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Research Article

EFFECTS OF MICROPLASTICS ON ENVIRONMENTAL POLLUTION

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Abstract

The environmental pollution caused by microplastics and nanoplastics is discussed. These materials, which are produced from the degradation of larger plastics, are present in the environment in increasing quantities. It should be noted that microplastics can be ingested by marine animals, which can then be consumed by humans. Nanoplastics, on the other hand, are smaller and can penetrate living tissues, which could cause damage to health. The main trends in research on microplastics and nanoplastics are presented through documentary research in the area of environmental pollution. The Lens.org database was used to analyze papers, conferences, and patent applications about the environmental milieu during the period 2012-2022. The increase in the number of scientific articles published on this subject is highlighted, as well as the development of new technologies to treat the pollution caused by these materials. By virtue of this, it is verified that microplastic pollution is a growing and serious problem worldwide that requires the attention of the scientific community and the general public. The negative impact they have on the environment and human health is shown. However, further research is needed to fully understand the effects of pollution caused by these materials. Emphasis is placed on the need to reduce the production and use of single-use plastics, as well as to develop new technologies to deal with the pollution they have already produced, and, lastly to educate the public about the risks of microplastic and nanoplastic pollution.

Keywords: Microplastics, Nanoplastics, Environmental contamination, Human and animal health

INTRODUCTION

Plastics have become widely used materials in the modern economy. They exhibit unmatched functional characteristics as well as low cost. Their use has increased twenty-fold in the last half century and is expected to double again in the next 20 years. Every year, more than 300 million tons of plastics are produced worldwide, half of which are destined for single use, and at least 8 million tons end up in the oceans [1]. The majority of the most commonly employed plastic waste comes from materials such as polyethylene, polypropylene, and polyvinyl chloride. These are not readily biodegradable, so they are subject to weathering and fragment into micro and nanoplastics, and remain in the environment for hundreds of years [2]. These small plastic particles can be ingested by marine fauna and thus enter the food chain. In addition, plastic materials often contain additives such as plasticizers, flame retardants, pigments, and stabilizers. These substances can also be released into the water. Currently, it is estimated that there are 150 million tons of plastic waste in the oceans and this includes about 23 million tons of additives. It is also estimated that 69-81% of microplastics in the marine environment come from secondary microplastics that originate from the degradation of larger plastics. The main primary microplastics released into the ocean come to a great extent from land-based activities [3]. The widespread damage caused by microplastics and their effect on the environment and human health is of greatest concern. However, it is still unclear to the international scientific community what the impact of micro- and nanoplastics in the food chain and their respective repercussion on human health could be [3].

This paper presents a study on micro and nanoplastics and the pollution they produce in the environment and their effect on humans and animals. For this purpose, relevant information published in articles and patent applications was analyzed, as well as the main trends envisioned in the world in the period 2012-2022. The methodology used to recover and analyze the information is described, as well as the characterization of these materials and their influence on the environment and living beings. Likewise, the main challenges to prevent their contamination are pointed out. Finally, the conclusions drawn from the analysis and interpretation of the information obtained are presented.

METHODOLOGY

In order to carry out this work, documentary research was conducted in the area of environmental and living beings pollution that are producing microplastics and nanoplastics. The Lens.org database was used to locate information related to the subject by combining keywords that characterize the topic of study. Internationally published information was found in articles, conferences, and patent applications during the period 2012-2022. The information was limited to the fields: title, abstract, keywords, and field of study in the case of papers, and for patent applications it was limited to the search fields: title, abstract, and claims. Once the information was obtained, the relevant documents related to the area of study were selected and duplicates were eliminated. The information was then analyzed using the content analysis technique. In the case of trends, the Analysis tool of the Lens.org database was applied, which allows achieving information according to the parameters to be represented in the trends. Finally, to obtain the trends, the bibliometric analysis technique was used to represent the different trends.

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Origin and characterization of microplastics

When plastic objects are in environment, the sun radiation, abrasion, ocean current dynamics, and other environmental conditions, are going to deteriorate it, and break into smaller particles that are known as microplastics. In the environment, microplastics can be found in different sizes, colors, forms, densities, polymer types, and combinations of plastic particles with other contaminants. The most common plastics found in the microplastics are Polyethylene Terephthalate (PET) coming from water bottles, liquid hand soap, mouthwash; the polyester (PES) from polyester clothes, bottles; the low density polyethylene (LDPE) from plastic bags, squeeze bottles; the high density polyethylene (HDPE) from detergent bottles, bleaches; the polyvinylchloride (PVC) coming from pipes, electric cables, clothing; the polypropylene (PP) from clothing, jars, stoppers; the polyamide (PA) from packaging, textile (nylon), tooth brush; the polystyrene (PS) from ready to-eat food, disposable cutlery, CD's & DVD cases; the acrylonitrile-butadiene-styrene (ABS) coming from pipe systems, musical instruments; the Polytetrafluoroethylene (PTFE) from plain bearings, gears, slide plates, seals, gaskets and bushings [4] [5] [6] [7].

