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REVIEW

Exploring Environmental Nanoplastics Research: Networks and Evolutionary Trends

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Abstract

Analyzing scientific advances and networks in NPs research can provide valuable insights into the evolving trends, research gaps, and priorities for future research efforts, highlighting the importance of scientific research in pollution control and risk management of uncontrolled and unknown nanoplastics (NPs) that pose a potential global threat, and have raised concerns in the scientific community and media. A total of 2055 nanoplastics (NPs) studies published from 1995 onwards were retrieved from the Web of Science Core Collection database. Bibliometric methods were applied to assess evolving scientific advances and networks. The general term, "nanoplastics," was first introduced in 1995 as "intelligent" materials. Before 2009, defined as the ambiguous stage, NPs were produced and applied in many different manufacturing areas and processes. The first research referring to nano-scale plastic particles/debris as potential hazardous contaminants appeared in 2010. Thereafter, the number of annual publications on NPs has increased rapidly, particularly from 2018 onwards. Results showed China published 822 scientific papers, overtaking the United States' 229 papers, whereas European researches, i.e., the Netherlands, Portugal, German, and the United Kingdom, led in quality and citation with extensive international collaborations. Furthermore, we concluded three main research themes from keyword cluster analysis: environmental monitoring (identification, quantification, fresh-water, marine-environment); environmental behaviors (fate, adsorption, aggregation, transport); and toxicology (toxicity, exposure, ingestion, oxidative stress). Toxicology and environmental behaviors of NPs were the leading themes. An overview of the current understanding of NPs in the above three major themes provides perspectives to identify future research directions based on knowledge gaps, e.g., advancing analytical methods, and exploring the mobility and fate of NPs in different ecosystems. Scientific research on NPs is a key fundamental requirement for their pollution control and risk management. To bridge the gap between research and reality, future efforts are required to promote the dissemination of scientific research findings and encourage actions in engineering, policy, education, etc., to support a sustainable society.

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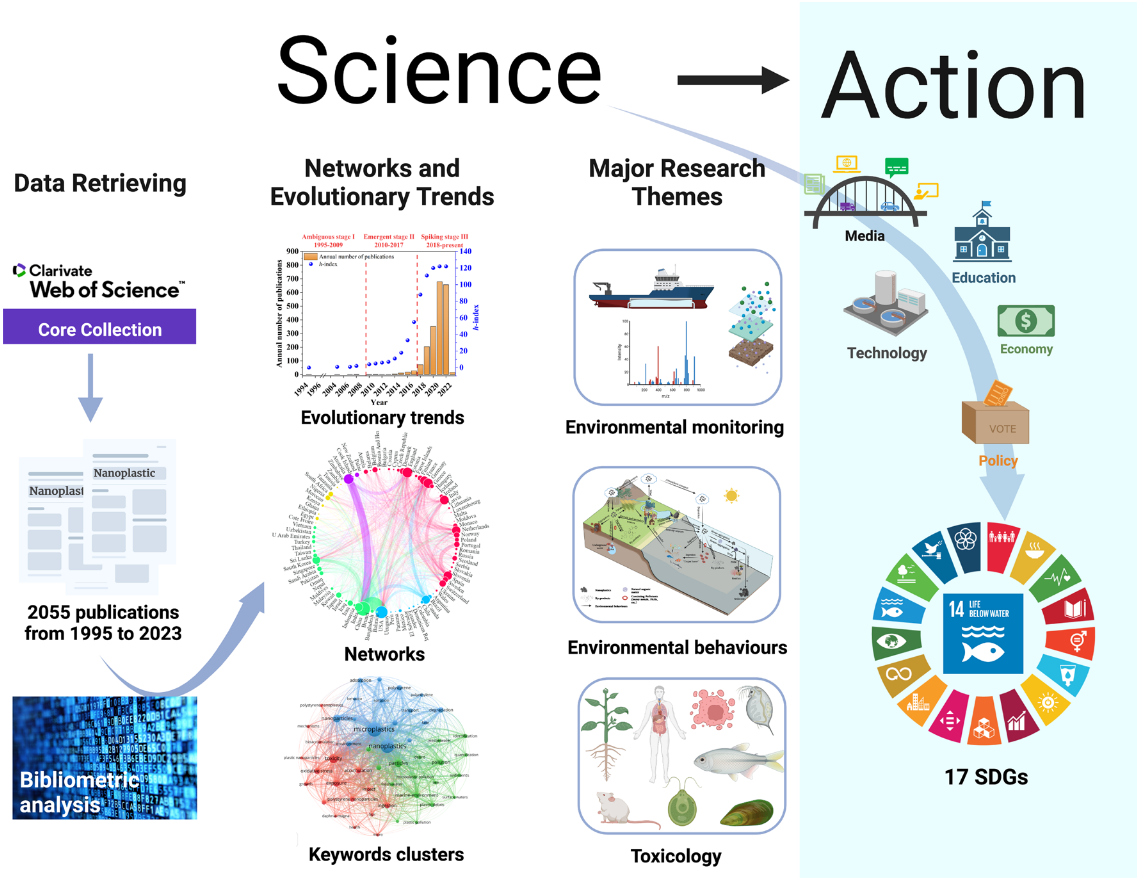
Graphical Abstract



Keywords Nanoplastics · Evolutionary trends · Networks · Environmental monitoring · Environmental behaviors · Toxicology

Abbreviations

MPs	Microplastics
NPs	Nanoplastics
PAHs	Polycyclic aromatic hydrocarbons
PET	Polyethylene terephthalate
PS	Polystyrene
PE	Polyethylene
PMMA	Polymethyl methacrylate
WoSCC	Web of Science Core Collection
DOM	Dissolved organic matter
POM	Particulate organic matter

Introduction

Since the 1950s global plastics production has surged, growing from 1.5 Mt (million metric tons) to over 359 Mt, and as a result, more than 4900 Mt of plastic waste had accumulated in landfills or the natural environment as of 2015 (Geyer et al. 2017). Plastic pollution has become a globally recognized issue, with plastics now ubiquitous in the environment and biological systems (Fischer et al. 2015; Allen et al. 2019; Pohl et al. 2020). Nevertheless, the study of plastic pollution is not a new research topic. In the early 1960s, records of marine animals ingesting plastic and becoming entangled in plastic litter were the first signs of plastic pollution (Ryan 2015). The occurrence of plastic waste in the North Atlantic Ocean was also reported many times in the 1970s (Carpenter et al. 1972; Carpenter and Smith 1972). Since then, plastic wastes in the oceans and their potential threats to the ecosystem and to humans have received increasing attention. In 2004, Thompson et al. (2004) used the term microplastics (MPs) to define microscopic plastic debris in the oceans for the first time. Later, a widely accepted definition of MPs including all plastic waste < 5 mm in at least one dimension was proposed in the meeting hosted by the NOAA (National Oceanic and Atmospheric Administration) in 2008 (Hartmann et al. 2019). A nomenclature based on size discrimination of plastic waste has been developed gradually, including mega-, macro-, meso-, micro-, and nano-plastics (da Costa et al. 2016).

Nanoplastics (NPs) are minuscule (within the size range 1–1000 nm, Gigault et al. 2018) solid fragments of plastic litter derived from degradation of larger plastic wastes. Intentionally produced NPs also can be emitted into the environment owing to their growing application in scientific research, diagnostics, and pharmaceutical products (Hoshino et al. 2008; Ensafi et al. 2017; Bartoš et al. 2022). For example, functionalized polystyrene nanospheres have been used for drug delivery, biomarkers, etc. due to their excellent loading capacity for dyes or biological molecules (Sapsford et al. 2013). These tiny particles are likely to be more reactive and mobile in environmental and biological systems, more readily ingested by fauna at the base of the food web, and have a high surface area to mass ratio, meaning that they may act as more effective "carriers" of other surface-adsorbed contaminants (and co-contaminants) than MPs (Galloway 2015; Koelmans et al. 2015). Therefore, caution is required in regarding NPs pollution as an extension of the MPs' problem, simply because of their distinct size-dependent properties. The potential impacts of NPs on ecosystems and human health are also far from clear and, as a unique class of plastic contaminants, require better understanding.

NPs are a growing area of concern for human and ecosystem health. A surge of NPs research papers have been published in journals and in the press in recent years and it is a challenge for the general public, and indeed scientists from diverse backgrounds, to digest this "flood" of scientific reports and be responsively involved in decision-making processes on NPs safety. The analysis of scientific advances and networks in nanoplastics (NPs) research can facilitate the identification of evolving trends and research gaps, and prioritize future research efforts. A visual bibliometric network can provide valuable statistical insights such as trends, academic collaboration intensity, and hotspots by mining massive scientific literature information (Tang et al. 2018; Wu et al. 2021; Zhu et al. 2021; Wong et al. 2020; Sorensen and Jovanovic 2021). For example, Zhang et al. (2020d) analyzed 2128 documents related to MPs using CiteSpace and VOSviewer software, and found that the number of publications on MPs has increased dramatically since 2011, mainly from Western Europe. Bibliometrics results showed that the impact of MPs on marine ecosystems is dominant in the field of MPs pollution. Currently, viewpoints from all sides on NPs are constantly evolving, and the body of research on NPs as an environmental contaminant is rapidly increasing, with an expanding number of scientific publications. It would be an arduous task to evaluate the performance of NPs research by reading these publications one by one. Recently, several in-depth reviews and bibliometric analyses have consequently been published, based on the combined microplastics and nanoplastics literature. Sorensen and Jovanovic (2021) performed a bibliometric analysis of 3820 publications with a focus on the presence of MPs and NPs in the environment; Wong et al. (2020) presented a review of the research landscape on MPs and NPs in global food webs based on a bibliometric analysis of 330 publications published in 2009–2019; Zhou et al. (2022) constructed social network maps through bibliometric analysis of existing articles related to both MPs and NPs in the marine environment; Koelmans et al. (2022) presented an overview of the adverse effects and underlying mechanisms of MPs on the environments and humans, and proposed a practical framework to assess the potential risks associated with MPs.

Here, a bibliometric analysis of the literature on NPs is conducted to comprehensively characterize relevant research output, contributions, and collaborations. Publication information such as annual publication output, citations, journals, countries, institutions, authors, and keywords is analyzed to elaborate space–time development characteristics and topics of NPs research. While recent studies have provided a broad overview of the literatures on MPs or the coupling of MPs with NPs, the uniqueness of our study lies in offering a more comprehensive and detailed analysis of literatures focused specifically to NPs. This includes an examination of their space–time development characteristics and research topics. Revealing the global distribution and collaboration in nanoplastics (NPs) research can identify research areas and knowledge gaps, foster collaboration, share best practices, and build public trust. Moreover, our study identifies key knowledge gaps and provides suggestions for future research, which are essential for addressing the environmental and health risks associated with NPs. NPs is a global issue that affects everyone through its ubiquity in the environment and potential impacts on food chains, water systems, and the air we breathe. By developing a comprehensive understanding of NPs' extent and nature, we can mitigate its impacts, effectively monitor, regulate and manage it, and work toward a sustainable future for all.

