ions with organic linkers. MOFs have a wide spectrum of characteristics suitable for physical and chemical functions such as thermal stability, discrete ordered structure, ultra-low densities, large internal surface area, and ease of synthesis (Gangu et al. 2016). The possible mechanism of MP removal by MOF is the interaction like hydrogen bonding or Van der Waals interaction with functional groups as shown in Fig. 2. These interactions are enhanced by the surface area and pore structure of MOF (Chen et al. 2020). The electrostatic attraction between negatively charged microplastics and positively charged functional groups

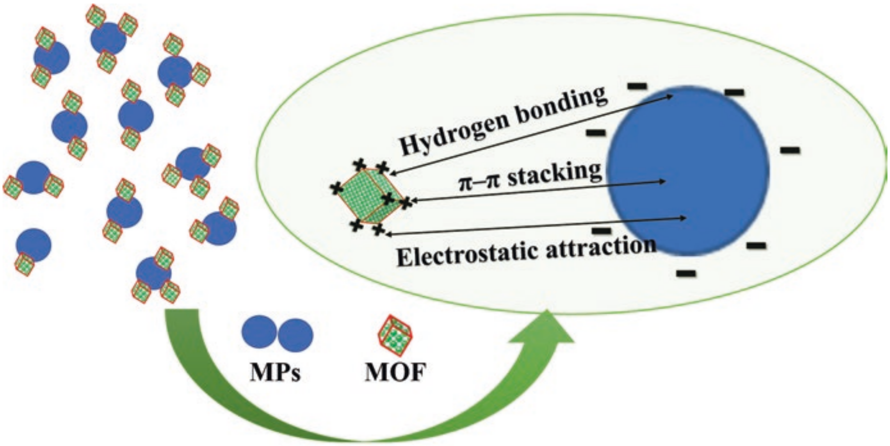

Fig. 2 Microplastic (MPs) removal by metal organic frameworks (MOFs)

of MOFs also plays a vital role in the adsorption of microplastics by MOFs (Chen et al. 2020).

Zeolitic imidazolate frameworks (ZIF) are MOFs with cobalt ion (Co^{2+}) and 2-methylimidazole acting as the central metal ion and organic ligand, respectively (Lin and Chang 2015). ZIF-67 removed polystyrene microplastics from water with an efficiency greater than 90% (Wan et al. 2022). Zirconium-MOF-based melamine form was found to be effective for the removal of microplastics such as polyvinylidene fluoride (PVDF), PS, and PMMA from water (Chen et al. 2020). The zinc MOFs-based wood aerogel composite, ZIF-8@Aerogel found to successfully remove poly(1,1-difluoroethylene) and PS microplastics from water (You et al. 2021). The Ag_2O/Fe-MOF showed a high potential for recycling microplastic into value-added chemicals and H_2 production (Qin et al. 2022). MOFs are feasible materials for the remediation of microplastics but future studies are required to verify the recyclability of MOF materials in the adsorption process.

2.6.3 Removal of Microplastics by Biochar

Biochar is a porous substance made by the pyrolysis of lignocellulosic biomass. Pristine and modified biochar is widely used for environmental remediation. The primary mechanism of removal of microplastics by biochar is adsorption and filtration. The hybrid biochar sand filter removed 10 µm microplastic spheres made of PS with an efficiency greater than 95%. The MP spheres were found 'stuck', 'trapped', and 'entangled' within the corn-straw and hardwood biochar (Wang et al. 2020b). The biochars produced from the bark of scots pine (*Pinus sylvestrus*) and spruce (*Picea* spp.) by slow pyrolysis at 475 °C and steam activated at 800°C are studied for their adsorption performance for microplastics removal and steam-activated biochar showed better removal efficiency (Siipola et al. 2020). When biochar is added as a thin permeable layer into the sand filtration column for testing the removal efficiency of PS microplastics, better performance is achieved (Hsieh et al. 2022). The biochar modified by magnetic nanoparticles showed a better performance for the adsorption of microplastics than raw biochar (Wang et al. 2021b). The positively charged surface functional groups of magnetic biochar attracted negatively charged microplastics resulting in an improved removal efficacy (Wang et al. 2021b).

2.7 Magnetic Separation for the Removal of Microplastics

Magnetic separation effectively removes microplastics from water using a magnetic carrier. A schematic representation of magnetic separation is shown in Fig. 3. The magnetic sepiolite prepared by the co-precipitation method can adsorb PE microplastics from water with a removal efficiency of 98.4% and the magnetic carriers are separated from microplastics under a strong magnetic field (Shi et al. 2022a). Iron oxide-impregnated magnetic carbon nanotubes (M-CNT) removed microplastics such as PE, PET, and polyacetate with efficiency greater than 80% after use for multiple cycles (Tang et al. 2021). Removing nano and microplastics from saline and freshwater conditions using iron nanoparticles coated with hydrophobic coating showed an efficiency of 90% (Martin et al. 2022). Microplastics from environmental samples such as surface waters, domestic sewage, and natural sea waters are removed with an efficiency greater than 80% using nanosized Fe_3O_4 (Shi et al. 2022c). Magnetic seeded filtration can remove microplastics from dilute suspensions with efficiencies reaching up to 95% (Rhein et al. 2019). A novel magnetic carrier was synthesized by functionalizing magnetic Fe_2O_3/SiO_2 core-shell nanoparticles with a polyoxometalate ionic liquid, to effectively remove polystyrene

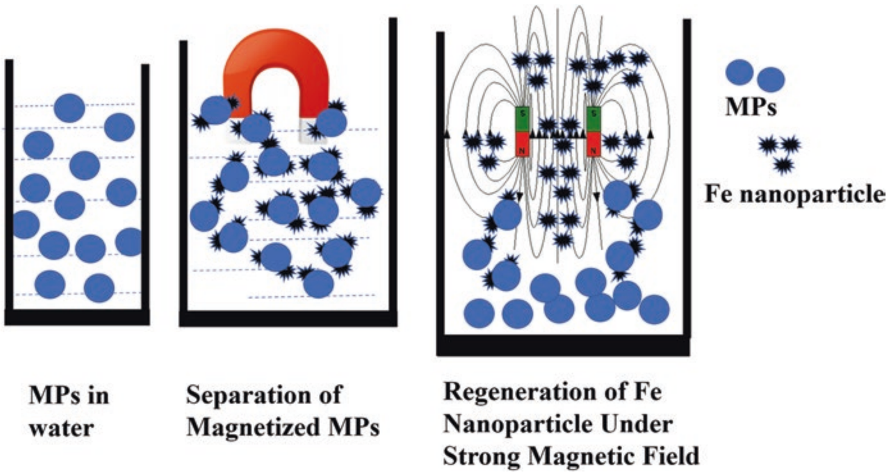

Fig. 3 Magnetic separation of microplastics (MPs)

microplastics (Misra et al. 2020). Magnetic separation is an efficient technique for the removal of microplastics, however, further research is needed to improve it for environmental remediation.

2.8 Advantages and Disadvantages of Microplastic Removal Techniques

The various strategies for the removal of microplastics from water such as coagulation, electrocoagulation, granular filtration, membrane process, froth flotation, adsorption and magnetic separation have their own merits and demerits. Coagulation is a rapid and easy process with less energy expenditure, but the process requires a huge amount of chemicals and produces a large quantity of sludge (Sillanpää et al. 2018; Xu et al. 2021; Zhou et al. 2021b). The main advantage of the process of electrocoagulation is the absence of chemical coagulants and formation of very small quantities of sludge but the high requirement of energy makes the process unsustainable (Shen et al. 2022b). Even though granular filtration is an easy and economical process for the removal of microplastics, the efficiency for removal of small microplastics is less (Pivokonský et al. 2020; Hidayaturrahman and Lee 2019). The pretreatment of water is a necessary condition for the membrane process even though it is an easy and cost-effective method with high efficiency (Bayo et al. 2020). Membrane fouling is also a major shortcoming of the process. Froth flotation is an easy and flexible method for both sediments and water samples, but the requirement of large amount of floatation reagents makes the process unsound (Jiang et al. 2022a; Wang et al. 2021c). Large quantities of magnetic material and high strength magnetic field is required for the magnetic separation of microplastics, but the process is easy and highly efficient (Tang et al. 2021). Adsorption is also a cheap and easy method and adsorbents can be regenerated for multiple cycles. The main short coming of adsorption is low specificity. The efficiencies of various physical removal methods and factors affecting the removal efficiencies are summarized in Table 1.

Table 1 Efficiency of physical methods

Physical treatment method	Average efficiency (%)	References
Conventional coagulation	61	Ma et al. (2019a, b)
Electrocoagulation	>90	Perren et al. (2018)
Membrane bioreactor	99.9	Talvitie et al. (2017)
Rapid sand filter	97	Talvitie et al. (2017)
Disc filter	40–98.5	Talvitie et al. (2017)
Air flotation	95	Talvitie et al. (2017)
Magnetic seeded filtration	95	Rhein et al. (2019)
Adsorption by MOF	90	Wan et al. (2022)
Biochar sand filter	95	Wang et al. (2020b)

3 Microplastic Degradation Methods and Mechanisms

Microplastics degrade in a natural environment through the same degradation processes of macro-plastic (mechanical, chemical, and biological processes). These processes break the chemical bonds in polymer molecules to convert them into smaller compounds of low molecular weight or mineralize them into carbon dioxide (CO_2) and water (H_2O) (Du et al. 2021). Different methods of microplastic degradation and their corresponding mechanism are described in the following sections.

3.1 Advanced Oxidation Processes

Advanced oxidation processes (AOPs) are one of the most powerful techniques used to degrade persistent organic pollutants (Du et al. 2021). They are considered as a green elimination technique due to the safe, effective and strong degradation potential (Shen et al. 2022a). These processes have high oxidation efficiency and don't produce secondary pollutants (Saravanan et al. 2022). AOPs produce reactive oxygen species (ROS), also called radicals (Kim et al. 2022), that have a high standard reduction potential (Chen et al. 2022). Light, heat, catalysts, and plasma are used individually or in combination to produce ROS (Kim et al. 2022). The ROS causes chain scission in microplastics (Hou et al. 2021). The commonly adopted AOPs for microplastic degradation such as photodegradation, photocatalytic degradation, electrochemical degradation, Fenton/Fenton-based AOPs, ozone degradation, etc. are discussed.

3.1.1 Photodegradation

In the decomposition of polymers, photodegradation is the most critical process. Long-time exposure to solar irradiation enriched by ultraviolet (UV) rays prompts the formation of free radicals, the addition of oxygen, hydrogen abstraction, and chain scission in microplastics (Du et al. 2021). Chain scission breaks covalent bonds within the polymer matrix (Dimassi et al. 2022). Such exposure causes morphology changes like cracks, crazing, pitting, discoloration, and embrittlement eventually leading to degradation (Akan et al. 2021). UV-A (315–400 nm), UV-B (280–315 nm), and UV-C (200–280 nm) are mainly responsible for photodegradation (Kim et al. 2022). Degradation fastens under radiations with shorter wavelengths as they possess high energy (Zhang et al. 2021a). Also, aromatic and carbonyl groups increase the photodegradation rate in plastics (Akan et al. 2021). Photodegradation is not the main method in aquatic environments as the availability of sunlight is limited (Du et al. 2021).

Microplastics have light absorbing chromophores in their structure that initiate photodegradation as they possess photooxidative sites (Dimassi et al. 2022). These chromophores absorbing the light activate the microplastic molecules and form carbon species (R•) by shedding a hydrogen atom. This reaction is known as a chain initiation reaction (Fig. 4). The activated carbon species (R•) thus formed reacts with oxygen to form ROO•, which removes hydrogen to form hydroperoxides (ROOH) and this reaction is called a hydrogen abstraction reaction (HAR) (He et al. 2022). Hydroperoxides can break the strong carbon bonds in the polymer matrix (Zhang et al. 2021a). ROOH further dissociates into ROO• and OH• species, continuing the HAR constituting a chain propagation reaction that leads to chain scission or crosslinking of polymers as shown in Fig. 4 (He et al. 2022; Ali et al. 2021). Finally, inert and stable compounds (ROOR, R_2, ROH) are formed by the chain termination reaction (He et al. 2022) by the combination of two radicals (Ali et al. 2021). The organics thus formed are finally mineralized into CO_2 and H_2O (Kim et al. 2022).

PE and PP are resistant to photodegradation due to the absence of unsaturated chromophores in their polymer matrix (Zhang et al. 2021a). The impurities, additives, and structural deformations in PE act as chromophores and facilitates photodegradation. Free radicals thus formed cause chain scission and crosslinking of long polymer chains in PE (Arpia et al. 2021). When exposed to near UV radiation, PET is susceptible to photodegradation. The presence of ester groups and methylene groups is mainly responsible for photodegradation in PET (Zhang et al. 2021a). PS absorbs UV irradiation from a medium UV region and phenyl chromophores present in PS moiety initiate the degradation process (Shi et al. 2022b). Polystyryl

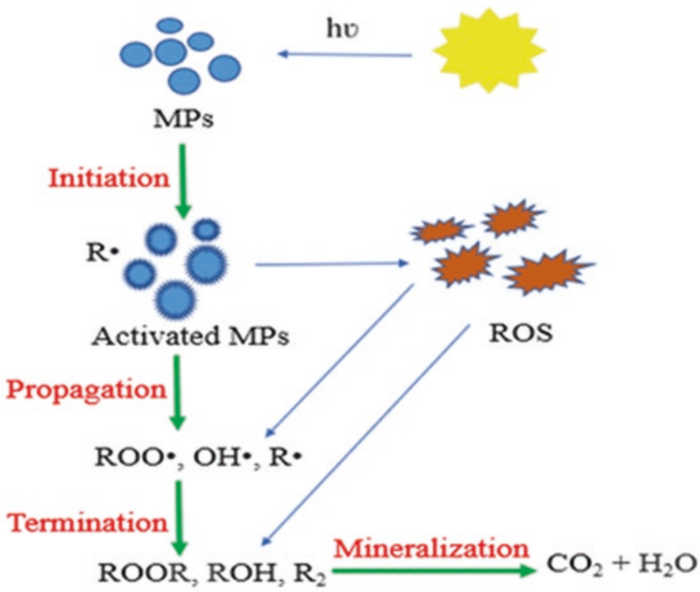

Fig. 4 Mechanism of microplastic degradation by photolysis. *MPs* microplastics, *ROS* reactive oxygen species

radical which is formed due to the dissociation of phenyl rings leads to chain scission and crosslinking in PS polymer (Zhang et al. 2021a).

3.1.2 Photocatalytic Degradation

Photocatalytic degradation is a solar energy-driven redox process that utilizes semiconductor photocatalysts to degrade microplastics efficiently from the environment (Du et al. 2021; Hu et al. 2021; Sharma et al. 2021). Photocatalysts are excited when a photon of light (UV/visible) whose energy is greater than or equal to the bandgap of the photocatalyst falls on it (Karimi Estahbanati et al. 2021). Upon activation, the electron from the valence band (VB) excites and moves to the conduction band (CB) of the photocatalyst. This leaves a hole (h^+) in the valence band (Nabi et al. 2021). The h^+ in the valence band can oxidize the organic compounds resulting in the formation of hydroxyl radicals and these radicals which are electrophilic can oxidize all electron-rich compounds. Electron in the conduction band reacts with oxygen to form superoxide radical, which in turn reacts with water to form HO_2•. HO_2• further produces H_2O_2, and H_2O_2 finally turns into OH• radical (Ricardo et al. 2021). These radicals attack the microplastic, leading to chain rupture, scission, crosslinking, and mineralization of the polymer (Hu et al. 2021). Ferric oxide (Fe_2O_3), Zinc oxide (ZnO), Zinc sulfide, Cadmium sulfide (CdS), Bismuth oxyl chloride (BiOCl), and Titanium dioxide (TiO_2) are the predominant photocatalysts used for microplastic degradation (Ricardo et al. 2021).

In photodegradation, ROS is generated from a photo-excited microplastic reacting with oxygen which in turn, reacts with another microplastic molecule. Therefore, the direct involvement of microplastic molecules is essential in photodegradation. Contrarily, the involvement of microplastic particles is not necessary for photocatalysis. In addition to the ROS formed from the interaction of microplastics and oxygen, ROS are formed from the interaction of holes and electrons from the photocatalyst and oxygenated species (He et al. 2022). ROS diffuses into the polymer matrix and forms carbon-centered radicals by oxygen insertion. This causes cleavage of the polymer chain. Intermediates with carbonyl and carboxyl groups are formed on the course of photo-oxidation and eventually, they are mineralized into CO_2 and H_2O. The mechanism of photocatalytic degradation is depicted in Fig. 5 (Hu et al. 2021).

Photocatalysts have high redox potential (Zhou et al. 2021a). ROS generation during photocatalytic degradation depends on photocatalysts' energy band structure and light absorption capacity (He et al. 2022). TiO_2 and TiO_2-based photocatalysts are mainly used for the photocatalytic degradation of microplastics. They are highly efficient with less toxicity, low price, excellent acid and alkali resistance (Kim et al. 2022), easy availability, and conservative nature (Sharma et al. 2021). Also, in TiO_2 the energy bandgap between VB and CB is very small, making it an excellent photocatalyst (Nabi et al. 2021). As photocatalytic degradation can trigger various environmental problems due to the smaller microplastic fragments, greenhouse gases,

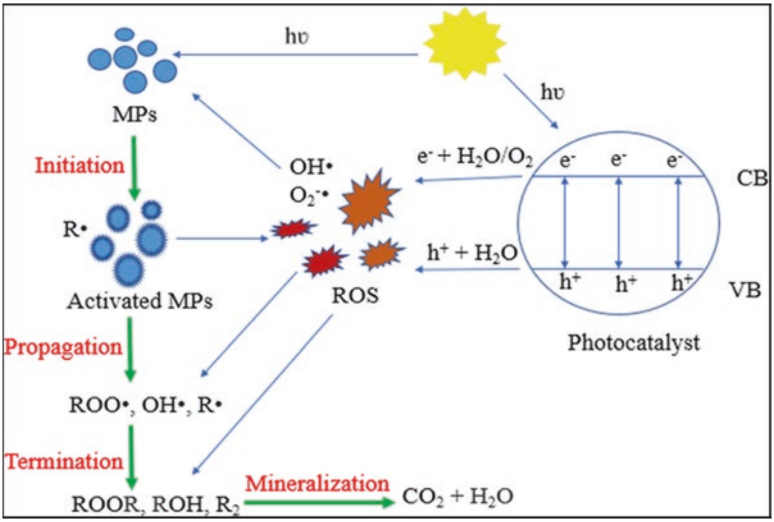

Fig. 5 Mechanism of microplastic degradation by photocatalysis

soluble organic pollutants, and catalyst residuals, a comprehensive assessment of such risks are essential (He et al. 2022).

3.1.3 Electrochemical Degradation

Electrochemical degradation is an electrochemical technology used to degrade pollutants that are difficult to oxidize (Karimi Estahbanati et al. 2021). Generally, electrochemical degradation is classified into two: anodic oxidation and indirect cathodic oxidation (Sutradhar 2022). Electrochemical oxidation is a process that is designed to degrade organic matter and ammonia nitrogen. However, the oxidizing agents and free radicals formed can degrade microplastics from environmental niches (Hou et al. 2021). Direct oxidation at an anodic surface takes place in two stages. In the first stage, hydroxyl radicals which are formed and adsorbed on active electrode sites, partially oxidize microplastic (Krishnan et al. 2021). The anodic discharge of water continuously produces hydroxyl radicals. A schematic representation of electrochemical degradation is depicted in Fig. 6. These radicals completely oxidize the partially oxidized microplastics and convert them into CO_2 and H_2O (Karimi Estahbanati et al. 2021). Indirect cathode oxidation is also known as electro-Fenton technology (Du et al. 2021; Sutradhar 2022).

The commonly used electrodes in electrochemical degradation are boron-doped diamond, platinum, carbon fiber, carbon graphite, carbon-felt, and lead oxide. Boron-doped diamond electrodes form a more significant amount of ROS and are identified as the best electrode (Krishnan et al. 2021). The electrochemical process is a promising method for deleting microplastics in industrial and municipal

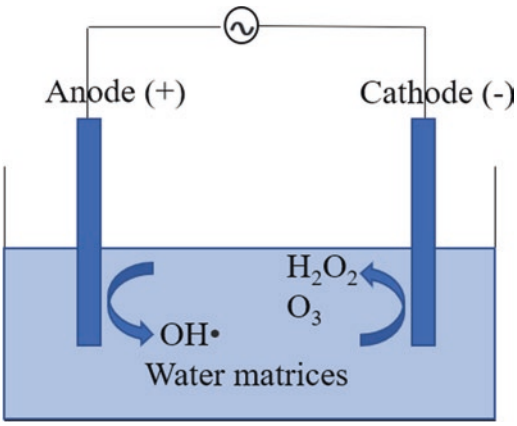

Fig. 6 Electrochemical degradation

wastewater effluents. But the process is costlier due to high energy consumption (Karimi Estahbanati et al. 2021).

3.1.4 Fenton Process and Fenton-Based Advanced Oxidation Processes

The Fenton process is an essential AOP widely used for microplastic degradation in wastewater treatment plants (Zhou et al. 2021a). It takes place through the catalytic decomposition of hydrogen peroxide (H_2O_2) in the presence of ferrous (Fe^{2+}) ions. An acidic pH of 2.5 and 3 is optimum for the Fenton process. Iron precipitates into iron hydroxides above a pH of 3, reducing the efficiency of the Fenton process. Hydroxyl radicals (HO• and HO_2•) are formed as a result of this process (Eqs. 1 and 2) (Ricardo et al. 2021). Here H_2O_2 acts as an oxidizing agent and iron acts as a catalyst (Deshmukh and Manyar 2021).

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + OH^- + HO\bullet \tag{1}$$

$$Fe^{3+} + H_2O_2 \rightarrow Fe^{2+} + HO_2\bullet + H^+ \tag{2}$$

Fenton reaction occurring in UV-visible region is known as a photo-Fenton process (Ricardo et al. 2021). In the photo-Fenton process, different light absorptive hydroxyl complexes of iron ($[Fe(OH)]^{2+}$, $[Fe(O_2H)]^{2+}$) are produced at an acidic or near neutral pH (Ahmed et al. 2021). Upon light irradiation, an electron from the ligand excites the metal and subsequently reduces the Fe^{3+} ion to Fe^{2+}, along with the formation of HO• radicals (Eq. 3) (Ricardo et al. 2021). The photo-Fenton process is much more efficient and rapid than the traditional Fenton process due to the combined effect of light irradiation and HO• radicals (Ahmed et al. 2021).

$$Fe(OH)^{2+} + h\nu \rightarrow Fe^{2+} + HO\bullet \tag{3}$$

The electro-Fenton process is another degradation method developed to overcome the shortcomings of Fenton process. The method uses continuous electrochemical generation of H_2O_2 under moderate conditions (Ahmed et al. 2021). It is achieved by reducing oxygen in the cathode and continuous regeneration of Fe^{2+} ions and OH radical formation (Ricardo et al. 2021). Miao et al. (2020) studied PVC microplastic degradation using the Electro-Fenton process based on TiO_2/graphite cathode. PVC was successfully degraded with a dechlorination efficiency of 75% and weight loss of 56% after 6 h of electrolysis (Miao et al. 2020).

3.1.5 Ozone Degradation

Ozone is a highly reactive and strong oxidizing agent with a standard reduction potential of 2.07 eV. They break down into dioxygen molecules and oxygen radicals as they are highly unstable (Deshmukh and Manyar 2021). Thus, the ozone reacts with a water molecule to form ROS (OH• radical). When reacting with microplastics, ozone produces oxygen-containing functional groups that lead to significant degradation (Kim et al. 2022). Experimental studies on PE, PET, and PP polymers showed a considerable increase in surface tension, water affinity, and adhesion properties when exposed to ozone. Additionally, ozone exposure alters many physio-chemical processes, such as melting point, solubility, and intrinsic viscosity (Hidayaturrahman and Lee 2019).

3.2 Thermal Degradation

Thermal degradation refers to the degradation of microplastic polymers at high temperatures. It leads to molecular deterioration in polymer chains as of photodegradation (Al-Thawadi 2020). It is usually done at temperatures above 100 °C because the antioxidant additives in plastics resist thermal degradation at low temperatures. Thermal degradation of microplastics depends on the type and characteristics of the polymer. PP, PVC and polybutadiene are susceptible to thermal degradation, while polysulfone, polysiloxanes, etc., are thermally resistant due to strong bonds in their matrix (Ali et al. 2021).

Long polymer chains are broken when the polymer molecule absorbs sufficient heat. Alkoxy and hydroxyl radicals are formed when oxygen reacts with hydroperoxide radicals. These radicals lead to chain scission and crosslinking in the polymer matrix, and subsequent molecular reduction is observed (Zhang et al. 2021a). Thermo-oxidative degradation of microplastics is defined as a slow oxidative molecular deterioration at moderate temperatures (Al-Thawadi 2020). Thermal degradation of microplastics requires more time and energy than photodegradation (Dimassi et al. 2022).

3.3 Hydrolytic Degradation

Hydrolysis or hydrolytic degradation is defined as the degradation of microplastics due to the action of water. The rate of hydrolysis depends on the ability of a polymer to resist the action of water. Hydrolytic degradation changes the physicochemical characteristics of microplastics (Ali et al. 2021). Rate of reaction increases in the presence of catalysts which is either an acid or a base. The mechanism involves the attack on carbonyl groups in ester and amide bonds. Further action of water forms hydroxyl radicals which degrade the polymer molecule (Ali et al. 2021).

3.4 Mechanical Degradation

Mechanical degradation is defined as the breakdown of microplastics by the action of external forces (Zhang et al. 2021a). It mainly occurs by abrasion when microplastic comes in contact with various natural and anthropogenic items in environmental niches. Abrasion with sand grains, human-made barriers, vehicles, etc., causes mechanical degradation of microplastics. Beaches are the main natural site for mechanical abrasion of microplastic (Corcoran 2022). The degradation process converts the plastics into small monomers, oligomers, and other modified versions. The process increases the surface area making it more susceptible to degradation (Vieira et al. 2021).

3.5 Biological Degradation

The biological degradation of microplastics refers to the decomposition of organic matter via microbial activity and other organisms. Microbes carry out biodegradation by using plastics as their carbon source. However, only a small portion of the waste can be biologically degraded due to the nature and properties of microplastics, which are weak substrates for the growth of microorganisms (Ali et al. 2021). Original or inoculated microorganisms are utilized to metabolize and convert plastics into harmless end products, but it is time-consuming (Xi et al. 2022; Ricardo et al. 2021). The biodegradation of microplastics proceeds through five steps (Fig. 7): conditional film formation, colonization, bio-fragmentation, assimilation, and mineralization (Arpia et al. 2021).

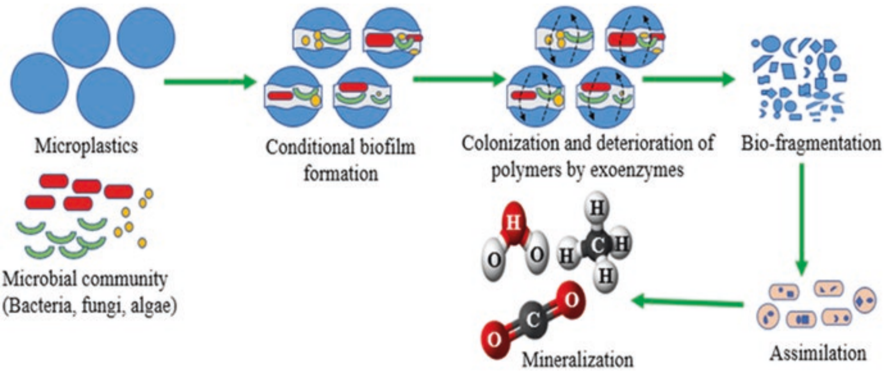

Fig. 7 Stages involved in biodegradation of microplastics

3.5.1 Conditional Film Formation

When the microplastic particle interacts with water, a conditional bio-film is developed in their surface (Corcoran 2022). The type of organisms that sorb on the surface of the conditional film is determined by the chemistry of the film (Arpia et al. 2021), and the biofilm formation causes severe damage to the microplastic particle (Ali et al. 2021). The film formation occurs rapidly through the adhesion of organic substances on the plastic particle (Lastovina and Budnyk 2021). As the biofilm grows, the surface of microplastics undergoes pitting and cracking that weakens the structure (Du et al. 2021). The biofilms provide structural support and defense against mechanical damage/shear forces and predators. It also enhances the diffusivity of the bacteria on the microplastic surface (Mammo et al. 2020). Microorganisms can easily metabolize additives like plasticizers and they promote the initial attachment of microbes and subsequent biofilm growth (Debroy et al. 2021).

3.5.2 Colonization

After biofilms are formed, colonization of microbes occurs along the microplastic dents and cracks (Arpia et al. 2021) and it is the longest stage in the biodegradation of microplastics (Lastovina and Budnyk 2021). The colonized surface of a microplastic with a microbial community growing in the biofilm is termed as "plastisphere" which includes a distinct and diverse microbial community that comprises bacteria, fungi, algae, bryozoa, etc. (Arpia et al. 2021; Corcoran 2022). The mechanical properties of polymers diminish due to biofilm colonization and growth. Exoenzymes produced by microbes deteriorate the physical integrity of microplastic polymers (Debroy et al. 2021). Exoenzymes like laccase and alkane hydrolase can degrade PE, PETase can degrade PET, and serine hydrolase can degrade PS (Othman et al. 2021).

3.5.3 Bio-fragmentation

Exoenzymes convert deteriorated polymers into oligomers, dimers, or monomers in the bio-fragmentation step (Corcoran 2022). Bio-fragmentation can be identified as an enzymatic depolymerization process that weakens the polymer skeleton. It promotes fragmentation and releases smaller oligomeric or monomeric units that can be assimilated by microbes (Debroy et al. 2021).

3.5.4 Assimilation

Microorganisms can assimilate the large polymers only if they are fragmented into sizes that can pass through their cell wall (Corcoran 2022). Depending on the type of microbes assimilation takes place through aerobic, anaerobic, and fermentation processes (Debroy et al. 2021). These fragmented molecules are used as carbon and energy source by the microorganisms (Arpia et al. 2021) and they cross the cell membranes of the microbes through active or passive transportation which produce energy through catabolic pathways. The impermeable oligomeric or monomeric units may require a biotransformation process for assimilation. If biotransformation is not possible, they remain in the surrounding medium as a non-assimilable pool of monomers. If secondary metabolites are produced after the assimilation process, they will join the pool of non-assimilable monomers as the microbes cannot transform the metabolite further or do not need to store it (Debroy et al. 2021).