According to their sources, microplastics and nanoplastics havebeen categorized into primary and secondary. Primary are the by-products of particulate emissions released from different industrial production and enter the environment in their original small sizes, which are associated with their specific applications and consumer products (include cosmetic and cleaning products such as toothpaste, raw materials used for plastic goods manufacture as well as textile fibers released during washing or drying). Secondary, are formed as a result of plastic debris degradation due to their exposure to physical, animal, and microbial [8]. Microplastics are generally defined as plastic fragments smallerthan 5 mm in any dimension with an indeterminate lower limit, nanoplastics have a particle size of less than 100 nm in any of its dimensions, and mesoplastics are plastics with sizes between 5 mm and 25 mm. [9]. As pollutants, the risk of microplastics is associated to their ubiquity and size, because a wide range of organisms may ingest them and consequently can suffer physical and toxicological damage. Characterizations of microplastics include visual and microscopic examination, including particle size (particles size lower of 0.5 mm or higher to 0.5 mm), shape (fragment, fiber, film, pellet, and foam) and color (it is an important factorenhancing the likelihood of ingestion by the marine organisms for resembling their target prey; polymer type identification were the microplastics can be analyzed for polymeric identification using FTIR spectrophotometer (PE, PP, PET, PS, and PV), Fluorescence microscopy (HDPE, PET, polyester and PS), Raman spectroscopy (polyethylene (PE) and PP), Stereoscopy, Stereoscopic microscopy (PE, PP, PS and nylon), chromatography coupled to mass spectrometry. To report the concentration of microplastics, can be used different units, most based on counting or weighing all the particles found in every sample point. A convenient, standardized way is to express the results in terms of mass of microplastics (mg), applied to a different basis, like kilogram ofsolid, liter, square meter, linear meter.

Impact of microplastics on environment

Microplastics found in the environment are originated from a variety of different sources, and is a very heterogeneous group of particles differing in size, shape, chemical composition and specific density. Environmental weathering (including abiotic degradation such as UV radiation, heat, and chemical reactions) results in plastic degradation in which long-chain polymers are broken into smaller ones. The distribution of plastic particles with a small size called mesoplastics, microplastics and nanoplastics has been increasing in the last decades across the various ecosystems is currently a subject of major environmental concern.At present, there is evidence to prove that these particles release toxic plastic additives and can adsorb various chemicals, in this manner serving as sinks for various poisonous compounds, enhancing their bioavailability, toxicity, and transportation. Additionally, there is a potential danger for the trophic transfer of MNPs to humans and other higher animals, after being ingested by lower organisms.[8][10][11][12]. This particles pollution is abundant in aquatic (marine and freshwater), terrestrial, and atmospheric environmental compartments, which are interconnected, and adsorb various toxic chemicals, transporting them within and between different habitats. Also, they can be consumed by diverse marine species, in this manner slowly entering the marine food web and posing severe threats to all marine and terrestrial life. Related with microplastic degradation, it is known biodegradation, hydrolysis, photo degradation, and thermo oxidative degradation [8], and the kind of each one depends of the habits in which the microplastic is present, for example hydrolysis will play a more dominant role in the aqueous habitats.

Effects of microplastics in aquatic habitats

Human activities such as tourism and wastewater treatment result in depositing microplastics in aquatic habitats (lakes, rivers and ocean). This debris in water bodies include PE, PP, PS and PVC interacting with organic matter, inorganic elements and microorganisms, and various toxic chemicals that are absorbed by microplastics. As these small particles of plastic could be consumed by diverse marine species, it is becoming part of the marine food web, posing threats to all marine and terrestrial life.

Effects of microplastics in terrestrial habitats

Domestic and agricultural activities are two potential sources of microplastics contaminating terrestrial habits, and this pollution is a major contributor to direct and indirect deleterious effects on various land-dwelling habitats, with multiple exposure pathways to the biota resulting in environmental toxicity. These particles can interact with other potentially harmful elements and organic contaminants, multiplying their potential and affecting terrestrial biota, for example reducing plant growth and productivity. Also have significant negative impacts on soil fauna, principally earthworms and nematodes, affecting their growth, reproduction, lifespan, and survival through various toxicity mechanisms, including bioaccumulation, DNA damage, and genotoxicityamong others.

Effects of microplastics in the atmosphere

Depending on their weight and density, microplastics can be transported through atmospheric or aquatic currents in the environment. It has been observed that microplastic can travel long distances and accumulate in a variety of terrestrial and aquatic environmental matrices, posing various threats to the biosphere. Also, can be inhaled directly and continuously, posing a serious health concern. The factors that affect the atmospheric transportation of microplastics have been identified to include wind direction, rainfall, particle dimension, human activities, and population densities, among others.