Methods

Data Sources

Web of Science, as the leading platform providing access to multiple databases, contains information on a significant number of reputable and influential journals in different academic disciplines (Wong et al. 2020; Li et al. 2010). We searched nanoplastics (NPs)-related literature in the Web of Science Core Collection (WoSCC) database from its inception in 1900 to 3 November 2022. To collect as many relevant research papers as possible, the following Boolean operators were used: TS = (nanoplastic$ OR "nano plastic$" OR "plastic nanoparticle$" OR "plastic nanomaterial$" OR "nano-plastic$" OR "nano-sized plastic$" OR "nano sized plastic$" OR "nanosized plastic$" OR "nano-scale plastic$" OR "nano scale plastic$" OR "nanoscale plastic$"). Then we further clarified the terms to excluded records on the plasticity of metallic materials on the nanoscale, nano/micro plastic deformation, and plastic flow of crystals using the following terms: "NOT TS = ("nanoplasticity" OR "nanoscale plasticity" OR "nanoscale plastic deformation$" OR "nano-scale plastic deformation" OR "nanoplastic deformation$" OR "nano-plastic deformation$" OR "nano-scale plastic deformation$" OR "polymer deformation$" OR "nano plastic forming" OR "nano-plastic forming" OR "nanoplastic forming" OR "nano/micro plastic forming" OR "nanoscale plastic work" OR "nanoscale plastic replication" OR "nanoscale plastic event$" OR "nanoplastic flow$" OR "nanoscale plastic flow$" OR "nanoscale plastic anisotropy" OR "plastic yielding")." There were no restrictions on the type, language, and time of publication.

Data Analysis

VOSviewer (Netherlands, v. 1.6.17) was used to analyze literature information and construct bibliometric networks into easy-to-understand maps, consisting of nodes and edges (van Eck and Waltman 2010). The edges indicate both relations between pairs of nodes and the strength of the relationship. The nodes examined are researchers (Fig. 2c) and keywords (Fig. 3), constructing the co-authorships and keyword co-occurrence relations. There were 97 subject categories of journals where the articles were published and the 15 groups of categories as defined by Journal Citation Reports (JCR) in which they belonged were listed and analyzed (Fig. 1b, Table S1). Groups of categories can be divided into three topics: application-related topics (such as engineering

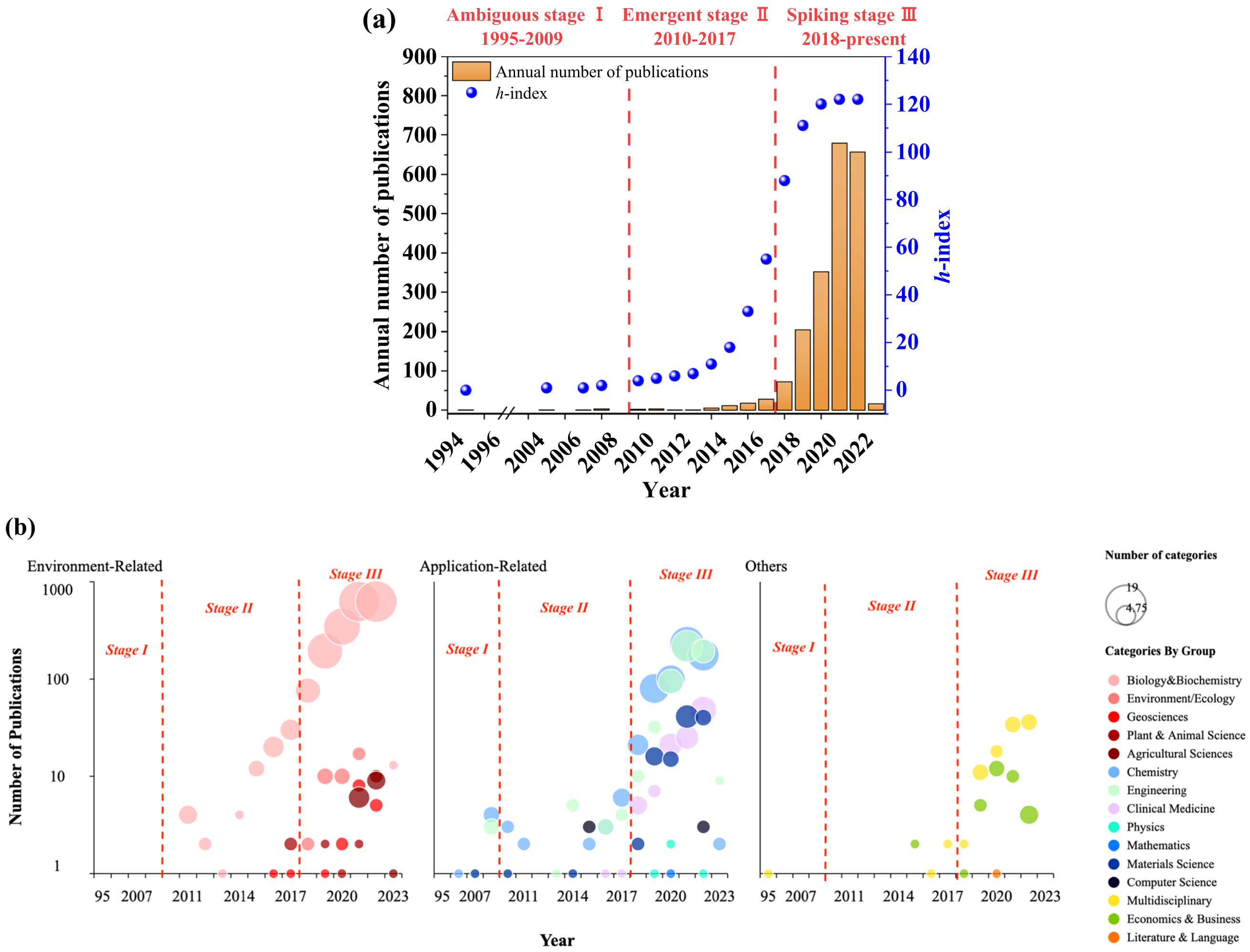


Fig. 1 **a** Annual number of publications and *h*-index for NPs research from 1995 to 2023. **b** WoS categories of publications on NPs research. *Note*: Data was collected on 3 November 2022

category groups, materials science category groups, and chemistry category groups), environment-related topics (such as biology & biochemistry category groups, environment/ecology category groups, and plant & animal science category groups), and others (such as multidisciplinary category groups and economics & business category groups) (Fig. 1b, Table S1).

Data refinement and analysis were performed on Microsoft Excel 2021 (Microsoft Corporation, USA, version 2021). Origin (Origin Lab, version 2021) was used to draw Fig. 1a. Scimago Graphica (Scimago Lab, Spain, version 1.0.24) was used to draw Figs. 1b, 2a and b.

Results

The Origin and Development of NPs Research

Publication Output Overview

A total of 2055 publications on nanoplastics (NPs) were retrieved from the Web of Science Core Collection (WoSCC) database, including 1615 research articles, 365 reviews, 44 early access articles, 43 editorial materials, and 27 conference reports. All collected papers were cited 65,877 times, and the average number of citations per publication was 32. The annual numbers of publications from 1995 to 2023 are shown in Fig. 1a. The *h*-index, which has been widely used to further evaluate a researcher/journal/research topic's scientific productivity and academic impacts, was 122, indicating that 122 articles published on the topic of NPs have each been cited at least 122 times within the WoSCC systems. The change in the *h*-index of cumulative published literature over time is shown in Fig. 1a. With the items classified by categories, environmental sciences (1417 articles, belonging to the environment-related biology & biochemistry categories group), engineering environmental (417 articles, belonging to the application-related engineering categories group), and toxicology (209 articles, belonging to the environment-related biology & biochemistry categories group) were the most significant three categories out of 97 categories of the retrieved publication records. Three stages of research progress were identified following the annual distribution of publications: an ambiguous stage I prior to, and including, 2009, an emergent stage II from 2010 to 2017, and a spiking stage from 2018 and onwards.

Ambiguous Stage I (1995–2009): "Nanoplastic" has not Yet Nanosized Plastic

There were only 6 papers collected from the database WoSCC with sporadic publications in 2009 and before (Fig. 1a). Most of these papers can be categorized into application-related groups, such as groups of engineering categories and materials science categories (Fig. 1b). The term "nanoplastics" first appeared in 1995 according to the search on WoSCC, but was not used to refer to nanosized plastics in this stage. McGuinness (1995) used the term "nanoplastics" instead to refer to plastic products based on nanotechnology as "intelligent" materials that were imaged to create interactive gadgets for homes in the future. In addition, NPs was also used to describe polymer/layered silicate nanocomposites, which were formed by dispersing nanosized inorganic fillers in the organic polymer matrix(Huang et al. 2005; Zhang et al. 2008).

On the other hand, nanosized plastic particles were already designed, manufactured, and sold before 2010 (Borisov et al. 2008), but these did not generate significant attention in terms of potential environmental and health risks. Environmental scientists and toxicologists however made important scientific progress in evaluating environmental processes and biological effects of manufactured nanomaterials such as nano-titanium dioxide (nTiO_2), nano-silver, and carbon quantum dots (Gigault et al. 2021). Polystyrene (PS) nanoparticles appeared sporadically as a type of "control/model" nanoparticle in publications studying the threat of emerging manufactured nanomaterials to environmental health and safety, without explicitly using the term "nanoplastics" (Xia et al. 2004, 2006; Nel et al. 2006; Palko et al. 2010; Johnston et al. 2010; Frohlich et al. 2010; Ward and Kach 2009). For instance, Xia et al. (2004) compared the effects of diesel exhaust particles with nanosized PS particles on the phagocytic cell, showing that organic pollutants isolated from diesel exhaust particles affected the structure and function of mitochondria, whereas PS nanoparticles could not. Additionally, fluorescent-labeled PS nanoparticles were used to study nanoparticles' uptake and biodistribution in human cells and animal bodies (Johnston et al. 2010; Palko et al. 2010).

Emergent Stage II (2010–2017): Emergent and Ascent Concern on NPs

The annual number of publications increased gradually during this stage, though this remained relatively low (<50). The *h*-index rose rapidly from 4 in 2015 to 55 in 2017 (Fig. 1a). Environment-related category groups, such as biology & biochemistry, were emergent in stage II with an upward trend (Fig. 1b). Research on the potential threat of nanoscale plastic particles/debris to environmental and human health began to appear in this stage, demonstrated by the number of collected publications. The application-related category groups also become more diverse than those of stage I; for example, computer science and clinical medicine were emerging category groups in this period (Fig. 1b).