3.5.5 Mineralization

Mineralization is the last step of biodegradation in which polymers are completely degraded to form carbon dioxide, nitrogen, water and methane (Arpia et al. 2021; Debroy et al. 2021). During the complete mineralization of polymers, the intermediary products of metabolism are utilized in other biochemical pathways. For example, acetic acid is an intermediary metabolite produced during the complete mineralization of PE, which can be used for lipid synthesis or energy production by the Krebs cycle (Debroy et al. 2021).

Bacteria, fungi, algae, and some invertebrate species were reported as degraders of microplastic polymers (Akan et al. 2021). Research studies have reported some specific bacterial strains which can metabolize various polymers. However, the biodegradation of polymers using a single bacterial strain can inhibit the growth of the culture as toxic metabolic products may be formed during the process. A bacterial consortium can eliminate this limitation (Debroy et al. 2021). Fungi can degrade petroleum-based plastic polymers by combining various intracellular and extracellular enzymes. They are efficient in the biodegradation of microplastics as they can be used as a sole carbon and energy source (Sánchez 2020). Several microalgae species were identified to have high biocompatibility and the potential for treating microplastics (Sharma et al. 2021). Ligninolytic and cellulolytic enzymes facilitate

Table 2 Biodegradation of microplastics using different organisms

Name of the species	Type of organism	Type of microplastics	References
Bacillus subtilis	Bacteria	Polyester	Arpia et al. (2021)
Bacillus cereus	Bacteria	Polyethylene terephthalate	Sharma et al. (2021)
Rhodococcus sp.	Bacteria	Polypropylene	Corcoran (2022)
Exiguobacterium sp.	Bacteria	Polystyrene	Arpia et al. (2021)
Aspergillus sp.	Fungi	Low density polyethylene	Corcoran (2022)
Zalerion maritimum	Fungi	Polyethylene	Corcoran (2022)
Penicillium citrinum	Fungi	Polyethylene terephthalate	Sánchez (2020)
Phanerochaete chrysosporium	Fungi	Polypropylene	Arpia et al. (2021)
Chlorella vulgaris	Algae	Bisphenol A (BPA)	Debroy et al. (2021)
Cladophora sp.	Algae	Polyethylene terephthalate	Peller et al. (2021)
Plodia interpunctella	Waxworm	Polyethylene	Akan et al. (2021)
Tenebrio molitor	Mealworm	Polyethylene and Polystyrene	Akan et al. (2021)

biodegradation by microalgae (Debroy et al. 2021). Invertebrates like waxworms and mealworms degrade ingested microplastics by a synergistic association with their gut microbiota population (Akan et al. 2021). Some of the microplastic degrading organisms are listed in Table 2. Genetically modified organisms (GMOs) can also complement existing physical methods to reduce microplastics. But GMOs can seriously threaten humans and ecosystems due to their mutated traits (Rodríguez-Narvaez et al. 2021).

3.6 Advantages and Disadvantages of Microplastic Degradation Methods

Photodegradation and photocatalytic degradation are environment friendly techniques that uses the naturally available solar energy for MP elimination. But the natural photodegradation is an uncontrollable process that takes a significantly long duration to complete. Photocatalytic degradation can cause secondary pollution due to the residual catalysts present on the effluent (Du et al. 2021). The other AOPs like electrochemical degradation, Fenton's process and ozone degradation are highly efficient degradation techniques but their applicability in a large scale is still under research.

Mechanical degradation significantly reduces size of microplastics and increases surface area by creating grooves, cracks and dents on the surface. In a natural environment, mechanical degradation of microplastics takes place by a combination of mechanical, thermal, chemical, hydrolytic and photo-oxidative forces. Majority of microplastics are resistant to degradation when mechanical forces are used alone (Arpia et al. 2021; Corcoran 2022). Thermal degradation of microplastics via gasification, hydrothermal liquefaction etc., can be used to generate alternative efficient fuels (Bai et al. 2020; Hou et al. 2021). However, its practicality in a natural environment is limited due to the high temperature requirement (Arpia et al. 2021). Biological degradation is a sustainable green technology that uses microorganisms to degrade microplastics. Due to the involvement of biological species, their colonization and enzymatic degradation, this process takes considerable time to complete (Debroy et al. 2021).

4 Conclusions

Many research works are currently going on in the degradation and removal of microplastics. It was found that the advanced drinking water and wastewater treatment plants can remove more than 80% of microplastics reaching their inlet but, the presence of microplastics in treatment plants interfere with the removal of other contaminants. Membrane filtration is a promising method for microplastics removal, but economic feasibility and membrane fouling are some of the shortcomings. Various other approaches are also found to be feasible for removing microplastics, but large-scale experiments are needed for these strategies to adapt to industrialization.

Advanced oxidation processes, thermal degradation, mechanical degradation, hydrolytic, and biological degradation are some microplastic degradation processes that are under research. Photodegradation, photocatalytic degradation, and biodegradation degrade the microplastics greenly, but these processes take much time for complete degradation and mineralization. Fenton and Fenton-based degradation processes are highly efficient approaches with relatively shorter time for degradation. However, these processes require a lot of energy and chemical inputs. Thermo-oxidative degradation is a long-term process occurring at moderate temperatures with the help of oxidizing agents. Mechanical degradation and hydrolytic degradation take much time in a natural environment. Even though microplastics can be degraded through different methods, the carbon elements finally evolved into carbon dioxide, a potent greenhouse gas. Thus, microplastic degradation can contribute to the global carbon footprint. Therefore, a better comprehension of the degradation mechanisms is necessary to propose novel strategies for removing microplastics from the environment.

The absence standardized procedures for the extraction and identification of microplastics are a major challenge to researchers. Microplastics or degraded products of microplastics ultimately reach the environment, so the final disposals after extraction and concentration is to be explored and development of economically feasible technologies for removal are necessary due to the ubiquitous nature of microplastics. Life cycle assessment of microplastic removal and degradation can identify the hidden opportunities and threats, equipment maintenance, labor cost, energy consumption, reagents dosage, pollution, and processing capacity are least explored in the field of microplastics removal.

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Occurrence and Removal of Microplastics in Wastewater Treatment Plants

Katekanya Tadsuwan and Sandhya Babel

Abstract Microplastics are emerging pollutants that are ubiquitous in a wide range of environments, yet the accumulation of microplastics in wastewater treatment plants is of particular importance because wastewater treatment plants pour their effluents in ecosystems. Here we review microplastics in wastewater treatment plants with emphasis on the sources of microplastics, analytical methods, and removal methods. Sources of primary microplastic in wastewater are from microbeads in personal care products, plastic pellets, and scrubbers used in industry. Secondary microplastics are derived from laundering, tire and road particles, and leachate from landfills. There are various methods for microplastic sampling and identification, yet these methods are not standardized yet. In a conventional wastewater treatment plant, the highest reduction of microplastics occurs during primary treatment during the skimming and settling stage. Microplastics are further removed during sedimentation in secondary treatment. Wastewater treatment plants equipped with membrane bioreactor systems in a tertiary treatment achieved the highest microplastic removal efficiency up to 99.9%. Despite high removal efficiency and low concentration of microplastic in the effluent, a wastewater treatment plant still releases a considerable number of microplastics daily due to the large volume of treated wastewater.

Keywords Microplastics · Wastewater treatment plants · Sampling and identification · Occurrence · Removal efficiency

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1 Introduction

Microplastic, commonly defined as plastic particles smaller than 5 mm, is an emerging pollutant that receives a lot of attention in recent years. It is known for its ubiquity in a variety of environments as well as a wide range of living organisms. Due to the high stability and durability of plastic materials, they tend to persist in the environment for a long time. Concerns have been raised due to their negative impacts on the environment, aquatic organisms, and human health. A broad range of marine species, such as zooplankton (Rashid et al. 2021), mussels (von Moos et al. 2012), and fish (Lusher et al. 2013), are likely to uptake microplastics. Microplastics ingested by species in one trophic level can be transferred to other organisms at higher trophic levels (Setälä et al. 2014). Hazardous substances leached from plastic materials and additives can cause chronic toxic effects on humans and living organisms (Li et al. 2018). Microplastics also act as vectors for pollutants such as persistent organic pollutants (POP) as they tend to absorb on the microplastic surface due to their high surface-to-volume ratio and hydrophobicity (Wang et al. 2019, 2021).

Studies have focused on the presence of this small-sized pollutant in both freshwater and marine ecosystem. Microplastics originate from aquatic- and land-based sources. Aquatic- or ocean-based sources of microplastics can be from material lost from fishing and aquaculture activities, and during shipping (Duis and Coors 2016). Land-based sources have been considered to be a major source of plastic debris in marine environments, while plastic debris from ocean-based sources accounted for only 10–25% (Andrady 2011; Mehlhart and Blepp 2012). The most important routes of land-based microplastics are waste dumping, accidental loss and mishandling of plastic waste, and mismanagement of landfills (Duis and Coors 2016). One of the land-based sources of microplastics is wastewater treatment plants (WWTPs) (Talvitie et al. 2015). Microplastics contaminated in wastewater treatment systems can be from households, industries, and landfills (Mahon et al. 2016). A wastewater treatment plant receives terrestrial microplastics and acts as a point source of microplastics to aquatic environments. It is necessary to understand the characteristics of microplastics from this source and the unit process that can remove microplastics from wastewater treatment plants. This chapter interrogates the current status of microplastics in wastewater treatment systems, their characteristics and possible sources, and the removal by different treatment technologies.

2 Sources and Origin of Microplastics in Wastewater Treatment Plants

Wastewater treatment plants receive domestic and industrial wastewater. The classification of microplastics can help identify their potential sources and mitigation measures for the reduction of microplastics (Kershaw 2015). Figure 1 shows a schematic illustration of various sources of microplastics in wastewater treatment plants.

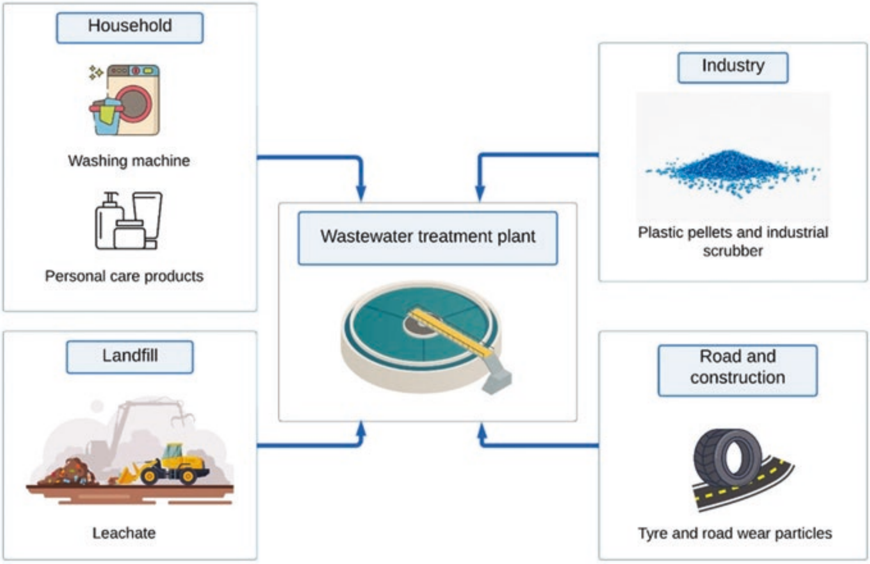

Fig. 1 Sources of microplastics in wastewater treatment plants

Microplastics can be divided into primary and secondary microplastics based on their origin. Primary microplastics are originally manufactured in small-sized spherical or cylindrical virgin pellets (Kershaw 2015). They are used for further conversion processes, technical applications, and cosmetics as microbeads to enhance cleansing effects (Hohenblum et al. 2015). Secondary microplastics are derived from the fragmentation and weathering of larger-size plastics which occur during the use phase of products (Kershaw 2015). The majority of microplastics in the environment are assumed to be secondary microplastics (Andrady 2011; Duis and Coors 2016; Hidalgo-Ruz et al. 2012; Li et al. 2018). Large plastic particles are prone to degradation due to severe environmental conditions.

The sources of primary microplastics in wastewater treatment plants are cosmetics and personal care products such as toothpaste, soap, and facial and body scrub (Carr et al. 2016). Primary microplastics in cosmetic products commonly described as ‘microbeads’ is mostly made of polyethylene (PE) (Napper et al. 2015). These products are directly rinsed down household drains and enter wastewater treatment plants through domestic discharge systems (Carr et al. 2016; Ngo et al. 2019). A single use of an exfoliant in cosmetic products can release up to 94,500 to the drainage system (Napper et al. 2015). Several countries, such as the US, UK, and Canada, have recently restricted the use of microbeads in consumer products (Conkle et al. 2018). Another form of primary microplastics is industrial scrubbers used in blasting clean surfaces, molding, and other processes (Ngo et al. 2019). They are discharged directly into municipal wastewater collection systems and end up in wastewater treatment plants.

There are many sources contributing to secondary microplastics in wastewater treatment plants since they originate from the breakdown of larger plastics. Secondary microplastic fibers and filaments in wastewater treatment systems arise from the breakdown during the washing of synthetic textiles (Hernandez et al. 2017). Microplastic fibers from clothes are mainly made of polyester, acrylic, and polyamide (Browne et al. 2011; Hernandez et al. 2017). A single garment can shed more than 1,900 fibers per wash (Browne et al. 2011), and an estimate of 700,000 fibers is released during the washing of 6 kg of acrylic fibers (Napper and Thompson 2016). A larger number of fibers shed with the increasing washing temperature and the use of detergent (Yang et al. 2019b). Fibers have a higher volume-to-area ratio when compared to other types of microplastics (Astrom 2016). It means that fibers are likely to absorb more chemicals. Wastewater containing microplastic fibers is drained from washing machines and transferred to wastewater treatment plants.

Another route of secondary microplastics in wastewater treatment plants is the wet sedimentation process (Ngo et al. 2019). Secondary microplastics are in the atmosphere or created by the breakdown of packaging, textile, and tires in concrete and highway constructions (Kole et al. 2017; Ngo et al. 2019). Tire and road wear particles contribute to a significant amount of microplastics in the environment (Kole et al. 2017). These particles are emitted into the air and soil and carried to sewage systems via surface runoff (Siegfried et al. 2017). Landfill leachate is another source of microplastics in wastewater treatment plants. Secondary microplastics are derived from the fragmentation of plastic waste buried in landfills under severe environmental conditions (He et al. 2019; Ngo et al. 2019). Microplastics are carried along with the discharge of leachate and enter wastewater treatment systems.

3 Occurrence of Microplastics in Wastewater Treatment Plants

To date, wastewater treatment plants are not specially designed to remove microplastics as they are an emerging pollutant. Wastewater treatment plants represent a point source of microplastics and an ultimate barrier before this type of pollutants enter freshwater bodies. It is important to understand the contribution of each treatment process to microplastic removal and microplastic abundance in wastewater treatment systems.

3.1 Function of Wastewater Treatment Plants

Wastewater treatment plants receive wastewater from households, businesses, and industries, and sometimes urban runoff entering through combined sewer systems. Wastewater treatment plants are designed for the removal of solid debris, nutrients, and other organic pollutants. A conventional wastewater treatment plant is a combination of preliminary, primary, and secondary treatment steps. Tertiary treatment is sometimes implemented to improve the quality of treated wastewater.

The preliminary treatment utilizes coarse and fine screens to remove large debris, and a grit chamber to remove sand and other heavy particles (Duis and Coors 2016; Tang and Hadibarata 2021). Sizes of coarse- and fine screens are typically varied in different wastewater treatment plants: coarse screen (6–150 mm) and fine screen (less than 6 mm) (Iyare et al. 2020). Air floatation is another technology in primary treatment that facilitates the removal of solids, oil, and fibers (Ngo et al. 2019). Air bubbles enhance the contaminants to float, allowing them to be captured along with oil and grease by mechanical skimming (Ngo et al. 2019). The sedimentation tank in primary treatment removes settleable solids which can reduce total suspended solids (Westphalen and Abdelrasoul 2018).

Secondary treatment employs a biological process to further remove suspended solids and nutrients (Mason et al. 2016). Biological treatments include activated sludge, trickling filters, and biological rotating contactors (Westphalen and Abdelrasoul 2018). Some chemical additives, known as 'flocculating agents', are used in primary and secondary treatment steps to aid the formation of flocs and remove suspended solids by sedimentation. Ferric sulfate and polyacrylamide are some examples of flocculating agents commonly used in wastewater treatment plants (Murphy et al. 2016). Flocs of activated sludge settle to the bottom of the tank and are removed. The residue from the settling tanks of wastewater treatment processes is called sewage sludge. The sludge undergoes some types of treatment e.g., lime stabilization, anaerobic digestion, composting, and thermal drying before land application (Mahon et al. 2016). The reuse of sewage sludge in the soil might introduce microplastic pollution to terrestrial environments.

Tertiary treatment steps are optional in some wastewater treatment plants. Tertiary treatments are designed to remove specific inorganic and organic pollutants to achieve higher discharge quality (Iyare et al. 2020). Two main categories of tertiary treatments are advanced oxidation processes and filtration technology. Advanced oxidation technology employs chemical reactions to remove pollutants, whereas, filters remove pollutants based on physical mechanisms (Liu et al. 2021). This treatment stage can further reduce organics, turbidity, nitrogen, phosphorus, metals, and pathogen (Gerba and Pepper 2019). Additional examples of physicochemical processes in tertiary treatment are coagulation, filtration, activated carbon adsorption, reverse osmosis, and disinfection (Gerba and Pepper 2019).

3.2 Methods for Microplastic Analysis from Wastewater Treatment Plants

There are three main steps for microplastic identification in wastewater treatment plants: sample collection, sample pre-treatment (sample processing), and microplastic characterization. These steps are applied to obtain the concentration of microplastics in wastewater and the types of microplastics that indicate the source and origin of microplastic pollution in wastewater treatment plants.

3.2.1 Sample Collection

There is a lack of standardized methods for microplastic sampling in wastewater treatment plants. The smallest mesh sizes are also varied in different studies. Microplastic samples are collected from wastewater in various ways. The grab sampling method is performed using either glass containers or a steel bucket. Pumping and filtration devices are widely used to obtain a large volume of wastewater. An automatic sampler is also used in some studies to yield representative samples (Dris et al. 2015; Simon et al. 2018). A stack of different sieve sizes assembled from coarse to fine is used for on-site filtration or in a laboratory to isolate microplastic particles. Mesh sizes for microplastics in wastewater samples range from 1 to 500 μm (Hamidian et al. 2021). A filter with a 300 μm mesh size has been used as common practice for microliter sampling since it is related to the size of trawl nets used for zooplankton sampling (Magnusson and Norén 2014). Mesh or pore sizes of sieves, filters, and sampling devices influence the number of collected microplastics (Magnusson and Norén 2014). The selection of mesh size for microplastic sampling should be decided carefully.

Sewage sludge is also collected in some studies to observe the level of microplastic retention because microplastics removed from wastewater are transferred into sewage sludge. Filtration of sewage sludge cannot be conducted directly due to the viscous matrix containing organic, inorganic materials, and microorganisms (Zhang and Chen 2020). Thus, sludge samples are commonly collected in a small amount from sludge treatment units (Koyuncuoğlu and Erden 2021). Sludge samples are subsequently filtered in a laboratory for further analysis.

3.2.2 Sample Pre-treatment

Microplastics collected are mixed with organic-rich wastewater. Samples require pre-treatment to isolate microplastic from wastewater samples. These steps lead to more accurate quantification and identification of microplastics.

Purification Pre-treatment step to remove biogenic organic matter in wastewater samples is a crucial step before spectroscopic analysis (Tagg et al. 2017). The purification processes of microplastic samples can be divided into chemical degradation and enzymatic degradation (Li et al. 2018). Wet peroxide oxidation is usually applied as a digestion step for organic matter (Razeghi et al. 2022). Hydrogen peroxide (H_2O_2) is applied solely for a small sample volume (Lares et al. 2018). However, the use of H_2O_2 alone is a time-consuming method. There is a newly developed method using a combination of H_2O_2 with iron (Fe (II)) catalyst, known as Fenton's reagent, in the digestion of a large volume of wastewater with less exposure time (Tagg et al. 2017). The application of Fenton's reagent also has an insignificant effect on microplastic surface and size (Tagg et al. 2017). Thus, this method facilitates the isolation of microplastic from wastewater and other complex matrices.

An alternative for purifying microplastic samples is enzymatic digestion. Specific enzymes including protease, cellulase, and chitinase, are used to eliminate lipids, proteins, and carbohydrates in the environmental samples (Löder et al. 2017). Enzymatic degradation is another purification method without affecting synthetic polymers before spectroscopic identification.

Extraction of Microplastics by Density Separation Density separation is applied to extract microplastics from environmental matrices. Saturated salt solutions are mixed with the samples to enable low-density particles like microplastics to float and denser sediment to sink (Quinn et al. 2017). Microplastics can be separated by collecting supernatant particles (Li et al. 2018). Sodium Chloride (NaCl: 1.2 kg/L) is the most commonly used brine solution among all due to its low-cost, availability, and environmental friendliness (Hamidian et al. 2021). However, this approach is suitable for the extraction of low-density microplastics rather than high-density polymers (Claessens et al. 2013). Denser salt solutions such as Sodium Iodide (NaI: 1.6–1.8 kg/L) and zinc bromide ($ZnBr_2$: 1.7 kg/L) have a higher recovery rate in the segregation of denser microplastics (Quinn et al. 2017). In addition, NaI solution is recyclable without density alteration which can reduce the cost of microplastic extraction (Kedzierski et al. 2017). Zinc chloride ($ZnCl_2$: 1.5–1.8 kg/L) is also recommended for density separation due to the recyclability by pressure filtration (Löder and Gerdts 2015). $ZnCl_2$ is an alternative solution for environmental and economic reasons.

3.2.3 Microplastic Characterization

Microplastic characterization is generally classified into physical and chemical characterization. Physical characterization assesses size distribution and morphologies such as shapes and colors of microplastics (Sun et al. 2019). Chemical characterization mainly focuses on the chemical composition of microplastic particles.

Visual Sorting Stereo-microscopy is the most widely used method for physical characterization (Sun et al. 2019). The number of microplastics can be quantified under a microscope. Moreover, sizes and morphologies of microplastic particles can be observed. However, visual identification depends strongly on the skill of an operator, and the quantity of microplastics may be underestimated due to limited magnification (Sun et al. 2019). It can lead to the misidentification of similar organic and inorganic particles (Li et al. 2018). Visual characterization by a microscope should be limited to particles larger than 500 μm to avoid possibility of mischaracterization (Hamidian et al. 2021). A staining approach is employed to aid the assessment of microplastic abundances by visual sorting and to distinguish plastics from non-plastic particles (Ziajahromi et al. 2017). Staining based on the lipophilic dye Nile Red is a quick and inexpensive method to enumerate microplastics in large sample volumes (Hengstmann and Fischer 2019; Tamminga et al. 2017).

Identification of microplastics should not be solely dependent on visual sorting as errors may occur during observation. Subsequent chemical characterization can improve the accuracy of microplastic identification. Polymer types obtained from chemical characterization can be used to trace sources and origins of microplastic pollution.

Chemical Characterization There are several methods for chemical characterization of microplastics that involve destructive methods such as gas chromatography coupled to mass spectrometry (GC-MS), liquid chromatography (LC), and non-destructive spectroscopic methods. The investigation of microplastics by spectroscopic techniques, such as Fourier-transform infrared (FTIR) spectroscopy and Raman spectroscopy, is the most well-known approach. Infrared (IR) or FTIR spectroscopy allows accurate identification of plastic polymers from their IR spectra (Löder and Gerdts 2015). Raman spectroscopy is another highly reliable method based on the scattering of light for identifying microplastics in different environmental samples (Löder and Gerdts 2015). However, these spectroscopy techniques are size-limited to >20 μm and >1 μm for FTIR and Raman, respectively (Okoffo et al. 2019).

On the other hand, GC-MS and LC-based techniques have been used for the fast identification of microplastic samples. The structural information of microplastics is obtained by analyzing characteristic decomposition products of polymers (Fries et al. 2013). LC-based method is used to determine the chemical composition of microplastics and the sorption of organic contaminants (Jiménez-Skrzypek et al. 2021). Both methods do not have size limitations for microplastic analysis unlike spectroscopic methods (Sun et al. 2019).

3.3 Removal of Microplastics by Wastewater Treatment Plants

Each wastewater treatment step is specifically designed to remove particular pollutants rather than small-sized particles like microplastics. Thus, microplastics can still escape from wastewater treatment plants. This section reviews the contribution of different treatment technologies to microplastic removal.

3.3.1 Preliminary and Primary Treatment

Preliminary and primary treatment steps remove microplastics based on physical mechanisms. A study by Murphy et al. (2016) showed the biggest reduction of microplastics during the grit and grease removal stage. Larger-sized microplastics are captured by skimming of floating grease and settling with the grit. Primary sedimentation can easily separate fibers and large-sized microplastics by settling of heavy particles and trapping them in solid flocs during gravitational settling (Liu et al. 2021). Microplastic particles larger than 300 μm can be efficiently removed during primary sedimentation (Wu et al. 2021). Smaller particles remain suspended in the liquid phase and further removed by secondary treatment.

3.3.2 Secondary Treatment

In secondary treatment, sludge flocs or bacterial extracellular polymers in the aeration tanks are capable to capture remaining microplastic particles. Flocs containing microplastics are subsequently removed by settlement in a clarification tank. Flocculation agents in the secondary treatment stage could enhance microplastic removal by aggregation of suspended solids (Murphy et al. 2016; Sun et al. 2019). Bioreactor exhibits a notable microplastic removal rate compared to other biological processes (Liu et al. 2021).

On the other hand, the entrapment of microplastics in unstable flocs might lead to the redistribution of microplastics in the tank (Carr et al. 2016). Consequently, some microplastics might escape the removal during the settling stage (Carr et al. 2016). Retention time and nutrient level are factors that influence microplastic removal in the activated sludge process (Carr et al. 2016; Rummel et al. 2017). Surface biofilm coating has a significant effect on the density, buoyancy, and sinking rate of microplastics (Rummel et al. 2017). This change increases the chance of microplastic removal by skimming and settling (Ngo et al. 2019).

In terms of morphology, fragments have a higher removal rate than fiber during secondary sedimentation (Talvitie et al. 2015). The lamellar structure of fragments makes them easily agglomerate and increases the chance of microbial colonization (Liu et al. 2021; Ngo et al. 2019). Fibers are easily skimmed or settled during preliminary and primary treatment. The remaining fibers might have a neutral buoyancy which is resistant to removal by the treatment technology (Ngo et al. 2019). Compared to other shapes of microplastics, fibers and pellets are less resistant to wastewater environment and more difficult to be captured due to their smooth surface (Ngo et al. 2019). Fiber is also considered the most difficult type of microplastics to be removed from wastewater (Long et al. 2019). This shape of microplastics has been reported as a predominant shape in wastewater effluents (Dris et al. 2015; Leslie et al. 2017; Ziajahromi et al. 2017).

3.3.3 Tertiary Treatment

The application of tertiary treatment technologies can increase the overall microplastic removal efficiency of wastewater treatment plants by 10–97% (Sun et al. 2019). A wastewater treatment plant with membrane bioreactor (MBR) technology exhibits excellent microplastic removal efficiency of 99.9%

(Talvitie et al. 2017). Within the MBR system, adsorption has a significant effect on microplastic removal (Liu et al. 2021). Membrane filters, such as ultrafiltration (UF) membrane, reduce the concentration of microplastics by intercepting larger particles than the pore size. Wastewater treatment plants equipped with a UF unit attained more than 95% of microplastic removal efficiencies (Mintenig et al. 2017; Tadsuwan and Babel 2022; Yang et al. 2019a; Ziajahromi et al. 2017). Biofilter as a final polishing step completely removed microplastic >100 μm (Liu et al. 2020). Sand filtration further reduced microplastic concentration in secondary effluent by 50% (Magni et al. 2019). The implementation of a sand filter in tertiary treatment is considered a simple and cost-effective method compared to membrane filtration (Iyare et al. 2020).

On the contrary, some types of tertiary filtration, such as granular filtration and biological active filter, are not effective for microplastic removal (Sutton et al. 2016; Talvitie et al. 2017). Small microplastic particles ranging from 20 μm to 100 μm were found to escape all treatment stages and released into recipient water (Cesa et al. 2017). Despite the utilization of advanced technologies, a considerable number of microplastic is being discharged daily with a large volume of treated wastewater.

3.3.4 Overall Microplastic Removal Efficiencies

The abundance of microplastics in wastewater treatment plants depends on a variety of complex factors such as population served, type of wastewater (municipal or industrial), economy, and lifestyle of surrounding communities (Liu et al. 2021). There is a positive correlation between population and the abundance of microplastics in wastewater treatment plants (Zou et al. 2021). A higher number of microplastics were detected in wastewater treatment plant receiving both municipal and industrial wastewater than treatment plants receiving only municipal wastewater alone (Liu et al. 2021). Sampling methods and mesh sizes employed also influence the number of microplastics. In addition, the number of microplastics in the effluent is affected by combined sewer systems, the flow rate of the wastewater treatment plant, and tertiary filtration (Mason et al. 2016). Thus, microplastic concentrations in wastewater treatment plants cannot be compared directly. On the other hand, the overall removal efficiency of a wastewater treatment plant indicates the performance of the treatment system on microplastic removal. Table 1 displays the percentage removal of microplastics by different schemes of wastewater treatment plants with removal efficiencies ranging from 40 to 99.9%.