Effects of microplastics on human health

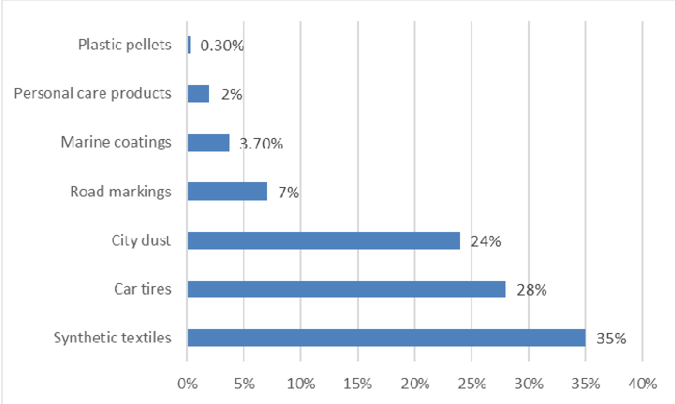
Microplastics have been found in different foods such as fish and seafood, table salt, beer, honey and sugar, and tap water. The pathways of human exposure to microplastics are oral intake, inhalation, and skin contact. Humans are at the top of many food chains, therefore microplastic can be accumulated in cells and tissues causing metabolic disorders and local inflammation, as well as cytotoxic effects, for example in lung cells, intestinal cells as well as cerebral and epithelial cells. [13][14]

Challenges to prevent microplastics pollution

Numerous intricate factors pose challenges in managing and mitigating the adverse environmental impacts of plastic pollution. Researchers like Austine *et al.* (2021) and Sharma (2017) [15] [16] concur that despite their small size, addressing microplastic pollution is a significant environmental challenge that necessitates collaborative efforts from individuals, industries, governments, and the scientific community. These minuscule plastic particles can have detrimental effects throughout the environment, extending around the world [17], impacting ecosystems, wildlife, and potentially human health, even within the bodies of humans and various animal species, as emphasized by the United Nations Environment Programme [2]. In this regard, here are some of the key challenges in preventing microplastic pollution:

Multiple sources of microplastics: Microplastics, despite having natural sources, have seen their prevalence in the environment significantly exacerbated by human activities, leading to ecological imbalances. They originate from a diverse array of sources, including the degradation of larger plastic items, the incorporation of microbeads in personal care products, the shedding of synthetic textile fibers, and industrial processes [18]. As noted by Osman [19], microplastics account for a substantial 75% of marine debris, with land-based sources contributing 80- 90% of this pollution, while ocean-based sources account for only 10-20%. According to Pew's report in 2016, just four sources of microplastics contributed to 1.3 million metric tons (Mt), equivalent to 11% of the overall ocean plastic pollution.Nevertheless, Paul Anastas (Director of the Center for Green Chemistry and Green Engineering) highlights a significant gap in our understanding, stating that there is considerably less information available regarding microplastics in the air and soil compared to those in water. The ease of detection, testing, and analysis of water-based microplastics has led to a predominant focus on this aspect within the research community [20].

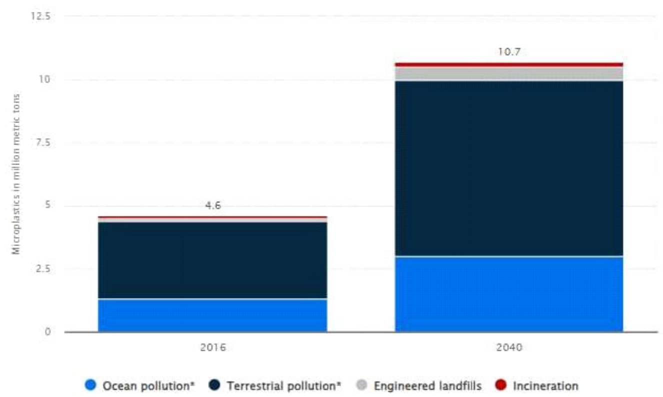
Statista's research study (2023) [21] estimates that as of 2018, a significant 87% of microplastics in the world's oceans originate from synthetic textiles (35%), car tires (28%), and city dust (24%), as shown in the chart in the Figure 1.



Source: Statista [21]

Figure 1. Distribution of ocean microplastics sources worldwide as of 2018

Another study by Statista [22] estimates that approximately 1.3 million metric tons of microplastics enter the world's oceans each year from sources like tire dust, pellets, textiles, and personal care products. If current trends persist, oceanic contamination from these microplastic sources is projected to reach three million metric tons annually by 2040. Additionally, terrestrial pollution from these sources is expected to increase to seven million metric tons by that year. It's important to note that the amount of microplastics incinerated or disposed of in sanitary landfills is significantly lower than the amount entering the environment, as can be observed in the figure 2.