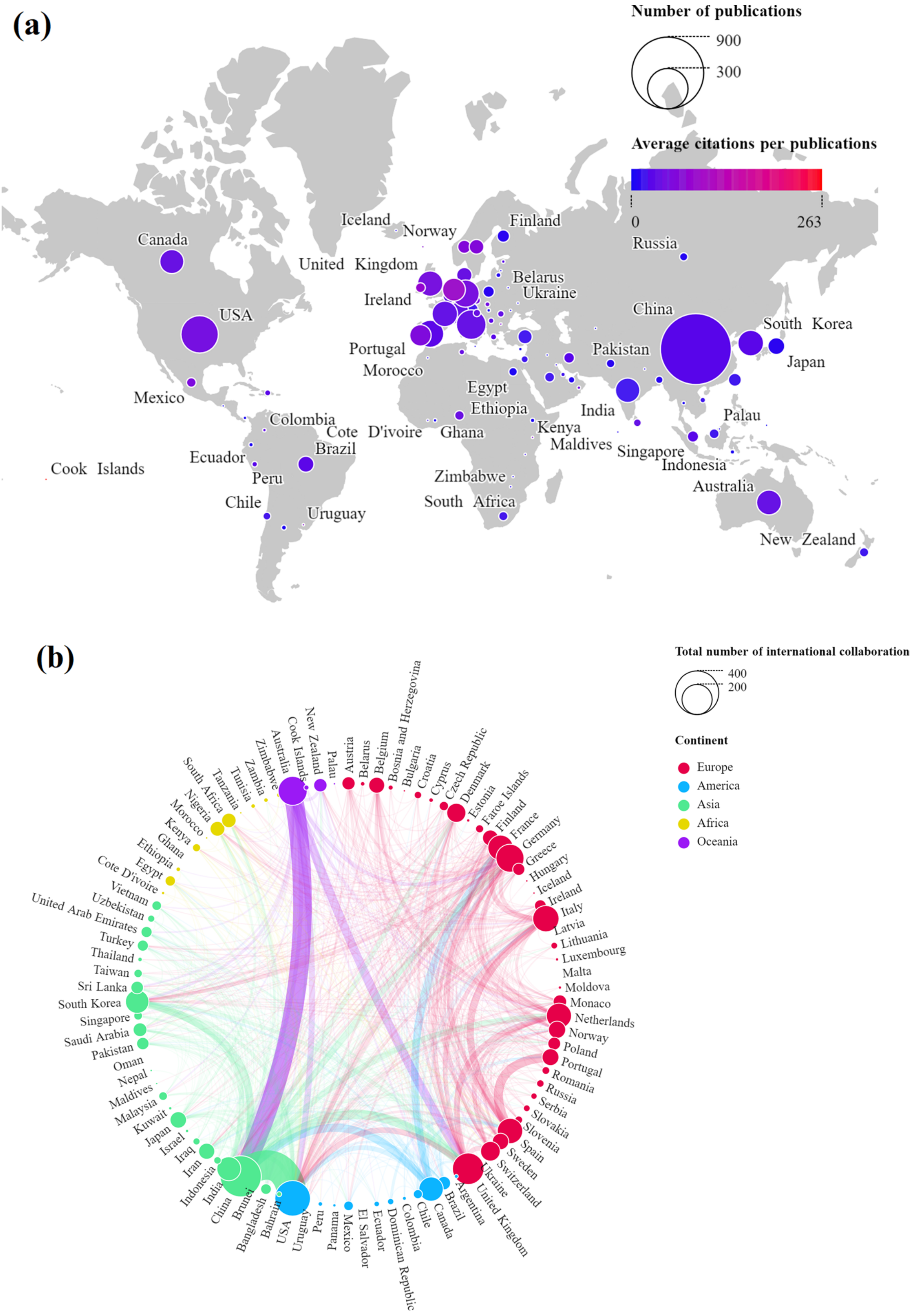


Fig. 2 **a** Global geographic distributions of publications on NPs. **b** Cooperation between each country/region. Note: If scholars from two different countries/regions publish papers once as coauthors, the number of international cooperation is 1 for both countries/regions. The line between the two nodes is roughly thick, which means more times of international cooperation. **c** Co-authorship network of prolific authors (publication counts ≥ 5). The size of the circle represents the number of papers by the author

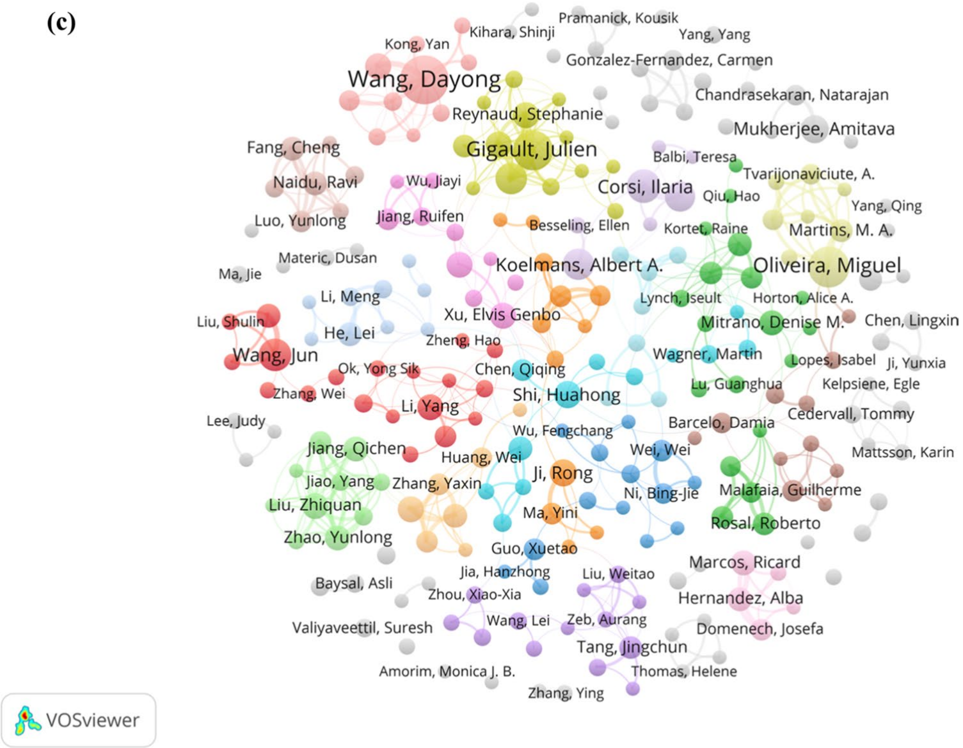


Fig. 2 (continued)

Nano-scaled plastics gradually shaped the mainstream understanding of the definition of "nanoplastics" in the scientific community. In 2010, Bhattacharya et al. (2010a) was one of the first studies using NPs to refer to plastic particles/debris in nanometers, comparing the binding capacities of NPs onto cellulose. Bhattacharya et al. (2010b) found that the negatively charged plastic nanoparticles adsorbed onto the surface of microalgae could affect photosynthesis. Andrady (2011) further discussed the potential threat of NPs in the marine environment due to possible endocytosis of NPs by micro- or nanofauna. This paper placed NPs into the nomenclature framework of plastics (including mesoplastics, MPs and NPs), arguing that nanosized plastics have the potential to be formed directly in the environment from the further degradation of MPs, which received extensive attention and citations (Table 1).

Spiking Stage III (2018-Present):A Spike of NPs Research

A rapid increase in annual publications following the increasing scientific concerns about NPs has been observed since 2018 (Fig. 1a). More than 96% of the collected papers were published in this stage, including a large number of highly cited papers. Environment-related category groups have become the most prevalent topics on which papers were published since NPs were viewed as emerging environmental contaminants. The annual number of publications, and the number of categories and category groups involved in other topics increased over the same period, such as multidisciplinary and economics & business. (Fig. 1b).

The *h*-index rose from 88 in 2018 to 120 in 2020, yet remained at 122 for the following two years with a large number of annual publications (Fig. 1a). The decelerated upward trend in the *h*-index is likely due to the dramatic increase in new publications, expanding the pool of citable references, in addition to the fact that newly published papers might have less time to accumulate citations than earlier ones (Chu and Evans 2021). Overall, NPs research has become a multidisciplinary topic integrating nanomaterials, plastic, environment, and society (Fig. 1b).

Key Scientific Publications and Journals

Citations of scientific papers can represent their influence on the scientific network and community. Highly cited papers usually play a pivotal role in the research development of related topics. The top 15 most highly cited papers are shown in Table 1, including 10 review and opinion papers and 5 research articles.

Among the 5 highly cited research papers, Bhattacharya et al. (2010b) is the earliest paper. Koelmans and colleagues from the Netherlands made a series of pioneering studies on the ecotoxicology and environmental behaviors of NPs

Table 1 The top 15 highly cited papers discussing nanoplastics

Paper type	Title	Author	Journal	Year	Total citation	Country	Institution of corresponding author
Review and opinion	Microplastics in the marine environment	Andrady, Anthony L	Marine Pollution Bulletin	2011	3155	the United States	North Carolina State University
Review and opinion	Microplastics in freshwater and terrestrial environments: Evaluating the current understanding to identify the knowledge gaps and future research priorities	Horton, Alice A.; Walton, Alexander; Spurgeon, David J.; Lahive, Elma; Svendsen, Claus	Science of the Total Environment	2017	1163	England Netherlands	Maclean Building University of Leiden University of Exeter
Review and opinion	Microplastics and nanoplastics in aquatic environments: aggregation, deposition, and enhanced contaminant transport	Alimi, Olubukola S.; Budarz, Jeffrey Farner; Hernandez, Laura M.; Tufenkji, Nathalie	Environmental Science & Technology	2018	858	Canada	McGill University
Review and opinion	Microplastics as an emerging threat to terrestrial ecosystems	Machado, Anderson Abel de Souza; Kloas, Werner; Zarfl, Christiane; Hempel, Stefan; Rillig, Matthias C	Global Change Biology	2018	673	Germany	Freie University Berlin
Research article	Nanoplastic Affects Growth of *S. obliquus* and Reproduction of *D. magna*	Besseling, Ellen; Wang, Bo; Lurling, Miquel; Koelmans, Albert A	Environmental Science & Technology	2014	587	Netherlands	Wageningen University
Research article	Microplastic particles cause intestinal damage and other adverse effects in zebrafish *Danio rerio* and nematode *Caenorhabditis elegans*	Lei, Lili; Wu, Siyu; Lu, Shibo; Liu, Mengting; Song, Yang; Fu, Zhenhuan; Shi, Huahong; Raley-Susman, Kathleen M.; He, Defu	Science of the Total Environment	2018	550	China the United States	East China Normal University
Review and opinion	Marine microplastic debris: An emerging issue for food security, food safety and human health	Antao Barboza, Luis Gabriel; Dick Vethaak, A.; Lavorante, Beatriz R. B. O.; Lundebye, Anne-Katrine; Guilhermino, Lucia	Marine Pollution Bulletin	2018	515	Portugal Brazil Netherlands Norway	University of Porto
Research article	Strong sorption of PCBs to nanoplastics, microplastics, carbon nanotubes, and fullerenes	Velzeboer, I.; Kwadijk, C. J. A. F.; Koelmans, A. A	Environmental Science & Technology	2014	493	Netherlands	Wageningen University
Review and opinion	Current opinion: What is a nanoplastic?	Gigault, J; ter Halle, A; Baudrimont, M; Pascal, PY; Gauffre, F; Phi, TL; El Hadri, H; Grassl, B; Reynaud, S	Environmental pollution	2018	489	France	French National Centre for Scientific Research

Table 1 (continued)