3.3.5 Microplastics in Sewage Sludge

Microplastics removed from wastewater are retained in the sludge through sedimentation in both primary and secondary treatment. The reported microplastic concentration in sewage sludge ranged from 1000 to 240,300 items/kg of dried sludge

Table 1 Microplastic removal efficiencies of wastewater treatment plants

Location	Type of facility	Influent (microplastics/L)	Effluent (microplastics/L)	Overall removal efficiency (%)	References
Scotland	Primary and secondary treatment	15.70 ± 5.23	0.25 ± 0.04	98.4	Murphy et al. (2016)
Italy	Primary, secondary, and tertiary treatment (sand filtration)	2.5 ± 0.3	0.40 ± 0.10	84	Magni et al. (2019)
China	Primary and secondary treatment	79.9 ± 9.3	28.4 ± 7.0	64.4	Liu et al. (2019)
China	A full-scale wastewater treatment plant with two parallel systems 1. Oxidation ditch 2. MBR	0.28 ± 0.02	1. 0.13 ± 0.01 2.0.05 ± 0.01	1. 53.6 2. 82.(1	Lv et al. (2019)
Finland	1. Conventional activated sludge process 2. A pilot-scale MBR	57.6 ± 12.4	1. 1.0 2. 0.4	1. 98.3 2. 99.3	Lares et al. (2018)
Finland	Tertiary treatment 1. MBR 2. Rapid sand filter 3. Dissolved air floatation 4. Disc-filter	1. 6.9 ± 1.0[a] 2. 0.7 ± 0.1[b] 3. 2.0 ± 0.07[b] 4. 0.5–2.0[b]	1. 0.005 2. 0.02 3. 0.1 4. 0.03–0.3	1. 99.9 2. 97.1 3. 95 4. 40–98.5	Talvitie et al. (2017)
Australia	Primary, secondary, and tertiary treatment (UF)	2.2[a]	0.28	87.27	Ziajahromi et al. (2017)

(continued)

Table 1 (continued)

Location	Type of facility	Influent (microplastics/L)	Effluent (microplastics/L)	Overall removal efficiency (%)	References
Korea	Three full-scale wastewater treatment plants 1. Ozone 2. Disc-filter 3. Rapid sand filtration	1. 4200 2. 31,400 3. 5840	1. 33 2. 297 3. 66	99.2 99.1 98.9	Hidayaturrahman and Lee (2019)
Turkey	Primary and secondary	23.44 ± 4.1–26.55 ± 3.17	4.11–6.99	73–79	Gündoğdu et al. (2018)
Thailand	Primary, secondary, and tertiary (a pilot-scale UF)	77 ± 7.21	2.33 ± 1.53	96.97	Tadsuwan and Babel (2022)

[a]Primary effluent
[b]Secondary effluent

(Okoffo et al. 2019). Sewage sludge undergoes some treatment such as anaerobic digestion, thermal drying, and lime stabilization, before land application or disposal. Anaerobic digestion potentially reduced microplastic abundance in sludge, whereas, the number of microplastics increased after lime stabilization due to the shearing effect (Mahon et al. 2016). Incineration is expected to be an ideal method for the elimination of microplastics from sewage sludge. However, microplastics were detected in bottom ash, a by-product of an incinerator (Yang et al. 2021b). The method for the elimination of microplastics from sewage sludge needs further investigation.

Sewage sludge is considered one of the important sources of microplastics in terrestrial environments (Bläsing and Amelung 2018; Chia et al. 2021). There is evidence of microplastic spread in agricultural soil after sludge application. Microbeads and fibers, similar to those found in wastewater treatment plants, were present in sludge-amended soil (Chen et al. 2020). More than 30,000 tons of microplastics annually entered the agricultural soil of Europe and North America (Nizzetto et al. 2016). Microplastics in soil negatively impact flora and fauna in the soil environment (Kumar et al. 2020). This type of pollution also alters soil nutrient cycles (Huang et al. 2022). Moreover, microplastics tend to accumulate at the roots of some edible plants and transport them to leaves (Li et al. 2021). When microplastics are transferred through the food chain, the chemicals pose harmful effects on human health (Kumar et al. 2020). Hence, sludge containing microplastics is a potential pathway of microplastic transport to the soil environment.

3.3.6 Major Treatment Unit for Microplastic Removal

Studies showed that the majority of microplastics were removed during the skimming and settling processes (Carr et al. 2016; Murphy et al. 2016; Zhang et al. 2021). The predominant shape of microplastics in these studies were fragments which are in contrast with other studies where the majority of microplastics are fibers. Large-sized fragments tend to settle during primary sedimentation. PE microbeads derived from personal care products can be easily skimmed during grease removal due to the positive buoyancy (Murphy et al. 2016). Thus, the studies achieved a high removal rate in preliminary and primary treatment regarding the characteristics of microplastics in wastewater.

On the other hand, some studies reported that biological processes in secondary treatment play an important role in microplastic removal (Jiang et al. 2022; Yang et al. 2021a). The removal rate of microplastics during this stage can be as high as 95.2% (Jiang et al. 2022). However, the most effective step for microplastic retention is still controversial. Secondary treatment can further remove <20% of microplastics in primary effluent (Okoffo et al. 2019). Anaerobic-anoxic-oxic (A^2O) process attained a lower removal rate than the activated sludge process (Liu et al. 2019; Yang et al. 2019a; Ziajahromi et al. 2017). In the A^2O process, microplastics are likely to return to the system when sludge is recycled (Liu et al. 2021). On the contrary, a study showed that there was no significant difference in microplastic removal from three different configurations of activated sludge process: A^2O, sequence batch reactor (SBR), and the Media processes (Lee and Kim 2018). Therefore, the results of removal efficiency by secondary treatment are still uncertain.

Tertiary treatments act as a final polishing step which can increase the overall percentage removal of wastewater treatment plants. In this stage, microplastics with specific properties and very small particle sizes are efficiently removed (Liu et al. 2021). MBR has become the most popular technology for removing contaminants, and it is the most efficient microplastic removal method among other advanced technologies (Hamidian et al. 2021; Ngo et al. 2019). Despite an effective removal by MBR, the wastewater treatment plant still releases 800,000 fibers daily (Michielssen et al. 2016). Fibers can pass through a filter with a pore size as small as 0.08 μm (Leslie et al. 2017).

Fibers are considered the most challenging type of microplastics to retain in wastewater treatment plants. Even though they are trapped during flocculation and settling, due to their longitudinal shape, fibers can easily escape treatment processes (Liu et al. 2021). The neutral buoyant property of fibers also hinders the removal by the skimming process (Ngo et al. 2019). Studies found that fibrous microplastics are the dominant shape in wastewater effluent (Tadsuwan and Babel 2021; Zhang et al. 2021; Ziajahromi et al. 2017; Zou et al. 2021). Since wastewater treatment plants cannot completely remove this type of microplastics regarding its nature, it is important to focus on the reduction of fibers at sources.

4 Conclusion

Microplastic is an emerging pollutant that receives much attention in recent years due to the impacts to the environment. Wastewater treatment plant is an important land-based source of microplastics. Wastewater treatment plant acts as a final barrier before microplastics enter the freshwater bodies. Since the plants are not specifically designed to completely remove these minute-sized particles, a substantial amount of microplastics is discharged daily with wastewater effluent. It is important to understand the characteristics and fate of microplastics in wastewater treatment plants. Each treatment units are capable of removing different types of microplastics in terms of shape and polymer density. It is still controversial which unit is the most important step for microplastic removal. However, the combination of primary and secondary treatment can efficiently remove microplastics in some wastewater treatment plants. The advanced tertiary treatments can further enhance the removal rate of microplastics. In addition, since microplastics are retained in the sludge, research attention needs to focus on the disposal of sludge containing microplastics to prevent the further spread of microplastic pollution in soil. Moreover, there is currently no standardized method for microplastic sampling from wastewater treatment plants. Thus, it becomes difficult to compare the pollution levels in different studies due to various methods and mesh sizes employed for sampling. Further studies should develop mitigation measures to prevent microplastic pollution at this point source.

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Microplastic Sources, Transport, Exposure, Analysis and Removal

Shweta Yadav, Syed Saquib, Shiuly Bhowmick, Ankita Gupta, Tjandra Setiadi, and Poonam C. Singh

Abstract Microplastics were first observed in the marine environment but they were found recently in freshwater ecosystems including lakes, rivers, and estuaries. He we review microplastics with focus on sources, transport and degradation in aquatic systems, contamination of plants and aquatic organisms, exposure by inhalation, food and skin, sampling and analytical methods, and removal methods. Removal can be done by algal biomass, membranes, chemical treatment, and biological treatment.

Keywords Urbanisation · Microplastics · Waste management · Water contamination

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1 Introduction

The presence of microplastics is an increasing concern worldwide. Approximately 8 billion tonnes of plastics produced per year globally and projected to reach 12 million tonnes in 2050 (Geyer et al. 2017) (Fig. 1). Due to the several advantages of plastics such as light weight, inexpensive, anti-corrosive, and indiscriminate use in several fields, led to the accumulation in the environment (Yadav et al. 2022). Microplastics are generated in terrestrial ecosystems and can be transported to aquatic environments. It is reported that 70%–80% of plastics comes from terrestrial sources and 20–30% are from marine activities (Li et al. 2016; Lebreton et al. 2018).

Approximately five trillion of plastics float on the sea surface (Eriksen et al. 2014). A considerable number of plastics in the ocean come from the terrestrial environment through surface runoff, industrial waste discharge, tourism, and fishing processes. Once it enters into the ocean, it can travel up to several kilometres due to oceanic currents and gyres (Kane et al. 2020). Oceanic currents are also responsible for the vertical mixing of microplastics and increase its availability from top to bottom layer. Therefore, the ocean sediments are reported to contain microplastics which are differing in colour, shape and size and their presence can further encourage their toxic effect on benthic organisms (Vianello et al. 2013; Kanhai et al. 2019; Kane et al. 2020). The increasing concentrations of microplastics lead to direct or indirect effects on marine biodiversity, economy, and human health. Understanding essential threats to critically important aquatic ecosystems requires an understanding of locating microplastics accumulation sites and their potential to enter the food chain.

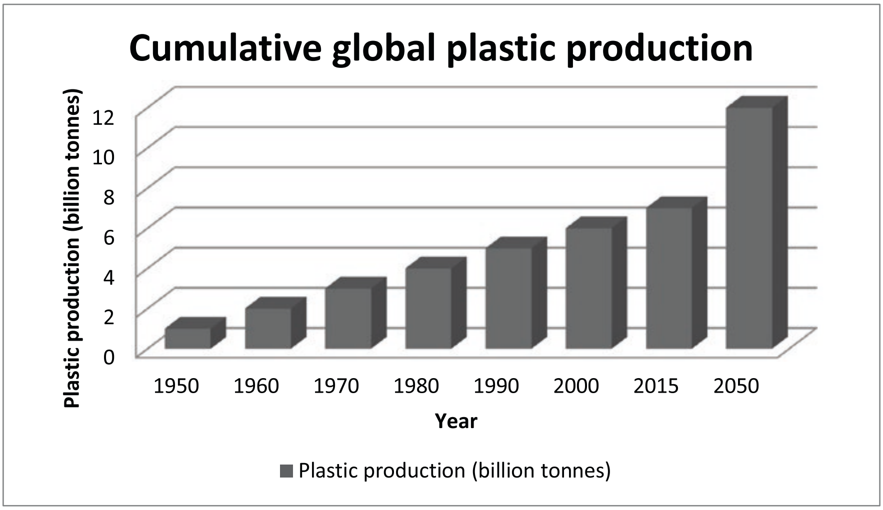

Fig. 1 Cumulative global plastic pollution

Each year, an estimated 10,000 marine animals and 1 million birds die due to the entanglement, suffocation, and ingestion of plastics (Green et al. 2015). The primary elements that might impact the abundance of microplastics in the environment are population density and proximity to metropolitan areas. According to Jiang et al. (2019), the quantity of microplastics in the sediment surrounding Lhasa, a popular tourist destination in China's Tibet Autonomous Region, is higher than in less inhabited places. Similarly, Cable et al. (2017) found higher concentration of microplastics (2 million particles/km^2) in Great lakes of the urban cities.

Microplastic pollution not only compromises the livelihoods of individuals who rely on marine resources for a living, but it may also cause plenty of health problems for all those who consume seafood contaminated with hazardous micro- and nano-plastics. Microplastics come with several unknown hazards and its impact on the environment is a fast expanding subject of study. For the separation, identification, and quantification of plastic particles in environmental samples, researchers from various fields have used a variety of analytical approaches. While research continues to determine the limitations of the several different approaches employed, obtaining a seemingly simple data type such as plastic counts with substantial throughput and accuracy remains a challenge.

2 Microplastics Types and Sources

Microplastics are plastic particles which are 5 mm to 100 nm in size (GESAMP 2016; Masura et al. 2015; Thompson et al. 2004). The latest definition of microplastic categorises the microplastic size range from 5 mm to 1 μm (Hartmann et al. 2019). These types of plastic debris are now prominently found in lakes (Vaughan et al. 2017), estuaries (Gray et al. 2018), oceans (Zhou et al. 2018), and also in the poles (La Daana et al. 2018) which can cause harm to the aquatic ecosystem.

Microplastics can be divided into six types based on the plastic properties: PE (polyethylene), PP (polypropylene), PS (polystyrene), PVC (polyvinyl chloride), PA (polyamide), and PET (polyethylene terephthalate) (Andrady 2017). Microplastics can also be classified depending upon their source as primary microplastic and secondary microplastic. Primary microplastics are the manufactured microplastics for certain applications and the secondary microplastics are the degraded plastic materials due to weathering and fragmentation (GESAMP 2016; Zeng 2018).

2.1 Primary Sources of Microplastics

Primary plastics are commercially designed in the size of 5 mm or less and directly released into the environment. Majority of primary plastics particles come from land based activities (98%) whereas rest from sea activities (Boucher and Friot

2017). These particles can also add from the shredding or abrasion of large plastics products during the manufacturing process. Plastic beads used to manufacture various things involving products made from thermoplastics. Microplastics in the form of microbeads are used in the cosmetic industry to manufacture products related to cleansing and exfoliation (Bashir et al. 2021). The type of plastic used to manufacture microbeads includes both thermoset plastic and thermoplastic. Microbeads are so small in size that they are unable to be removed during the sewage treatment process and thereby transported to the aquatic ecosystem. Microplastics are also released during the laundry process from households and industries in the form of microfibers and these fibres cannot be removed during sewage treatment thereby encouraging its release in the water bodies (Cheung and Fok 2017). Microplastics are also released by the wearing of tires in the vehicles, which is a main cause for the occurrence of microplastics in the road dust (An et al. 2020).

2.2 Secondary Sources of Microplastics

The secondary microplastics include the plastic debris which are derived from the disintegration and fragmentation of macro-plastics due to UV-radiation and various other environmental factors. Plastic bags are the major secondary source for the release of microplastics in the environment. Plastic is a non-biodegradable substance, but it can degrade into smaller fragments due to weathering and erosion processes, thereby making the utilization of plastics a major concern for the near future. Disposable plastic bottles are composed of PET, PE, and PP. They are majorly used in the food industries for storing and selling eatables such as pickles, cold drinks, fruits. After use, plastic bottles are thrown away in the environment without any proper disposal, thereby increasing the prevalence of microplastics in the environment. Another secondary source of microplastics includes the equipment used in the fishing manufactured from plastic such as fishing rods and fishing nets, which directly contributes to the elevation of microplastic levels in the marine ecosystem (An et al. 2020).

3 Transport and Fate of Microplastic in Water Bodies

Microplastics originate from land and sink into ocean via large network of fresh water rivers, lake, and estuaries (Wang et al. 2020a). The availability of microplastics in freshwater ecosystem is due to increasing activity of industrialization, agriculture, direct discharge of waste effluents and other human activities (Alam et al. 2019). Spatial distribution of microplastics mainly depends on population density, distance from human settlement, the type of land use, existence of dam, and wastewater treatment plants near the water body (Estahbanati and Fahrenfeld 2016; Weithmann et al. 2018). Terrestrial system acts as conduit for the transportation of

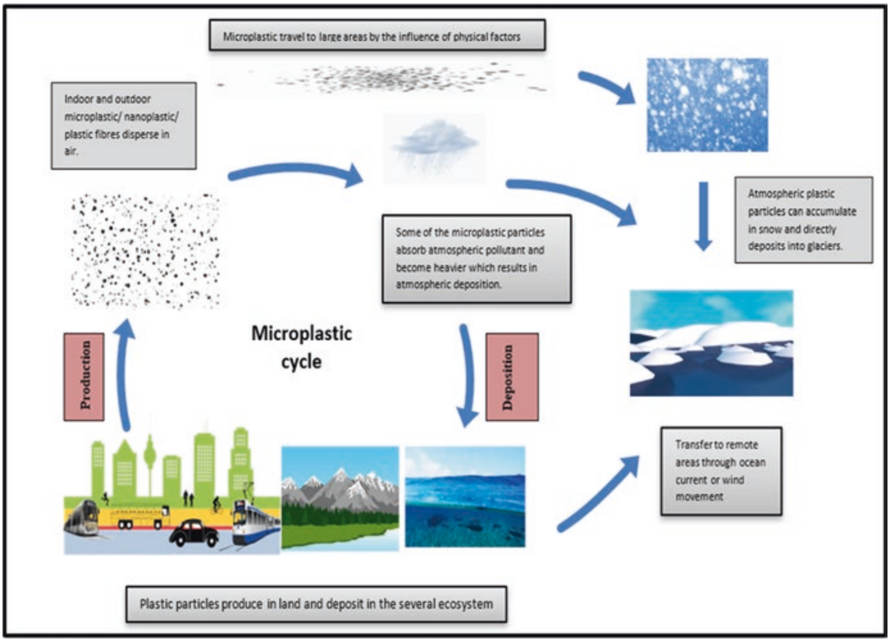

Fig. 2 Transport and fate cycle of microplastics in the atmosphere

microplastics in aquatic system (Fig. 2). Landfills constantly add plastic debris in the soil and also contaminate groundwater (Blaesing and Amelung 2018; Li et al. 2019). According to the American National Academies of Sciences, Engineering, and Medicine (2022) predicted that eight million metric tonnes of plastic per year were dumped into the ocean from all around the world. The effectiveness of removing microplastics ranges between 88% and 99.9% in wastewater treatment plants, suggesting the likelihood of drowning most of the MP in the sludge (Uddin et al. 2020). Organic fertilizers from biowaste fermentation of organic sewage wastes contaminated with plastics non-anthropogenic factors such as rain, wind, atmospheric fallout, and groundwater has an important contribution towards the distribution of environmental contaminants into the water bodies (Wagner et al. 2014). Rain is the most direct and effective way for surface runoff and accumulation of the microplastics from land to rivers (Xia et al. 2020). The microplastics in freshwater system are transported to ocean ecosystem. So, freshwater system can be considered as conduit in the transportation of microplastics in the ocean (Luo et al. 2019). In addition, to a great input from fresh water systems, a large amount of plastic debris may also enter directly into the sea from wastes generated from fishing activities, illegal dumping, accidental cargo loss, and tourist activity (Horton and Dixon 2018).

A widespread abundance of MPs in aquatic environments has been reported worldwide, starting from shallow lakes to the deepest ocean trenches including subpolar to subtropical oceans (Woodall et al. 2014; Egger et al. 2020; Peng et al. 2018;

Table 1 Occurrence and concentration of microplastics (MP) in aquatic ecosystems

Study site	Sample	Concentration of microplastics	Types of abundant microplastics	References
Ciwalengke River, Indonesia	Sediment and water	3.03 MPs particles/100 g, 5.58 particles/L	Polyester and nylon fibres	Alam et al. (2019)
River Kelvin, Glasgow, Scotland		161–432 MPs kg^{-1}	Microfibres, microbeads, and micropellets	Blair et al. (2019)
Dongting Lake and Hong Lake, China	Surface water, sediment	900–2800 n/m^3 in surface water, 1250–4650 n/m^3 in sediment	PE, PP	Wang et al. (2018)
Lakes in Tibet Plateau	Sediment	8–563 particles/m^2	PP, PE, PS, PET, PVC	Zhang et al. (2016)
Wei River, China	Surface water, sediment	3.67–10.7 items/L in surface water and 360–1320 items/ L of sediments	PS	Ding et al. (2019)
North Pacific Ocean	Water	<0.1 μg/m^3	PP, PE	Egger et al. (2020)
Mariana Tench	Sediment, water	200–2200 pieces/L sediment, 2.06–13.51 pieces/L bottom water	PP, PA, PVC	Peng et al. (2018)
Northwest Pacific Kuril–Kamchatka Trench	Sediment	60–2000 pieces /m^2	Fibres	Fischer et al. (2013)
Coastline of Bandar Abbas	Surface water	3252 ± 2766 MPs /m^2	PS, PA, PET, PP	Nabizadeh et al. (2019)
Arctic Central Basin	Surface water	0.7 particles/m^2	Polyester fibres	La Daana et al. (2018)
South West Indian Ocean	Sediment	1.4–40 pieces/m^2	Rayon and polyester fibres	Woodall et al. (2014)

La Daana et al. 2018) (Table 1). A huge amount of microplastic is found from these regions. Most of the recovered plastic debris are PE, PS, PVC, PP, and PET having different sizes and shapes (Li et al. 2019; Lei et al. 2018; LeMoine et al. 2018). A pilot study on ombrotrophic peatland to identify the trends in microplastic pollution and its deposition in the atmosphere showed the increased microplastic pollution from <5(±1) particles/m^2 /day in the 1960s to 178(±72) particles/m^2/day in 2015–2020 (Allen et al. 2021). Microplastics were eventually transported from freshwater to the ocean system via several conduits. Kole et al. (2017) reported the global annual average per capita generation of tire wear particles is 0.81 kg which is approximately 6.1 million tonnes of total plastic waste production. An additional 0.5 million tonnes are produced by brake wear particles emissions. Evangeliou et al. (2020) reported that the microplastics are mainly transported to remote regions through atmospheric transportation. They found that ~34% of emitted tire wear microplastics and ~30% which is up to 100 kt per year and 40 kt per year, is settled into world ocean. These findings imply that man-made plastics have contaminated even the most inaccessible and deepest regions of the world. The hadal zone is most likely one of the planet's major repositories for microplastic waste, with unknown but potentially harmful effects on this delicate environment. Understanding dispersion and accumulation patterns can help to predict the microplastics abundance in remote locations, and possibly helps to identify hotspotswhere microplastics concentrations are high. This will make it easier for management and the scientific community to identify where to focus mitigation efforts.

3.1 Transportation of Microplastics in the Aquatic Environment

After entering the water body, the plastic debris are either carried away with the water current, remain suspended or get deposited into the bottom depending on their size and density (Besseling et al. 2017). Physical factors play a crucial role in movement and transport of plastic debris in aquatic media. Water currents, convergence zones, and wave actions are more likely to affect dispersal and occurrence of microplastics in water bodies (Eerkes-Medrano and Thompson 2018). In the ocean environment, buoyant plastic particle which includes plastic bottles, wrappers, polyethylene, polypropylene, and polystyrene floats on the upper layer of water and get transported to other places by the movement of wind or natural occurring water current (Kooi et al. 2017).

Oceanic current may play a major role in transportation of microplastics and carry out far away from its source of origin. A number of mechanisms might have an impact on how microplastics are vertically distributed within the water column and how they are carried out of surface waters. Introduction into marine aggregates, biofouling, incorporation into faeces, and hydrodynamic forces like wind are few of these processes (La Daana et al. 2018). Eriksen et al. (2014) reported that approximately five trillion plastic particles float on the surface of the sea. Non buoyant and buoyant plastic particles will become submerged through vertical mixing and reach up to the bottom of the ocean by following the similar process of sedimentation of natural colloids (Kooi et al. 2017).

Biofouling is another confusing issue to take into account because it can enhance their density and hasten their assimilation into sediments. Some other natural factors such as diffusion, advection, and dispersion are also responsible for transportation of microplastics in aquatic environments (Fischer et al. 2013). In addition, the transportation of microplastics is also dependent on the physical (shape, size, density, degradability, and buoyancy) and chemical properties (Yadav et al., 2022). Isobe et al. (2014) concluded that mesoplastics (>5 mm) in ocean environments are influenced by a combination of forces like Stoke drift and terminal velocities, responsible for their selective onshore transport. The continued forcing and onshore transportation resulted in degradation of meso plastics and microplastics (<5 mm) on beaches having small size and lower density and intensely mixed with uppermost turbid layer and forced to move upward due to the buoyancy force. This suggests the selective transport of plastic particles due to variation in their sizes. Microplastic consumption has been documented in the body of fish, invertebrates, vertebrate, larvae, and planktonic organisms (Steer et al. 2017). To comprehend the movement of microplastics and risk evaluations, models must be developed with the use of data and practical verification.

3.2 Transportation of Microplastic in Atmosphere

Microplastic is present in all ecosystems such as air, water, and soil and follows cyclic behaviour (from land to air or vice versa) in the environment. Many researchers worked on their occurrence, transportation pathway and degradation (Wang et al. 2020c; Eerkes-Medrano et al. 2015). Air borne microplastic is the prominent source of microplastic in air. The transportation is influenced by climatic condition, topography, and meteorological condition. For, example, Zhou et al. (2017) found higher presence of air borne microplastic in summer, winter and spring season and least in autumn season. In terms of climatic condition, Allen et al. (2019) reported the higher occurrence of polystyrene (PS) in the month of November and December where as in February and March period, polyethylene (PE) was higher and low in November and December. In the air, atmospheric pollutants follow transportation, deposition and dispersion mechanism. The transportation is dependent on the atmospheric temperature, rainfall, pressure, humidity, and snowfall as well as wind speed. Plastic particles also follow same mechanism and transported to wider areas. The movement process is facilitated by the shape, size, and length of microplastic. For example, small size particles can travel up to large distance in comparison with large particles and have potential to long term persistence in the atmosphere. Zhou et al. (2017) reported that with decreasing particle size, amount of small plastic particle increases in Yantai, China.

Due to the dispersion of microplastic, atmospheric microplastic can travel up to large distance in atmosphere and eventually may sink into land or remote areas. For example, Evangeliou et al. (2020) conducted research to study the susceptibility of road born microplastic in remote areas. They found that approximately 15% of smaller size (PM 2.5) road born microplastic transfers to Atlantic Ocean. They also reported that due to the production of microplastic from Southeastern Asian region, approximately 2% of road borne microplastic deposit in South China Sea. Arctic is another important recipient of microplastic particles. As it is reported that aerosol can travel up to arctic region, it is evident that fine plastic particles can reach up to Arctic region and leads to deposition in ice and snow (Stohl 2006).

3.3 Degradation and Settlement of Microplastics

The settlement of microplastics into the sediments is due to the combined effect of gravity and buoyancy. Previous studies showed that microplastic concentration is higher in sediments than those in surface water (Wang et al. 2018; Yao et al. 2019). Song et al. (2018) detected more microplastics particles in middle layer (423 ± 342 n/m^3) and benthic layer (394 ± 443 n/m^3) in Korean Coastal water. In contrary, Li et al. (2020a) reported the average size of microplastics particles is 668.36 μm in Pacific Ocean or 645.14 in Indian Ocean. They found the higher concentration of microplastics particles in surface water with an average size of microplastics were 711.51 ± 616.15 μm in West Pacific Ocean and 826.46 ± 1284.19 μm in East Indian Ocean whereas deeper layer water column contained 482.20 ± 285.15 μm in Pacific Ocean and 589.54 ± 794.53 μm in Indian Ocean. This study suggested that the average concentration of microplastics decreases with the increasing depth.

Furthermore, microplastics do not always exist in a single form rather they aggregate either homogeneously or heterogeneously with other microplastics and non-plastic particles which is a critical physiochemical process for transportation and ultimately have different fates and ecotoxicity (Yan et al. 2021). This is one of the factors that regulate the retention and availability of microplastics in surface water and responsible for the loss of nano and microplastics in inland water. Also, the retention and sedimentation of microplastics is directly related with its size and density (Wang et al. 2020a). Plastic particles with low density are generally found on the surface water and do not settle down easily. Once the microplastics settled into the bottom it is difficult to re-float on the water surface.

However, wind force may resuspend the microplastics from the bottom and allow vertical mixing within the water column (Yan et al. 2021). These floating particles provide surface area to microorganisms and algae to grow and as a result produce biofilm and secrete exopolysaccharides which ultimately increase the density and help them to settle down. Previous study on *Cladospora*, a green alga revealed that these macrophytes interact with microfibers of PET by adsorptive forces and physical entanglement and serve as a potential sink for microplastics (Peller et al. 2021). Rogers et al. (2020) emphasized the interaction between the microplastics and aquatic microorganisms and their influence on biogeochemical cycle of marine water and sediment, sedimentation and degradation of aggregates. Moreover, biofilm growth on microplastics influences the residence time in water columns, vertical and horizontal transportation, uptake and degradation by organisms, sedimentation and fate of microplastics. Formation of biofilm is greatly influenced by environmental conditions such as availability of light, temperature, pH, nutrient availability, and turbulence (Leiser et al. 2020).

4 Threats to Aquatic Flora and Fauna

4.1 Microplastic Contamination in Aquatic Animals

Although plastic pollution starts from land but it also reached up to aquatic environment and showed severe impact on its biological community. When these plastics exposed to the aquatic environment they start to degrade and break down into small sized particles, fibres, fragments or thin films having diameter of less than 5 mm under the action of physical, chemical and biological factors (Klein et al. 2015; Bellasi et al. 2020). These small pieces of microplastics are bioavailable to various aquatic organisms, most likely to the invertebrates and fishes (Ding et al. 2018) (Table 2). Microplastics have had a negative impact on about 700 aquatic species around the world, including sea turtles, penguins, and various crustaceans (Marn et al. 2020). In the biological system, these microplastics accumulate in different tissues cause bioaccumulation and biomagnification in successive trophic levels. As a result, changes in physiological and biochemical properties such as lipid homeostasis, fatty acid biosynthesis, β-oxidation of mitochondrial fatty acids can be observed and eventually death occur at a higher concentration (Wang et al. 2020b).

Microplastics can be up taken from the sediments and water columns by the organisms due to their resemblance with food particle. Small invertebrates are generally unable to discriminate between small microplastics particles and food particles and ingest them during their normal feeding activity (Akindele et al. 2019). Previous studies on aquatic organisms suggest that microplastics of different sizes, texture, and shapes have different effect on living systems (Su et al. 2018; Jemec et al. 2016; Yang et al. 2020a). For example, fresh water invertebrate, *Hydra attenuata* are capable to readily ingest polyethylene microplastics <400 µm in size obtained from face wash product. These microplastic flakes deposited inside the gastric cavity of *H. attenuata* and affect feeding activity, reproduction, and caused morphological changes (Murphy and Quinn 2018).