Source: Statista [22]

Figure 2. Managed and mismanaged microplastics worldwide in 2016 with a forecast to 2040 under business-as-usual scenario (in million metrictons)

Although it takes centuries for larger plastic waste to naturally break down into microplastics, secondary sources currently dominate environmental microplastics. The shift from primary to secondary microplastics involves a fundamental reduction in particle size, rendering them more prone to ingestion by organisms, thereby increasing the potential for ecological and human health repercussions [23]. However, accurately identifying the source of detected microplastics in the environment remains a formidable task, often approaching the realm of impossibility. Given the intricate nature of dealing with this array of sources, it becomes essential to gain a comprehensive understanding of their diversity to effectively implement precise measures aimed at mitigating the problem of microplastic pollution.

Difficult to Track: Microplastics are challenging to monitor and quantify in the environment due to their small size and widespread distribution. While some authors propose narrowing the definition to plastics in the micrometer size range (less than 1 mm), the 5 mm upper limit is still recognized because plastics of this size can be ingested by marine [24]. Monitoring them in remote or deep-sea environments remains a significant challenge due to logistical constraints and high costs. In practical implementation, mitigating microplastic pollution in water bodies faces an obstacle: the limited availability of technology capable of efficiently capturing these materials at wastewater treatment facilities. Various techniques, including microscopy, spectroscopy, and chemical analysis, are used to detect and quantify microplastics [16]. However, each method has inherent limitations, such as selective detection of specific plastic types or size ranges, further complicated by the absence of standardized protocols and methods for comparative analysisbetween studies.

In the professional realm, isolating, identifying and quantifying microplastics and nanoparticles presents a significant challenge. According to research conducted by Adhikari et al. (2022) [25], most analytical instruments commonly found in research laboratories were not originally designed for the precise analysis of micro and submicron-sized particles. Besides, collecting representative samples of microplastics in various environments, such as oceans, rivers, sediments, and soils, is challenging due to their heterogeneity and dispersion. The difficulty varies based on the sample type, with complications arising from factors such as high pigment content and alterations due to extreme weather conditions over time, which can further complicate spectroscopic analysis. Overcoming this challenge often requires access to sophisticated equipment like micro-FTIR and micro-Raman machines [15]. Likewise, in the report titled "From Pollution to Solution: A global assessment of marine litter and plastic pollution", published in 2021, the United Nations Environment Programme highlights that despite notable progress in improving global observation and survey systems and refining protocols for detecting and quantifying litter and microplastics in both physical and biological samples, scientists still voice concerns about potential sampling biases. This complexity hampers precise quantification of microplastics in different habitats due to variations in their physical and chemical characteristics. That's why developing effective monitoring techniques is crucial.

Global Distribution: Microplastics have been discovered in remote and unspoiled environments, ranging from the deep sea to beaches worldwide, including protected areas, and even in Polar Regions such as Arctic Sea ice and the ocean floor [29]. The increase in microplastic concentration worldwide, while primarily attributed to human activities such as tourism, fishing, marine traffic, and others, is also influenced by environmental phenomena and factors such as wind patterns, ocean currents, and even cyclones, which can transport these particles to remote areas across the globe [26]. National Centers for Environmental Information of the United States (2022) claims that the majority of microplastics originate on land and are carried to the ocean by rivers and wind, becoming part of the global ocean circulation system. Once they enter the ocean, this widespread distribution makes it challenging to identify their exact sources, and controlling their dissemination becomes a complex task.

Persistent Nature: Changing environmental conditions can cause larger plastic debris to gradually degrade into smaller fragments, spanning various size ranges from meters to micrometers [27]. Microplastics have emerged as one of the foremost environmental threats owing to their persistence, widespread presence, and inherent toxic properties [28]. They, as observed by Sharma (2017) [16], exhibit remarkable chemical stability that enables them to endure in the environment for extended periods, often spanning hundreds to thousands of years. This longevity presents a significant challenge in terms of removal once they are present, contributing to the continuous increase in the quantity of microplastics in our surroundings. Consequently, a growing global concern regarding their pollution persists. It is important to note that, in the case of wastewater treatment plants, they may be capable of capturing some microplastics, but they are not designed to remove all of them.

Limited Regulations: The scarcity of comprehensive regulations for microplastics presents a pressing concern within the realm of environmental management and pollution control. Despite the extensive prevalence of microplastics and their documented adverse environmental impacts, the existing regulatory framework addressing these pollutants remains fragmented and insufficient. Even though some countries and regions have implemented regulations addressing specific aspects of microplastic pollution, such as bans on microbeads in cosmetics, these regulations often focus on limited aspects and vary widely between jurisdictions.