Paper type	Title	Author	Journal	Year	Total citation	Country	Institution of corresponding author
Review and opinion	Potential health impact of environmentally released micro- and nanoplastics in the human food production chain: experiences from nanotoxicology	Bouwmeester, Hans; Hollman, Peter C. H.; Peters, Ruud J. B	Environmental Science & Technology	2015	487	Netherlands	Wageningen University
Review and opinion	An overview of microplastic and nanoplastic pollution in agroecosystems	Ng, Ee-Ling; Lwanga, Esperanza Huerta; Eldridge, Simon M.; Johnston, Priscilla; Hu, Hang-Wei; Geissen, Violette; Chen, Deli	Science of the Total Environment	2018	486	Australia Netherlands Mexico	The University of Melbourne
Review and opinion	(Nano)plastics in the environment—Sources, fates and effects	da Costa, Joao Pinto; Santos, Patricia S. M.; Duarte, Armando C.; Rocha-Santos, Teresa	Science of the Total Environment	2016	457	Portugal	University of Aveiro
Research article	Characterization of nanoplastics during the degradation of polystyrene	Lambert, Scott; Wagner, Martin	Chemosphere	2016	449	Germany	Goethe University Frankfurt am Main
Review and opinion	Environmental exposure to microplastics: An overview on possible human health effects	Prata, Joana Correia; da Costa, Joao P.; Lopes, Isabel; Duarte, Armando C.; Rocha-Santos, Teresa	Science of the Total Environment	2020	429	Portugal	University of Aveiro
Research article	Physical adsorption of charged plastic nanoparticles affects algal photosynthesis	Bhattacharya, Priyanka; Lin, Sijie; Turner, James P.; Ke, Pu Chun	Journal of Physical Chemistry C	2010	425	the United States	Clemson University

“Review and opinion” refer to all types of non-research articles. Total citation indicates the number of times this document was cited by all documents in the Web of Science Core Collection

(Koelmans et al. 2015), including the most cited research article with 587 citations (Besseling et al. 2014), which illustrated the teratogenic effects of NPs on zooplankton and has raised widespread concerns. Another paper published in the same year confirmed the strong sorption of polychlorinated biphenyls (PCBs) to NPs (Velzeboer et al. 2014).

As the most cited non-research paper with 3155 citations, Andrady (2011) mainly focused on MPs topics, but also proposed and discussed three important questions on NPs pollution in the oceans as early as 2011: (1) It is unclear whether NPs aggregate and primary NPs have the same physiological impact on organisms; (2) research on the effects of NPs on marine flora and fauna is insufficient; (3) the physiological impacts of endocytosed NPs carrying persistent organic pollutants in planktonic organisms have not been studied. Nevertheless, the terminology "nanoplastic" has been widely accepted in the context of plastic pollution since Andrady (2011) with its influence on the dissemination and development of NPs research.

In most highly cited reviews, NPs and MPs are often discussed together as fragments of plastic waste due to their similar composition and sources (Horton et al. 2017; Alimi et al. 2018; de Souza Machado et al. 2018; Bouwmeester et al. 2015; Dong et al. 2018; Andrady 2011; Barboza et al. 2018). There were only two highly cited reviews focused only on NPs (Table 1). da Costa et al. (2016) reviewed the sources, fates, and effects on the environment and human health of NPs. Gigault et al. (2018) summarized the physical and chemical properties of NPs, and proposed a detailed definition of NPs to be within the size range of 1 to 1000 nm.

The collected publications on NPs were published in 390 journals or sources in total. The top 10 productive journals publishing NP papers are shown in Table 2. *Science of the Total Environment* was the journal with the highest number of publications on NPs (256 publications), accounting for 12.5% of all collected publications, followed by *Journal of Hazardous Materials* (179 publications, 8.7%) and *Environmental Pollution* (164 publications, 8.0%). *Marine Pollution Bulletin* ranked first in average citations per publication (99 citations per publication), with the most cited paper (3155 citations) published in 2011, followed by *Environmental Science & Technology* (94 citations per publication). In addition, *Environmental Science Nano*, *Chemosphere*, and *Water Research* also contribute significantly to publication of NPs research.

Global Distribution and Collaboration in NPs Research

NPs is a global issue that affects everyone, regardless of whether they are directly involved in NPs research or not. NPs are ubiquitous in the environment, and they can enter food chains, water systems, and the air we breathe. Thus, the impacts of NPs can be felt in different regions of the world, and by different communities and ecosystems. Revealing the global distribution and collaboration in NPs research, firstly, can identify areas where research efforts are concentrated, and highlight regions where more research is needed. This can help to ensure that research funding and resources are allocated effectively, and that knowledge gaps are addressed. Secondly, collaboration between researchers from different regions and disciplines can lead to a more comprehensive understanding of the environmental impacts of NPs, and foster the development of innovative solutions. Thirdly, global distribution and collaboration in NPs research can help to identify common challenges and facilitate the sharing of best practices and strategies for addressing these challenges. Finally, by promoting transparency and collaboration in NPs research, we can build public trust and support for scientific inquiry and innovation.

Table 2 The top 10 productive journals publishing NP papers

Journal	Publication numbers	Percent of the total publications %	Citations	Average citations per publication	Impact factor$_{2021}$
Science of the Total Environment	256	12.5	10,268	40	10.753
Journal of Hazardous Materials	179	8.7	3654	20	14.224
Environmental Pollution	164	8.0	7699	47	9.988
Chemosphere	134	6.4	2959	23	8.943
Environmental Science & Technology	76	3.7	7181	94	11.357
Environmental Science-Nano	69	3.3	1878	27	9.473
Water Research	62	3.0	1589	26	13.400
Marine Pollution Bulletin	52	2.5	5127	99	7.001
Environmental Science and Pollution Research	41	2.0	776	19	5.190
Ecotoxicology and Environmental Safety	36	1.8	896	25	7.129

Data of the Impact factor$_{2021}$ from the website of Journal Citation Reports

Publication Distribution of Countries/Regions

The global geographical distribution and scientific cooperation of countries in NPs research are shown in Fig. 2a and b. Figure 2a shows that a total of 94 countries or regions contributed to the study of NPs over the assessed period. The size of the node in Fig. 2a represents the number of publications, and the color of the node represents the number of average citations per publication. China published the highest number of articles (822), followed by the United States (229). Europe published relatively high numbers of highly cited publications. For example, the Netherlands, Portugal, Germany, and the United Kingdom (U.K.) have a considerable number of publications (86, 75, 122, and 105 publications, respectively), with a high average number of citations per publication (93, 55, 48, and 48 citations per publication, respectively), which are higher than the average number of citations per publication as mentioned in 3.1.1 (Fig. 2a). China has extensive cooperation with 52 countries in NPs research, ranking the first, followed by the USA (United States of America) with 50 countries and Italy (45 countries) (Fig. 2b). The intensive connections among Netherlands, Portugal, German, and England etc. as shown in Fig. 2b imply that the academic exchanges and cooperation are extensive among European countries.

Regions with high publication numbers, such as China, the United States, and Europe, are also great contributors to the production of plastic waste. In 2016, Law et al. (2020) indicated that the United States contributes the majority of global plastic wastes (42.0 Mt), followed by the European Union countries (EU-28) (29.9 Mt), India (26.3 Mt), and China (21.6 Mt). The higher research publication numbers of these countries or regions may be at least partly related to the level of public awareness of plastic pollution. It is noteworthy that the calculation method of plastic waste production is based on an estimated percentage of plastic in municipal solid waste. The lack of detailed information on plastic waste production in many countries may introduce bias. However, this should be considered when a comparison is made with research productivity on NPs topics among different countries or regions.

Network Analysis of Collaborations Among Authors

An academic network map could help researchers identify the researchers and research institutions of influence, and therefore potential collaborators in NPs research. A total of 8086 researchers from over 1900 institutions have participated in studies of NPs. However, about 3.2% of the authors have published five or more papers on the topic of NPs. A co-authorship analysis for prolific authors (publication counts ≥ 5) in NPs research was conducted and the results are shown in Fig. 2c. Among all authors, Dayong Wang (publication counts = 42, Southeast University, China), Miguel Oliveira (31, University of Aveiro, Portugal), Julien Gigault (29, French National Centre for Scientific Research, France), Ilaria Corsi (22, University of Siena, Italy) published the highest number of papers.

Co-authorship analysis showed distinct collaborations between Dayong Wang and his colleagues at Southeast University (China). They have made great contributions to analyzing the toxic effects of NPs on the nervous system's development and function based on the model nematode *Caenorhabditis elegans* (Dong et al. 2018; Qu et al. 2019; Li et al. 2020a). Miguel Oliveira (University of Aveiro, Portugal) and M. A. Martins et al. (University of Aveiro, Portugal) formed a collaboration network to study the threats of NPs to various types of marine biota, such as mussels and fish (Brandts et al. 2018; Venancio et al. 2019). Julien Gigault at French National Centre for Scientific Research and his co-authors published many papers reporting evidence on the existence of NPs in the environment, making important contributions to the field of NPs environmental monitoring (Ter Halle et al. 2017; Davranche et al. 2020; Wahl et al. 2021). Ilaria Corsi and Elisa Bergami at the University of Siena (Italy) started studying the toxicity of NPs in marine biota relatively early. These researchers looked at the accumulation and embryotoxicity of NPs in the early development of sea urchin embryos in 2014 (Della Torre et al. 2014), and they worked closely with Albert A Koelmans at Wageningen University (Netherlands), whose team has also made a series of pioneering studies on NPs.