Australian glass shrimps (*Paratya australiansis*) commonly found in the rivers and estuaries in Australia were reported to accumulate polyester and rayon fibres having diameter less than 1 mm and blue in colour (Nan et al. 2020). In addition, some small invertebrates also adhere microplastics on the outer surface of their body and act as carrier of microplastics to fishes and other organisms which feed on them (Gutow et al. 2019). Omnivorous freshwater fishes such as Sunfishes generally feed upon eggs, earthworms, and molluscs were found to have microplastic contents in their stomach along with other organic matters. The study reveals that sunfish ingest microplastics incidentally during their normal feeding habits (Peters and Bratton 2016). Study of microplastic contamination in D. magna showed reduced growth rate, reproduction, and population growth rate. Chronic exposure to microplastics even caused mortality and recovered from several generations of D. magna (Martins and Guilhermino 2018). A 14-day laboratory experiment on freshwater Red Tilapia (*Oreochromis niloticus*) treated with polystyrene, observed different concentration of polystyrene in tissues such as liver, gills, gut, and brain.

Table 2 Effect of microplastics (MPs) on freshwater flora and fauna

Types of microplastics	Name of organism	Route of exposure	Concentration of microplastics exposed/recovered	Size	Impact	References
PE flakes	*Hydra attenuata*	Gastrointestinal tract	0.02–0.08 g/mL	<400 μm	Changes in morphology and feeding habits	Murphy and Quinn (2018)
PE	Zebrafish (*Danio rerio*)	Gastrointestinal tract	5 and 20 mg/L	10–45 μm	Change in larval gene expression	LeMoine et al. (2018)
Polyemide, PE, PP, PVC, PS	Zebrafish (*Danio rerio*)	Gastrointestinal tract	0.001–10.0 mg/L	70 μm	Cracking of villi, splitting of enterocytes, causing intestinal damage.	Lei et al. (2018)
Fluorescent PS	Zebrafish (*Danio rerio*)	Chorion membrane	1, 5, 10 mg/mL	10 μm	Decreased heart rate and blood circulation, inhibition of body length of larvae and embryo, also causing death of embryo	Zhang et al. (2020)
PS	*Caenorhabditis elegans*	Digestive system	5.0 mg/m	1.0 μm	Reduction of Ca^{2+} level and increased expression of glutathione S-transferase enzyme, inhibition of survival rates, body length and reproduction	Lei et al. (2018)
PS	Red tilapia (*Oreochromis niloticus*)	Gut, gills, liver, brain	100 μg/mL	0.1 μm	Inhibition of AchE activity and cause neurotoxicity, induction of SOD in liver	Ding et al. (2018)
Pristine polymers	*Daphnia magna*	Gastrointestinal tract	0.1 mg/L	1–5 μm	Decreased growth rate, reproduction, population growth rate up to F_3 generation	Martins and Guilhermino (2018)
PS	*Dreissena polymorpha*	Gills	5 × 105 MP/L and 2 × 106 MP/L	1 and 10 μm	Modulation of protein expression involved in structural and molecular activity, catalytic activity, energy metabolism, cellular trafficking	Magni et al. (2019)
PS microbeads	*Epinephelus moara*	Hepatic	7.03 ± 0.37% (w/w)	75 μm	Disruption of hepatic lipid homeostasis, causing oxidative stress and mitochondrial depolarization, inhibition of growth	Wang et al. (2020b)

(continued)

Table 2 (continued)

Types of microplastics	Name of organism	Route of exposure	Concentration of microplastics exposed/recovered	Size	Impact	References
PS	*Utriculata vulgaris*	Bladder	140 mg/L	1, 2, 5 μm	Inhibition of relative growth, chlorophyll content, photosynthetic activity, and oxidative damage	Yu et al. (2020)
PE	*Lemna minor*	Root tissue	10, 50, 100 mg/L	30–600 μm	Damage root cell membrane and cell viability, alter root growth	Kalčíková et al. (2017)
PS	*Chlamydomonas reinhardtii*	Cellular	100 mg/L	63–75 μm	Reduction of growth and bio mass, chlorophyll content and photosynthetic activity, increased level of soluble proteins and MDA content, decrease in extracellular polymeric substances, generation of ROS and lethal damage to cell organelles	Li et al. (2020b)
MP-metal co-contamination	*Chlorella vulgaris*	Cellular	50, 100, 1000 mg/L	0.5 μm	Reduction of growth and chlorophyll a content	Tunali et al. (2020)
PS	*Chlorella sorokiniana*	Cell membrane	240 mg/L	<70 μm	Alteration in synthesis of essential fatty acids and photosynthetic activity	Guschina et al. (2020)

And the concentration was higher in gut, and gills followed by liver and brain. Furthermore, exposure to different concentration of polystyrene caused neurotoxicity due to inhibition of acetylcholinesterase (AChE) activity and increased activity of SOD which clearly reflects oxidative stress from microplastics (Ding et al. 2018).

Compared with adult fishes, larvae are more sensitive to environmental pollutants due to their active feeding habits. Microplastics exposure to larvae could significantly affect growth by damaging liver, intestine, and gill tissues and also increase heart rate and blood circulation. In the muscular tissue, microplastics destroy nerve fibres, alter AchE activity and affect larval movement (Yang et al. 2020a; Zhang et al. 2020). Other consequences of microplastics toxicity may include decreased head/body ratio, DNA breakage, increased ethoxyresorufin-O-deethylase (EROD) activity, modification of cyp 1A gene, change in swimming behaviour and mortality in fish larvae after treated with 0.1% of microplastics (Pannetier et al. 2020; Cormier et al. 2019).

Other than pelagic organisms, studies on benthic animals are also very limited. Benthic animals are next to vulnerable to microplastics pollution due to close interaction with sediments (Bellasi et al. 2020; Guimarães et al. 2021). A number of benthos (gastropods, polychaete worms, molluscs, echinoderms, and amphipods) act as carrier of food, energy, and nutrients in aquatic food web (Su et al. 2018; Gutow et al. 2019; Naji et al. 2018; Nobre et al. 2015). The risk posed by microplastics to benthic animals is high because they are unable to discriminate between small food and microplastic particles (Akindele et al. 2019). These microplastic particles get accumulate throughout the digestive system and damage intestinal cells by cutting and splitting of villi and enterocytes also reduce Ca^{2+} level and increased synthesis of glutathione S-transferase enzyme in intestine which is an indication of oxidative stress in *Caenorhabditis elegans* (Lei et al. 2018). On the contrary, *Gammarus pulex*, a fresh water invertebrate is capable to tolerate high concentration of synthetic polymers like PET and did not show negative impact on molting, survival, metabolism and feeding habits of *G. pulex* (Weber et al. 2018). Thus, benthic organisms can be used as a bioindicators of microplastics pollution in aquatic ecosystems (Su et al. 2018). These invertebrates play a key role in structuring the aquatic ecosystem including food webs. Consuming microplastics will eventually transfer to the higher trophic level and increase biomagnification many fold. If the trend of declining population of these important taxa will remain constant, the whole food chain will be disturbed and may cause huge loss to the whole ecosystem. Although the study on such environmental contaminants are emerging fast, a comprehensive study on the quantification of microplastics and their possible impact on aquatic flora and fauna and human beings needs to be explored.

4.2 Microplastic Contamination in Plants

Despite a vast study of microplastic accumulation in animals and their impact, investigation on aquatic plants are rarely been reported. Aquatic plants are only source of food for herbivores, play a key role in food chain and also provide shelter to a variety of species (Kalčíková et al. 2020). Thus, a comprehensive study for impact of microplastic on aquatic plants is needed. Microplastics of different sizes and textures affect plants in different ways (Yokota et al. 2017). Large pieces of microplastics do not alter plant growth directly but sharp edges of microplastics can damage root membranes and affect root length (Kalčíková et al. 2020) and in some cases plastic particles get entangled in the root of vascular plants and transfer to herbivores by ingestion (Dovidat et al. 2020).

Other floating large microplastics particles such as PP, PVC, PE reduced availability of sunlight to primary producers like algae. As a result, a significant reduction of chlorophyll content and photosynthetic activity can be observed and ultimately hamper plant growth (Andrady 2017; Wu et al. 2019; Li et al. 2020b). On the other hand, small sized microplastics exerts inhibitory effect on PSII activity, chlorophyll content, root growth, cell viability, and oxidative damage to cell wall (Kalčíková et al. 2017; Yang et al. 2020b). Various studies on toxicity of microplastics on fresh water plants like- *Utriculata vulgaris*, *Lemna minor*, *Chlamydomonas reinhardtii, Chlorella vulgaris*, were observed to have changes in morphological and physiological activities consequently changes photosynthetic rate of leaf tissue, induced high ecotoxicity and oxidative damage to the plant (Yu et al. 2020). Generation of reactive oxygen species ROS resulted in cellular death and consequently increased level of malondialdehyde (MAD) as a product of membrane lipid peroxidation, soluble proteins, and decreased amount of extracellular polymeric substances (EPS) (Li et al. 2020b).

Similarly, microplastics pollution in microalgae *Chlorella sorokiniana* was reported to impede synthesis of fatty acids such as linoleic acids, α-linolenic acids, and a group of other polar lipids located mainly in photosynthetic membranes which not only reduce algal growth but also affect the whole food chain because these fatty acids act as a precursor of PUFAs (polyunsaturated fatty acids) which are highly required by the fishes and invertebrates as a major source of nutrient and energy (Guschina et al. 2020). The studies clearly reveal that higher concentration of microplastics are lethal to plant cell. On the contrary, plants like *Spirodela polyrhiza*, a duckweed species do not show any harmful symptoms after exposure to PMs (Dovidat et al. 2020). Combination of microplastics with other contaminants organic pollutants, metals, increase the toxicity many folds. Microplastic particles provide surface to metals for adsorption and help in transportation and ingestion by the organisms which cause a series of toxicological effects (Tunali et al. 2020; Kalčíková et al. 2020). Exposure of microalgae to organic pollutants resulted in generation of ROS like super-oxides (O_2^-), hydrogen peroxide (H_2O_2), and hydroxyl radicles

(OH) and causes lipid peroxidation damage consequently increase level of MDA in algal cells (Yang et al. 2020b; Wang et al. 2020a).

The studies suggest that microplastics are ubiquitous and the aquatic ecosystem is more likely to be affected by these emerging contaminants. These microplastics adversely affect growth and development of aquatic flora and fauna, causes ecotoxicity and hamper food web. Therefore, a comprehensive study for assessment of microplastics in aquatic animals and plants are required.

5 Effect of Microplastics on Human Health

Plastic is greatly resistant to degradation, hence, recalcitrant in nature. Due to wider exposure and toxicity, microplastic is continuously being a global threat. The main key concern of microplastic is its persistence and disintegration in environment which directly poses risk to human health. Microplastic less than 20 µm are reported to cross the biological membrane. Bio monitoring studies on human stools (Schwabl et al. 2019), placenta (Ragusa et al. 2021), foetus, and blood (Leslie et al. 2022) advocate the presence of microplastic particles in human body. As it has size in microns, it can easily spread to wider areas and reach in human body through various exposure pathway described in below (Huang et al. 2013; Steer et al. 2017; Van Cauwenberghe and Janssen 2014) (Fig. 3).

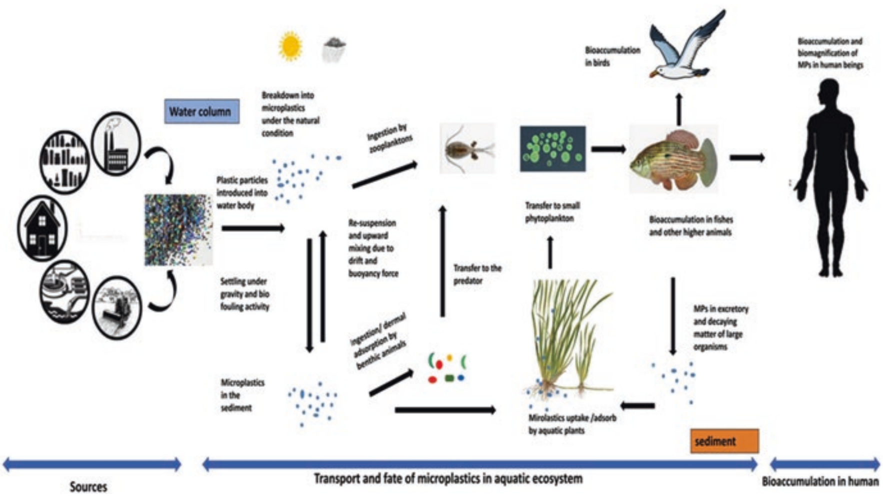

Fig. 3 Sources, sink and microplastics contamination in food chains

5.1 *Exposure Pathways*

5.1.1 Inhalation

The atmosphere works as a vehicle in transportation of microplastic or nano plastic to wider areas (Allen et al. 2019; Trainic et al. 2020). The microplastic particles in air mainly come from atmospheric outburst, natural degradation by sunlight, tyre wear, manufacturing of plastic products, and recycling of plastic waste. These sources incorporate microplastics in surrounding atmosphere and increase the risk to enter in human body through inhalation (Huang et al. 2013). In addition, regular usage of plastic items contribute to plastic microfibers, microplastic, nano plastic, synthetic and non-synthetic fragments in indoor environment which make direct exposure of plastic particles to human (Vianello et al. 2019). Individual inhalation of airborne microplastic is reported up to 26 up to 130 plastic particles per day (Prata 2018). Airborne plastic particles ranging from 1 nm and 20 μm are considered respirable. Ultrafine plastic particles (<0.1 μm) get absorbed through inhalation and accumulate into lungs and affect the respiratory system by damaging the lungs cells or tissues (Wright and Kelly 2017; Brown et al. 2001). Similarly, Pauly et al. (1998) reported the existence of micro fibres in human lungs tissues. However, inhalable small size microplastic particles accumulate in the deep lungs while others deposit in the upper airways such as the nose, throat, and mouth. Some of these particles can be eliminated through muco-cilliary clearance (Wright et al. 2019). The exposure of microplastic/nanoplastic toxicity on human body is largely unexplored. For further investigation, the estimation of indoor or outdoor microplastics concentration is needed to assess the risk associated with microplastics consumption through inhalation.

5.1.2 Exposure Through Food

Consumption of microplastic/nanoplastics contaminated food is considered as major entry route of microplastics in human system. In 2016, UN report published that approximately 800 animal species were polluted with microplastics through water current, entanglement, and ingestion. Microplastic particles enters in human body through the intake of sea food (Karbalaei et al. 2018; Naji et al. 2018), salt (Karami et al. 2017), sugar (Liebezeit and Liebezeit 2013), honey and beverages (Diaz-Basantes et al. 2020). Approximately 83% of tap water contains plastics particles (https://www.un.org/pga/73/plastics/).

Kosuth et al. (2018) reported that the maximum consumption of plastic particles per person/year is 4000 from tap water. Van Cauwenberghe and Janssen (2014) recovered microplastic from the tissues of bivalves which were commercially grown for human consumption. Long term use of plastic products may lead to disintegration of plastics into surrounding food and water and directly intake by humans. Cox et al. (2019) reported the annual intake of microplastics of American peoples is

39,000–59,000 particles per kg which get increased with consumption of bottle water. However, the consumption, accumulation and toxicity of microplastics is largely depends on the sex and age group (Campanale et al. 2020).

Eventually, the generated microplastics may enter into human body and reported to pass in blood through ingestion and likely to cross the placental barrier where it may transfer to unborn child (Grafmueller et al. 2015; Leslie et al. 2022). Despite this, number of researches have been documented that human eliminates more than 90% of microplastic via their faeces (Smith et al. 2018; Wright and Kelly 2017). The presence of microplastic in human body is well reported in the studies but their interaction with cellular component or macromolecules is still unknown. To know the degree of toxicity and associated risk related to microplastics, it is important to investigate the interaction of microplastic/nanoplastics with the cellular component and biomolecules and their movement in human system. There is also need to conduct biomonitoring studies to determine the most commonly occurring polymer and their toxicokinetic in human system.

5.1.3 Exposure Through Skin Pores

Dermal contact is the least occurring entry of microplastic in human body. As we know, microplastics are used in cosmetic or personal care products such as cream, daily soap, shampoo, shower gel, facial masks, body lotion, tattoo ink containing acrylonitrile butadiene styrene particles contributing in the ingestion of plastic particles in human system (Duty et al. 2005; Bhattacharya 2016). The commercial products not only contain micro particles but also contain nanoparticles. Application of plastics containing cosmetic products may facilitate the entry of microplastics directly into human or increases exposure risk. Microplastics may clog skin pores, cause inflammation, itching, and can damage skin cells (Sedano et al. 2020). To uncover the toxic effect of microplastics, method should be developed to identify the physical and chemical changes in microplastics after interacting with biological systems.

5.2 Effect of Plastic Additives on Human Health

A number of chemical additives such as colouring agents, plasticizers, toxic polymers are used during plastic manufacturing to enhance their shelf life and make resistant to natural degradation against UV, ozone and sunlight, humidity and microorganisms (Smith et al. 2018). Microplastic less than 130 μ in diameter have the capacity to translocate into human tissue and release the monomers, additives or induce the localized immune response (Wright and Kelly 2017). The adverse effect of microplastic on human health can be categorised into two categories; first is physical effect and other is chemical effect. The physical effect of microplastic is less understood than chemical effect, but also considered as main concern regarding human health. Physical effects include the several problems such as dermatitis, inflammation, and respiratory problems (Smith et al. 2018). Plastic associated toxic chemicals have been reported in human blood, breast milk, and urine resulting in damage of internal cells or tissues (Meeker et al. 2009). These chemicals alter the physiology of human system by affecting the internal body organs such as kidney, stomach, heart, brain, digestive system, nervous system, and reproductive system (Campanale et al. 2020; Frederiksen et al. 2009) (Table 3). In addition, chemicals additives may cause cancer, damage DNA, cells and tissues of the body and weakened immune system. The presence of chemical components such as bisphenol A (BPA), polybrominated diphenyl ethers (PBDE) tetra-bromo-bisphenol A (TBBPA), and phthalates used in plastic manufacturing, is also reported in human body (Lang et al. 2008; Matsumoto et al. 2008; Talsness et al. 2009; Godswill and Godspel 2019). These components exposed human to variety of risk by modulating the endocrine system. The microplastic exhibited several risks by inhibiting the equilibrium of endocrine hormones, mimic the endocrine hormones, and modify the synthesis of these hormones. For example, Phthalates and PBDE exhibited anti androgen

Table 3 Chemical used for microplastic synthesis, and their harmful effects on human health

Chemicals	Use	Effect on humans	References
Bisphenol A	Used in baby milk bottles, water bottles, food packaging	Acts as endocrine disruptor, mimics the oestrogen hormone, affects the function of thyroid hormone by altering axis gene expression, impaired development, sterility, increase the possibility of breast cancer, early sexual maturation, decrease sperm production, neuro-behavioural disorders, liver enzyme and decrease the thyroid hormone receptor activity	Vandenberg et al. (2009) and Eskenazi et al. (2007)
Phthalates	Used in manufacturing of toys, raincoats, food packaging, cosmetics and personal care products	Acts as endocrine disruptor, cause rhinitis and eczema in infants and children, alters the level of hormone, cause reproductive system disorder	Duty et al. (2005) and Matsumoto et al. (2008)
Flame retardants	Used for safety purposes in plastic, prevent from fires	Act as hormone disruptor, inhibit the equilibrium of oestrogen and thyroid hormone and affect the development of reproductive and nervous system	Meeker et al. (2009) and Frederiksen et al. (2009)
PCBs	Used in paints, rubber products, electrical equipments	Causes reproductive disorders, alters hormone level, increase the proliferation of diseases by disrupting the function of immune system	Lee et al. (2001) and Ryan et al. (1988)
Pigments	Used for colouring purposes	Considered as neurotoxic, immunotoxic, genotoxic, and causes cancer in human body	Skocaj et al. (2011)
Biocides	Use to protect from several microbial degradation	Acts as anti-biotic and destroy the gut microflora community, causes skin related problems	Galloway (2015)

activity, BPA exhibited the oestrogen like activity and TBBPA and PBDE inhibited the balance of thyroid hormones (Talsness et al. 2009; Wetherill et al. 2007; Guillette Jr et al. 1995). The result of non-equilibrium of endocrine hormones may lead to transient or permanent alteration in gene expression or phenotypic modifications (Skinner and Anway 2007).

Suspended atmospheric plastic particles may adsorb harmful pollutants from the surroundings which will be more severe for human because it exposes to both pollutants simultaneously and leads to arise of numerous health associated problems (Verla et al. 2019). It has been reported that the harmful pathogens or microorganisms formed biofilm on the surface of microplastics. In this way, human pathogenic microbes may enter into human body through the formation of biofilm and may cause infection. For instance, Kirstein et al. (2016) and Zettler et al. (2013) isolated Vibrio spp. from the microplastic. Besides this, it may also possible that the metals may transfer through biofilm because it acts as sequestering agent for heavy metals (Verla et al. 2019; Enyoh et al. 2019). Apart from the toxic effect of microplastics, its resident time in human body is still unknown. Research gap also exist in the threshold limit of microplastics in human body where deleterious effects occurs.

5.3 Heavy Metals

Heavy metals are naturally existing high molecular weight compounds but the anthropogenic activities increased its deposition in the surrounding environment. These metals are considered as a major cause of concern due to their detrimental effect on environment as well as on human system. Heavy metals are used as additive to increase the self-life of polymer. It is used during plastic manufacturing for colorants, flame retardants, heat stabilizers, UV stabilizers, pigments, and fillers, to enhance the qualities of plastics. Abiotic and biotic factors such as light, temperature, moisture, pH, and microbes lead to leaching of heavy metals from plastics in the surrounding environment. Microplastics may carry other heavy metals from environment through adsorption which can double the effect of toxicity on human. Exposure to heavy metal results in malefic effect on human health by disrupting the cells or tissues and metabolic processes. For example; Antimony, Barium, Aluminium and Zinc used as heat stabilizers, anti-slip agent, flame retardant and causes breast cancer (Hahladakis et al. 2018); Copper used as biocide or inorganic pigments and leads to the formation of ROS (reactive oxygen species) in body and susceptible to damage DNA bands (Campanale et al. 2020); Cadmium used as heat stabilizers causes osteomalacia, cellular apoptosis (Engwa et al. 2019); Bromine used as flame retardants causes genotoxicity and apoptosis (Nusair et al. 2019); Mercury used as biocide and act as mutagen or carcinogen for human (Engwa et al. 2019; Campanale et al. 2020); Cobalt used as inorganic pigments, induces the formation of ROS and causes neurological and cardiovascular disorders (Leyssens et al. 2017). Lead is used as pigments in plastics causing brain damage, cell damage, nervous system disruptions and oxidative stress (Byrne et al. 2013; Engwa et al.

2019). The toxicity of metal depends on the several factors such as age, gender, sex, nutritional status of human body, and way of exposure with the metal (Campanale et al. 2020).

6 Separation and Detection of Microplastics in Aqueous Systems

As of now we got an insight regarding various sources, transport and harmful effects of microplastics on living forms. These evidences advocate for an urgent need of remediation tools and techniques to mitigate the problems related to microplastics. In this regard, the very first step should be the separation & identification of microplastics using various novel detection techniques. Although there are lots of challenges, as microplastics are very diminutive in size & varies in spatial & temporal scale with 1million pieces per m^3 to >1 per 100 m^3. Also still there is a lack of commonly accepted quantification & qualification tools or guidelines. The microplastics analysis usually consists of two steps, i.e., extraction & purification and later on detection & quantification. Commonly used analytical tools for quantification are Fourier transform infrared (FTIR), Raman spectroscopy, and Scanning electron microscopy (SEM). Despite of rigorous studies on collection to quantification & identification of microplastics, still there is no such standardized method for the same. Results of these studies vary significantly.

6.1 Methods for Sampling Microplastics

Sampling and collection are the most important step in order to further quantify microplastics & to implement effective removal techniques. Due to lower density than water, microplastics floats on top surface which can be retrieved using two common methods – volume-reduced sampling and bulk sampling. In volume-reduced sampling there will be a gradual reduction in sample volume during sampling duration and it usually consist of neuston plankton net or manta trawl (Hidalgo-Ruz et al. 2012). A flow meter is also used along with mesh of approx. 330 μm as suggested by NOAA to calculate the flow of water sample and to concentrate it respectively (Ryan et al. 2009; Eriksen et al. 2013; Free et al. 2014; Baldwin et al. 2016; Anderson et al. 2017). Very few studies were done based on the use of Bulk-water sampling due to the variation among sampling size. Reportedly water samples were ranges from 100 ml to 2 L and also as high as up to 100 L (Dubaish and Liebezeit 2013; Leslie et al. 2017).

Apart of these common methods, surface microlayer is another manual sea water sampling method performed in two steps: firstly, a sieve of about 2 mm collects top 1 mm sample followed by a glass drum to collect surface water of 50–60 μm (Song et al. 2014; Ng and Obbard 2006). Hand-net sampling is another manual sorting method used in aquatics environment to collect microplastics from surface water unto 20 cm (Moore et al. 2011). Due to lack of standardization it is unsuitable to put in marine sampling methods for fresh water or wastewater sampling of microplastics. So, therefore a dire need of suitable optimized & standardized sampling methods for various particular environments. Wastewater is another major source of microplastics. Previous studies focus on microplastic extraction & degradation in wastewater uses basically four common methods: grab & catch, composite samples, neuston/plankton nets and extraction pumps. A single sample was drawn out manually using containers in most of the studies under grab sampling. The sample ranges from 1 to 38 L (Talvitie et al. 2017; Tagg et al. 2017). Composite samples are aggregate of equal, discrete sample volumes taken at regular temporal variation ranging between 3.6 and 5 L (Conley et al. 2019). Both of these are either filtered through membrane filter or by-passing sample thorough stack sieves. In extraction pump technique water directly pumped on stack of sieves of mesh size between 20 and 5000 μm using electricity driven pumps (Carr et al. 2016). Neuston or plankton nets are widely used to sample surface water up to10 cm depth. Mesh size of nets ranges from 150 to 330 μm (Carr et al. 2016; McCormick et al. 2016).

6.2 Microplastics Detection and Quantification

After sampling and extraction quantification will be the next crucial step. Majority of the researchers used visual sorting for identification of potentially suspected microplastics for further analysis (Hidalgo-Ruz et al. 2012; Qiu et al. 2016). Although it is not a universally accepted and not able to give accurate results. Currently there are several techniques used by global researchers in order to identify microplastics in various environments that includes: GC/MS, Modified Raman and FT-IR spectroscopy, chromatography and tagging methods (Nuelle et al. 2014; Shim et al. 2016; Qiu et al. 2016; Zhao et al. 2017) (Table 4). Among all FT-IR and Raman spectroscopy are widely used techniques. During testing, the microplastics samples are excited and structure specific vibrations can be detected. The produced characteristic spectra allow the identification of nature of material. The polymer identification was achieved by comparing the obtained spectra with the known reference spectra.

FTIR is a non-destructive technique with wide polymer database. On the basis of type of plastic particles different FT-IR spectroscopy are used. Large plastics with >500 μm analyzed using ATR-FTIR whereas micro-FTIR cab be utilized for smaller microplastics. The micro-FTIR analyses can be done in either transmission or reflectance mode. The transmission mode gives high-quality spectra, but requires substrates to be IR transparent. Otherwise distortion in spectral lines can be occurred which is a major drawback. FPA based FTIR was also applied which able to generate and record thousands of spectra in a single run with detailed results (Tagg et al.

Table 4 Microplastics detection and concentration in various aquatic environment

Detection technique		Principle	Water sample type	Mean abundance microplastics pieces/m^3	References
Visual method	Microscopic	Manual identification and quantification of pretreated samples by microscopy	Freshwater	0.317	Lechner et al. (2014)
			Brackish water	4.14×10^3	Dris et al. (2015)
			Freshwater	0.35	Zhao et al. (2014)
			Wastewater effluent	50	Mason et al. (2016)
Spectroscopic technique	Furrier-transform infra-red	Pretreated samples are exposed to IR within a range and the vibrational excitement was recorded on the basis of composition of substances	Freshwater	1×10^5	Leslie et al. (2017)
			Wastewater	Influent: 1.57×10^4 effluent: 250	Murphy et al. (2016)
			Wastewater	Influent: 1.5×10^4	
				Effluent: 8.25	Magnusson and Norén (2014)
	Raman spectroscopy	Raman spectroscopy is a scattering method. The laser light with the single wavelength is put in to excite the molecule and atoms of substance and the radiation interacted with the sample is detected.	Freshwater	4.70×10^3	Di and Wang (2018)
	Scanning electron microscope	The secondary ions are measured and images are produced by the interaction between sample and a beam of electron	Freshwater	4.30×10^4 p/km^2	Eriksen et al. (2014)
			Freshwater	1.93×10^3 p/km^2	Anderson et al. (2017)

2017). Raman spectroscopy on the other hand is a surface-based scattering method which allows the detection of visually sorted particles. The micro-Raman microscopy combined with Raman spectra technique could able to analyse at below 1 µm spectral resolution.

7 Removal of Microplastics from Water and Wastewater Systems

7.1 Removal by Algal Biomass

The persistence and lower degradability of microplastics need to be tackled efficiently. In order to that green algae were used by many researchers in order to find adoption removal of microplastics through them. Sundbaek et al. (2018) studied a marine microalga named- *Fucus vasiculosus* and its adhesive behaviour with microplastics. The polystyrene microplastics showed a very high sorption near the areas of algae where alginate compound was released. Due to presence of anionic polysaccharide, algae show higher sorption toward positively charged microplastics.

7.2 Removal by Membrane Technologies

Membrane assisted filtration in potable and wastewater treatment is one of the important techniques to separate out microplastics. One of the studies reveal that the decrease in turbidity from 195 NTU to <1 in effluent increases the microplastics filtration tremendously (Horton and Dixon 2018). Ward (2015) constructed a novel an elongated mesh screen for microplastic removal and claimed for higher durability and increased removal efficiency. However, membrane bioreactors are proved to be more effective in comparison to simple membranes for treating high strength industrial effluent with polymeric contaminants & lesser sized microplastics (up to 99.9%) (Gurung et al. 2016).

7.3 Removal by Chemical Treatment

Chemical treatment is another effective method to treat microplastic laden water sample. Coagulation and agglomeration using Fe, Al or other salt-based coagulants used to combine smaller particles in many water & wastewater treatments systems for easy separation of agglomerated enlarged contaminants. Recent studies incorporated Fe and Al salt coagulants & ultrafiltration for the removal of polyethylene microplastics (Ariza-Tarazona et al. 2019). The results show that Al^{3+} had better removal efficiency than iron. Herbort et al. (2018) removes agglomerated inert microplastics comes from textile industries using alkoxy-silyl bond formation via sol–gel reactions. Still due to lack of sufficient manuscripts and data on the pathway, the degradation of microplastics is not known fully and is highly debatable.