- Lack of uniform definition: Mitigating the entry of these minuscule particles into the environment poses a formidable challenge due to their lack of uniformity in terms of shape, size, and plastic type [30]. This characteristic makes plastics exhibit a wide range of properties, so the share of such materials in the global economy will rise. The various regulatory bodies and organizations involved in addressing microplastics often use different definitions, leading to confusion and inconsistencies in regulations. Some definitions emphasize size criteria, while others consider chemical composition [17], further complicating the development of cohesive regulations.
- Multiple entry points: As mentioned earlier, microplastics can be introduced into the environment through various sources, both primary and secondary, making it difficult to pinpoint specific sources and establish effective regulations [31].
- Global nature of the issue: Microplastics constitute a global problem that transcends national borders, necessitating international cooperation and harmonized regulations, which can be complex to achieve, at both national and international levels. A research conducted by Ajith et al. (2020) [32] indicates that out of 192 countries worldwide, only 22.9% (44) have conducted studies on microplastics. Furthermore, these studies have predominantly focused on fish (38%), with limited documentation regarding the impacts on other highly affected organisms like turtles (1%). It is a fact that the distribution and abundance of microplastics vary according to geographical location, where environmental and anthropogenic factors play a crucial role in the existence and determination of patterns related to microplastic pollution [27]. Broadly, the general consensus is that Asian countries are the primary global contributors to plastic pollution [33], at least when it comes

to the marine environment [27]. On the other hand, an analysis of microplastic concentrations, basedon data from 196 studies conducted across 49 countries made by Koutnik *et al.* (2021) [34], reveals several key findings: First, microplastic concentrations can exhibit significant variations of up to eight orders of magnitude, depending on the specific location. Second, there is a notable decline in concentration, amounting to up to two orders of magnitude, when transitioning from urban areas further inland to estuaries in coastal regions or terrestrial boundaries.

- Microplastics have only recently gained recognition as an environmental concern, and regulations have struggled to keep pace with their rapid proliferation and evolving scientific understanding. Since microplastic pollution is a global issue, international cooperation is necessary to establish common standards, regulations, and best practices for prevention and mitigation
- Regulatory capacity: In response to these challenges, thereis an urgent need for governments, policymakers, and international organizations to collaborate in formulating comprehensive regulations specifically targeting microplastics. Such regulations should encompass clear definitions, source-specific control measures, monitoring protocols, and robust enforcement mechanisms. Additionally, efforts should focus on promoting research and data collection to inform evidence-based regulations and facilitate international cooperation to effectively address this global environmental issue. Still, many regulatory agencies may lack the capacity, expertise, or resources to develop and enforce comprehensive microplastics regulations.

Consumer Habits: Consumer choices, such as the use of single- use plastics, contribute significantly to microplastic pollution. Changing consumer behavior is a major challenge. The consumption, disposal, and usage choices made by individuals significantly contribute to microplastic pollution. As per Pew's report, it is worth noting that high-income countries played a prominent role, contributing to over one-third of the global total of the microplastics in 2016. In 2018, the global production of various plastic materials reached 359 million tons, with a significant portion being utilized for single-use products, resulting in non-biodegradable waste. Despite the growing emphasis on plastic recycling, 25% of post-consumer plastic waste from that year found its way into landfills, and additional waste arose from littering and unauthorized dumping, as noted by Domenech and Marcos (2021) [31]. If no prompt actions are taken, the data indicates that ocean microplastic pollution will surpass 3 million metric tons annually by 2040, more than doubling the current levels [30] [36].

Hence, the development of strategies to change behavior, including public awareness campaigns, educational programs, and policy incentives, is essential to shift consumer habits towards sustainability. It is crucial to disseminate information about the environmental impact of microplastics, promote sustainable alternatives, and implement initiatives that reduce single-use plastic consumption, fostering more sustainable practices. Industrial practices and innovative solutions: Some industrial processes release microplastics into the environment, and modifying these practices can be expensive and technically challenging. Sectors like packaging, cosmetics, textiles, and paints make substantial contributions to microplastic pollution [37]. Encouraging industries to adopt responsible production practices and eco-friendly packaging can curtail the introduction of microplastics into the environment. Nowadays, a growing consumer trend is the shift towards adopting bio-based products, mainly driven by increasing health and environmental concerns. In response, many countries have banned microbeads in cosmetic products and replaced microplastics with natural alternatives like seeds or rice, achieving the desired exfoliating effects without harming the environment [37]. The packaging industry, a significant source of secondary microplastics, relies on various thermoplastic resins to manufacture flexible and rigid plastics for various packaging purposes. The real issue is that many packaging materials break down over time into smaller fragments, generating microplastics released into the environment during their use, disposal, or recycling [37]. Biodegradable and compostable plastics, derived from natural sources like sugars, vegetable fats, cellulose, and more recently seaweeds and insects, are gaining popularity as alternatives to traditional plastics [38]. As stated in the report titled "Global Biodegradable and Compostable Plastic Market (2022-2027)" by Research and Market, the market for these environmentally friendly plastics was valued at USD 7.89 billion in 2022 and is expected to reach USD 23.9 billion by 2027. Elevating public awareness and instilling a sense of responsibility in both consumers and industries are essential measures for preventing microplastic pollution. However, the development of cost-effective and environmentally friendly technologies for removing microplastics from diverse environments, including oceans and rivers, poses a substantial challenge, given the expense involved in enhancing these facilities, methods, and products to achieve greater efficacy. To overcome these obstacles, companies should make sustainability a top priority in their decision-making processes, allocate financial resources to sustainable solutions, and strive for increased visibility and openness within their supply chains.