Research Hotspots and Major Themes of NPs

Keywords are used to summarize the focus of papers and illustrate the specific objectives of research. Therefore, co-occurrence and cluster analysis for keywords can disclose research hotspots and knowledge structure/development in a research field. Using VOSviewer, a total of 6398 keywords from 2055 NPs publications were extracted, counted, and summarized. The co-occurrence and clusters of the 50 most high-frequency keywords are shown in Fig. 3. The size of the nodes represents the frequency of keywords and the width of the line represents the co-occurrence frequency of keywords. Microplastics is the most essential keyword, with the highest occurrence of 1159 times. This is followed by nanoplastics with an occurrence of 1029 and toxicity with 471. Six pairs of co-occurrent keywords with the highest occurrence are microplastics and nanoplastics (co-occurrences = 686), microplastics and toxicity (310), nanoplastics and toxicity (277), microplastics and nanoparticles (233), microplastics and particles (229), and nanoplastics and particles (212). The environmental and health risks of plastic

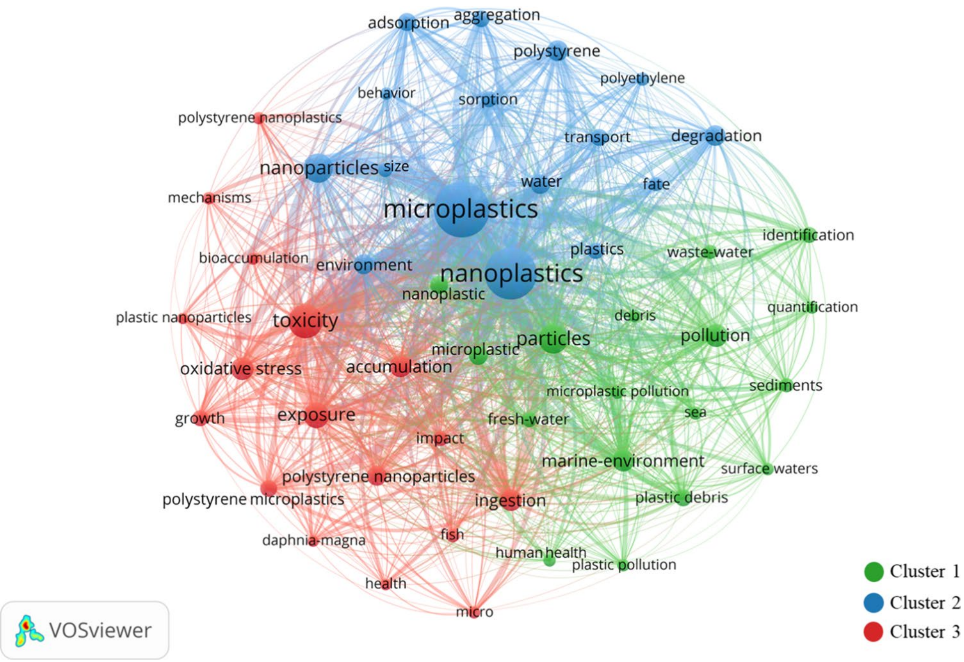


Fig. 3 Co-occurrence network of the top 50 frequent keywords. The size of the circle represents the frequency of keywords. The width of the line represents the co-occurrence frequency of keywords

particles (e.g., toxicity and exposure), including both MPs and NPs, have emerged in the area of NPs research in the last decades (Chae and An 2017; Alimi et al. 2018; Dong et al. 2018).

The top 50 keywords are divided into three clusters expressed with different colors in Fig. 3, reflecting three research hotspots of NPs. Keywords in cluster 1 (in green color) are related to contaminants such as particles (365), plastic debris (137), and debris (73); pollution survey such as identification (116) and quantification (74); environmental media such as marine-environment (212), fresh-water (114), sediments (96), waste-water (94), sea (89), surface waters (72). These studies focused on environmental monitoring, including investigations regarding the type and level of NPs found in the environment, and the development of analytical methods. Cluster 2 (in blue color) focused on the various environmental behaviors of NPs, including the migration and transformation of contaminants, such as degradation (194), adsorption (151), aggregation (130), transport (128), sorption (116), fate (96), and behavior (70) of NPs. These studies examined the migration, transformation, and mobility processes of NPs, and the various factors influencing these processes. Based on Fig. 3, keywords showing the highest frequency in cluster 3 (in red color) are toxicity (471), exposure (280), oxidative stress (223), accumulation (211), ingestion (211), growth (123), impact (103), and so on, reflecting a focus on the toxicology and potential threats of NPs to ecosystems and human health. These three clustered themes are further discussed in the following sections.

Discussion

Sources and Challenges of Measuring Nanoplastics in the Environment

Sources and Field Investigation

Since the 1960s, plastic wastes could be traced in almost every ecosystem on earth, even in remote mountains and the deep seas, but there are very few reports about nanoplastics (NPs) in the environment (Thompson et al. 2009; Allen et al. 2019; Pohl et al. 2020; Bergmann et al. 2017; Carpenter et al. 1972; Carpenter and Smith 1972). Questions of where NPs come from and how many NPs are actually in the environment remain largely unknown.

Primary sources of NPs originate from manufactured nanometer-sized plastics and plastic nanoparticles, e.g., incidental nanometer-sized plastics from cosmetics and industrial powders. Secondary sources arise from plastic degradation processes, i.e., hydrolysis, photo-oxidation, thermo-oxidation, and biodegradation. It has been reported that NPs are observed ubiquitously in drinking water, food, and pharmaceutical & personal care products (Dang et al. 2022). Hernandez et al. (2017) investigated commercial facial scrubbing creams and found the presence of NPs with particle sizes ranging from 24 ± 6 to 52 ± 14 nm. In 2019, they further found that we might unwittingly ingest about 11.6 billion microplastics (MPs) and 3.1 billion NPs particles co-leached from a plastic tea bag while drinking tea (Hernandez et al. 2019). “These levels were thousands of times higher than those reported previously in other foods,” stated by the American Chemical Society (Press-Pacs 2019).

While the amounts of primary NPs wastes could potentially be estimated through information on industrial production, major uncertainties arise around secondary NPs, as degradation processes vary between different environmental conditions. Secondary NPs could however be produced and accumulated at unprecedented rates (Bond et al. 2018; Jahnke et al. 2017). Lambert and Wagner (2016) observed that a single-use plastic coffee cup lid could release from 0.32×10^8 particles/mL to 1.26×10^8 particles/mL of NPs, after being exposed at 30 °C, 24 h light, for 56 days. Song et al. (2020) also found that an expanded polystyrene (PS) box could produce approximately 6.7×10^7 particles/cm^2 of MPs and NPs in a month via photodegradation.

NPs were first reported in aquatic environments in 2016. Gigault et al. (2016) showed that MPs from the North Atlantic accumulation zone could produce NPs under solar light exposure in the laboratory. The following year, Ter Halle et al. (2017) detected the presence of NPs from different origins, including polyethylene (PE), polystyrene (PS), polyvinyl chloride (PVC), and polyethylene terephthalate (PET) in natural samples collected from the North Atlantic Subtropical Gyre. Davranche et al. (2020) also reported that PS- and PVC-NPs with size ranging from 200 to 1000 nm were present in sand water extracts from Sainte Marie Beach (Guadeloupe, France). As for terrestrial ecosystems, Materic et al. (2020) first found PET-NPs in snowpit and surface snow samples at the Austrian Alps. Wahl et al. (2021) reported the presence of nanoscale PE, PS, and PVC plastics in plastic-contaminated soils collected from central France, with sizes ranging from 20 to 150 nm. Concentrations of NPs, 563 µg/L and 51 µg/L, in forests landscape in southern Sweden and surface water in Siberia, respectively, were first quantified and reported by Materić et al. (2022b). They also found PE-NPs in polar ice cores sampled from Greenland and Antarctica, at concentrations of 13.2 ng/mL and 52.3 ng/mL, respectively (Materić et al. 2022a). The presence of NPs in these remote areas, distant from major waterways, may result from atmospheric deposition.

Beyond all doubt, there is an imperative need for probing NPs in drinking water, food, and all environments according to their potential sources; and further, to examine the health risks caused by exposure to NPs from different origins (Busse et al. 2020; Hernandez et al. 2020).

The Challenge and Progress of Measurements

Analyzing NPs in environmental matrices is challenging (Mintenig et al. 2018; Li et al. 2020c). Small size and low-mass NPs are difficult to separate from complex environmental samples and only provide limited signals for qualitative and quantitative analysis (Nguyen et al. 2019). Additionally, high environmental (and laboratory) background values can also be an issue for those low-concentration field samples (e.g., open ocean, sea ice). For example, airborne fibers can impact the experimental monitoring data of MPs during sampling processes (Zhu and Wang 2020), and such impacts are likely to be common for NPs sampling and analysis.

Li et al. (2020c), Wang et al. (2021), and Cai et al. (2021) have systematically reviewed the research progress of environmental monitoring of NPs in terms of methodology development. In general, the methods of environmental monitoring of NPs include the following major steps: pre-treatment, concentration or separation, and qualitative or quantitative analysis.

The pre-treatment step is critical for NPs analysis to remove the organic/inorganic fractions in the samples without changing the characteristics of NPs. Correia and Loeschner (2018) compared the effects of two preparation approaches, acid digestion and enzymatic digestion with proteinase K, to digest fish samples. Results showed that enzymatic hydrolysis performed better for subsequent NPs analysis because acid digestion may result in larger PS-NPs aggregates (> 1 µm). Similarly, Jiang et al. (2019) found that proteinase K was not only more efficient in sample digestion than H_2O_2 or KOH, but also had a higher recovery rate.

Further concentration and separations are needed when the numbers of NPs in the sample are too small to be detected, or where NPs are still mixed with other impurities after pretreatment. Many technologies such as multi-stage membrane filtration, ultrafiltration, cloud-point extraction (CPE), and field-flow fractionation (FFF) have been applied in sample treatments for NPs. For example, a grade 5 filtration with decreasing pore sizes of Whatman filters and Millipore Millex Sterile Syringe filters could remove all > 100 nm particles in a facial scrub suspension (Hernandez et al. 2017, 2019). Ultrafiltration could further separate, concentrate, and purify colloidal components of a large number of samples reproducibly (Li et al. 2020c; Mintenig et al. 2018; Ter Halle et al. 2017). Cloud-point extraction (CPE) is another unique method to concentrate trace NPs in environmental water samples. Zhou et al. (2019) proposed a triton X-45 based CPE method for concentrating NPs in environmental waters. Under optimum extraction conditions, an enrichment factor of 500 was obtained for PS-NPs and polymethyl methacrylate (PMMA) NPs, without changing their original morphology and sizes. Field flow fractionation (FFF) was considered one of the most promising methods to obtain relatively pure NPs after concentration, typically applied to engineered nanoparticles. A simple programmed asymmetrical flow field flow fractionation (AF4) method could filter out NPs with sizes ranging from 1 to 800 nm (Gigault et al. 2017). Monikh et al. (2019) also successfully extract NPs spiked within eggshells via an AF4 system with a recovery of over 60%.

The qualitative analysis of NPs includes physical morphology characterization and chemical composition identification. Laser light scattering is a common method used to measure the size of NPs by irradiating the particles with a laser and analyzing the scattered light spectrum, such as multi-angle light scattering (MALS), dynamic light scattering (DLS), and nanoparticle tracking analysis (NTA) (Li et al. 2020c). Applying these light scattering analytical techniques to environmental samples however suffers from their high limits of detection (LOD) for NPs, e.g., 4 mg/L for PS-NP suspension (Mintenig et al. 2018). However, with advancements in lowering LOD using electron microscopy and diffraction-unlimited light microscopy, the surface morphology of NPs can be better observed (Wang et al. 2021; Gigault et al. 2021).

Spectroscopy and mass spectrometry (MS) approaches are two major analytical processes used to identify the chemical composition of NPs. Raman tweezers (RTs) can capture, identify, and characterize NPs from other sediment particles at the single-particle level from 20 μm to 50 nm (Gillibert et al. 2019). Surface-enhanced Raman spectroscopy (SERS) can further solve the problem of the low Raman signal of NPs. Lv et al. (2020) suggested that Raman signals of NPs in pure water and seawater can be enhanced significantly when a silver colloid was used, which allowed detection of 100 nm NPs at a concentration as low as 40 μg/mL. Analytical methods based on mass spectrometry (MS) provide another promising avenue for the chemical composition analysis of NPs in complex matrices (Velimirovic et al. 2020). For example, pyrolysis gas chromatography-mass spectrometry (Pyr-GC/MS) has excellent reproducibility and sensitivity to detect NPs, such as PS-NPs and PMMA-NPs (Zhou et al. 2019).