7.4 Removal by Biological Agents

Significant number of studies have been done in past on the extraction and identification of potential plastic degrading microorganisms from various environments. Harrison et al. (2011) in his study focused in the potential of microbes especially-archaebacteria and picoeukaryotes and their interaction with microplastics to degrade them in coastal environment. *Antarctic Krill (Euphausiasuperba)* a zooplankton was studied reveal its interaction and fragmentation of polyethylene microplastics through ingestion (Dawson et al. 2018). Scanning electron microscopic analysis indicates the reduction of polyethylene through fragmentation, with size decrement from ~31 to >1 μm of fragments. Another study uses two marine microbial communities namely- *Agios consortium* and *Souda consortium* for the degradation of secondary polyethylene. Study suggest that carbon content of both consortia increases as microplastics acted as rich carbon source and eventually helps in adhering properties for efficient fragmentation (Cocca et al. 2020). Paço et al. (2017) the fungus *Zalerion maritimum*, a naturally occurring fungus in marine ecosystems, under a batch reactor for microplastics biodegradation based on mass and size variations. Ingestion by higher animals in marine ecosystem was also reported by number of papers in recent past. *Scleractinian corals* were reported to ingest microplastics at the rate of 50 μg plastic cm^{-2}/h (Hall et al. 2015).

8 Perspective

- The presence of microplastics particles is well reported in studies but the actual amount or quantification in freshwater and marine water has not been done yet. Therefore, a clearly, accurately, reliable quantification protocol in aquatic water is needed.
- There is need to gather information on the presence, type, and amount of microplastics in food, as well as information on the transportation of microplastics through the aquatic food chain and the human food system. New strategies should be employed to reduce the load of microplastics pollution in aquatic environment including the creation of eco-friendly polymers (starch-based plastic or polylactic acid) and “green” additive chemicals.
- The differences between laboratory-based exposures and environmentally applicable exposure situations make the process of developing thresholds much more difficult. The majority of research employ single polymer type of virgin microplastics whereas ambient exposures involve a variety of particle differing in sizes, shapes, and chemistries, including a significant amount of microfibers and other chemical contaminants from various simultaneous exposures.
- There could not be a single threshold to determine the way to reduce the risk related to microplastics. A set of guidelines along with monitoring strategies

should be developed to assess their source, fate, transportation and human health effect.

- The separation and removal of microplastics from aquatic system is still very limited. Microbial technology based methods should be employed to extract, filter and degrade microplastics at commercial level.

9 Conclusion

Microplastics are termed as one of the most important emerging pollutant on global scale with its existence in almost all ecosystems. In this chapter we tried to summarize the sources, types, transport & fate, serious health and physiological effects on flora & fauna as well as on human being due the occurrence of microplastics. The major cause of such plastic pollution is urbanization, industrialization & mass dependence on plastic products. Discharge of untreated sewage, industrial wastes containing plastic products, and waste water treatment plants are also a major source of microplastics in various aquatic ecosystem. The chapter also try to find out various reported identification and quantification techniques to easily separate out microplastics from environmental samples. Spectroscopic analysis shows higher potential for microplastics identification for larger to smaller plastics (>1 μm). Several studies reveal the effective removal techniques including- physical, chemical and biological agents. However still there is a need of standardized and optimized detection as well as removal techniques in order to combat microplastics efficiently. Lack of standards toxic limits at universal level also need to be administered.

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Atmospheric Microplastics in Outdoor and Indoor Environments

Yubraj Dahal and Sandhya Babel

Abstract Microplastics pollution is arising health concern due to the presence of microplastics in many ecosystems and human organs. This chapter reviews the abundance, source, and factors affecting microplastics in the outdoor and indoor environment. We found that microplastics pollution is higher indoor than outdoor. Therefore, humans are at higher risk of health diseases caused by microplastics inhalation and ingestion in the indoor environment. Microplastic fibers are the dominant shapes in both indoor and outdoor environments. The outdoor environment is characterized by diverse polymers, whilst indoor air exhibited limited polymeric diversity. Numerous sources and factors affect microplastics abundance in the outdoor environment, whereas limited factors and sources control microplastics abundance in the indoor environment. The major sources of microplastics in the indoor environment are textiles and carpets. However, research on indoor microplastics pollutions is actually limited.

Keywords Microplastics · Indoor · Outdoor · Source · Abundance · Morphology

1 Introduction

The majority of plastics are consumed as packing and construction utilities because of their key features like lightweight, resistance to temperature, chemicals, and light, mouldability, strength, and toughness (Polymer Science Learning Center, 2005 in Andrady and Neal 2009). With the increasing consumption of plastics, plastic waste mismanagement has also spiked up. A very few proportion (9%) of the plastic ever produced has entered into recycling. In the present scenario of plastic

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consumption and plastic waste management, the global accumulation of plastic waste will total about 12 billion tons by the end of 2050 (UNEP 2018). However, except for the 10% of the plastics that makes its ways to the marine environment, the rest remains in the terrestrial environment in the form of macro, micro, and nano plastics (Mattsson et al. 2015; Allen et al. 2019).

Plastic particles less than 5 mm in diameter have been described as microplastics (Arthur et al. 2009). Primary microplastics are those that are intentionally shaped into microscopic sizes, such as plastic pellets or scrubbers (Cole et al. 2011; Filella 2015). Personal care products, facial products, and air blast cleansing are the major application areas of the primary microplastics (Cole et al. 2011). Similarly, secondary microplastics are formed by the degradation of larger plastics, such as fibers and plastic fragments (Filella 2015). Among various secondary sources, textiles and laundry processes should be given special care and attention as they release small-sized plastic during their service period (Dris et al. 2015).

The ubiquity of microplastics in all the environmental compartments like marine sediments (Peng et al. 2017), river and lake water (Ta and Babel 2020; Xiong et al. 2018), outdoor and indoor air (Dris et al. 2017), table salt (Yang et al. 2015), seafood (Van Cauwenberghe and Janssen 2014), plastic food container (Fadare et al. 2020), drinking water and water treatment plants (Kankanige and Babel 2020, 2021), glacier snow (Zhang et al. 2021), planetary boundary level (Gonzalez-Pleiter et al. 2021), along with recent identification of microplastics in human stool and placenta (Harvey and Watts 2018; Ragusa et al. 2021) have recognized microplastics pollution as a global and serious issue. However, outdoor microplastics pollution (atmospheric deposition) has got very little attention from researchers. Additionally, negligible studies have been carried out on indoor microplastics pollution compared to the outdoor environment. The first evidence of the microplastics in atmospheric deposition was reported in Greater Paris by Dris et al. (2015), where an average microplastics count of 118 p/m^2/d was observed. Similarly, Dris et al. (2017) explored microplastics abundance in the indoor environment first and reported a microplastics abundance of 5.4 fibers per m^3.

Indoor microplastics pollution is a serious concern since an individual spends a majority of the time in the indoor environment. Prata et al. (2020) suggested that microplastics can enter the human body during inhalation, ingestion, and via dermal routes. Indoor microplastics can contaminate open food and drinks in the household (Zhang et al. 2020a). A study reveals that human exposure to microplastics ingestion is minimal via mussel consumption, 123–4620 p/y/capita, when compared to microplastics fallout on the food, 13,731–68,415 p/y/capita, in the indoor environment (Catarino et al. 2018). This further highlights the threat of microplastics ingestion through aerial routes. The size of the particle determines its possibility of inhalation and its destiny in the respiratory system. Thus, a particle, either gets deposited on the upper passageways after entering through the nostrils/mouth (inhalable) or travels to the deeper part of the lungs (respirable) (Gasperi et al. 2018).

Outdoor microplastics pollution cannot be overlooked. Microplastics can be sourced in the indoor environment from the outdoor environment through wind blowing and adhering to the clothes (Zhang et al. 2020a). Researchers believe that about 80% of marine debris originates from the terrestrial environment (Allsopp et al. 2006; Andrady 2011). The terrestrially deposited microplastics may find their way to rivers through surface runoff and finally end up in the seas/oceans. Thus, the knowledge of abundance and source and factors affecting microplastics abundance in both indoor and outdoor environments is imperative to access and minimize human health risks, limit the pollution source, trace the transportation route and influencing factors, and calculate microplastics contribution to water bodies by direct atmospheric deposition and through the medium of cleaning activities and runoff.

The main objective of this chapter is to present a comprehensive view of abundance, source, and factors affecting microplastics in the outdoor and indoor environment. Furthermore, a comparison between outdoor and indoor microplastics pollution highlights differences between indoor and outdoor microplastics pollution in terms of average abundance, dominant size range, shapes, polymers, sources, and factors influencing the abundance.

A rigorous review was made of the available research articles on outdoor and indoor microplastics pollution. This review considered both studies employing passive samplings, such as collecting road dust and passive samples, and active sampling techniques. Google Scholar search engine tool was used to search the articles. Regarding outdoor microplastics pollution, microplastics deposition over terrestrial and sea/ocean were only considered in this study. Articles accessing microplastics deposition over soil or snow were excluded from the review.

2 Microplastics in the Outdoor Environment

2.1 Abundance of Microplastics

Atmospheric microplastics deposition has been reported in all studies carried out on the land surface and over the seas or oceans. However, the method of sample collection varies among different studies. Researchers have employed a variety of sampling techniques, such as road dust collection, suspended air sampling with an active sampler, and passive collection of atmospheric deposition over a sampling device for a certain duration. Microplastics abundance has been reported in all the studies suggesting the omnipresence of microplastics in the environment.

When considering passive sampling, the highest count of microplastics observed was 771 particles per square meter per day (p/m^2/d), whilst the lowest count was 14 ± 9 p/m^2/d for wet deposition and 7 ± 5 p/m^2/d for dry deposition (Szewc et al. 2021; Wright et al. 2020). This significant difference in microplastics abundance suggests site dependency of microplastics contamination. Similarly, Abbasi et al. (2019) reported microplastics count of 900 particles per gram (p/g) of the road dust, which was again considerably higher than 20.6–529.3 p/kg (Su et al. 2020) and

227.94 ± 89.82 p/100 g (Patchaiyappan et al. 2021), suggesting a site-specific relationship.

Allen et al. (2019) reported an abundance of most of the microplastics in the size range of 100–200 micrometers (μm) and 200–300 μm. Similarly, Su et al. (2020) also reported that microplastics less than 1000 μm accounted for 30–62 percentage of the total microplastics. Similarly, the reported dominant size ranges are 50–1000 μm (Ding et al. 2021), 200–400 μm and 400–600 μm (Dris et al. 2016), 10–70 μm (Gonzalez-Pleiter et al. 2021), and 400–1000 μm (Wang et al. 2020). More than 75% of the microplastics were less than 100 μm (Abbasi et al. 2019). Thus, the prevalence of small-sized microplastics in the atmospheric air is non-deniable. Although the small size range rules over the microplastics abundance, the dominant size range of the microplastics varies between the sites. This disparity can be due to the differences in source and degradation pattern of the microplastics.

As per the present studies, fiber is the most dominant shape in the atmospheric air. Fibrous microplastics originate from the textiles during washing (Napper and Thompson 2016; Pirc et al. 2016). Similarly, films and fragments come from disposable plastic bags and other recyclable thicker plastics (Cai et al. 2017; Wright et al. 2020), and foams may come from expanded polyester (Wright et al. 2020). So far, the highest concentration of the fibers reported was 92% (Wright et al. 2020), followed by 90% (Dris et al. 2015). Only three studies (Cai et al. 2017; Klein and Fischer 2019; Patchaiyappan et al. 2021) reported the dominance of the fragments, where the proportion of the fragments (84.6, 95, 92.46%) was considerably higher than the highest concentration of fibers observed in other studies.

When considering the dimensions of the fibers, the smallest size of the fibers reported was 84 μm (Gonzalez-Pleiter et al. 2021), 50 μm (Huang et al. 2021), 75 μm (Szewc et al. 2021), and 228.29 μm (Wang et al. 2020). In a study, a fiber of length 250 μm was observed in human lung cancer tissue, wherein cellulose and polymeric fibers were observed in 97% of the malignant lungs and 83% of the non-neoplastic lungs (Pauly et al. 1998). Barlow et al. (2017), in their review article, concluded that fibers longer than 10 μm, mainly 20 μm have greater potency to develop asbestos-related human disease and the risk associated with fibers less than 5 μm is minimal. Considering the width of the fibers, Berman and Crump (2008) suggested that asbestos fibers between 0.7 to 1 μm are respirable and of 1.5 μm can be inhaled through mouth breathing. Longer fibers can be easily retained by the alveolar macrophages and, therefore, are more harmful (Barlow et al. 2017). Support to this, Berman et al. (1995) concludes that the potency of developing lung tumor rises 500 times with the inhalation of fibers longer than 40 μm than with the inhalation of fibers between 5 and 40 μm. Thus, we conclude that the observed length of the fibers in the recent studies is enough to cause lungs issue. However, the dearth of information on the diameter of the fibers adds complexity in deciding whether these fibers are respirable/inhalable.

Limited studies have reported on the fibers' diameter. Wright et al. (2020) found fibers of an average diameter of 24 ± 10 μm with the thinnest and thickest diameter to be 5 and 75 μm, respectively. In another study, the diameter of the fibers ranged from 4 to 97 μm (Gonzalez-Pleiter et al. 2021). These two studies presented non-respirable/non-inhalable fibers. However, the likelihood of the presence of fibers of smaller diameter cannot be denied because analytical constraints have limited the analysis of fibers down to a smaller size range, for example, 1 μm or below. Nevertheless, future research on microplastics should attempt to analyze microplastics down to the respirable/inhalable size range.

Moreover, Abbasi et al. (2019) studied the microplastics abundance in both road dust and suspended air. Spheres were found to be dominant in the road dust, whilst fibers dominated suspended air. Thus, it can be suggested that the source of microplastics in suspended air/atmospheric deposition and road dust are different, and the results cannot be compared. Furthermore, it also suggests that the microplastics in the road dust do not necessarily come through atmospheric deposition. Assisting this statement, Yukioka et al. (2020) suggested that the waste management practice of a particular place greatly influences the characteristics of the microplastics in road dust. The team found the lowest microplastics abundance (2 ± 1.6 p/m^2) in Japan, which has sound waste management practice, whilst the highest was observed in Vietnam and Nepal, where waste management facility is extremely poor compared to Japan. This was further supported by the study carried out by Su et al. (2020) on rural and urban road dust in Australia. The study reported microplastics count of 10.15 p/100 g in Goulburn Broke and 34.27 p/100 g in Port Philip and Westernport.

The commonly observed polymers are polyethylene, polyamide, polypropylene, polystyrene, polyethylene terephthalate, and polyvinyl chloride. Polystyrene and polyethylene are the major constituents of single-use plastics and packaging materials (Allen et al. 2019). Polypropylene is used in packaging, textiles, and reusable products (Allen et al. 2019). Owing to its better strength, elasticity, heat insulation, and resistance, Polyethylene terephthalate, also known as polyester, is widely used in textiles, especially clothing and curtains (Ding et al. 2021; Huang et al. 2021). Polycarbonate being an engineering plastic is widely used in automobiles, construction materials, telecommunication, and electrical appliances (Kausar 2017). Polyvinyl chloride is the second most highly produced and used plastic that is broadly used in building and construction work for piping, guttering, window profiles, flooring and wall covering, electrical cables, and other applications, including packaging, automobiles, and the medical sector (Mulder and Knot 2001). Knitted clothes, such as socks, hats, and sweaters, use polyacrylonitrile filaments (Wright et al. 2020). Polyacrylonitrile is also used in outdoor appliances such as tents, yacht sails, and similar other items because of its ability to resist sun damage (Polymer Science Learning Center, 2005 in Wright et al. 2020). Thus, when considering the dominant polymer type in the atmospheric air, the polymer type varies among all the studies suggesting that microplastics contamination comes from several sources.

When considering the average microplastics and sampling height, a negative correlation (−0.67) was observed, meaning that microplastics abundance increases with decreasing sampling height from the ground surface. This may be due to the change in wind dynamics when moving above the earth's surface. The wind velocity is zero on the ground surface and increases with increasing height (Wizelius 2015). At the ground surface, the wind experiences obstacles that reduce the speed of the wind and create horizontal and vertical velocity components leading to turbulence (Dalgliesh and Boyd 1962). In return, this turbulence causes vertical mixing of the air moving at different horizontal heights, thereby inducing dispersion of the pollutants (Charles 1998), dust, airborne sand, and soil particles (Lal 2006). Thus, it can be speculated that the microplastics count might have been underestimated in the studies with significant sampling height. For accessing accurate microplastics deposition on the earth's surface and the possibility of microplastics ingestion via inhalation, we recommend that the sampler should be placed at human breathing height, e.g., ~1.5–2 m above the ground surface.

A diverse range of polymers has been observed in the studies with significant sampling height ($\geq$ 10 m), whilst the polymers are limited and more common in low-level sampling. In this regard, it is suggested that further research should take into account microplastics deposition near ground level and at some significant height at the same site. This would help apprehend the difference between microplastics abundance in the atmosphere and the actual microplastics deposition on the ground. Polymers with a higher density, such as polyester (1.24–2.3 g/cc), polyethylene terephthalate (1.37–1.45 g/cc), polyvinyl chloride (1.16–1.58 g/cc), epoxy resin (1.11–1.40 g/cc), and alkyd (1.67–2.1 g/cc), were observed at high altitude sampling stations (Choong et al. 2020). This refers that microplastics are omnipresent in the atmosphere despite their size and density, which govern their movement and settling velocity in the atmosphere.

Table 1 contains sampling details, abundance, and factors affecting microplastics in the outdoor environment. Similarly, Table 2 summarizes the observed shapes, polymer types, and characteristics of the microplastics in the outdoor environment.

2.2 *Factors Affecting Microplastics Abundance*

To grasp a better understanding of microplastics abundance in atmospheric air, researchers have studied several possible factors influencing the abundance of microplastics. The commonly investigated facets are wind speed and direction, precipitation, rainfall volume and intensity, duration of rainfall, relative humidity, pressure, air temperature, urban and rural characteristics, population size and density, and human activities.

Several researchers have reported no effect of precipitation/rainfall/cumulative rainfall over microplastics count (Dris et al. 2015; Huang et al. 2021; Klein and Fischer 2019; Truong et al. 2021). Also, Roblin et al. (2020) found no correlation with rainfall volume. However, Allen et al. (2019) and Huang et al. (2021) recorded a positive correlation with snowfall/rainfall events. Similarly, Allen et al. (2019) recorded a negative correlation with the duration of rainfall events and snowfall events. This implies that the effect of rainfall on the abundance of microplastics is still unclear and requires profound research and analysis.

Furthermore, meteorological conditions, such as wind speed and direction, air temperature, humidity, and pressure, have also depicted varying effects in the

Table 1 Sampling details, abundance, and factors affecting microplastics in the outdoor environment

Samples/ stations/duration	Data type	Mean concentration & range	Remark (factors affecting microplastics count)	References
10 samples; 2 stations; 5 months	Dry and wet; Monthly data	365 ± 69 p/m²/d	Rainfall intensity, wind events, and snowfall events (+ve correlation); Duration of rainfall event and snowfall event (−ve correlation)	Allen et al. (2019)
48 samples; 4 stations; 1 year	Wet and bulk; Monthly data	80 p/m²/d	Relative humidity, wind speed, and wind direction (+ve correlation); Rainfall volume and marine sources of microplastics (no correlation)	Roblin et al. (2020)
3 stations; 92 days	Wet and dry	36 ± 7 p/m²/d 31–43 p/m²/d	Population size and density (correlation)	Cai et al. (2017)
1 station 3 months	Wet and dry; Weekly – monthly data	118 p/m²/d; 29–280 p/m²/d	Precipitation (no correlation)	Dris et al. (2015)
2 stations (urban (U), semi-urban (SU)); 24 samples (U), 9 samples (SU); 1 year (U), 6 months (SU)		Urban 110 ± 96 p/m²/d 2–355 p/m²/d; Semi-urban 53 ± 38 p/m²/d	Mean daily rainfall (no correlation); Cumulative rainfall (no correlation)	Dris et al. (2016)
108 samples; 6 stations; 12 weeks	Bulk; Biweekly	275 p/m²/d (median) 136.5–512 p/ m²/d	Precipitation (no correlation); Wind speed and direction (strong correlation); Temperature (no correlation)	Klein and Fischer (2019)
72 samples; 3 sites; 1 year	Dry and wet; Twice a week	71–917 p/m²/d	Occupational space and surrounding activities (correlation); Rainfall, wind velocity, and wind direction (no correlation)	Truong et al. (2021)

(continued)

Table 1 (continued)

Samples/ stations/duration	Data type	Mean concentration & range	Remark (factors affecting microplastics count)	References
1 station	Biweekly	771 ± 167 p/ m^2/d 75–1008 p/m^2/d Fibrous 712 ± 162 p/ m^2/d; 510–925 p/m^2/d Non - fibrous 59 ± 32 p/m^2/d; 12–99 p/m^2/d	Wind direction (SW) and non-fibers (+ve correlation); Wind direction (NE-E) and non-fibers (+ve correlation); Wind direction (SW-NW) and fibers (+ve correlation)	Wright et al. (2020)
15 samples (road dust); 2 stations (suspended air)	Road dust and suspended air	Road dust 900 p/g; 50–1000 p/g Suspended air 0.3–1.1 p/m^3	Wind direction, wind speed, temperature, and humidity (no correlation)	Abbasi et al. (2019)
Active sampling; 12 samples; 12–25 hours	Suspended air	0.035 ± 0.015 p/ m^3; 0.013–0.063 p/ m^3	Wind speed and pressure (+ve correlation); Ambient temperature (−ve correlation)	Ding et al. (2021)
3 flights in air; 4 h	Atmospheric air	Urban area 65.4 p/m^3 Rural area 13.8 p/m^3	Pollutant emitter, forest cover, highway, and other meteorological conditions (correlation with the dominant shape)	Gonzalez-Pleiter et al. (2021)
12 samples; 1 year	Dry and wet; 22–40 days frequency	114 ± 40 p/ m^2/d; 51–178 p/m^2/d	Cumulative rainfall (no correlation); Wind speed (+ve correlation); Rainfall events (+ve correlation)	Huang et al. (2021)
4 stations; 16 samples; 24 h	Weekdays and weekends	Residential 116.25 ± 26.4 p/d; Dump yard 96 ± 38.1 p/d; Commercial 62.75 ± 17.9 p/d; Industrial 99.25 ± 57.2 p/d	Human activities (residential, dump, commercial) during weekdays (correlation); Human activities in industrial area (no correlation)	Narmadha et al. (2020)
16 stations; Dry season	Road dust	227.94 ± 89.82 p/100 g; 17–408 p/100 g	Highly dense population and congested service sectors (correlation)	Patchaiyappan et al. (2021)

(continued)

Table 1 (continued)

Samples/ stations/duration	Data type	Mean concentration & range	Remark (factors affecting microplastics count)	References
16 samples; 16 sites; Two months	Road dust	20.6–529.3 p/kg	Seasonal variance between sites (no correlation); Percentage variance between the sampling time (−ve correlation); Population size (+ve correlation); Annual rainfall (−ve correlation)	Su et al. (2020)
1 station; 49 samples; 289 days	1–8 days frequency	Wet deposition 14 ± 9 p/m^2/d; 1–30 p/m^2/d Dry deposition 7 ± 5 p/m^2/d; 2–19 p/m^2/d	Precipitation height (+ve correlation with wet deposition); The mixture of rain and snow (strong correlation than rain alone of the same intensity); Wind speed (+ve correlation with dry deposition)	Szewc et al. (2021)
21 samples; 10–48 h; 53–259 m^3 air per sample	Suspended air	1 p/100 m^3; 0 - 7.7 p/100 m^3	Pressure, wind speed, humidity, and gust velocity (correlation); Wind direction (no correlation)	Wang et al. (2020)
Kusatsu (12), Da Nang (12), Kathmandu (13)		Kusatsu 2 ± 1.6 p/m^2; Da Nang 19.7 ± 13.7 p/m^2; Kathmandu 12.5 ± 10.1 p/m^2	Site-specific waste management practice (correlation)	Yukioka et al. (2020)

Note: *p/m²/d* (particles per square meter per day), *p/m²* (particles per square meter), *p/100 m³* (particles per hundred cubic meter), *p/kg* (particles per kilogram), *p/100 g* (particles per 100-gram), *p/d* (particles per day)

studies. Many studies found a positive correlation with wind speed, wind direction, or both (Allen et al, 2019; Ding et al. 2021; Huang et al. 2021; Klein and Fischer 2019; Roblin et al. 2020; Szewc et al. 2021). However, Wang et al. (2020) suggested wind speed as the influencing factor but wind direction as a non-influencing factor for microplastics abundance. Interestingly, Abbasi et al. (2019) and Truong et al. (2021) reported no correlation with wind speed and wind direction. This depicts that no apparent relationship has been observed between microplastics abundance and precipitation and wind. Thus, we speculate that there are also other factors that work in combination with meteorological factors to determine the rate of microplastics

Table 2 Characteristics of polymers and shapes in the outdoor environment

Dominant shape	Observed shapes	Dominant polymers	Observed polymers	Remarks (characteristics of polymers and shapes)	References
Fragments	Fibers, Fragments, Films	Polystyrene	Polyethylene, Polystyrene, Polypropylene	Fragments <50 μm dominant; Films (50–200 μm) observed; Majority of PS as fragments; PET or PP as fibers	Allen et al. (2019)
Fibers	Fibers	Polyethylene terephthalate	Polyethylene terephthalate, polyacrylonitrile, polyethylene, polypropylene	Median fiber length (880 μm); 85% of the fibers were organic	Roblin et al. (2020)
Fragments	Fibers, Fragments, Films	Cellulose	Polyethylene, polypropylene, Polystyrene, Cellulose	84.6% of the non-fibers were microplastics; 77% of the fibers were non-plastics; Majority of fibers were natural fibers	Cai et al. (2017)
Fibers	Fibers Fragments			90% fibers; 50% of the fibers >1000 μm in length	Dris et al. (2015)
Fibers	Fibers	Polyethylene terephthalate	Polyethylene terephthalate, Polyamide	50% of the microplastics were natural fibers (cellulose); 21% were transformed into natural polymers, such as rayon and acetate; 29% synthetic polymers	Dris et al. (2016)

Fragments	Fibers, Fragments	Polyethylene	Polyethylene, polyvinyl acetate, polytetrafluoroethylene, polyvinyl acetal, Polyethylene terephthalate	Fragments (95%), fibers (5%); Majority of fragments <63 μm; Majority of fibers (5000–300 μm)	Klein and Fischer (2019)
Fibers	Fibers, Fragments	Polypropylene	Polyethylene, polyvinyl chloride, silica	Median fiber length (301 - 4872 μm);	Truong et al. (2021)
Fibers	Fibers, Fragments, Films, Granules	Polyacrylonitrile,	Polyacrylonitrile, polyethylene terephthalate, polyamide, polyethylene, Polystyrene, polyurethane, polyvinyl chloride, acrylic polymer, polymerized petroleum resin	Fibers (92%), Non-fibers (fragments (64%), film (25%), granules (5%), and foam (4%); Mean fibrous diameter 24 ± 10 μm; Majority of fibers 400–500 μm; Majority of non-fibrous 75–100 μm; 17% of fibers were synthetic (petrochemical-based); 69% of fibers were cellulose-based	Wright et al. (2020)

(continued)

Table 2 (continued)

Dominant shape	Observed shapes	Dominant polymers	Observed polymers	Remarks (characteristics of polymers and shapes)	References
Spheres (road dust) Fibers (suspended air)	Road dust Spheres, Films, Fragments, Fibers Suspended air Fibers			74% spheres in road dust; 14% films in road dust; 6% fibers in industrial road dust; 30% fibers in urban road dust; Fibers dominated in suspended air	Abbasi et al. (2019)
Fibers	Fibers, Fragments, Films, Foams, Granules	Polyester	Polypropylene, rayon, polyethylene, polyamide, polyester, polystyrene, phenoxy resin, cellulose	65% were fibers; 50–1000 μm (dominant size); 50–2210 μm (observed size range); 599 ± 513 μm (mean microplastics size); Polyester, rayon, and polypropylene made more than 60% of the polymers	Ding et al. (2021)
Rural area Fibers Urban area Fragments	Fibers, Fragments	Polyamide	Polyester, polyamide, acrylic, polyurethane, polystyrene, polybutylene, polyethylene/ polypropylene	59.6% of microplastics (10–70 μm); Length of fibers (84–1709 μm); Width of fibers (4–97 μm); Length of fragments (42–815 μm); Width of fragments (17–408 μm)	Gonzalez-Pleiter et al. (2021)

Fibers	Fibers, Fragments, Films, and Microbeads	Polystyrene	Polystyrene, polyacrylonitrile, alkyd, epoxy resin, acrylonitrile butadiene styrene	Length of fibers (50 μm–5 mm); 78.7% of fibers were microplastics; 50% of microbeads were microplastics; Majority of fragments and films (naturally occurring plastics like cellulose and rayon); 34.1% of non-fibers were microplastics	Huang et al. (2021)
Fibers	Fibers, Fragments, Films, Spheres	Low -density polyethylene (LDPE)	LDPE, chlorinated polyvinyl chloride, cellulose/ rayon, polystyrene, polyethylene, polyolefins, poly(ethylene:propylene:diene), polyaniline	Fragments dominated PM_{10} particles; Films dominated $PM_{2.5}$ particles; Fibers in PM_{10} (dominated residential area); Fibers in $PM_{2.5}$ (dominated dump yard); Fibers in PM_{10} and $PM_{2.5}$ (minimum in the commercial area); Weekdays (fibers in PM_{10} dominated all sites except commercial one); Weekdays (fragments in PM_{10} dominated all four sites)	Narmadha et al. (2020)

(continued)

Table 2 (continued)

Dominant shape	Observed shapes	Dominant polymers	Observed polymers	Remarks (characteristics of polymers and shapes)	References
Fragments	Fragments, Fibers	Polyvinyl chloride	Polyvinyl chloride, p-tetrafluoroethylene, AC-395, Poly-ethylene co-vinyl acetate, High-density polyethylene (HDPE), Wax – 1032, Lyocell, Cellulose, Superflex-200	Fragments (92.46%), Fibers (7.54%)	Patchaiyappan et al. (2021)
Fibers	Fibers, Fragments	Polyethylene terephthalate, polypropylene, rayon	Polyethylene terephthalate, polypropylene, rayon	Fibers (45.7–100%); Fragments (0–45.7%); Pellets (< 5%); Pellets were detected in only three sites	Su et al. (2020)
Fibers	Fibers, Fragments, Films		Polyethylene, polypropylene, polymethyl methacrylate	Fibers, fragments, and films 60, 26, and 14% Fibers' size (75–5000 μm); Fragments' size (5–750 μm); Films ranged from 10 to 1520 μm; Fragments were (polyethylene, polypropylene, and polymethyl methacrylate); Films were (polyethylene and polypropylene)	Szewc et al. (2021)

Fibers	Fibers, Fragments	Cotton, cellulose	Cotton, cellulose, rayon, cellophane, polyethylene terephthalate, polypropylene, polyamide, phenoxy resin, polyacrylonitrile-co-acrylic acid, polyethylene-co-propylene, polyethylene-co-vinyl acetate,	Fibers (88.89%), fragments (11.11%); Microplastics were 58.59–2251.54 μm; Mean microplastics 851.09 ± 578.39 μm; Diameter of fragments (58.59–286.10 μm), Length of the fibers (228.20–2251.54 μm, 935.94 ± 556.63 μm); 55.56% of microplastics (400–1000 μm)	Wang et al. (2020)
Fragments	Fibers, Fragments, Films, Granules	Polyethylene	Polyethylene, polypropylene, polystyrene, polyethylene terephthalate, polyacrylate, polyvinyl stearate, ethylene/propylene copolymer, styrene / butadiene rubber, ethylene/propylene/diene rubber, polyurethane	Container/packaging microplastics were generally fragment types; The proportion of containers/packaging microplastics decreased with decreasing size; The proportion of rubber increased with decreasing size; Polyethylene was mainly fragments and films; Polypropylene was mainly fragments and fibers; Rubbers microplastics were mainly fragments and granules	Yukioka et al. (2020)

abundance. Wright et al. (2020) suggested that the meteorological conditions are more influential to the sites lying away from the center of the sources but not for urban centers carrying local sources within themselves. This may be a reason for no correlation between microplastics abundance and meteorological conditions, such as precipitation, wind speed, and wind direction, in some studies.