Lack of Awareness: Many people are not aware of the issue of microplastic pollution or the potential harm it can cause. While microplastics are increasingly considered potential human health risks, there's a shortage of comprehensive studies in this field. Human biomonitoring studies assessing their health effects are notably lacking, mainly due to challenges in detecting, characterizing, and analyzing microplastics in human samples. These difficulties arise, as will be explained later, from the absence of guidelines and standardized protocols, making data comparison challenging among different researchers [31]. Raising public awareness is a crucial step.

Research Gaps: Substantial gaps persist in our understanding of the environmental fate, transport, and toxicity of microplastics. These gaps remain in regulating microplastics in products, plastic waste management, and industrial practices that release microplastics. Insufficient scientific data can hinderthe establishment of evidence-based regulations. Despite the growing interest of the scientific community in this field and the increasing number of published studies, the absence of a robust and universally accepted definition for microplastics hinders the comparison of findings across various research investigations. The study conducted by Jenkins et al. (2022) [39] indicates that between 2013 and 2021, the sharing of microplastics datasets has expanded, albeit not as rapidly as the proliferation of peer-reviewed publications. This suggests that while a substantial volume of data is being generated, often with public funding, a significant portion remains inaccessible or lacks the necessary metadata for rigorous quality assessment and potential reuse. Gathering comprehensive, long-term data on microplastics has proven to be a formidable challenge, resulting in notable gaps in our comprehension of the extent of microplastic pollution and its repercussions on ecosystems and human health. Traditionally, the handling of marine debris data, particularly data obtained from extensive visual surveys conducted along coastlines and in open ocean areas, has fallen short of meeting the requirements of the scientific and decision-making communities [29].

The insights derived from the study conducted by Jenkins et al. (2022) [39] underscore the critical need for the environmental microplastics community to not only advance scientific research but also to seamlessly incorporate effective data management practices through education and the adoption of best practices. According to their findings, researchers should actively leverage data management resources and specialized repositories specifically tailored for microplastics data. Furthermore, the creation of standardized metadata reporting templates remains a fundamental necessity to ensure the reproducible and user- friendly reporting of that data. Collaborative efforts among science, policy, industry, and environmental organizations are essential to combat microplastic pollution. To do so effectively, we must prioritize further research. This multifaceted approach encompasses policy shifts, technological advancements, education, and changes in consumer behavior. Preventing microplastic pollution is vital for safeguarding ecosystems and human health.

Main trends

The generation of nanoplastics and microplastics and their effect on the environment and the population is increasing every day. It is estimated that 83% of the water for consumption is contaminated with these materials [3]. As a result, public agencies and governments of different countries, as well as the international scientific and academic communities are more and more interested in conducting research to assess and address the situation in order to contribute to the solution to this problem [40]. The importance and concern about this problematic issue are evidenced by the publication of articles at the international level (see Figure 3) which shows an accelerating growing trend and the development of technologies related to nano and microplastics through patent applications in the world.

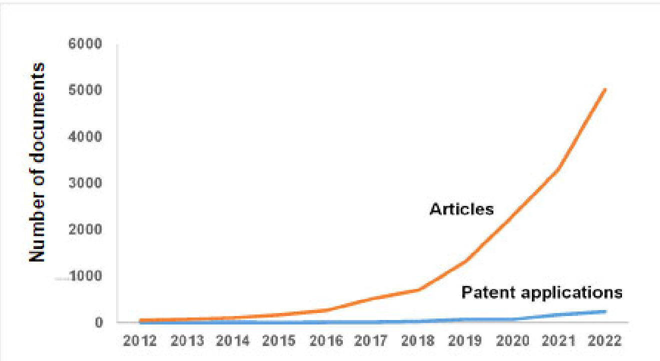


Figure 3. Evolution of published articles and patent applications

Different countries have been monitoring nano and microplastic pollution and its effects on human beings and have established new policies and initiatives. Specifically, the business sector has implemented new policies, regulations, and technologies whose common objective is aimed at reducing such pollution. It is observed that China is the dominant country with the highest number of papers and patent applications published in the period studied and the United States is placed in second place (see Figures 4 and 5). Another important aspect is that there are a number of international patent applications (WIPO), which indicates that these are technologies with a high potential commercial impact. As to main organizations and companies that are developing research related to microplastics, it can be observed that companies have predominantly focused their research efforts on developing improvements or new technologies to treat or reduce microplastic pollution; while universities or research and development institutions concentrate more on the dissemination of their research through the publication of articles (see Figures 6 and 7).