Precisely quantifying NPs at environmentally relevant concentrations is essential for risk assessment. A few semi-quantitative or combined quantitative methods under specific environmental conditions have been proposed. For example, Materic et al. (2020) presented a new method for semi-quantification of MPs and NPs based on thermal desorption-proton transfer reaction-mass spectrometry. The concentration of PET-NPs was up to 27 ng/mL in high-altitude surface snow and snowpit samples. Jimenez-Lamana et al. (2020) coupled NPs with functionalized metal (Au)-containing nanoparticles to determine NPs concentrations via inductively coupled plasma mass spectrometry.

Without doubt, advances on the specific analytical methods, techniques, and applications for the extraction, separation, and analysis of NPs in environmental matrices are the key to improve environmental NPs monitoring and risk assessment.

The Role of Nano-Fragmentation in Closing the Plastics Cycle: Environmental Behaviors and Fates of Nanoplastic Particles

Along the movements of plastics from source to sink, a substantial loss is found when the estimated global load of plastics is transported into the open ocean, the so-called "missing ocean plastic sink"(Jimenez-Lamana et al. 2020; Law et al. 2010; Thompson et al. 2004). Cozar et al. (2014) proposed that nano-fragmentation may be one of the missing size-selective sinks, removing millimeter-size floating plastic fragments on a large scale. Distinct from other types of plastic wastes, NPs possess unique properties due to their high surface area and nanoscale size, behaving similar to natural colloids with strong mobility and reactivity (Li et al. 2020c; Brewer et al. 2021). Environmental behaviors of NPs, such as sorption, aggregation, aging, degradation, migration, deposition, and, ultimately, their fates, are largely determined by these physicochemical characteristics.

Significant research progress has been made in understanding the behavior and fate of NPs, including to bridge the gap in the plastics cycle. An overview of reported environmental behaviors of NPs in water, soil, and the air is summarized in Fig. 4, and can be categorized as follows: (1) Sorption and aggregation; (2) Aging and degradation; (3) Migration and deposition.

Sorption and Aggregation

The surface-volume ratio and surface characteristics are two main physical–chemical properties of NPs, providing binding sites to interact with organic and metallic pollutants. For example, Davranche et al. (2019) showed the binding constants of NPs to Pb(II) were close to other strong adsorbents of metals such as ferrihydrite, nano-goethite, and humic acid. The surface characteristics of NPs, such as hydrophobicity, charge, polarity, and functional groups, determine the sorption capacity of NPs. For example, Zhang et al. (2020a) illustrated that the sorption capacities of two fluoroquinolones (norfloxacin and levofloxacin) on carboxyl-modified PS-NPs were higher than those on pristine PS-NPs through polar, electrostatic, and hydrogen bindings. With higher aromaticity and surface-volume ratio of NPs, polychlorinated biphenyls (PCBs) showed stronger sorption to PS-NPs than to PE-MPs (Velzeboer et al. 2014). Furthermore, organic matter on the surface of NPs can form a "protein corona," altering the environmental behavior and thereby the biological effects of NPs. The negatively charged bovine serum albumin adsorbed on the surface of NPs promoted the dispersion of NPs due to the induced colloidal steric hindrance (Dong et al. 2020).

The aggregation of NPs in aquatic environments is strongly influenced by their surface characteristics. Like

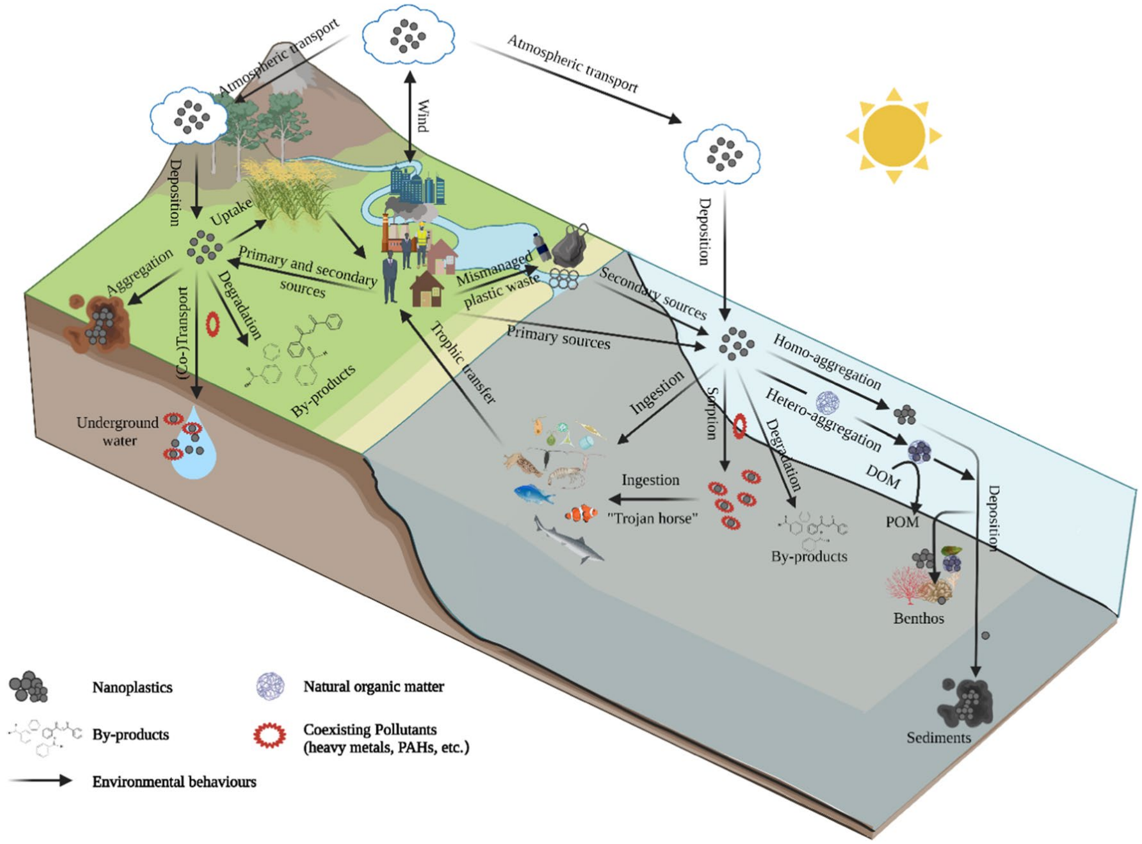


Fig. 4 Environmental behaviors and fate of NPs. *Note*: Created with Biorender.com

natural colloids, the aggregation processes of NPs can be identified as homo-aggregation and hetero-aggregation (Cai et al. 2018; Dong et al. 2021), following the Derjaguin-Landau-Verwey-Overbeek force (DLVO) theory (Li et al. 2020c). A few recent studies have shown that the critical coagulation concentration (CCC) of PS-NPs and PET-NPs was significantly higher than the ionic strengths in environmental waters, such as lakes, rivers, and estuaries (Mao et al. 2020; Dong et al. 2021), suggesting that homo-aggregation rates of NPs are relatively low in freshwater environments. Hence, factors such as pH, electrolyte concentration, and salinity, may affect the aggregation of NPs. Dong et al. (2021) showed that the aggregation of PET-NPs increased with increasing electrolyte concentrations and decreasing pH. Wu et al. (2019) also observed that increasing salinity significantly accelerated the aggregation of NPs. Besides, there is also apparent heterogeneous aggregation between NPs and natural organic matter in aquatic environments, such as dissolved organic matter (DOM), particulate organic matter (POM), and extracellular polymeric substances (EPS). NPs may alter DOM-POM assembly in the marine carbon pool when forming agglomerates/agglomerates. Summers et al. (2018) revealed that NPs could induce agglomerates containing mucilaginous materials and microbes in natural seawater within 24 h. Additionally, de Oliveira et al. (2020) reported that marine and freshwater cyanobacteria formed aggregates with PS-NPs, bound together by EPS. Shiu et al. (2020b) found that 25 nm PS-NPs in lake and river water can promote POM formation and accelerate the DOM-POM transition. They also suggested that NPs could interact with organic matter to form large organic particles, which may undergo further settling in response to specific salinity levels. Similarly, Chen et al. (2018) reported that 25 nm PS-NPs and PMMA-NPs present in a seawater column accelerated the kinetic assembly rate of DOM-POM transition. However, it is not well documented whether the aggregates/agglomerates are reversible. The long-term fate of NPs aggregates needs to be further studied.

Aging and Degradation

NPs in the aquatic environment will continue to age, decompose, or even become undetectable via weathering and biodegradation. Previous studies have found that NPs could age and degrade faster than larger plastic specimens due to larger surface areas exposed to environmental stresses, such as sunlight, oxidants, and physical stress (Gewert et al. 2015; Mattsson et al. 2018).

Photooxidation and biodegradation are two major routes of NPs aging and degradation in aqueous environments. Ultraviolet ray (UV)-induced hydroxyl radicals could degrade the sulfate groups of pristine PS-NPs and amino groups of amino-modified PS-NPs (Wang et al. 2020c); this could also degrade the surface corona and change the surface charge, and even the organic content in the solution (Liu et al. 2019b; Zhang et al. 2020e). Besides, exposure to natural sunlight or UV irradiation might lead to the formation of C-O groups and even organic compounds on the NPs surface with a release of significant amounts of small molecular weight by-products and CO_2 (Tian et al. 2019; Bianco et al. 2020). As for biodegradation by microbes, *Klebsiella pneumoniae* can break down NPs, and the C=O, C–O, and $–CH=CH_2$ groups on the surface of NPs are obviously affected (Saygin and Baysal 2020).

The aggregation of NPs could also be affected by this aging process. For example, UV irradiation could inhibit the aggregation of aged PS-NPs in NaCl solution; however, it promoted the aggregation of aged PS-NPs in $CaCl_2$ solutions due to the interactions between Ca^{2+} and carboxyl groups on the surface of aged PS-NPs (Liu et al. 2019b). On the contrary, Wang et al. (2020c) observed that UV irradiation promoted the aggregation of pristine PS-NPs and amino-modified PS-NPs in NaCl solutions. Based on functional group indices analysis, these authors showed that the most influenced functional groups were carbonyl, carbon–oxygen bond, and vinyl groups. When the ratio of oxygen to carbon increased, the hydroxyl groups and crystallinity were not significantly affected. Thus, the aging process can change the properties of NPs, such as functional groups, hydrophobicity (Wang et al. 2020c), and even impact the environmental behaviors of NPs, e.g., aggregation.

Migration and Deposition

The sedimentation of NPs in water is ruled by their colloidal nature, Brownian motion, and buoyancy (Gigault et al. 2021). Moreover, the colloidal instability caused by aggregation complicates the migration and deposition of NPs. Aggregation increases the effective settling rate and reduces the migration rate of NPs. Venel et al. (2021) used a microfluidic method to simulate the flow and diffusion of NPs in the mixing zone of fresh and salty water, i.e., in estuaries and mangrove swamps. They suggested that a significant fraction of NPs in the river rapidly aggregates to the micro-scale, floating near the water surface or settling into the sediment. Only a small portion of the NPs remained stable and were transported to the sea. Similarly, Besseling et al. (2017) used a numerical model to study the transportation of different sizes plastic particles from rivers to the sea. They found that most nanoscale particles were likely to be retained in rivers.