However, a clear relationship (positive) was observed with human activities and population size and density (Cai et al. 2017; Narmadha et al. 2020; Patchaiyappan et al. 2021; Su et al. 2020; Truong et al. 2021). Truong et al. (2021) observed significant variation in the size of the microplastics between household and landfill site. They suggested that the anthropogenic activities at the landfill and construction site were responsible for the variation of morphological characteristics of the microplastics rather than the abundance. In order to consolidate human activities as a factor influencing microplastics abundance, we recommend carrying out day and night deposition of the microplastics separately; this is because human activities are minimal during the night compared to daytime.

2.3 Sources of Microplastics

Allen et al. (2019), who found short-range transport of microplastics from local town with a population less than 25,000 to the remote catchment, suggested that regional microplastics can be transported over 100 km to the remote areas. Roblin et al. (2020) suspected that the abundance of the small-sized MP with lower variation at the coastal site was either due to the long-range transport of microplastics during dry deposition or from marine sources, such as sea-spray. In contrast, the resemblance of the degradation pattern of microplastics with that of lakes and marine beaches indicates that atmospheric fallout is the source of microplastics in water bodies (Cai et al. 2017; Dris et al. 2015).

Dris et al. (2016) speculated synthetic fibers from clothes and houses, degradation of macroplastics, and landfill or waste incineration as the sources of microplastics in atmospheric fallout. Klein and Fischer (2019) observed the highest count at a station in the Douglas fir forest and suggested a comb-out effect to be the reason for this higher deposition. Furthermore, the authors speculated that the second-highest abundance in the open field, which has a highway interchange in its vicinity, was from secondary microplastics originating from road dust, tires, and road paint. The recipient of higher abundance in the residential site during the sampling period followed by the new year was speculated to be due to the introduction of microplastics into the atmosphere by the fireworks celebration (Klein and Fischer 2019).

Microplastics can be introduced into the air by the UV light degradation of the clothes, bed sheets, pillows, and blankets kept for drying in open spaces like balconies (Truong et al. 2021). Wright et al. (2020) suggested multiple sources of microplastics, such as the degradation of the plastic in the landfill and the open environment and the abrasion of the plastic waste during waste management processes, such as waste transfer and processing activities. In addition, authors suspected polystyrene, polyethylene, and polypropylene to come from packaging materials, and granules to come from accidental release at the production and transportation stages. In agreement with this, Yukioka et al. (2020) reported that the source of microplastics may be rubber products like tires, hoses, bands, shoe soles, electrical insulation, and plastic bags (polyethylene and polypropylene).

Abbasi et al. (2019) suspected domestic, vehicular, and industrial emissions as the source of microplastics in road dust. Similarly, the authors suggested clothing, soft furnishing, and ornaments as likely sources of fibrous microplastics in road dust (Ding et al. 2021) and suspended air (Wright et al. 2020). Ding et al. (2021) speculated mechanical breakage and physical tear of the construction materials, such as paints and additives, to be the source of phenoxy resin, whilst polypropylene, polyethylene, and polyethylene terephthalate originate from industrial products.

Gonzalez-Pleiter et al. (2021) studied microplastics abundance within and above the planetary boundary level and suggested highly dense urban cities as one of the major sources of microplastics. Huang et al. (2021) observed polyethylene terephthalate as the dominant polymer and suggested textiles as the major source of microplastics, namely fibrous type. Similarly, the authors speculated that microplastics, especially microbeads, originate from the aerosolization of microbeads from the Pearl River surface/estuary (Huang et al. (2021). Narmadha et al. (2020) studied microplastics abundance in a residential area, dump yard, commercial area, and industrial area and suggested plastic wrapping and covering as a potential source of films in the commercial area, clothes/textiles (household washing and laundry) as the major source of fibrous microplastics in the residential area, and small-scale industry nearby the sampling point as the source of micro-rubbers. A mixture of diffused pollution sources contributes to roadside microplastics rather than a single specific source (Su et al. 2020). Wang et al. (2020) speculated breaking down of synthetic fibers used in clothing as the source of polyethylene terephthalate in the samples. Moreover, the authors also suggested packaging and products from textiles as the source of polypropylene observed in the samples.

Intriguingly, Wang et al. (2020) reported that the microplastics over the South China Sea originated from the Philippines, which indicates that microplastics can be transported from continental sources to the oceanic atmosphere. Patchaiyappan et al. (2021) performed scanning electron microscopy- energy dispersive spectroscopy (SEM-EDS) analysis of the microplastics particles and speculated that the larger particles with calcium originated from common plastics, whilst the smaller particles delineating the presence of trace elements originated from automobile exhaust.

Source apportion of the microplastics is in its infancy. To date, researchers have attempted to predict the source of the microplastics based on the observed polymer types and shapes, variation in microplastics abundance between sites, and analysis of the air mass trajectory. Few researchers have analyzed the trajectory of the air masses to predict the origin of the microplastics. However, analysis of air masses trajectory seems applicable only for long-distance transport of the microplastics to the distal zones with minimal or no abundance of microplastics within it.

3 Microplastics in Indoor Environment

3.1 Abundance of Microplastics

Average microplastics count as high as 2100–29,000/m^2/d was observed in the indoor environment (Zhang et al. 2020a). All the studies carried out in indoor environments depicted average microplastics count greater than 1000 p/m^2/d suggesting that indoor microplastics abundance is at a critical level. Similarly, Jenner et al. (2021) found a majority of microplastics in the indoor environment in the size range of 5–250 µm. The majority of the microplastics, greater than 90%, were less than 100 µm (Liao et al. 2021). Also, Zhang et al. (2020a) reported that 80% of the microplastics are in the size range of 50–2000 µm. This proves the prevalence of small-sized microplastics in the indoor environment. Based on the discussion made in the previous Sect. 2.1, on fibers observed in human lungs, again, we conjecture that the fibers in the indoor environment may have the ability to travel to the deepest part of the lungs. Since an individual spends the majority of the time in bed or rest position in the household, we recommend setting up a sampling device at the height of half a meter to calculate the microplastics deposition rate; this would help to estimate the inhalable microplastics abundance in the indoor environment and the possible human health risks.

Considering the shapes of the microplastics, fibers are the dominant shapes in the indoor environment, whilst the most dominant polymer type is polyethylene terephthalate. However, the commonly observed shapes in the indoor environment are fibers, fragments, and films. Similarly, the commonly observed polymers are polyethylene terephthalate, polyethylene, polystyrene, polyamide, and polypropylene. Soltani et al. (2021) reported the highest abundance of fibers (99%) in the indoor environment. Similarly, the highest percentage of polyethylene terephthalate observed in the indoor environment was 90% (Jenner et al. 2021). Regarding the polymeric characteristics, Soltani et al. (2021) reported the abundance of polystyrene to be 77% in rooms with carpets.

Table 3 contains sampling details, abundance, and factors affecting microplastics in the indoor environment. Similarly, Table 4 summarizes the observed shapes, polymer types, and characteristics of the microplastics in the indoor environment.

3.2 Factors Affecting Microplastics Abundance

Researchers have studied a number of factors seeming to influence the abundance of microplastics in the indoor environment. As reported by most authors, one of the potent factors influencing the abundance of microplastics in the indoor environment is human activities (Dris et al. 2017; Jenner et al. 2021; Zhang et al. 2020a, b). When considering the possibility of the exchange of microplastics between indoor and outdoor environments, Liao et al. (2021) observed no correlation between the

Table 3 Sampling details, abundance, and factors affecting microplastics in the indoor environment

Samples/stations/ duration	Data type	Limit (μm)	Mean concentration & range	Remarks (factors affecting microplastics abundance)	References
Two apartments; 2–5 m^3; 4– hours	Active sampling	>50	Median 5.4 fibers per m^3 0.4–59.4 fibers per m^3	Differences in the building material, furniture, cleaning habits, and activities (correlation); Seasonal influence (no correlation); Sampling site (correlation)	Dris et al. (2017)
Two apartments; 4–14 days	Passive sampling	>50	Range 1600–11,000 fibers/ m^2/d		
20 households; 118 samples; 6 months	Passive sampling		1414 ± 1022 p/m^2/d; 0–5412 p/m^2/d	Outdoor environment, household activities, household occupancy, and seasonal clothing habit (correlation); Sampling months (no correlation)	Jenner et al. (2021)
5 apartments, 2 offices, 2 classrooms, 2 hospitals (main corridor), 2 transit station waiting halls; 39 samples; 2–3 dry periods	Active sampling	>5	Mean 1583 ± 1181 p/m^3	Indoor and outdoor microplastics abundance (no correlation)	Liao et al. (2021)
22 sites; 32 samples	Passive sampling		Mean 3095 p/m^2/d; Range 22–6169 p/m^2/d	Frequency of vacuum cleaner use (−ve correlation); Number of occupants (no correlation); Number of children (no correlation); Road vehicular density (no correlation); Ventilation rates in the room, local weather conditions, and distance between the room and the nearby road (correlation)	Soltani et al. (2021)

(continued)

Table 3 (continued)

Samples/stations/ duration	Data type	Limit (μm)	Mean concentration & range		Remarks (factors affecting microplastics abundance)	References
A room, an office, a corridor; 24 h sampling; 3 months	Passive sampling		Site	Range (p/ m^2/d)	Amount of textile material at each site (correlation); Human activities, clothing, and airflow speed (correlation); Shedding capacity of the textile (correlation)	Zhang et al. (2020a)
			Dormitory	2100–29,000		
			Office	620–4500		
			Corridor	500–600		
12 countries; 286 samples	Active sampling		38–120,000 μg/g (polyethylene terephthalate microplastics) 0.11–1700 μg/g (polycarbonate microplastics)		Polyethylene terephthalate plastic consumption (+ve correlation); Human activities and economic activities (+ve correlation)	Zhang et al. (2020b)

Note: *p/m²/d* (particles per square meter per day), *p/m³* (particles per cubic meter), *μg/g* (microgram per gram)

indoor and outdoor microplastics abundance. Similarly, Jenner et al. (2021) also reported no correlation between indoor microplastics abundance and outdoor environment. Thus, we speculate that there is significanltly less possibility of outdoor microplastics being transferred to the indoor.

In contrast, Soltani et al. (2021) observed a correlation between the ventilation rates in the room and the microplastics contamination. However, no conclusions can be drawn on the exchange of microplastics between indoor and outdoor environments based on the current level of studies. More subtle and rigorous research is intrinsic to understanding the relationship between indoor and outdoor microplastics concentration. Zhang et al. (2020a) suggested that the shedding capacity of the textile also determines the abundance of microplastics in the indoor environment. Thus, we conclude that, unlike the outdoor environment, fewer factors affect microplastics abundance in the indoor environment. However, rather than a single factor, a hybrid of influencing factors, such as human activities, clothing, and airflow speed, determine the microplastics abundance in the indoor environment (Zhang et al. 2020a).

Table 4 Characteristics of polymers and shapes in the indoor environment

Dominant shape	Observed shapes	Dominant polymers	Observed polymers	Remarks (characteristics of polymers and shapes)	References
Fibers	Fibers	Polypropylene	Polypropylene, polyamide, co-polymers of polypropylene and polyethylene	67% of natural fibers; 33% synthetic fibers; The longest fiber was 3250 μm	Dris et al. (2017)
Fibers	Fibers, Fragments, Films, Spheres	Polyethylene terephthalate	Polyethylene terephthalate, polyethylene, polyamide, polypropylene, polyacrylonitrile, polymethyl methacrylate, acrylates, co-polymer blends	90% of the total particles (microplastics and non-microplastics) were fibers; 90% of the samples depicted the presence of polyethylene terephthalate;	Jenner et al. (2021)
Fragments	Fragments, Fibers	Polyester	Polyester, polyamide, polypropylene	Fibers were mainly polyester, polyamide, and polystyrene; Fragments were mainly polyethylene, polypropylene, and polystyrene; Fragments (89.6%)	Liao et al. (2021)
Fibers	Fibers, Fragments, Films	Polyethylene	Polyethylene (25%), polystyrene (17%) including polyethylene terephthalate, polyamide (16%), and polyvinyl chloride (15%)	Fibers (99%); Fiber's concentration decreased with decreasing length; PS (77%) in rooms with carpet	Soltani et al. (2021)
Fiber	Fibers, Fragment	Polyethylene terephthalate and rayon	Polyethylene terephthalate, rayon, acrylic, cellophane, polypropylene, polystyrene, polyamide	Fibers (60%) were non-microplastics; Polyethylene terephthalate and rayon made up 90% of the microplastics	Zhang et al. (2020a)

3.3 Sources of Microplastics

Dris et al. (2017) suggested that tearing clothes and household furnishings, such as carpets (polyethylene terephthalate or polypropylene carpets), curtains, and textiles, is the potential source of fibers in the indoor environment (polyethylene terephthalate or polypropylene carpets). Also, Zhang et al. (2020a) infered textiles as the prominent source of microplastics in the indoor environment. In contrast, Jenner et al. (2021) reported that regular clothes hanging and the use of dryers and carpets depicted no significant difference in the abundance of microplastics within the households. Soltani et al. (2021) observed a double proportion of polymers in houses with carpets than in houses without carpets and presented carpets as the major source of microplastics, especially polyethylene, polyester, polystyrene, and polyacrylic. Similarly, the authors suggested polyvinyl chloride floor varnishes and linoleum surfaces as the source of polyvinyl chloride fibers. In addition, microplastics can be sourced into the indoor environment from the outdoor environment through wind blowing and adhering to the clothes (Zhang et al. 2020a). With the results from the number of studies, we speculate that microplastics in indoor environments originate from a very limited number of sources.

4 Comparison Between Indoor and Outdoor Microplastics Pollution

When comparing the average count of microplastics in the outdoor and indoor environments, the observed indoor microplastics pollution is remarkably higher than the outdoor environment. Since an individual spends most of the time in the indoor environment, humans are at higher risk of microplastics ingestion and inhalation in the indoor environment and subsequent possible health hazards.

Fibers are the dominant shapes in both indoor and outdoor environments. The abundance of fibers is considerably higher in the indoor environment compared to the outdoor. A diverse range of polymers has been observed in the outdoor environment, whilst limited polymers have been observed in the indoor environment. This may be due to the limited source of microplastics in the indoor environment.

The sources of microplastics in the outdoor environment are numerous, not easily avoidable, and may be local or distant. However, there are limited sources in the indoor environment, which are easily avoidable and traceable. With current studies, it is apparent that the effect of meteorological conditions, such as precipitation and wind, on the abundance of microplastics is still not clear and requires more in-depth research and analysis. The factors affecting the abundance of microplastics in the indoor environment are apparent, with no contradiction among the studies. The common factor that affects the prevalence of microplastics in both environments is the human activities. When considering the most abundant size range, the indoor air has depicted the prevalence of small-sized microplastics compared to the outdoor air.

5 Conclusion

Microplastics are present in both indoor and outdoor environments. Owing to the higher abundance of microplastics and maximum human exposure in the indoor environment, it can be anticipated that the associated human health risk is also higher in the indoor environment. However, to date, the study on indoor and outdoor microplastics abundance is in its early stage of infancy. Nevertheless, very limited studies have been carried out on indoor microplastics abundance compared to outdoor. Moreover, the extent of microplastics inhalation and ingestion in the indoor and outdoor environment is another field awaiting profound and subtle research. Fibers are the dominant shapes in both indoor and outdoor environments. Regarding polymers, divergent polymer groups have been recognized in the outdoor air, whilst limited polymers are identified in the indoor environment. The sources and factors influencing the abundance of microplastics in the outdoor environment are numerous but with an unclear relationship with microplastics abundance. Similarly, the indoor air has exhibited limited sources (textiles and carpets) and factors affecting the microplastics abundance.

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Nanoplastic Sources, Characterization, Ecological Impact, Remediation and Policies

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Abstract The presence of plastic in abundance in the environment has been confirmed, and scientists are taking measures to assess the accumulation of macroplastic and microplastic in populated and remote locations. Here we review microplastics and nanoplastics with focus on sources, characterization, ecological impact and toxicity, remediation, and policies.

Keywords Microplastic · Nanoplastic · Plastic pollution · Environment · Contamination

1 Introduction

Plastics are polymer based synthetic or semi-synthetic materials. The plasticity associated with these materials makes it possible for plastics to be molded, extruded or given various shapes by pressing. This flexibility, together with many other novel properties like durability, lightweight and low production cost, has resulted in its widespread use (Plastics Division: life cycle of a plastic product). Typically, plastics are chemicals derivatives of fossil fuel like natural gas or petroleum. Of late, industries synthesize plastic variants from renewable materials like corn or cotton derivatives. Plastics have proved to be one of the most popular materials ever developed for various advantages which include, amongst others, easy molding and low cost. The obvious advantages led to huge production of plastics, to the tune of some 300 million metric tons global production in 2013 (http://www.worldwatch.org/global-plastic-production-rises-recycling-lags-0) showing a 4% increase over the 2012 production. A study on the outcome of the plastic products developed during 2012 showed that 26% was recycled, 36% incinerated and the remaining ended up in

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landfills. Production increased to 380 million metric tons in 2021. The packaging end-use segment held the largest market revenue share of more than 36.0% of the overall demand in 2021. Packaging segment uses maximum plastic with very low penetration and plastic has remained an inherent part of the packaging industry. The advent of bio-based plastics has also played a significant role in the pharmaceutical, food and beverage packaging sectors (Plastic Market Size, Share & Trends Report, 2022–2030).

Extensive use of plastics has become a matter of serious concern as plastics are not biodegradable and can remain in the eco-system for hundreds of years. Plastic pollution in the form of persistent plastic debris and may end up at considerable distances from their source. The biggest problem, no doubt, is the burgeoning human consumption and subsequent disposal of plastics (Rist et al. 2018; Toussaint et al. 2019). The Great Pacific Garbage Patch is a horrendous example of the disposal of used plastics (Moore 2011; Lebreton et al. 2018). The patch covering 1.6 million square kilometres with about 80 thousand metric tons of plastic garbage, is so huge that it is referred to as the 7th continent. The major constituents of this patch were found to be micro and nanoplastics.

2 What Are Nanoplastics?

What are nanoplastics and why should we be concerned about them? Nanoplastics are basically plastic materials in nanometric sizes, typically less than 100 nm in one or more of the three dimensions. It is believed that nanoplastics are created by gradual disintegration of macroplastics into mesoplastic (5–25 mm) (Allen et al. 2020), then into microplastics (sizes below 5 mm) (Toussaint et al. 2019) and subsequently into nanoplastics (sizes below 100 nm) (Ambrose et al. 2019). Nanoparticles are not human made but result from human creation and activities resulting in appalling environmental pollution that has started affecting adversely the whole eco-system. Nanoplastic occurrence, transformation and toxicity has been recently reviewed (Atugoda et al. 2023). Nanoplastics are probably more dangerous than microplastics (Sharma et al. 2022)

3 Sources of Nanoplastics

Be it the coastline or the deep sea, marine ecosystems have been found to be the most important destination for micro and nano plastics. In a study conducted in 2016, it was estimated that about 23 million metric ton of plastic waste, which is almost 11% of its global production, ended up in both freshwater and marine ecosystems (Borrelle et al. 2020). Only about 10–25% of the marine plastic is actually from marine sources and the major contribution is from terrestrial activities. The marine sources may include oil and gas exploration, fishing and nautical activities, etc. (EFSA Panel on Contaminants in the Food Chain (CONTAM) 2016; Gies et al. 2018) Waste water treatment plant and activities like laundry, domestic cleaning as well as the use of cosmetics have also been found to contribute to the addition of nanoplastics into the ecosystem (Kazour et al. 2019; Lutz et al. 2021). Another major contributor is industrial and commercial runoff (Mak et al. 2020; Materić et al. 2022) that carries plastic wastes into water bodies and the process of disintegration also continues during runoff. A study carried out by (Mintenig et al. 2017) in 2018 in a waste water treatment plant in Vancouver, estimated the formation of 1.76 trillion micro/nanoplastic particles annually, of which 17% ended up in the marine environment. The observations of Gies et al. corroborates with the findings of a similar study carried out in Finland by Talvitie et al. (Nguyen et al. 2019) in 2015 which suggested that waste water treatment plant effluent discharge act as a major transport pathway for marine plastic pollution. Recent studies have shown that plastic micro and nano particles are formed largely due to terrestrial activities like exposure to solar UV radiation, wind, or other degradation processes (e.g. mechanical and biological) (Rakib et al. 2022).

Figure 1 shows the various pathways of formation of micro and nano plastic particles, as they proceed from plastic sources to final accumulation destinations. It is interesting to note that nano plastic particles have been detected even in the north and south poles indicating movement of these pollutants to the remotest of locations with sparse or no population (Stock et al. 2019). Nanoplastics are consumed by microorganisms while filter feeders consume both micro as well as nanoplastic particles. Small fishes eat filter feeders like planktons and nanoplastics enter their

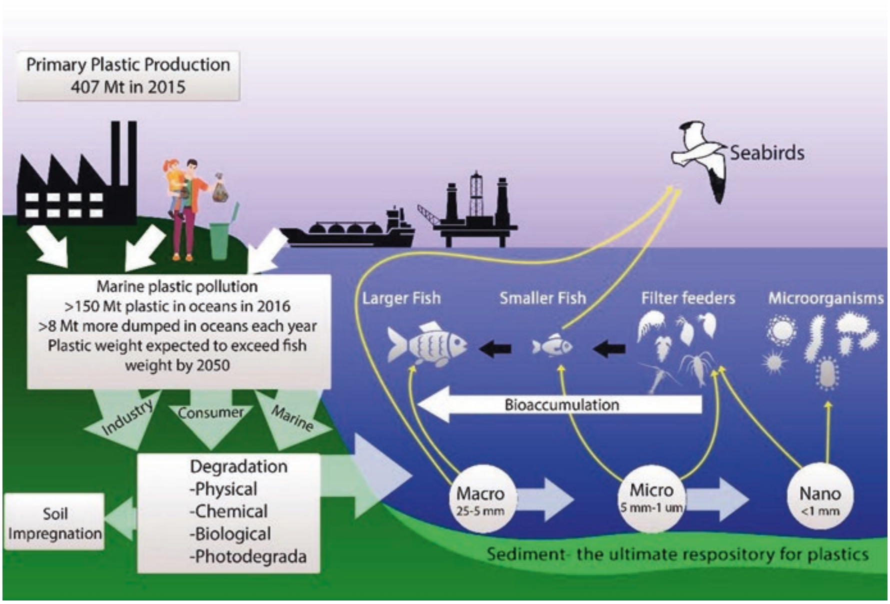

Fig. 1 Formation and movement of micro and nanoplastics leading to plastic pollution

bodies. Microplastics also enter the bodies of small fishes which finally land up in bigger fishes which prey on them. Macro, micro and nano plastics are also consumed by aquatic birds directly or indirectly.

4 Characterization of Microplastics and Nanoplastics

The difficulty in separation of plastic particles is found to be inversely proportional to their size; smaller the size more complex is the separation process from environmental samples. Existing isolation techniques are incapable of separating microplastics and nanoplastics. Alternative techniques are proposed by Nguyen et al. (Talvitie et al. 2015) which are used in other research fields to have better separation of the smallest plastic particles. These techniques include adapting active density separation (centrifugation) from cell biology and taking advantage of surface-interaction-based separations from analytical chemistry. Micro and nano plastic particles are extracted from different end destinations for identification and characterization. The samples collected for characterization may be biological samples, water and wastewater samples as well as sediment samples as shown in Fig. 2. Typical separation methods like Density separation, Digestion and Filtration are preceeded by preseparation techniques which include Dissection and In-situ

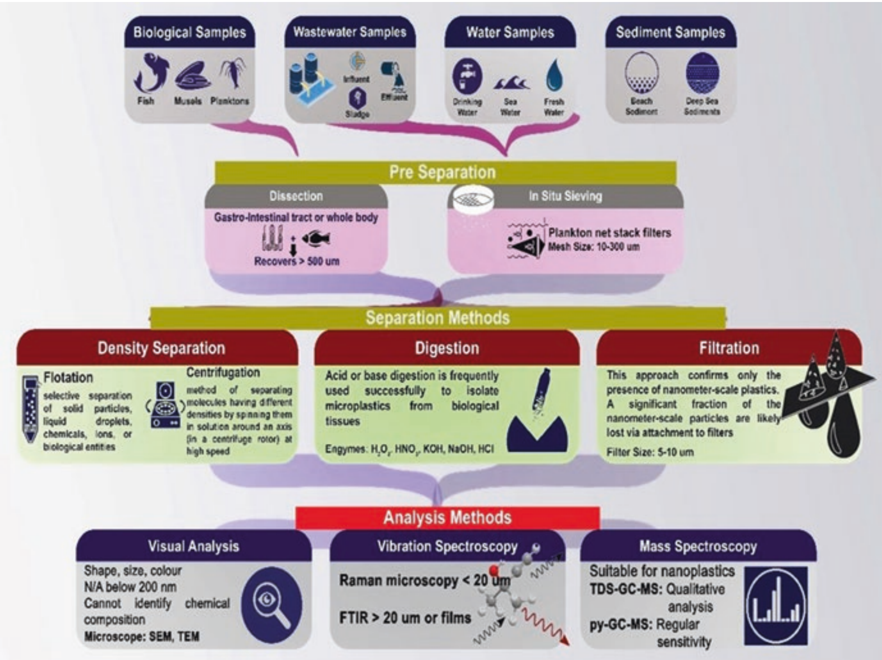

Fig. 2 Techniques for separation and analysis of microplastic and nanoplastic particles

sieving. The pre-separation and separation methods are detailed in Fig. 2. Once separated out, the microplastic and nanoplastic particles are characterized using techniques like visual analysis using scanning and transmission electron microscopy (SEM and TEM), vibrational spectroscopy using Raman spectroscopy and Fourier Transform Infra Red (FTIR) spectroscopy and mass spectroscopy techniques like Gas Chromatography Mass Spectroscopy (GC-MS) and Thermal desorption – gas chromatography – mass spectrometry (TDS-GC-MS).

Scientists from ETH Zurich have recently published their observations on monitoring the condition of nanoplastics in Nature Nanotechnology (Mitrano et al. 2019). They used laboratory synthesized plastic nanoparticles consisting of a metallic core thereby allowing easy traceability with conventional analytical techniques used for metals analysis. Their research opened up the possibility of the synthesis of metal-doped nanoplastics that can be used for precise assessment of the impending threat to our environment posed by nanoplastics.

5 Nanoplastics as a Contaminant

The harmful effects of microplastics and nanoplastics are mainly mechanical and/or toxicological in nature. Plastic particles release chemicals during leaching that are carcinogenic in nature. Some such chemicals, like monomers, polymers and plastic additives adversely affect the endocrine system. A research team led by the International Atomic Energy Agency (IAEA) published a comprehensive review deliberating on how often fishes consume micro or nano plastic particles and its outcome (www.iaea.org/newscenter/news/new-research-on-the-possible-effects-of-micro-and-nano-plastics-on-marine-animals). Their study confirmed that the biological functions of these fishes including their metabolism, neurological activity, intestinal permeability and gut microbiome diversity are significantly affected because of the consumption of the plastic particles. It is debatable whether the term nanoplastics should be used to indicate environmental polluting plastic particles at nanometric scales keeping in mind the advantages of natural as well as engineered nanoparticles. As properties like high surface to volume ratios provide extremely high surface reactivity to nanoparticles, can the nanoplastic particles also be used for useful applications instead of considering them as undesirable product of disintegration of larger particles?

6 Ecological Impact and Toxicity

Plastic pollution occurs from both terrestrial and aquatic sources. However, the impact on the aquatic environment is comparatively high as maximum plastic debris migrates to waterways which influence various biological functions and processes. A massive number of research topics are being focused on the sources, fate, and ecological effects of plastic trash pollution, a problem that affects the environment globally and may have effects on human health (Lwanga et al. 2017). Of the two forms of nanoplastics, the primary nanoplastics reach the environment in their original minuscule size as a result of different applications and consumer products, whereas the secondary nanoplastics are a result of macro/microplastic deterioration. The microbeads of plastic have a high affinity to be absorbed by organic pollutants which subsequently have the potential to enter the food chain (Barnes et al. 2008; Lusher et al. 2022; Cole et al. 2013). The impact on the food chain is a channel to carry pollutants into human bodies. Exposure to microplastic and nanoplastic particles have been linked to toxic effects, such as slowed growth, increased immune response, and other effects that have an adverse effect on future generations. The microplastics (MPs) affect marine organisms in physical, chemical, and biological ways that might have an influence on the food chain and human health (Thompson et al. 2004). The plastic particles are difficult to degrade even in animal guts, where after oral ingestion, more than 90% of the ingested MPs and NPs are excreted in animal faeces.