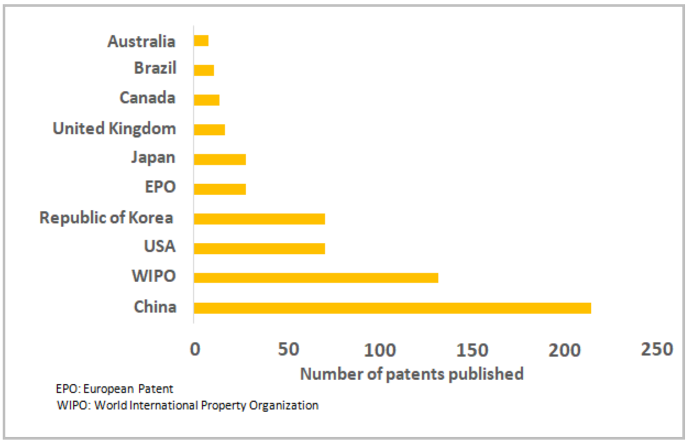


Figure 4. Countries with the highest number of patent applications

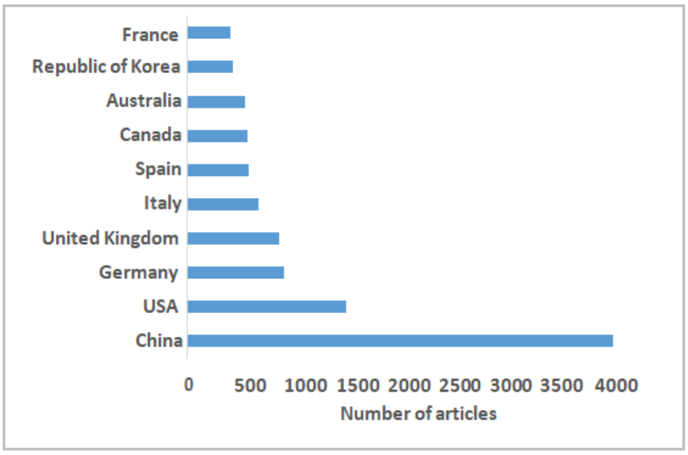


Figure 5. Countries with the largest number of papers

It is also worthwhile mentioning that the Chinese Academy of Sciences completely dominates publications in the area. In relation to the different techniques used to eliminate microplastics from the different environments where they are found, research reveals that the most used techniques are membrane bioreactors, filtration, and water treatment plants; while flocculation, coagulation and flotation are the least used techniques [41]. Likewise, the most relevant technology (with 32 citations, see Table 1) is related to a method to reduce contamination in marine environments produced by personal care products (exfoliants, cosmetics, and toothpastes).