The migration and retention of NPs in marine environments were strongly predicated by NPs surface functionalities, size, and salinity (Dong et al. 2019, 2020). These altered the migration ability of NPs by affecting their aggregation. Compared to sulfonic and amino capped NPs, carboxylate functional groups inhibited the aggregation and enhanced the migration ability of NPs in seawater-saturated sea sand (Dong et al. 2019). As mentioned previously, NPs can interact with organic matter, and can possibly transport organic pollutants. The studies included above were mostly carried out in laboratory settings and conditions. More efforts are still needed to understand NPs distribution and migration in complicated field environments with advanced technologies and instrumentation methods.

In Soils

It is estimated that around 60% of all plastics ever produced, from 1950 to 2015, have been discarded in landfills or in the natural environment (Geyer et al. 2017). Moreover, applications of municipal biosolids containing MPs and NPs as soil amendments and other substances can cause NPs pollution of soil directly (Chai et al. 2022). The physicochemical properties of terrestrial media (soil and groundwater) are substantially different from aquatic environments. For example, van der Waals forces and gravitational effects affect the aggregation between colloidal soil particles and NPs. The surface characteristics of both the soil colloids and NPs, and the physical properties of the NPs, such as size, shape, and density, can also influence their aggregation processes. Zhang et al. (2020e) highlighted that the interaction of PS-NPs with minerals was mediated by surface charge. The stability of a PS-NPs colloidal suspension decreased with the presence of positively charged goethite or magnetite but was not affected by the negatively charged montmorillonite and kaolinite. Furthermore, Astner et al. (2020) showed that smaller-sized NPs (50 nm) remained dispersed in water without undergoing size reduction or self-agglomeration, nor forming agglomerates with vermiculite, while larger-sized NPs (300−1000 nm) formed self-agglomerates and agglomerates with vermiculite, leading to their significant adhesion to the soil.

The transport and fate of PS-NPs in natural soil are highly sensitive to soil properties such as ionic strength and cation type. NPs showed high mobility in soils with high pH and low Fe/Al oxides contents, posing potential risks to the soil and groundwater environment (Wu et al. 2020). Characteristics of NPs (e.g., size, shapes, surface charge, surface functional groups) could also affect their transportation through saturated soil or an organic matter (OM)-rich aquifer (Shaniv et al. 2021; Song et al. 2019). Shaniv et al. (2021) showed that the maximum elution rate of PS-NPs from soil was 90% and 45% for 50 nm and 110 nm nanoparticles, respectively. Pradel et al. (2020) further stated that irregular and asymmetrical particles are more likely to be trapped in porous media than spherical particles. Compared to particle size or concentration, the deposition rate seems to be largely determined by the particle shape.

Moreover, NPs can serve as a vector, adsorbing other pollutants, and cotransport those contaminants deeper into the soil. Liu et al. (2018) showed that 10 mg/L PS-NPs remarkably enhanced the transport of nonpolar and weakly polar compounds, including pyrene and 2,2’,4,4’-tetrabromodiphenyl ether. The co-transportation was related to the polarity of the organic pollutants and the surface properties of the NPs. Nonpolar compounds tend to adsorb in the inner matrices of the glassy polymeric structure of PS-NPs, resulting in slow desorption kinetics and strong co-transportation (Liu et al. 2019a). In particular, the aging processes of NPs can aggravate this trend due to modification of the polymeric structure (Liu et al. 2019a). Plus, NPs to pollutants concentration ratio and soil porewater ionic strength also play a role. For instance, Hu et al. (2020) found that PS-NPs dramatically enhanced the mobility of naphthalene at low ionic strength (0.5 mM), but this effect was inhibited at high ionic strength (5 mM and 50 mM).

In the Atmosphere

Restricted by the current technologies in separation and identification, the existence of NPs in the atmosphere has been difficult to determine quantitatively. Thus far, only limited studies have concentrated on atmospheric nanosized polymeric particles and possible health effects of airborne NPs (Zhang et al. 2020c; Gibson et al. 2021). We have known that atmospheric currents transport airborne aerosols, leading to plastic (MPs & NPs) pollutants migration over long-distances, and their existence in every environmental compartment (Allen et al. 2019; Wang et al. 2020a; Bianco and Passananti 2020). For example, PET-NPs were identified in a snow pit from the Austrian Alps (Materic et al. 2020). However, it is unclear whether the existence of NPs in the high-altitude snow was due to atmospheric migration or the in-situ decomposition of MPs. Bianco and Passananti (2020) described possible mechanisms of how NPs could be transported for longer distances than MPs, making NPs studies an urgent priority. Undoubtedly, advances in systematic and efficient methodologies for the accurate determination of atmospheric NPs existence and determination of ecotoxicological effects are keys to better environmental and health risk assessments.

The Ecotoxicological Effects of NPs: Emphasizing the Outcome of Exposure to Nanoparticles

Studies on the toxicological effects of plastic waste can be traced back to the 1960s (Kenyon and Kridler 1969). Early ecotoxicological studies on marine plastic debris mainly focused on the physical effects of the ingestion and entanglement of marine animals from field observations (Laist 1987; Kenyon and Kridler 1969). Large plastic items and debris caused a range of effects including intestinal obstruction, asphyxia, skin abrasions, and skeletal injuries (Alimba and Faggio 2019). When marine vertebrates and invertebrates ingested or inhaled smaller plastic particles, such as MPs and NPs, it caused not only abrasion and irritation of mucosa but also dysregulation in the expression of oxidative stress-response genes (Anbumani and Kakkar 2018; Alimba and Faggio 2019; de Souza Machado et al. 2018). Moreover, NPs were able to pass across cell membranes and affect organisms at a cellular or subcellular level, e.g., inducing various adverse effects such as inflammation, changes in membrane permeability, and oxidative stress (Zhao et al. 2020; Wang et al. 2013a, 2013b).

Toxic effects induced by exposure to NPs on the cell surface or in the cytosol, interacting with biological membranes, biomacromolecules, and organelles, have been reported in several studies. For example, when NPs adsorb onto the cell surface, they can cause direct membrane injury, leading to cell leakage and cell death (Nel et al. 2009). As revealed by molecular dynamics simulations, PE-NPs permeated into the hydrophobic core of lipid bilayers and induced structural and dynamic changes in the bilayer, leading to alterations of vital functions of the cell membrane and even the death of the cell (Holloczki and Gehrke 2020). The interaction between NPs and proteins can also change the secondary structure of the proteins, resulting in the misfolding and denaturation of proteins (Holloczki and Gehrke 2019, 2020). NPs can further disrupt mitochondrial energy production and damage deoxyribonucleic acids via biophysicochemical interactions (Trevisan et al. 2019; Zheng et al. 2019; Sokmen et al. 2020). Additionally, NPs can induce the formation of Reactive Oxygen Species (ROS) and strengthen oxidative stress. Wang et al. (2013a) demonstrated that the accumulation of NPs in lysosomes induced the production of ROS, leading to swelling of the lysosomes and releasing of cathepsins into the cytosol, and ultimately apoptosis.

In complex biological or environmental media, NPs usually existed as hybrid polymers, coated by proteins and various biomolecules, forming a “corona” on the surface (Wang et al. 2013b; Tan et al. 2020). The structure of protein coronas significantly affected the morphology and cytotoxicity of NPs (Kihara et al. 2019, 2020). In particular, the morphology of fractal-like aggregates formed by hard corona complexes were harmful to cellular membranes (Kihara et al.

2020; Gopinath et al. 2019). The soft corona protected the cells from damage induced by cationic nanoparticles (Wang et al. 2013b).

Overall, understanding the interactions between NPs and biological macromolecules in the physicochemical interface and the underlying molecular and cytotoxic mechanisms are essential to better evaluate the ecotoxicological effects of NPs. More importantly, investigations should be performed under environmentally relevant conditions and ensure that liabilities and risks are properly evaluated and addressed, as we know little about the exposure and intake of NPs of free-living organisms in the real environment.

NPs on Aquatic and Terrestrial Organisms

Phytoplankton As the primary producers and the foundation of the food web in the aquatic ecosystem, phytoplankton play a key role in energy flow and mediate biogeochemical cycles in the water column (Falkowski 1994). Toxic effects of NPs on phytoplankton includes growth inhibition, morphological damage, organelle damage, physiological disturbance, oxidative stress, and disruption in cell division (Zhao et al. 2020; Wang et al. 2020b; Mao et al. 2018; Besseling et al. 2014; Bhattacharya et al. 2010b; Bellingeri et al. 2019). Oxidative stress and membrane destruction are two major types therein (Feng et al. 2019). Mao et al. (2018) showed that NPs caused dose-dependent adverse effects on *Chlorella pyrenoidosa* growth from the lag to the earlier logarithmic phase. *C. pyrenoidosa* responded via cell wall thickening and aggregation in the end of the logarithmic and the stationary phase. The aggregation, including both homo- and hetero-aggregation, is a stress coping strategy by actively modifying the chemical composition of exopolymers, subsequently affecting the fate of NPs and their impact on algal cells. Gonzalez-Fernandez et al. (2019) found that a high concentration of transparent exopolymer particles (TEP) at the stationary phase of *Chaetoceros neogracile* could lead to NPs aggregation, thus minimizing the adverse effects of NPs. Furthermore, NPs could trigger the production of protein-rich extracellular polymeric substances by phytoplankton (Shiu et al. 2020a). Zheng et al. (2020) and Feng et al. (2020) found that PS-NPs stimulated the production of microcystin by *Microcystis aeruginosa*.

Zooplankton It has been well documented that NPs affected the growth, behavior, physiology, and reproduction of zooplankton, i.e., *Daphnia magna* (Besseling et al. 2014; Brun et al. 2017; Rist et al. 2017; Ma et al. 2016), *Artemia franciscana* larvae (Bergami et al. 2016), and *Brachionus plicatilis* (Manfra et al. 2017). Results of (Besseling et al. 2014) firstly showed that exposed *Daphnia* shrank in body size and presented severe alterations in reproduction. A shifted life history of *Daphnia* populations was observed as a result of exposure to NPs over the long-term and across multiple generations. Though 1 μg/L NPs did not affect the survival or body length of *Daphnia pulex* in parents (F_0) under long-term exposure, the growth rate and reproduction were reduced in the F_2 generation (Liu et al. 2020). Besides, NPs could be transferred from parents to the offspring and cause transgenerational toxic effects from chronic exposure (Xu et al. 2020; Zhang et al. 2020b).

Benthos: Bivalves Marine sediments are home for many benthic organisms and act as a sink for contaminants, including plastic wastes after degradation and aggregation. Activities of benthic organisms, such as feeding, excreting, and burrowing, play an important role in the biological, chemical, and physical properties of sediments and affect the biogeochemical dynamics between the seabed and overlying water (Kristensen et al. 2012).

