Nanoplastic Sources, Characterization, Ecological Impact, Remediation and Policies

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

Keywords Microplastic · Nanoplastic · Plastic pollution · Environment · Contamination

1 Introduction

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

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

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

2 What Are Nanoplastics?

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

3 Sources of Nanoplastics

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

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

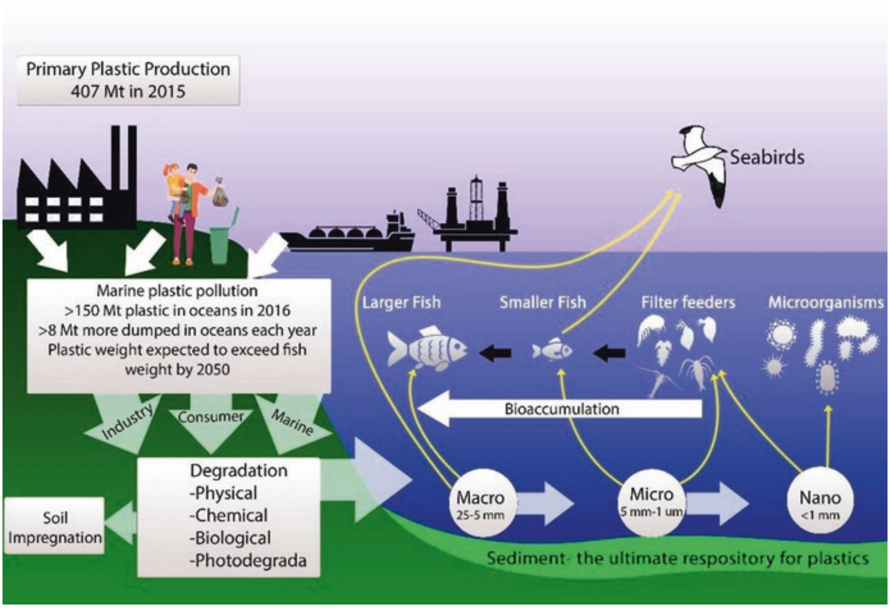

Fig. 1 Formation and movement of micro and nanoplastics leading to plastic pollution

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

4 Characterization of Microplastics and Nanoplastics

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

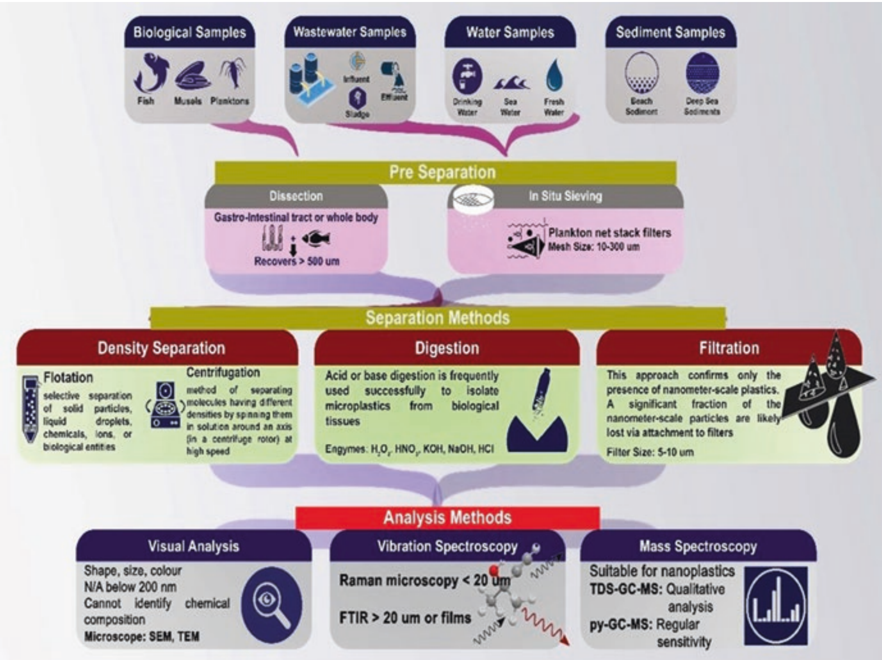

Fig. 2 Techniques for separation and analysis of microplastic and nanoplastic particles

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

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

5 Nanoplastics as a Contaminant

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

6 Ecological Impact and Toxicity

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

6.1 Impact on Marine Organisms

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

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

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

6.2 Human Health

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

6.3 Impact on the Food Chain

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

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

7 Preventive Measures and Controlling Pollution

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

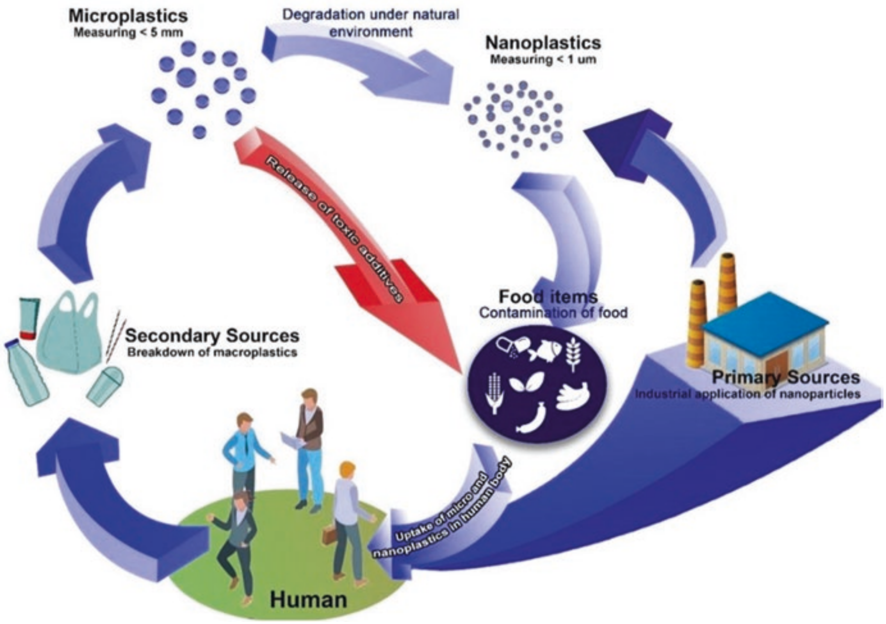

Fig. 3 Microplastic and nanoplastic particles are generated from different sources (primary as well as secondary) through consumer as well as industrial uses. These particles ultimately enter the food chain and drinking water sources, resulting in uptake and bioaccumulation of micro and nano plastic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

7.1 Strategies for Managing Nanoplastics

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

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

7.2 Policies and Regulations

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

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

8 Conclusion

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

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