6.1 Impact on Marine Organisms

The biomagnification of plastic occurs when organic materials from plastic penetrates the lower trophic level organisms that include zooplankton, microphytobenthos, etc. and then migrate to higher trophic level organisms such as fish and other fauna, where plastic particles are swallowed and accumulated at high concentrations. This might eventually lead to human contamination of seafood owing to plastic contamination in marine food webs (Ferreira et al. 2016).

Furthermore, as observed in MPs from surface water samples in Thailand, the decomposition of plastics into the environment may spread harmful metals such as Chromium, Copper, Nickel, Lead, Cadmium, and Zinc (Ta and Babel 2020). Nevertheless, the heavy metals are soluble harmful contaminants that may persist in aquatic systems for long time durations resulting from their absorption, adsorption, accumulation, and other channels of their transfer into organisms (Tangahu et al. 2011; Gaballah et al. 2019; Naqash et al. 2020; El-Rayis et al. 2014). Micro and nano plastic particles interact with heavy metals in the marine environment and impede chlorophyll A production (Tunali et al. 2020). Recently, Naqash et al. (2020) reported that the interaction of MPs with biota and heavy metals on polystyrene and polyvinyl chloride was 800 times greater than in the surrounding environment, resulting in a chronic effect on the endocrine disrupting and inhibiting the predatory behavior of aquatic carnivores.

MPs and NPs have also been discovered to have an impact on the biological growth and reproduction of aquatic life, such as the growth, development, metabolism, and reproductive toxicity of flora and fauna (Sussarellu et al. 2016). Researchers have confirmed that various invertebrates, including amphipods, lugworms, mussels, crabs, and barnacles, have accumulated plastic particles in their tissues mostly due to marine plastic pollution. (Browne et al. 2008; Murray and Cowie 2011; Graham and Thompson 2009) Certain Echinoderms such as sea cucumbers, which reside in the pelagic and benthic zones and have numerous feeding strategies, are negatively impacted by the MPs/NPs present in the seawater or ocean water ecosystem (Graham and Thompson 2009). The National Oceanic and Atmospheric Administration (NOAA) forecasts that 10×10^4 marine animals and many fish as well as other fauna die each year, implying that plastic trash might have a negative impact on the aesthetics of beaches, shorelines, coastlines, sea floors, and coral reef life.

6.2 Human Health

Microplastics are so widely dispersed and abundant in the planet that many scientists view them as important markers of time, indicating a new historical era called "Plasticene" (Campanale et al. 2019). The microplastics release highly toxic and dangerous chemical substances that can affect a single as well as multiple cells, one or more organs, or the complete body. The chemicals that are deemed to be the most dangerous include those that alter hormones, induce cancer, mutate DNA, have hazardous effects on reproduction, are persistent in the environment, and produce other adverse consequences (Schubert 1972). The liver, kidneys, heart, neurological system, including the brain, and reproductive system are the internal organs that are frequently damaged (Cingotti et al. n.d.). Recent research has linked Endocrine-disrupting chemicals (EDCs), a toxic chemical released from MPs and NPs to a number of illnesses and conditions, including hormonal cancers (testis, breast, prostate), reproductive issues (infertility, genital malformations), metabolic syndromes (obesity, diabetes), asthma, and neuro-developmental conditions (learning and autism spectrum disorders) (Cingotti et al. n.d.). A common carbon-based synthetic industrial plasticizer, Bisphenol A (BPA) is associated with obesity, reproductive disorder, cardiovascular disease and breast cancer (Cingotti et al. n.d.; Hirai et al. 2011; Chen et al. 2018; Ortiz-Villanueva et al. 2018).

6.3 Impact on the Food Chain

As micro and nano plastics are prevalent in all sections of the environment, thus comprehending their contamination routes into our foods and beverages is critical to determining the level of contamination (Dris et al. 2016). Various sources of microplastic particles (like household, industrial, agricultural, and fisheries) and the potential pathways through which these particles are discharged into the environment and may eventually enter the food chain, typically through air and water causing long-term damage to the environment as also the food and beverages for human consumption (Toussaint et al. 2019). Decontamination and treatment of surface water, including lakes and rivers, as well as groundwater are the main sources of drinking water. But it is a well-known issue that microplastics are contaminating the lakes and rivers, as shown by several studies (Alencastro 2012; Eriksen et al. 2013; Eerkes-Medrano et al. 2015). Air is another pathway for micro and nano plastic to entry into the human food chain. In atmospheric fallout from indoor and outdoor air, textile fibres, which also have components of microplastics (about 33%), are present in amounts ranging from 0.3 to 1.5 fibers/m^3 and from 1.0 to 60.0 fibers/m^3, respectively (Dris et al. 2016). These microplastic fibres can enter and persist in lungs, and their inhalation is more likely due to their smaller size (Prata 2018; Gasperi et al. 2018). However, larger fibers that are not inhalable can deposit as dust (Toussaint et al. 2019).

The presence of micro-and/or nanoplastics has been documented to have an impact on 201 edible species, 200 of which are marine species and one of which is terrestrial. An approach of highlighting potential food contamination was described by (Barboza et al. 2018). The authors differentiated between contamination and/or adulteration of processed foods and beverages (as 7 different "food items") that are prepared for human consumption and contamination of marine species (90 species were studied) that can be consumed by humans. They also compiled a list of contaminated organisms. Majority of research work on the contamination of micro and nano plastics entering the human food chain focuses on mussels, oysters, scallops, fish, edible seabirds, and marine mammals (Toussaint et al. 2019; Huerta Lwanga et al. 2017) as they form the main focus of marine pollution. Microplastic contamination of marine organisms is explained through trophic transmission and direct ingestion, respectively. Many marine animals may easily consume microplastics floating in seawater because their size range matches that of fish eggs and plankton (Browne et al. 2008; Boerger et al. 2010). Boerger and his co-workers in 2010 and Possatto and his co-workers in 2011 discovered plastic debris in the stomachs of 33–35% of plankton-eating fish species collected in the North Pacific Gyre and Brazilian estuaries respectively. Figure 3 pictorially explains the entry of micro and nano plastic particles into the food chain.

7 Preventive Measures and Controlling Pollution

There is no doubt from the numerous studies carried out till date that plastic has emerged as one of the most toxic environmental pollutants with extremely high persistence. If the production and use of plastics is carried on at the current rate, it is imperative that very soon the micro and nanoplastic pollution problem will go beyond control. The diagnosis is done and it is high time we start the treatment before it is too late. Unfortunately, plastic is a polymer that has very poor biodegrability and can persist in the environment for centuries. As such, in order to minimize plastic pollution, the challenge is to develop techniques (chemical or biological) to degrade the plastic into benign fragments.

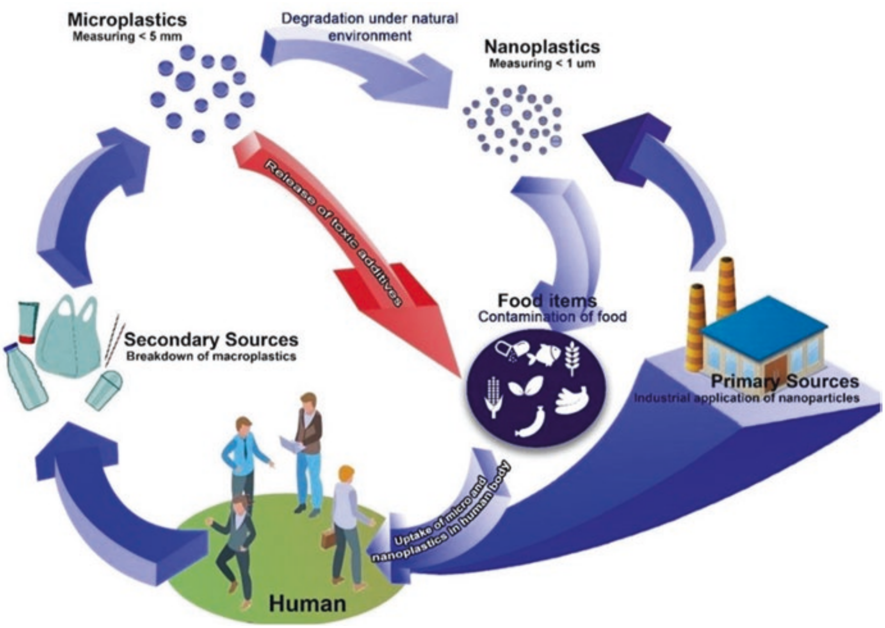

Fig. 3 Microplastic and nanoplastic particles are generated from different sources (primary as well as secondary) through consumer as well as industrial uses. These particles ultimately enter the food chain and drinking water sources, resulting in uptake and bioaccumulation of micro and nano plastic particles in the human body

7.1 *Strategies for Managing Nanoplastics*

It is the need of the hour to design an effective model for environmental plastic management and to chalk out strategies for the mitigation of damage to the ecosystem because of plastic pollution. Strategies that need to be included are the determination of impacts at the cellular level and also how ultimately, they affect the ecosystem. Scientists believe that formulation of novel degradable plastics that would not have any footprint in our environment would be a necessary step to resolve the problem of plastic pollution. Photocatalysis using wide bandgap semiconductors and their composites have been proposed as prospective candidates for photocatalytic degradation of polymers like plastics (Bratovcic 2019). Photocatalysis has been proven to be very effective in the degradation of environmental pollutants, both chemical as well as biological (Baruah et al. 2016; Mahmood et al. 2011). Photocatalytic degradation of plastic forms intermediates of lower molecular weight that can serve as raw materials for the production of fresh plastics, petrochemical products or in organic molecule synthesis.

In 2016, scientists from Kyoto Institute of Technology and Keio University of Japan made a remarkable discovery of a bacteria which had developed the ability to decompose plastic. The discovered bacteria, *Ideonella sakaiensis*, however are able to consume only one type of plastic namely polyethylene terephthalate, PET in short. PET is used for manufacturing bottles. This is however not the ultimate solution as *Ideonella sakaiensis* bacteria are observed to be a very slow plastic eaters and will need ages to finish off the existing plastic wastes, not to mention the addition every year. Many researchers are now concentrating their efforts to develop bacteria and enzymes that can feast on plastics.

7.2 Policies and Regulations

The burgeoning problem of plastic wastes escalated even further during the COVID-19 pandemic. In addition to the unavoidable increase of single-use plastics for personal protective equipment (PPE) like face masks and shields, scrapping of plastic bags was also instituted by many governments and business houses. Prior to the COVID-19 pandemic, World Resources Institute and United Nations Environment Programme noted that regulation on single-use plastic bags was in place in more than 100 countries (www.wri.org/insights/4-ways-reduce-plastic-pollution).

Since the pandemic, 50 U.S. cities moved away from plastic regulation. The city of Vancouver, Canada deferred fees for disposable cups and ban on plastic bags for over a year. A few recycling programs were dropped in the United States and European Union because of curtailment in budget during the pandemic. In order for countries to get back on the fight against plastic use, legislative reforms are essential. Policy modifications can minimize plastic pollution by encouraging behavioral changes in both businesses as well as consumers.

8 Conclusion

Plastic pollution is gradually becoming the major environmental pollutant with microplastic and nanoplastic particles accessing into the ecosystem in even the remotest areas with negligible population and human activities. Nanoplastics have entered into the food chain and have been detected in the gut of aquatic as well as terrestrial life including humans. Diagnosis of the damage is very clear yet the remedial measures are not known or still under exploration. Unless concerted efforts are put in by all countries under the leadership of the developed countries, the earth will not be habitable for future generations. Stringent steps need to be taken to prevent further accumulation of plastic wastes, if not minimizing the already accrued load. Scientists have proposed certain techniques to degrade microplastic and nanoplastic particles like photocatalytic degradation using heterogenous photocatalysis on wide bandgap semiconductors and biodegradation using bacteria and enzymes.

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Microplastics in Soil-Plant Systems

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Abstract The amount of plastic waste, has crossed 350 million tonnes, inducing pollution of most ecosystems by macro and microplastics. Here we review microplastic pollution in terrestrial systems with focus on effect of microplastics on soil properties, pollutants and plant growth. We detail the mechanisms of microbial biodegradation of microplastics. We also present common methods for the analysis of microplastics.

Keywords Microplastic · Soil ecosystem · Microbial degradation · Phytotoxicity · Anthropogenic biome · Quantification techniques

1 Introduction

Plastic has a negative effect on economic development, anthropogenic life, and aesthetics which results in high concern about its uses. Microplastics (MPs), which are generally referred to as plastic particles having a diameter of less than 5 mm, are one form of plastic particles that may be found (Andrady 2011). Microplastics are generally sourced from either primary or secondary sources (Duis and Coors 2016). Primary microplastics are created intentionally for a variety of uses, such as air

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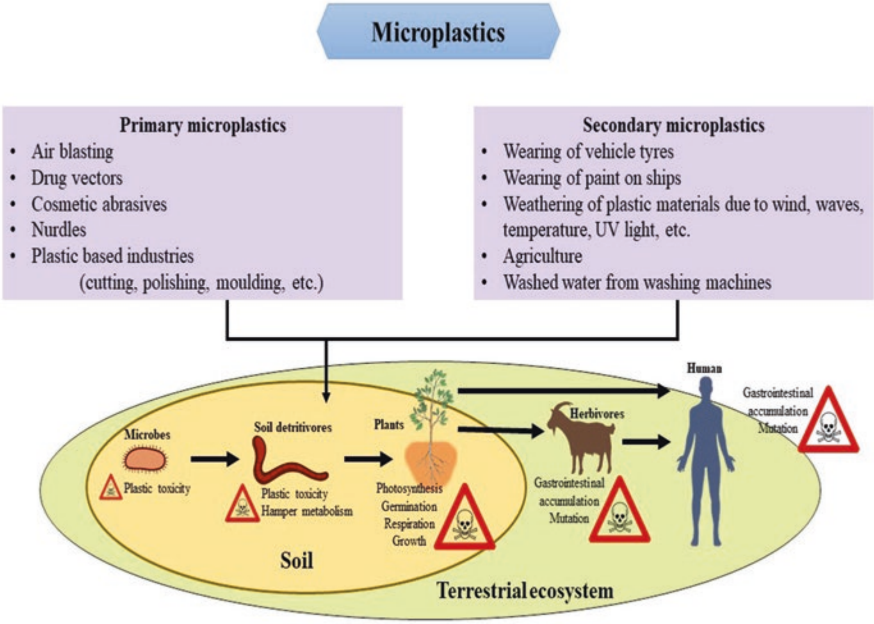

Fig. 1 Schematic representation of various sources of primary and secondary microplastics and their resonating toxicity from one trophic system to another in an ecosystem: Generally, microplastics are of two types, primary microplastics and secondary microplastics that have various sources. When the microplastics enter into the soil it obviously enters into the food chain. As the trophic level increases the bioaccumulation and biomagnification increases. The danger symbol size depicts the intensity of toxicity. The human is the apex organism in the food chain. Therefore, the concentration is highest in the human body

blasting, drug vectors, cosmetic abrasives, and engineering and industrial applications (Auta et al. 2017) (Fig. 1).

When these microplastics enter wastewater, which is often impossible to eliminate using sewage disposal techniques, they eventually get concentrated (Castaneda et al. 2014). Secondary microplastics are generated when larger plastics are repeatedly broken down into tiny bits by numerous, complex abiotic factors like wind, temperature, waves, UV light, etc. (Andrady 2011; Cole et al. 2011; Rocha-Santos and Duarte 2015). The most common plastic components that are released into the environment as microplastics are polyethylene (PE), polyvinyl chloride (PVC), polyethylene terephthalate (PET), polystyrene (PS) and polypropylene (PP), leading to a global hazard of ecosystems and human health. Due to its poor decomposition and difficulty in collecting all plastic particles, plastic pollution has long been viewed as an issue that will have an adverse impact on the functioning of the biogeochemical cycles. Thus, in order to limit the amount of microplastics that are lost to the environment during manufacture, consumption, and disposal, certain strategies have been recommended (Lambert and Wagner 2018).

However, it can be quite difficult to isolate microplastics in environmental matrices (Lambert and Wagner 2018). Though large plastics are eliminated during water processing, nano- and microplastics are impossible to be retained (Mintenig et al. 2017) because they are too tiny to be recognized and removed in an economical manner (Andrady 2017). According to a recent review by Sun et al. (2019), wastewater treatment plants can have concentrations as high as 447 MP particles per liter, with PS being one of the most often found polymers. Additionally, microplastics will inevitably enter the ecosystem due to the usage of municipal sludge as organic fertilizers (Klein et al. 2018). Consequently, there has been a critical need to learn more about the incidence and distribution of microplastics in environmental compartments as well as the defined definition and techniques for quantification, characterization, and extraction (Lambert and Wagner 2018). The most congenial strategy to reduce concentration of microplastics in the environment is bioremediation.

Applying multidisciplinary research methods such as MP assessment, characterization, and screening of productive microflora using cutting-edge assessment tools (genomics), and assessment of *in situ* toxicity are needed to deal with challenges relating to MP contamination bioremediation. By adopting chemical depolymerization techniques like glycolysis, microbial activity can be used to utilize plastic waste as raw material for biodegradation or biotransformation of certain resistant microplastics (such as polyolefins). Therefore, to create suitable feedstock for biotransformation, microplastics must be examined. Improving the effectiveness of enzyme-assisted degradation and crystalline formations that obstruct enzymatic degradation represent the other issue in the bioremediation of microplastic pollution and bio-utilization of microplastics. To better understand the microbial breakdown of plastic monomers, including complex aromatics formed from polyurethane (PU) and polyethylene terephthalate (PET) as well as long-chain aliphatic monomers derived from poly-ethylene (PE), more study is needed (Wierckx et al. 2018).

From the equator to the poles, microplastics contamination has been discovered to be widespread and persistent polluting terrestrial and aquatic ecosystems mostly. 79 percent of all plastic garbage generated worldwide is stored in landfills, indicating that soil is probably a significant source of microplastics (Ng et al. 2018). According to recent data, farmlands annually add between 63 and 430 thousand tonnes of microplastics to Europe and 44 to 300 thousand tonnes of microplastics to North America, both of which are greater than the estimated annual emissions of microplastics to ocean surface waters (Nizzetto et al. 2016a, b). There were 62.5 MP particles per kilogram of deep soil and 78.0 particles per kilogram of shallow soil in Shanghai, China's agricultural areas (Liu et al. 2018). In Campeche, Mexico, microplastics concentration of 0.87 ± 1.9 particles per g have been found in residential garden soils (Huerta Lwanga et al. 2017). Additionally, Scheurer and Bigalke (2018) observed microplastics in 90 percent of Swiss riverbank soils, and they estimated that the mean concentration of microplastics was between 5 to 55.5 mg per kg. In non-urban soil reserves, like remote mountainous regions, microplastics make up approximately 0.002 percent of the dry weight of the soil (Scheurer and Bigalke 2018).

Fuller and Gautam, (2016) found that soil samples from an industrial area in Australia contained 0.03–6.7 percent microplastics, with concentrations varying from 300 to 67,500 mg per kg. Inevitably, soil organisms will unintentionally consume microplastics because of microplastic contamination in the soil. For instance, microplastics have been found to be consumed by earthworms, and as the concentration of microplastics rises, so does the rate of consumption and it was found that Earthworm castings contain 14.8 to 28.8 MP particles per g. Moreover, Huerta Huerta Lwanga et al. (2017) also found around 130 particles per g in the chicken excreta from home garden soils. Microplastics also paved their way to the snails (Panebianco et al. 2019) with nearly 1 particle per 5 snails. In a nutshell, the microplastics have entered almost every food chain in all ecosystems risking the health of every living being. Thus, its concern is highly significant to scrutinize the interactions of microplastics at different ecosystems and the ways to manage microplastic are of utmost importance. This chapter focuses mainly on the significant effect of MP on terrestrial ecosystem and the interaction of it with the soil dwellers. The authors have discussed the role of microplastics in dissemination of various soil pollutants, impact on plant growth and anthropogenic biomes. We have also briefly summoned the methods to extract, quantify and remediate the microplastic pollution in terrestrial ecosystem.

2 Microplastics in Soils

Soil ecosystem harbors diverse microflora, soil organisms and plants which creates a unique and dynamic environment (Guo et al. 2020). It is also known as 'ecosystem engineers' for providing and regulating various ecological services (Pereira et al. 2018). Soil ecosystem is source and sink of various pollutants from heavy metal, xenobiotic compounds, organic pollutants to microplastics (Duraes et al. 2018). The interplay between these abiotic and biotic entities facilitates in bioconversion of the pollutants into less or more toxic form, their transmission and migration via food chain along with groundwater and surface water contamination (Duraes et al. 2018; Sarkar et al. 2021). Accumulation and fate of microplastics in soils after application of biosolids on land have been reviewed (Huang et al. 2023). Recent research on microplastic contamination has reported presence of microplastics to be 4–23 times more in terrestrial ecosystem than the ocean. (Horton et al. 2017; Jacques and Prosser 2021). These huge amount of microplastics is not only due to various point and non-point sources such as agricultural practices, industrial process, runoff, and atmospheric deposition but also due to constant rapid soil dynamics, environmental factors such as wind abrasion and UV illumination. The interplay between the microplastics and the soil ecosystem has reciprocal impacts on both, influencing physical properties, dispersal, and toxicity attributes of former, while changing physical structure, chemical attributes and biological entities of later. Some studies on the effect of microplastic interactions on the soil's physico-chemical and biological attributes are presented in Table 1.

Table 1 Effect of microplastics on soil's physicochemical and biological properties

S.no	Study location	Experiment	Microplastic properties			Soil type	Effects on soil properties			Reference
			Particle type	Particle size	Particle conc.		Physical	Chemical	Biological	
1	Chenggong experimental station of Yunnan university, China	Physical parameters of polyester microfibers affected soil	Polyester microfibers	<5 μm	0.1%–0.3%	Nitisol (a clay loam with 24% sand, 41% silt And 35% clay)	Decreased volumes of <30 μm pores Reduced water holding capacity Increases the proportion of macropores Promotion of soil aggregation	–	Enhanced microbial and biological activity	Zhang et al. (2019a, b)
2	Agricultural Field in Eschenau, Lower Austria	The effect of polyethylene microplastics on the transport of two selected organic plant-protection agents in soil	Polyethylene microplastics	<250 μm	10%	Sandy loam soil	Increment in the mobility of organic contaminants In soil Reduction in the soil's natural retention capacity	Reduction in the sorption of the plant-protection agents	–	Huffer et al. (2019)
3	Ansai County in the loess plateau of China, Institute of Soil and Water Conservation, Chinese Academy of Sciences	Interactive effects of microplastics and glyphosate on the dynamics of soil-dissolved organic matter	Homopolymer polypropylene	<250 μm	7–28%	Loess soil	Increased porosity and air circulation in the soil	Promoted the accumulation of dissolved organic carbon (DOC) Increased inorganic nitrogen	Increased soil microbial activity with increase in porosity and surface area	Liu et al. (2019)

(continued)

Table 1 (continued)

			Microplastic properties				Effects on soil properties			Reference
S.no	Study location	Experiment	Particle type	Particle size	Particle conc.	Soil type	Physical	Chemical	Biological	
4	Agricultural farms located in northern Italy, southern Italy and the Mississippi Delta (U.S.)	Effect of compostable film microplastics (CFMPs) on soil and aspergillus flavus population	Compostable film microplastic particles (CFMPs)	~ 12 μm	8%	Sand silt clay	–	Soil is contaminated by aflatoxins	The size of the soil A. Flavus (aflatoxigenic) population increased which is a concern for asthmatic and immunosuppressed individuals	Accinelli et al. (2020)
5	The experimental garden of Freie Universität Berlin, (Berlin- Germany)	The effects of various types of microplastics on the soil biophysical properties.	Polyacrylic fibers, polyamide beads, polyester fibers, and polyethylene high-density fragments.	Length:3000 μm–5000 μm Diameter: 8–10 μm	0.05%–2.00%	Loamy sand	Soil bulk density decreased with the application of different types of microplastic Polyester fibers increased the water-holding capacity of the soil	–	Polyacrylic and polyester microplastics decreased the soil microbial activity	de Souza Machado et al. (2018a)
6	Peking University, Beijing, China	Effect of LDPE microplastic films on microbial community composition and Enzymatic activities in soil	Low-density polyethylene (PE) film	Thickness: 0.01 mm Dimension: 2 mm x 2 mm	0.076 g/kg	Cinnamon soil	–	There was an increase in urease and catalase activities in the soil after 15 days, and no discernible alteration of invertase activities was detected	A different taxonomic composition was observed between the control and amended. Additionally, several taxa including plastic-degrading bacteria and pathogens were more abundant	Huang et al. (2019)

7	Keshan County, Heilongjiang Province, China, Ansai County, and Yangling County, Shaanxi Province, China	Effect of microplastics on soil hydraulic properties considering soil texture as crucial factor	Polypropylene particles	20, 200, and 500 μm	≤ 6%	Loam, clay, and sandy soil	Reduction of water infiltration and retention, therefore, restricting water movement Alteration in pore-size distribution and reduced pore availability	–	–	Guo et al. (2022)
8	The agricultural land adjacent to the historical mining areas of the Tancheon mine in Gongju-si, Chungcheongnam-do, province, Korea	Effect of LDPE microplastics on chemical properties and microbial communities in soil	Low-density polyethylene mulching films	100 μm	≤ 7%	Sandy loam soil	–	Higher LDPE MP concentrations (≥1%) decreased the pH and increased the EC of the soil	The relative abundance of Firmicutes and Actinobacteria increased on application of higher dose of LDPE MP	Palansooriya et al. (2022)

2.1 Impact of Microplastics on Soils

2.1.1 Effects on Soil Physical Properties

There is profound effect of microplastic on the soil's inherent physical structure and properties such as bulk density and water holding capacity of soil, soil aggregation, pore size distribution, soil water evaporation, evapotranspiration, hydraulic conductivity, and desiccation as microplastics can alter the soil physical features (Mbachu et al. 2021). Terrestrial ecosystem has a diverse form of soil types, which has similar or different effect of microplastics on their physical structure and integrity (de Souza Machado et al. 2019; Zhang et al. 2019a, b). Various studies relates soil bulk density with soil erosion indicator (Gholami et al. 2020). Loamy soils are susceptible to decrease in soil bulk density with increase in the concentrations of microplastics dosage of various types (de Souza Machado et al. 2018a; 2019). Type of microplastic particle morphology also influences the bulk density for example; fibrous polyesters decreases the soil bulk density to much extent than the fragments and beads (de Souza Machado et al. 2018a). Stability of soil aggregation is very important for soil biological activity and soil function (Mbachu et al. 2021; Zheng et al. 2016). Increase in microplastic dosage leads to decrease in soil binding forces. Like soil bulk density, aggregation stability of soil is influenced by particle morphotype i.e., Linear microplastic particles causes more instability as compared to non-linear microplastics (de Souza Machado et al. 2018a; 2019; Mbachu et al. 2021; Zhang et al. 2019a, b). Soil porosity is significantly influenced by microplastic contamination. Zhang et al. (2019a, b) on his experiment on nitisol soils has shown that both the macropores and micropores are influenced by the microplastic dosage. Macropores volume was increased due to clod formation by interaction of soil and linear polyester microfiber, while the micropores volume decreased due to hydrophobic nature of polyester fibres. Since large pores indicates poor soil structure due to rapid surface water drainage and small pores mediates water retention and water availability to plants therefore, microplastic contamination provide useful insights on impacts on decrease habitats for soil microbial community and increase water drainage (Greenland et al. 1977; Zhang et al. 2019a, b). Water holding capacity is greatly dependent on the porosity of the soil and increases with increase in pore size. It's been observed that water holding capacity of loamy soil increased on treatment with various kind of polymers in varying concentration (de Souza Machado et al. 2018a). Hydraulic conductivity of soil is important physical parameter which influences the water transmit ability of soil depending on the soil type (Klute and Dirksen 1986; Mbachu et al. 2021). Soil hydraulic conductivity increases due to organic matter and microfibers presence but microplastics alone are not evident to have any impact on the soil hydraulic conductivity (Zhang et al. 2019a, b). Above physical properties altogether have significant impact on soil-water, soil-gas flux, evapotranspiration, and breakdown of soil. Incorporation of microplastics in soil leads to reduced water retention, therefore increasing the evapotranspiration rates (Wan et al. 2019). This will create a liquid limit stage in the soil altogether reducing the tensile strength of soil structure and promoting cracks on soil surface and soil desiccation.

2.1.2 Effects on Soil Chemical Properties and Pollutants

Earlier we have discussed how microplastics impacts on physical properties of soil, but this interactions are not limited to the former only, any impact on soil physical structure and properties have direct or in direct influential role on its chemical profiling (Zhang et al. 2021). Various studies have shown that microplastic contamination impacts pH, Electrical conductivity, exchangeable cations such as Na^+, K^+, Ca^{2+} and Mg^{2+}, influence the concentrations of primary macronutrients N, P and K, total organic carbon (TOC), dissolved organic carbon (DOC), and impact on various soil enzymatic activity (Yu et al. 2021; 2020).

Most studies have reported minimal or no impact on the pH of microplastic contaminated soil, while in one study pH of the HDPE treated soil had significantly lower pH than the other treatments as well as control (Boots et al. 2019; Yu et al. 2020; Zhang et al. 2021). It was discussed that the altered cation exchange due HDPE treatment possibly allowed free proton exchange with soil water (Boots et al. 2019). The macroaggregates (>250 μm) and microaggregates (53–250 μm) of Polyethylene (PE) has shown difference in pH while former was slightly neutral and later more alkaline than the control. In the same experiment, there was reduced cation exchange capacity (CEC) in microaggregates contaminated soil and increased CEC in macroaggregates than control (Hou et al. 2021).

Total nitrogen, phosphorous and potassium is significantly reduced in the soil contaminated by different varieties of microplastics. Soil carbon content was negatively influenced by different microplastic residues that is dissolved organic carbon (DOC), total organic carbon (TOC) (Hou et al. 2021; Yu et al. 2021, 2020; Zhang et al. 2021). In contrast to this, total organic matter (TOM) of soil has been reported to be increased (Yu et al. 2021) as well as decreased (Hegan et al. 2015) when contaminated with plastic residues. Many studies also suggest that the influence on soil nutrients content and cycling may also depend upon the degradation rate of humic-like substances (Zhang et al. 2021).