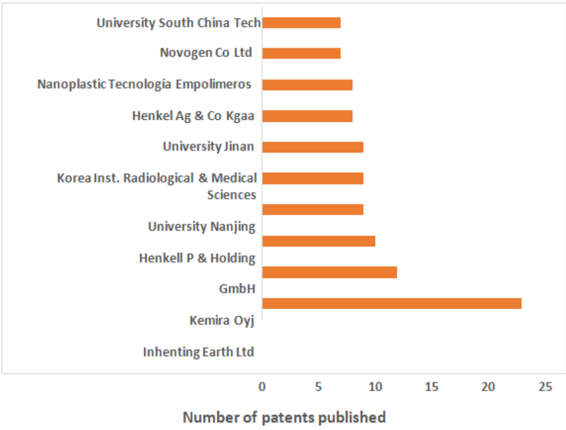


Figure 6. Main organizations with the highest number of patent applications

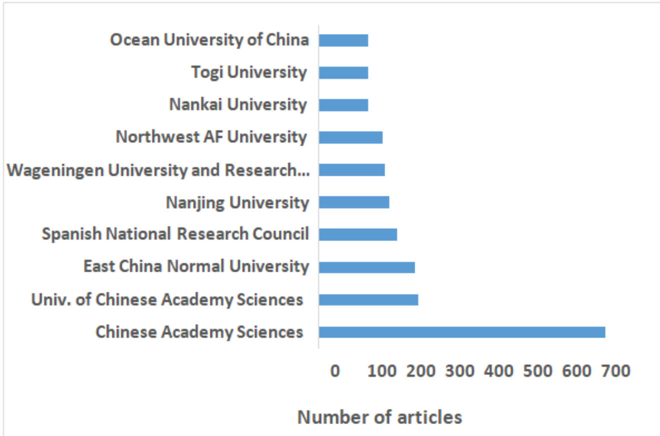


Figure 7. Organizations with the largest number of articles

Table 1. Most cited patent applications

Technology	Inventors	Organization/country	Number of citations	Reference/Patent
Method for Reducing Marine Pollution Using Polyhydroxyalkanoate Microbeads	Havens Kirk J., Bilkovic Donna Marie, Stanhope David M., Angstadt KoryT. [42]	College William & Mary/USA	32	US2014/0026916 A1
Flotation gathering deviceand screening method for microplastics	Ji Min, Liu Yuan, Zhai Hongyan, Wang Rumeng[43]	Univ Tianjin/China	17	CN109655321 A
Aquatic Sampler andCollection Apparatus	Billings Andrew S., Kaiser Cari L., Van DoverCindy Lee [44]	Woods Hole OceanographicInst/USA	17	US2018/0210 29 A1
Method for separating microplastics in environmental soil or sediment based on combination of flotationand centrifugation	Zhang Chengli, Zhang Weiping, Qian Jing, Lei Yuchen, Guo Zhiyong, Zhou Yanmei, Ma Jianhua[45]	Univ Henan/China	16	CN110715835A
Method for detecting density distribution of micro-plastics in water environment sediments.	Li Yanhong, Cui Yaozong, Zhang Chunfang, Zhang Lihao, Zhu Yinian, Xie Qinglin,Zhang Dongdong, Zhou Hanghai [46]	Univ Guilin Technology, Univ Zhejiang/China	14	CN109238948A

Table 2. Most cited articles

Technology	Numberof citations	Organization/country	Reference
Microplastics in the marine environment: A review of the methods used for identificationand quantification	3031	Catholic University of the North; Alfred Wegener Institute for Polar andMarine Research University of Plymouth/Chile, Germany,United Kingdom	Hidalgo-Ruz, *et al.* (2012) [47]
Plastic pollution in the world'soceans: More than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea	2965	Five Gyres Institute, Wellington Management Company, University of Hawaii at Hilo, Catholic University of the North,California State University, Coast Limited, IFREMER, Percy Fitz Patrick Institute of AfricanOrnithology, University of Cape Town, University of Western Australia/NewZealand, Chile, France, South Africa, Australia	Eriksen, *et al.* (2014) [48]
The physical impacts of microplastics on marineorganisms: a review	2655	University of Exeter University of Plymouth/United Kingdom	Wright, Thompson & Galloway (2013) [49]
Plastic debris in the open ocean	2003	University of Cádiz King Abdullah University of Science andTechnology University of Las Palmas de Gran CanariaUniversity of Barcelona Spanish Institute of Oceanography, Balearic Islands Oceanographic Center, Spanish National Research Council/Spain, Chile, Saudi Arabia	Cózar, *et al.* (2014) [50]
Microplastics in freshwater andterrestrial environments: evaluating the current understanding to identify the knowledge gaps and future research priorities	1818	Leiden University, University of Exeter, Centre for Ecology and Hydrology/TheNetherlands; United Kingdom	Horton, *et al.* (2017). [51]

This technology adds polyhydroxyalkanoate microspheres with an average size of less than 400 microns to formulations. These microspheres have the property of being biodegradable [42]. With respect to the articles, it is found that the most relevant research projects are joint projects carried out by different organizations from different countries (see Table 2); and the article with the greatest impact (3031 citations) is related to a study on the methods used to identify and quantify microplastics.

This research was carried out by personnel from universities in Chile, the United Kingdom, and a research institute in Germany. The countries and governments of the different countries, as well as the scientific and academic community, should focus their efforts on how to limit pollution from micro and nanoplastics in order to reduce the emissions produced by these materials, so as to establish standardized monitoring frameworks or policies that make it possible to surveil global trends and create binding international agreements applicable in the long term to prevent polluting emissions from these materials.

Conclusion

Contamination due to nanoplastics and microplastics is increasing in different environments such as soils, seas, rivers, drinking water, beverages, and food, as well as in the air. Thesematerials are present in the formulation and manufacture of different types of products such as textiles, personal care and cosmetic products, rubbers, road markings, marine coatings, pellets, artificial grass, paints, among others. That is why research centers and universities around the world show great interest and concern in conducting research that willlead to the elimination or reduction of the use of these materialsin order to decrease the pollution they produce in the environment and the possible consequences on the health of human beings. It is there where the effort of the published research works is evidenced, which shows an accelerated growing trend in the period 2012 to 2022. As for the development of technologies, its trend remains almost constant, except for the year 2021, which presents a slight increase. China is the leading country in terms of publications in this area, followed by the United States. The published works with the greatest impact are carried out through joint projects involving institutions from different countries. Likewise, research reveals that the most widely used techniques to deal with the problem of nanoplastic and microplastic pollution are membrane bioreactors, filtration, and water treatment plants. In summation, microplastic pollution poses an intricate and pervasive challenge with far-reaching consequences for our environment, ecosystems, and human well-being. Effectively addressing these multifaceted challenges necessitates concerted efforts from diverse stakeholders, including individuals, industries, governments, and the scientific community. A holistic approach, encompassing enhanced monitoring, strengthened regulations, innovative technologies, shifts in consumer behavior, and global collaboration, is paramount in preventing and mitigating the detrimental impacts of microplastic pollution. As we deepen our understanding of this issue, the urgency of our collective response to safeguard our planet and its ecosystems from the insidious threat of microplastics becomes increasingly apparent.

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