NPs are known to impact uptake mechanisms, internalization, and depuration processes in filter feeders, such as mussels and oysters. It was reported that NPs could reduce the filtering activity of *Mytilus edulis* (Wegner et al. 2012). Fecal and pseudo-fecal production of *Corbicula fluminea* increased after being exposed to PE-NPs, suggesting the implementation of cleaning mechanisms for inedible particles (Baudrimont et al. 2020). The gill, intestine, and stomach were the main accumulation organs for NPs (Liu et al. 2020). Sendra et al. (2020) found that *Mytilus galloprovincialis* revealed a rapid and size-dependent cell translocation of PS-NPs to the hemolymph within a 3-h exposure.

Some studies also reported that NPs could affect immunological response and sexual reproduction in bivalves. An in vitro experiment was carried out to test the effects of amino-modified PS-NPs on *Mytilus edulis* hemocytes. Reduced phagocytic activity and increased lysozyme activity were observed (Canesi et al. 2015). A short-term exposure of PS-NPs at low concentration down to 0.05 mg/L also affected the expression of genes associated with the immune function in *Mytilus galloprovincialis* (Brandts et al. 2018). Moreover, clear signs of genotoxicity and spermiotoxicity resulting from NPs exposure were evident in these filter feeders. Gonzalez-Fernandez et al. (2018) showed that NPs were adsorbed onto the surface of spermatozoa and oocytes of Pacific oyster (*Crassostrea gigas*). NPs exposure reduced fertilization success and embryo-larval development rate of *C. gigas* via inhibition of sperm motility (Tallec et al. 2018, 2020).

Fish In most studies on fish, critical increased mortality or developmental abnormalities due to NPs exposure were not observed. However, embryotoxicity and neurotoxicity of fish induced by NPs exposure have been widely documented (Bhagat et al. 2020; Chen et al. 2017; Hu et al. 2021). Notably, studies on the NPs toxicity to fish have been mostly carried out under laboratory conditions using zebrafish as a model organism. Sun et al. (2021) showed that exposure of NPs could induce severe pericardial edema of zebrafish embryos. Lee et al. (2019) showed that exposure of PS-NPs could adversely affect the cell viability of zebrafish embryos. Results presented in Duan et al. (2020) also found NPs had high affinity to embryonic chorions and caused an antioxidant system disorder in the zebrafish embryos. Furthermore, several important neurotransmitter biomarkers were shown to be altered after one week exposure to PS-NPs (Sarasamma et al. 2020). Transcriptomic analysis revealed dysregulation in nervous system development and neurological disease pathways (Pedersen et al. 2020). It is also evident that the exposure route affected the biodistribution and toxicity of NPs in zebrafish (*Danio rerio*). Waterborne exposure was reported to cause greater toxic effects to zebrafish compared to direct injection (Li et al. 2020b). As for endocrine and immune systems, Brun et al. (2019) demonstrated that the accumulation of NPs in the pancreas led to disruption of glucose homeostasis; the accumulation and distribution of PS-NPs in the gut induced dysfunction of intestinal immune cells and increased the abundance of pathogenic bacteria (Gu et al. 2020). Moreover, Chae et al. (2018) showed that the NPs absorbed onto the surface of *Chlamydomonas reinhardtii* were found in the digestive organs of fish, showing the possibility of trophic transfer of NPs.

Terrestrial Organisms Studies on ecotoxicological impacts of NPs on aquatic environments have been reported since 2011. However, research which focused on terrestrial ecosystems only began to emerge in 2018. For instance, a significant decrease in microbial biomass, dehydrogenase activity, and activities of enzymes associated with carbon, nitrogen, and phosphorus cycles in the soil were observed after 28 days exposure to PS-NPs at the concentration of 100 and 1000 ng/g (dry mass soil) (Awet et al. 2018). Zhu et al. (2018) examined feeding 10% PS-NPs to the soil oligochaete, *Enchytraeus crypticus*, a widespread soil invertebrate, an Organization for Economic Cooperation and Development standard ecotoxicological soil model species, and a significant reduction in weight, together with microbial community succession in the gut microbiome, were observed. Moreover, Sun et al. (2020) found that both positively and negatively charged NPs in the soil, with size up to 200 nm, can be taken up by *Arabidopsis thaliana* roots. NPs widespread in wastewater treatment discharges or sewage sludges may penetrate the stele via a crack-entry mode to enter the roots and subsequently be transported into other parts of the crop plants (Li et al. 2020b). The trophic transfer of NPs from plants to snails and reduction in the growth and foraging speed of snails were also observed (Chae and An 2020).

The "Trojan Horse" Effect and Risk of NPs The concept of the "Trojan horse" effect is applied to describe the cotransport and deposition of NPs and soluble contaminants, such as persistent organic pollutants and heavy metals adsorbed onto NPs, further aggravating the ecological risk of NPs pollution (Bouwmeester et al. 2015; Ma et al. 2016). For instance, Chen et al. (2017) reported that NPs could act as transport vectors for BPA (Bisphenol A), which could facilitate the uptake of BPA and increase the bioaccumulation in the head and viscera in zebrafish. Conversely, NPs can also act in an opposite direction to reduce chemical toxicity by adsorbing the contaminants. Trevisan et al. (2019) showed that NPs could mitigate the toxicity of PAHs (polycyclic aromatic hydrocarbons) in developing zebrafish by sorbing PAHs onto the surface of the PS-NPs, decreasing its bioavailability. Hence, the interaction between coexisting pollutants and NPs is particularly critical for the ecological risk assessment of NPs.

Given these discoveries of the potential ecotoxicological effects of NPs on aquatic and terrestrial organisms, determining how these findings translate into the field environment is the next required step for scientists. The following three directions need to be further pursued: First, many of the reported studies used NPs concentrations that far exceed expected field concentrations (Lenz et al. 2016). Second, the chemical composition and surface morphology of secondary NPs in real environmental settings are quite different from plastic nanoparticles used in the laboratory. Third, the change of behavior and exposure pathway of NPs under complex environmental conditions, and biological escape or adaptation mechanisms, will affect the ecosystems effect of NPs.

Perspectives and Future Directions

Here, we propose several critical research gaps for future studies, including the need for more comprehensive field studies on the environmental behavior of NPs in different media, environments or ecosystems, evaluation of NPs transport fluxes, and a better understanding of their toxicology via different exposure routes to plan for effective risk mitigation strategies. Most research on the environmental behavior of NPs has been based on relatively simplified laboratory simulations. Field studies on separation and decomposition process from complex environmental samples and plastic debris to NPs in different media, environments or ecosystems are critical and warranted. In particular, little work has been done on atmospheric samples and media. Also, it is important to evaluate the transport fluxes of NPs among and between aquatic, terrestrial, and atmospheric environments. Some environmental behaviors of NPs such as aging, releasing, or sorbing hazardous chemicals, and forming protein corona, may modulate exposure and NPs physicochemical properties. Moreover, while NPs are known to be transported into cells and tissues, the chronic biological effects of NPs in organisms are largely unknown. In parallel with studying fates of NPs in the environments, pushing for more comprehensive understanding of NPs toxicology via different exposure routes will allow us to proactively accommodate risks and plan for effective risk mitigation strategies.

Comprehensive scientific research on NPs is a key to effective pollution control, and this provides opportunities for the prevention and management of NPs risks. While science is evolving, policymaking also needs to be adaptive, and take into account the latest research findings. The media can exert its influence to enhance public awareness and participation in debates and the decisions that shape people's lives and the environments they live in. The search frequency of "nanoplastic" has increased steeply in leading search engines, such as Google, since 2018 (Supplementary Fig. S1). Influence through the public voice and the press pushes national governments and international organizations to respond via policy making and implementation. For example, plastic pollution was considered as a target (14.1) under a collection of 17 interlinked Sustainable Development Goals (SDGs), which were set up in 2015 by the United Nations General Assembly. Resolution 4/6 "Marine plastic litter and microplastics" was assembled in 2019 by the United Nations Environment Assembly to reaffirm the importance of the long-term elimination of discharge of plastic litter. A Plastics Policy Inventory, https://nicholasinstitute.duke.edu/plastics-policy-inventory, was created thereafter to monitor the status of the global plastic pollution problem and efforts to address it, including existing activities and actions by governments (Karasik et al. 2022). Since 2015, microbead bans have been adopted across the United States, Canada, France, the United Kingdom, and New Zealand to phase out microbeads in cosmetics, soaps or similar products (Karasik et al. 2022).

We have searched and examined the entire list of plastics policies (from January 2000 to February 2019, 97% of the total number of known international policies) using the term "nanoplastics" and so far only six policies responded to the nanoplastics problem (Karasik et al. 2022). Existing policy calls for increased research on NP, but provisions for next steps are still lacking (Kasa and Kaur 2021; UN 2018; G20 2019). More recently, the European Commission is promoting the revision and legislative process of policy responses spanning a large range of topics, from MPs to nanomaterials and polymers, which may have a significant impact on the future regulation of NPs, especially manufactured NPs (Abdolahpur Monikh et al. 2022). Abdolahpur Monikh et al. (2022) recommended that it is more practical to incorporate manufactured NPs into the regulation of the European Commission law for Registration Evaluation, Authorization and Restriction of Chemicals. Notably, secondary sources of NPs from the weathering of mismanaged plastic waste could be produced and accumulated drastically at an unprecedented rate and may not be included in these regulations (Mitrano and Wohlleben 2020; Abdolahpur Monikh et al. 2022) – this flags the importance of overall management (and reduction) of environmental plastics inputs to help address emerging NPs issues. Last but not least, to better promote the dissemination of scientific research findings and encourage policymakers to act on scientifically sound grounds, efforts in engineering, policy, education, etc. should be combined to support our societies toward being more sustainable.

Conclusion

Thousands of researchers from over 90 countries have devoted significant effort toward the environmental monitoring, environmental behavior, health implications, and ecotoxicology of NPs for more than a decade. To better digest the large resulting literature, we applied bibliometric analysis to provide a systematic review on the evolutionary trend, interrelationships, and frontiers of NPs research from 1995 to 2023. Research outcomes increase exponentially after 2018. The main publication efforts are contributed from Europe, East Asia and North America. China is the most active and influential country through international collaborations. Chinese collaboration with the USA produced the most articles. European countries such the Netherlands, Portugal, Germany, the United Kingdom have close cooperation with each other, and gained higher attention through high average citations.

Our review provides a comprehensive and systematic analysis of the evolutionary trend, interrelationships, and frontiers of NPs research, which can be a valuable resource for new researchers in the field to understand the current state and trends of NPs research. Additionally, our review identifies critical research gaps that need to be addressed in future studies, including the need for more field studies involving NP quantification in (and their separation from) complex environmental samples, and their accumulation, degradation, and decomposition processes in different media, environments, or ecosystems, as well as the need to evaluate the transport fluxes of NPs among and between aquatic, terrestrial, and atmospheric environments. Toxicology was consistently the main concern of NPs studies in the last decade, partly because this addresses the growing need of NPs pollution risk assessment. We also highlight the importance of comprehensive scientific research on NPs for effective pollution control and the need for policymakers to be adaptive and take into account the latest research findings. Ultimately, our review highlights the importance of initiatives in fields such as engineering, policy, and education to facilitate the transition toward sustainability in our societies.

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