Microplastic residues also effects the enzymatic activity of various soil enzymes such as urease, catalase, sucrase, phenol oxidase, manganese oxidase, laccase and β-oxidase. In an 80 days experiment, with increase in number of days the activities of sucrase, urease as well as catalase had decreased significantly under the extreme effect of different treated microplastic residues (Yu et al. 2021). Similarly reduced soil activity was discussed to be influenced by the reduction in soil nutrients, reduction of availability of substrate for enzymes by competitive binding via adsorption with soil microorganisms decreasing microbial activity and subsequently enzyme activity on addition of microplastic residues (Hou et al. 2021; Yu et al. 2020).

Microplastic contamination tends to influence the dispersal of other soil pollutants in terrestrial ecosystem which tends to deteriorate the soil chemical environment (Guo et al. 2020; Zhang et al. 2021). Certain soil pollutants are used as additive in plastic production such as diethylhexyl phthalate (DEHP) and adsorption of heavy metals such as Cu, Pb and Zn, as well as noxious organic chemicals such perfluorochemicals (PFOS) and polybrominated diphenyl ether (PBDE) and antibiotics. The plethora of these soil pollutants slowly migrate to the surface of microplastics, then dispersed along with microplastics as they spread in the soil ecosystem (Guo et al. 2020; Hahladakis et al. 2018). This dispersion is also caused by the weakening of absorptive forces such as non-specific Vander wall interactions between the pollutants and the soil particles due to addition of microplastic entities, which renders the increased mobility of soil pollutants (Huffer et al. 2019).

Dispersion of antibiotics via microplastics is concern for dissemination for antibiotics resistance genes in the superbugs (Zhu et al. 2022). Antibiotics such as amoxicillin, ciprofloxacin, and tetracycline having carbonyls group have high surface assimilation capacity on polyamide microplastics due to its porous structure and hydrogen bonding with carbonyl groups of antibiotics (Antony et al. 2010; Li et al. 2018a, b).

Heavy metals adsorb to the microplastic residue under varying pH levels, also as earlier discussed various metals are also inherently added to the polymers during production. Therefore microplastics also act as vector for transfer of heavy metals in soil environment (Zhou et al. 2019). Microplastics and other soil pollutants causes synergistic pollution adversely affecting soil ecological system.

2.2 *Interactions of Microplatics with Microbes*

Soil nutrient content and characters are interconnected with the soil microbial diversity and action (Naveed et al. 2016; Rillig et al. 2017). The change in physicochemical soil parameters due to microplastic affects the soil microbial diversity and community structure. The physical changes like soil aggregation imparts the linear microfibers (Zhang et al. 2019a, b) probably affects the evolution of microbes in a different way from the non-contaminated soil without microfiber (Rillig 2018; Rillig et al. 2017). The distribution of aerobic and anaerobic bacteria is influenced by changes in soil moisture and porosity due to microplastic contamination altering the ability of oxygen in soil (Rubol et al. 2013).

Pore spaces are altered by microplastics leading to the loss of microhabitat and their native microbes (Veresoglou et al. 2015). Recently a research group have found after an addition of microplastic to the soil has decreased the substrate – induced respiration (SIR) and intervened the microbial dynamics, signifying the alterations in soil microbial function due to microplastic (Judy et al. 2019). Dissolved organic matter (DOM) is linked to the greenhouse effect and water eutrophication (Marschner and Kalbitz 2003). While dissolved organic matter (DOM) act as an important carbon source for the microbes, any change in the in DOM due to microplastic affect the soil parameters and simultaneously the microbial diversity (DeForest et al. 2004a, b).

Soil enzymes has role in the substrate availability for microbes which effects the microbial activity therefore microplastic changes the soil enzymes affecting the soil microorganisms. Root colonization of fungus was also changed at different level of microplastic contamination (Rillig 2018). Overall, the microplastic has wide range of effects on the soil parameters and soil microbes therefore creates a selection criterion on soil microbes which direct to change in microbial evolution and dynamics (Rillig 2018).

In bioremediation, microorganisms are employed to degrade the natural and synthetic plastic polymers, which fulfil their requirement for energy and carbon source (Caruso 2015). The solution for the microplastic degradation requires combine action of physical & chemical, degradation methods (i.e., thermal degradation, oxidation, photodegradation, etc) and bioremediation through microbes would give better degradation (Shah et al. 2008). The clearance of microplastics through biodegradation has caused extensive interest in recent years to save the environment and energy. Plastic polymers are broken down by physical, chemical, and biological processes up until they reach a size of less than 5 millimetres (microplastic), at which point bacteria take over.

Potential and environmentally favourable solution for bioremediation of microplastic contaminants is bacteria. Polyethylene (PE) which includes low-density polyethylene (LDPE), high density polyethylene (HDPE), polyvinyl chloride (PVC), polyurethane (PU), polyamide (PA), polyethylene terephthalate (PET), polystyrene (PS), polypropylene (PP), nylons, poly (caprolactone) (PCL), polyethylene succinate (PES), polylactic acid (PLA) are some of the different types of plastic. Depending on the environment, plastic can breakdown under anaerobic conditions in landfills and sediments, aerobic conditions in the natural world, and partially aerobic conditions in compost and soil. Microbial degradation of microplastics isolated from different environment is shown in Table 2.

Aerobic degradation primarily takes place in waste disposal sites, and in this setting, aerobic microorganisms are involved in the breakdown of organic plastic polymers using oxygen as an electron acceptor, resulting in the production of carbon dioxide and water as by-products. Anaerobic degradation occurs through anaerobes without the presence of oxygen, anaerobes degrade materials using the sulphate, nitrate, manganese, carbon dioxide and iron as electron acceptors releasing water, carbon dioxide and methane as by-products.

3 Biodegradation of Microplastics

The steps involved in microplastic biodegradation are (1) microbial colonization; (2) enzyme assisted fragmentation; (3) biological Intake and degradation.

3.1 Microbial Colonization

A combination of biological and other factors causing the plastic to breakdown physically and chemically on the surface. The first step of degradation is the abiotic elements including ultraviolet, and other chemical reactants, that damage the polymer structure (Helbling et al. 2006; Ipekoglu et al. 2007). The microbes first colonize on

Table 2 Microbial degradation of microplastics isolated from different environments

S.No	Environment	Plastic category	Microbial strain	Exposure	Key outcomes	Region	References
1	Compost	MP	*Pseudomonas sp.*	----	Degradation of 5% dry weight of MPs with a lower molecular weight After 40 days.	USA	Wilkes and Aristilde (2017)
2	Compost	MP	A thermophilic microorganism (*Streptomyces sp.*)	In vitro	Poly (D-3-hydroxybutyrate) Degradation at 50 °C	India	Pathak (2017)
3	Compost		*Rhodococcus ruber, Brevibacillus Borstelensis, aspergillus Niger, Pseudomonas sp., vibrio sp., Flavobacterium sp., staphylococcus Sp., micrococcus sp., bacillus sp., Chelatococcus sp.*	In vitro	Degrade MP in compost	India	Skariyachan et al. (2018)
4	Sewage sludge	MP	Microbes through the activity of depolymerization	In vitro	In anaerobic digesters, MP can be broken down to produce biogas	China	Li et al. (2018a, b)
5	Sewage sludge; Hyperthermophilic Composting (hTC)	MNPs	*Thermus, bacillus*, and *Geobacillus*	In situ	Among the MPs, 43.7% declined from the sewage sludge	China	Chen et al. (2020)

6	Municipal solid Waste (MSW)	MPs	*Pseudomonas fluorescence, P. aeruginosa* and *Penicillium Simplicissimum*; *Rhizopus delemar*, *R. Arrhizus*, *Achromobacter sp.* and *Candida cylindracea*	In vitro	Polymers like poly (ethylene adipate) (PEA) and poly (caprolactone) hydrolyzed (PCL)	Pakistan	Rana (2019)
7	Municipal solid Waste (MSW)	MP and polymers	*Pseudomonas sp.*	In vitro	28 and 7 per cent by weight of polypropylene (PP)	Australia and the USA	Judy et al. (2019)
8	Wastewater (WW)	MP	*Alteromonadaceae* and *Burkholderiales*; *Alcanivorax Borkumensis*	In vitro	Bacteria capable of degrading; LDPE Degradation	UK and China	Yang et al. (2021)
9	Leaf-branch Compost	MP	*LC-cutinase*; *Saccharomonospora Viridis*; *Thermobifida fusca cutinase*	In vitro	Low-crystallinity PET package film (lcPET-P, 8.4%) was hydrolyzed at 50 °C	China	Ru et al. (2020)
10	MPs wastewater (WW)	MP	*Vibrio*, *campylobacter*, and *Arcobacter*	In vitro	MP breakdown	USA	Kelly et al. (2021)

the plastic surface forming a biofilm, this depends on the environment conditions as well as the plastic structure and content (Lugauskas et al. 2003). *Rhodococcus ruber* C208 forms the biofilm on the polystyrene and polyethylene, which initiates degradation within 3 days (Sivan 2011). The bacterial biofilm secretes extracellular polymeric substances (EPS) which aid in adherence to the plastic, and this starts the chemical and physical deterioration. This EPS percolates inside of plastic pores, promoting microbial growth therein increasing pore size, and causing physical degradation of plastic (Bonhomme et al. 2003). The diverse microbial community acts upon the plastic, their biofilm may produce different acid compounds like sulphuric acid (e.g., *Thiobacillus* spp.), nitric acid (e.g. *Nitrobacter* spp.), nitrous acid (e.g. *Nitrosomonas* spp.) through the chemolithotrophic microbes (Zettler et al. 2013). Also, the chemoorganotrophic microbes produce organic acids like citric, gluconic, oxaloacetic, fumaric, oxalic, glutaric, and glyoxalic acids. The acid changes the pH thus influencing the degradation through modifications in plastic structure.

3.2 Enzyme-Assisted Fragmentation

The plastic polymers are fragmented into oligomer and monomer with the help of UV, radiations, mechanical, chemical, thermal, and biological process. The microorganism secretes free radicals and extracellular enzymes that catalyzes the plastic polymers into small monomers. Plastic is quite stable due to long chain of hydrogen and carbon with charges. The microbes secrete the extracellular oxygenases enzyme, which imbalances the charges by adding oxygen to the carbon chain that aid in lysis. Di-oxygenases and mono-oxygenases adds the oxygen groups therefore helps to convert peroxyl or alcohol group that are easily degraded. Other modifications are done through the catalysis of endopeptidase, esterases and lipases when the carboxylic groups are formed (Lugauskas et al. 2003). Some monomers are also formed in this step.

3.3 Biological Intake and Degradation

The fragmented plastic molecules are transported through carriers across the cell wall or plasma membrane. The transported monomers in the cytoplasm are metabolized via oxidation to produce the energy and cell biomass. The metabolism of the fragments depends on the microbe which could be aerobic, anaerobic and fermentation thus producing the energy for reproduction, structural and cellular processes. The metabolism results into secondary metabolites that are not useful for cells are excreted out which can be utilize by other microbes. The complete degradation of monomers refers to the complete oxidation into nitrogen, methane, carbon dioxide and water.

There are enormous types of bacteria which can degrade plastic into monomers (Ghosh et al. 2013). We will discuss some bacterial genera with various polymer degradation properties. *Bacillus brevis* is known to degrade polycaprolactone, while Pseudomonas is a dominating genus which degrades PVC, polythene, PHB, poly (3-droxypropionate), and poly (3-hydroxybutyrate-co-3-mercaptopropionate), even PVC can be degraded by *Ochrobactrum* sp. The isolated strains of *Bacillus* sp.YP1 and *Enterobacter absuriae* YT1 from the mealmoth (*Plodia interpunctella* larvae) gut are capable for polyethylene (PE) degradation (Yang et al. 2014). Similarly, isolated strain *Exugiobacterium* sp. YT2 from the mealworm (*Tenebrio molitor* larvae) was found to degrade the polystyrene (PS) (Yang et al. 2014). Streptomyces genus is capable to degrade poly (3-hydroxybutyrate-co-3-hydroxyvalerate), PHB, polyester or starch. Two isolated Gram-positive bacteria Firmicutes and Actinomycetes phylas from the earthworm gut has the capability of degrading the low-density polyethylene (LDPE) (Huerta Lwanga et al. 2018). The isolated *Kosakonia* sp. and *Citrobacter* sp., from the mealworm gut and demonstrated degradation of both plastic PS and PE. *Rhodococcus ruber* and *Pseudomonas putida* bacteria were also discovered to be able to degrade plastics (Caruso 2015; Mor and Sivan 2008).

There are many bacterial species having potential for degrading the plastics belong to *Pseudomonas* sp., *Staphylococcus* sp., *Diplococcus* sp., *Micrococcus* sp., *Bacillus* sp., *Streptococcus* sp., and *Moraxella* sp., (Kumar and Hatha 2007). The solution for the microplastic degradation requires combine action of physical & chemical, degradation methods (i.e. thermal degradation, oxidation, photodegradation, etc) and bioremediation through microbes would give better degradation (Shah et al. 2008). Bacterial source for bioremediation of microplastic pollutants are potential and environment friendly system.

4 Impact of Microplastics on the Environment

The terrestrial ecosystem may be at risk from microplastic contamination because of their ubiquity, environmental persistence, and varied interactions with continental biota. Due to their high longevity and poor recycling rate, they bioaccumulate in the ecosystem (Barnes et al. 2009;Souza Machado et al. 2018). As a result, challenges to biodiversity and ecological services are primarily caused by human activities (Meybeck 2004). Therefore, it is probable that microplastics initially interact with the biota in terrestrial systems, where they may change the geochemical and biophysical environment and lead to environmental toxicity. Despite this, the pollution of microplastic on land maybe 4–23 times more than that in the water (Horton et al. 2017). Additionally, microplastics can alter the physical and chemical composition of soils, impacting the whole soil biosphere (Zhang et al. 2019a, b). Agricultural soils may contain more microplastics than ocean basins (Nizzetto et al. 2016a).

4.1 Impact on Terrestrial Plant Growth and Diversity

Plastic degrades and fragments on the topsoil layer. Once the plastic decomposes in the top layer of soil, it goes to the depth where physical variables like low temperatures and a lack of oxygen reduce its biodegradation. Plastic fragments in fields rise crop by crop due to the repeated application of plastic mulches, reducing agriculture productivity (Serrano-Ruiz et al. 2021). By plugging soil pores, microplastics can prevent water from seeping and reduce water holding capacity (Qi et al. 2020a, b). Essential soil attributes, including bulk density, water holding capacity, and soil structure, are all affected by plastics (de Souza Machado et al. 2018b) (Lozano and Rillig 2020). When more plastic particles are present in the soil for extended periods, the soil structure is compromised, resulting in soil infertility.

4.1.1 Transportation of Microplastics in Plant Tissues

Plant cells can accommodate microplastics by several pathways, including endocytosis, symplastic pathway, translocation via plasmodesmata, facilitated diffusion, and passive diffusion, among other mechanisms (Maity and Pramanick 2020). Osmotic pressure and capillary action are responsible for delivering certain tiny particles into the endodermis (Lin et al. 2009). Microplastics may also be internalized through the stomata and transported through the xylem tissue (Hong et al. 2014).

4.1.2 Effect on Seed Germination

Toxins can enter seeds through pores in the seed capsule as they absorb water from the environment during germination (Coen and Magnani 2018). Microplastics may obstruct cress seeds pores, prevent water absorption, and speed down germination and root development (Bosker et al. 2019). Plant germination, growth, and photosynthesis in terrestrial plants may be influenced by several microplastic forms, as shown in Fig. 2.

PLA microplastics hindered the germination rate of Perennial ryegrass (*Lolium perenne*) and PLA content was adversely linked with shoot height (Boots et al. 2019). They proposed that this reduction may be caused by plastic particles obstructing the seed capsule. Later, these microplastics may obstruct the root hairs, impeding nutrient absorption. Therefore, plastic particles tiny enough to block seed capsule pores can slow down seed germination, which leads to fewer seeds that germinate.

4.1.3 Effect on the Plant Vascular System

So far, no study has explicitly addressed microplastics in plant vascular systems. Neither the xylem nor the phloem exhibits any accumulation (Li et al. 2020). Even though PS beads measuring 0.2 mm were clumps found in the xylem and on the cell wall of cortical tissue in wheat roots. After entering the central cylinder, the

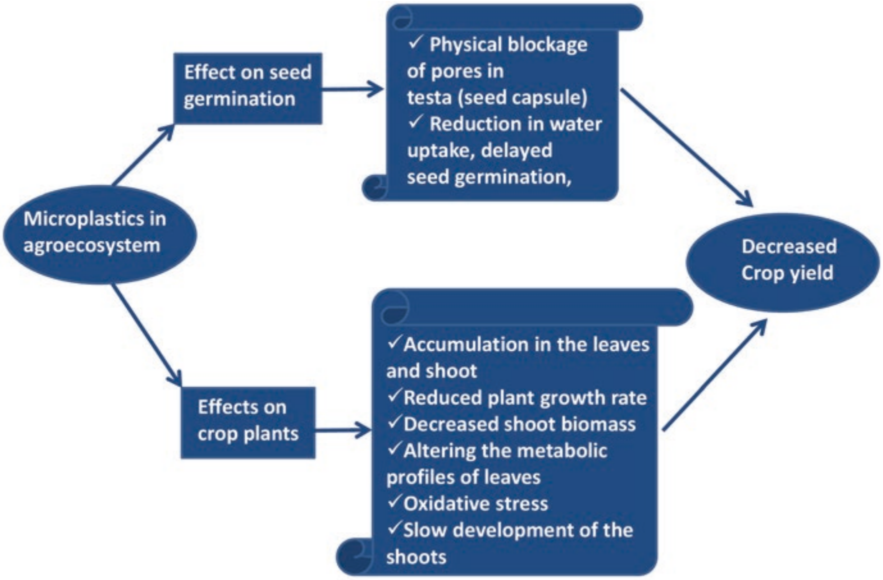

Fig. 2 Schematic representation of impacts of microplastics on seed germination and plant growth: in the agroecosystem the effect of microplastic can be seen in the seed germination and also directly on the crop plants, which eventually leads to decline in the crop yield

particles are transported toward the plant's aerial portions via the vascular system of the xylem tissue in the transpiration stream (Lian et al. 2020). The transfer of beads to the periphery of plants may significantly reduce as microbead size (2.0, 5, 7, and 10 m) increases (Li et al. 2020).

4.1.4 Effect on Shoots and Roots

Plant cells can absorb microplastics, which may then be transported to various plant segments and deposited in the roots and shoots (Sun et al. 2020; Rajput et al. 2020). Studies have demonstrated that microplastics can adversely affect root growth by reducing root growth rate or biomass. Shoot height may also decrease due to exposure to microplastics (Boots et al. 2019). The aquatic duckweed species *Lemna minor*'s roots were mechanically obstructed by the polyethylene microbeads, which also further shortened the roots (Kalcikova et al. 2017). The suppression of root development after micro PS exposure to *A. cepa* occurred dose- and time-dependent (Maity et al. 2020). The suppression of the apical meristem of root tips is linked with the reduction in root development caused by toxicant exposure (d'Aquino et al. 2009). The onion's decreased root length serves as a biomarker for the phytotoxicity of environmental pollutants. Like polyamide microplastics, increased root length and decreased average root diameter can reduce the dry biomass ratio from roots to leaves (de Souza Machado et al. 2019). Additionally, nano plastics may accumulate in plant leaves and hinder the root development of mung bean plants (Chae and An 2020).

4.1.5 Effect on Plant Growth

Microplastics present in the soil have negatively affected wheat plants' vegetative growth and reproduction (Qi et al. 2018). Microplastics were found to negatively affect the development of lettuce, photosynthesis, and antioxidant defense mechanisms (Gao et al. 2019). Tomato plants grew more quickly in soils containing microplastic sludge, but their fruit production was delayed and decreased (Hernández-Arenas et al. 2021). The development of spring onion (*Allium fistulosum*) was also affected by different microplastics (de Souza Machado et al. 2019). Additionally, microplastics can alter the rhizosphere, plant growth conditions, and soil nutrient availability, leading to decreased plant growth. Evidence suggested that biodegradable mulch had a more detrimental effect on wheat development than LDPE because it increased the relative number of bacteria like *Bacillus* and Variants in the wheat's rhizosphere biome (Qi et al. 2020a, b). Research on the possible effects of microplastics on terrestrial plants is currently inadequate in several areas, such as plant stress responses, accumulation, and mobility of microplastics in plant tissues, and toxicity of microplastics on plants. Furthermore, consuming crops with accumulated microplastics will increase human exposure to microplastics (Dong et al. 2021). Future studies should thoroughly evaluate the impacts of various plant species and different classes of microplastics on terrestrial ecosystems.

4.1.6 Effect on Ecosystems

Plastics have transformed our way of life and are one of the main components of anthropogenic waste seen across the biosphere in modern culture. Plastics and their chemical homologues are produced in large quantities, permeating aquatic ecosystems and terrestrial (Thompson et al. 2004; Ryan et al. 2009). The widespread presence of microplastics in the environment has raised concerns about their harmful effects on biota and the potential connection between them and invasive species' migratory patterns, which is a severe environmental issue. Microplastics harm the ecosystem for two primary reasons: (1) their small size makes them more accessible for biota to internalize, which leads to an accumulation in the food chain, and (2) they may absorb contaminants on their surfaces (Rillig 2012). However, it is hypothesized that microplastics are often resistant to biodegradation. When they decompose, trophic level consumers eat or passively absorb them, which causes a mechanical blockage of the digestive system and systemic inflammation. As per the available scientific evidence, microplastic has a broad range of adverse effects on the organisms of different trophic levels, including disruption of feeding, decreased reproductive efficiency, physical ingestion, perturbations in metabolic activities, and alternations in hepatic biology. Plastic polymers are the most frequently discovered anthropogenic compounds in the environmental samples (Whitacre and Whitacre 2008). The ability of weakly soluble bio-persistent microplastics ($< 1\ \mu m$) to react with the cellular membrane, organelles, and molecules cause the second part of the chemical reaction. This may cause a variety of consequences frequently brought on by hazardous compounds, including inflammatory response, alterations in permeability of cell membrane, and oxidative stress, among others (Forte et al. 2016; Hamoir et al. 2003; Jeong et al. 2016).

5 Analysis of Microplastics

Several new methods for locating and removing microplastics from water, particularly PE and polypropylene (PP) polymers have been developed in recent years (Hidalgo-Ruz et al. 2012; Wang et al. 2017). Saturated solutions of NaCl, NaI, $ZnCl_2$, or sodium polytungstate (SPT) can be used to extract plastics from water body soils due to their variable concentration (Hidalgo-Ruz et al. 2012; Imhof et al. 2012; Nuelle et al. 2014). By flotation using a high-density solution, microplastics are easily recovered from sediment with minimal contaminants and organic debris (Hidalgo-Ruz et al. 2012; Wang et al. 2017). However, microplastics are difficult to recover by flotation because they are highly adsorbed on soil particles.

The LDPE and PP are often used in agriculture to increase soil temperature and reduce evaporation (Huerta Lwanga et al. 2016; Steinmetz et al. 2016; Yan et al. 2015). According to Wang et al. 2017, microplastics may be divided into small and large microplastics (SMP and LMP) based on their particle size and number of particles (Imhof et al. 2012; Van Cauwenberghe et al. 2015). Microplastics with a diameter more than or equal to 1 mm are readily available, but those with a measurement not exactly or equivalent to 1 mm are harder to find (Hidalgo-Ruz et al. 2012; Lenz et al. 2015). Usually, only greater quantities of more important, more obvious microplastics may be used to determine mass.

It is most often made from LDPE and PP, which account for the bulk of agricultural plastic mulching. Other high-density solutions may be used to extract and float microplastics, but because density of soil microplastics is not known, the extraction and flotation method would be the same with or without distilled water. Soil cleanup expenses and environmental contamination may be reduced by floating microplastic in distilled water, which has an average density of 1 g cm^{-3} (Fuller and Gautam 2016; Huerta Lwanga et al. 2016). However, these extraction techniques could overstate the amount of microplastic present and help soil organic matter dissolve at 180 °C.

5.1 Visual Identification

Even though visual identification under a light microscope is the most basic and oldest method of microplastic analysis, it is biased and has error rates varrying from 20 to 70 percent. Eriksen et al. (2013) and from 70 percent to 90 percent Hidalgo-Ruz et al. (2012) Others recommend the “hot needle test” to alleviate the visual differentiation between plastic and natural particles that may be difficult to distinguish. The thermoplastic properties of various synthetic polymers are used in this test. To easily identify soil low-density polymers, Zhang et al. (2018) expanded on this idea using microscope pictures taken before and after providing heat to the sample upto 130 °C for 35 s, the residual in the supernatant is determined. It is possible to find melt particles of thermoplastic polymers. Despite its simplicity and practicality in most field labs, this technique of identification fails to account for the fact that certain natural materials (such as wax) melt at certain temperature and get destroyed, and does not allow for the identification of the precise kind of polymer.

5.1.1 Microscopy

Larger plastic particles, typically larger than 500 m, are usually analyzed manually under a stereomicroscope. Non-destructive particle count and size measurements may be performed at minimal cost and without harming the sample material. The complexity of the matrix may be considered when determining the level of sample preparation. Plastic recuperation from soil fluctuates incredibly with the immaculateness of the example and the administrator's information on the visual attributes of the particles (Zhang et al. 2018). Extra fluorescent staining with calcofluor white, Evans blue, and indigo, red colors might help recognize microplastics from the encompassing network. If you're sifting through a bunch of dirt, you're looking at a 20% to 70% chance of getting it wrong (Blasing and Amelung 2018) physically or mentally. As a result, it should be used in conjunction with spectroscopic methods such as FTIR or thermoanalytical procedures (He et al. 2018).

5.1.2 Spectroscopy

FTIR and Raman micro spectroscopy, with resolutions of 20 m and 1 m, may be used to simultaneously examine synthetic and actual properties of microplastics, for example, polymer type and molecule shapes and sizes (Xu et al. 2019). Both micro spectroscopic procedures are typically used for particles with diameters of 500 m and need the sample to be resting on a level channel plate. Spatial estimation additions of a few micrometers stretch obtaining lengths, making full filter scans almost unachievable at average disc diameters of 13–47 mm. Instead, automatic pattern recognition or randomized subsampling are used to manually choose specific regions of interest (Xu et al. 2019). The choice of thought microplastic particles by hand is particularly inclined to botch since white and straightforward things on a splendid channel foundation are not entirely obvious (Lares et al. 2019). Indeed, even computerized methods might misjudge or underrate molecule counts when microplastics are unevenly appropriated on the channel circles during test arrangement (Anger et al. 2018). Utilizing a FTIR micro spectrometer with a central plane cluster, measurement errors and time may be minimized (FPA). Grid detector components allow for more thorough chemical mapping of the filter and may provide several observations for a single particle (Simon et al. 2018). Even when utilizing

FPA-FTIR micro spectroscopy, a solitary 47 mm channel might require 10 hours to procure (Mintenig et al. 2017). The responsiveness of FTIR and Raman micro spectroscopy, as well as their ability to be influenced by water, CO_2, SOM, and clay particles, demands comprehensive matrix removal during sample preparation (Anger et al. 2018).

5.1.3 Thermodynamics

Compared to particle counts, it has been shown that microplastic mass items are more solid and more fit to cross-concentrate on examinations and PC demonstrating. This might be on the grounds that microplastic masses are not much affected by test treatment and less powerless against size selectivity predisposition (Simon et al. 2018). To extrapolate particle masses, one must consider the non-uniform conveyance of molecule sizes, shapes, and densities in natural examples. As a result, a variety of mass-sensitive thermoanalytical approaches are increasingly being used in addition to or in instead of FTIR and Raman imaging. Thermogravimetry (TGA) (Boyron et al. 2019; David et al. 2018), thermoextraction and desorption (TED) (Dumichen et al. 2017), and pyrolysis (Py) combined with GC/MS are among these approaches (Fischer and Scholz-Bottcher 2017, 2019).

5.1.4 Other Techniques

Various deeply grounded Liquid chromatographic (LC) strategies, including Liquid chromatography-Mass spectrometry (LC/MS), Size-exclusion chromatography (SEC), and Gel permeation chromatography (GPC) (Elert et al. 2017), have been rediscovered for microplastic discovery as of late. Although LC/MS is very sensitive and reproducible, it is only applicable to polymers like PS that can be easily dissolved in organic eluents at ambient temperature. Then again, high-temperature GPC and SEC frameworks can examine an expansive scope of polymers and give extra data on the polymer's sub-atomic weight, however their UV and refractive identifiers regularly need polymer fixations in the mgmL^{-1} territory (Elert et al. 2017). They may along these lines be less material to genuine soil tests, and soil parts might be more inclined to meddle. As a further example of the exciting new developments in science, (Peez et al. 2019) used quantitative NMR spectroscopy to quantify PET in environmental materials.

6 Perspective

Soil is a complex environment which is a hub for multiple interactions of soil components and anthropogenic pollutants (Wang et al. 2019). Despite in-depth scientific advances in understanding of soil microplastic contamination, still various research gaps are there which need to be addressed. Comprehensive understanding of migration behavior of microplastic is needed along with their potential to disseminate other pollutants in the soil environment. Microplastics are compositionally and morphologically variable and influence the soil biophysical parameters in intricated way. Their study needs improved sampling and analysis techniques as present methods are not robust and efficient enough for detection of micro and nano-plastics (Bilal and Iqbal 2020). Heavy metal pollution of soil has thorough scientific studies and pollution risk assessment, but microplastic pollution lacks ecological risk assessment models and quality assessment standards which is need of hour given the impending threat of microplastic pollution. In literature, technology for removal of microplastics from wastewater has been applied and reported (Iyare et al. 2020), but no such efficient technology has been applied in soil environment which is necessary for studying the distribution, abundance and source and sink of microplastic pollution (Ya-di et al. 2022).

7 Conclusion

Terrestrial ecosystem compromise of precious lifeforms where prevalence of the microplastic pollution is at much higher extent posing greater threat to their sustainable well-being. Soil is an important entity of terrestrial ecosystem which affects all the lifeforms directly or indirectly. The majority of important soil activities and processes are carried out by the soil microbiome residing in the soil. Microplastics and soil microbiome have profound interplay between each other, former influencing the soil microbiome diversity, their inherent functioning and involved in enzymatic/ physical degradation and later involved in the physical/ enzymatic degradation of former. It is recommended to further demystify such interaction for better biotechnological application for microplastic degradation and soil and amelioration.

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Owing to an oversight, the chapter author name was misspelled.
Previously it was Mukrram Ijaz, and this has now been corrected as 'Mukkaram Ejaz'.

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