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Microplastics in the environment: Sources, distribution, impacts, and mitigation strategies

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Abstract

The exponential growth of global plastic production has resulted in the pervasive presence of microplastics (MPs) across aquatic, terrestrial, and atmospheric environments. These particles, typically less than 5 mm in size, originate either as intentionally manufactured materials (primary microplastics) or as fragments generated through the degradation of larger plastic debris (secondary microplastics). Due to their small size, persistence, and complex chemical composition, microplastics readily bypass conventional waste and wastewater treatment processes, facilitating their accumulation in ecosystems worldwide. Of particular concern are microfibers released from synthetic textiles during routine laundering, which represent one of the most dominant sources of microplastic pollution. Once released, microplastics undergo physical, chemical, and biological transformations that influence their transport, aggregation, biofouling, and ultimate fate. These processes enable microplastics to act as vectors for toxic additives, persistent organic pollutants, and pathogenic microorganisms. Growing evidence indicates that exposure to microplastics poses significant risks to aquatic organisms, ecosystem functioning, and human health through ingestion, inhalation, and trophic transfer. This review synthesizes current knowledge on the sources, environmental distribution, transport mechanisms, ecological and human health impacts, and governance and remediation strategies related to microplastic pollution, highlighting critical research gaps and the urgent need for coordinated global action.

Keywords: Microplastics, Sources, human health, Aquatic environment, Microbeads

Introduction

Over the past decade, microplastics have emerged as a major environmental and public health concern worldwide. These microscopic plastic particles originate from diverse sources, including the degradation of synthetic textiles, discarded plastic products, and everyday consumer items such as soaps and facial cleansers. Due to their small size, microplastics are not efficiently removed by conventional water treatment and filtration systems, allowing them to persist and accumulate in aquatic and terrestrial environments [1]. The COVID-19 pandemic significantly intensified this issue by driving a sharp increase in the use of single-use plastic products, including face masks, gloves, and medical waste. This surge added to an already critical situation; in 2016 alone, approximately 19–23 million metric tons of plastic waste were discharged into oceans and freshwater systems [2]. Global plastic pollution has continued to escalate, largely due to the growing dependence on disposable plastic materials, particularly during and after the pandemic.

Municipal solid waste generation is projected to increase by nearly 70% by 2050, with plastic waste accounting for an increasingly large proportion. While plastics offer undeniable societal benefits, improper handling and disposal of plastic waste pose severe risks to ecosystems. The escalating impact of global plastic pollution represents one of the most significant environmental challenges facing humanity today. Aquatic organisms, including endangered polychaetes, crustaceans, zooplankton, and other marine biota, are particularly vulnerable to plastic debris and microplastics, leading to adverse effects on marine biodiversity [3]. Microplastics also contaminate organic waste–derived materials, facilitating their accumulation in soils. Urban terrestrial environments act as major sinks for microplastics due to surface runoff, industrial discharges, and inefficient waste management practices. Street dust—composed of debris from construction activities, discarded waste, tire abrasion, and road wear—serves as an additional source of microplastics to adjacent soils and aquatic systems. Furthermore, the laundering of synthetic textiles releases large quantities of microfibers into wastewater, which subsequently enter terrestrial and aquatic ecosystems.

Microplastics pose a particularly severe threat to marine ecosystems (Figure 1). Numerous studies have demonstrated that these particles disrupt reproductive processes in marine organisms, leading to reduced fertility and declining population sizes [4]. Acting as endocrine disruptors, microplastics interfere with hormonal signalling pathways essential for normal reproductive function.

Fig 1 Shows how microplastics get created, move around, and end up inside living things—basically, how they spread through the whole ecosystem. Everyday activities—like tossing out trash carelessly or relying on poor waste systems—let microplastics leak out into the environment. These tiny bits of plastic work their way into all kinds of foods and end up in animals, and even people, as they climb the food chain. Microplastics come from all sorts of sources: broken-down plastic litter, industrial waste, paint flakes, road markings, tire dust, and even stuff as ordinary as face wash and toothpaste. Microfibers released from synthetic textiles represent a major and often underestimated contributor to global microplastic pollution. Routine laundering of garments leads to the shedding of large quantities of microscopic fibres, which subsequently enter wastewater streams and the environment. This review synthesizes existing research on microfiber release from textiles, with particular emphasis on washing-related emissions. It is estimated that approximately 80% of microplastics originate from land-based sources, including domestic activities, while the remaining 20% are derived from marine sources. Owing to their low density, high durability, and distinctive morphological characteristics, microfibers are readily transported over long distances, facilitating their widespread global distribution. Microplastics are ubiquitously present in terrestrial ecosystems as a result of daily human activities, with land-based environments serving as the primary sources and transport pathways for microplastics entering marine systems [5]. Microplastics are now detected throughout the world's oceans, including coastal beaches, seabed sediments, surface waters, rivers, lakes, and polar sea ice in both the Arctic and Antarctic regions. Their dispersion is largely governed by ocean currents and atmospheric transport processes. Beyond aquatic systems, microplastics have also been identified in the atmosphere and within both indoor and outdoor environments. Sea ice, in particular, has been shown to act as an effective sink for microplastic fibres, concentrating them in polar regions.

The physical, chemical, and biological weathering of plastics leads to material embrittlement, resulting in fragmentation into progressively smaller particles, ultimately forming microplastics. These particles are readily transported through water, air, and food webs, enabling their accumulation across diverse ecosystems and disrupting ecological processes. In marine environments, microplastics interfere with trophic interactions, alter predator–prey dynamics, and serve as vectors for the long-range transport of chemical contaminants and pathogenic microorganisms, thereby threatening biodiversity and ecosystem stability [6]. Microplastics readily adhere to microalgae such as Chlorella, Scenedesmus, and Skeletonema costatum, obstructing light penetration and gas exchange, which can inhibit photosynthetic activity and primary productivity. Assessing the ecological impacts of microplastics and associated chemical contaminants constitutes a central objective of the European Union's Marine Strategy Framework Directive (MSFD 2008/56/EC). This directive emphasizes the need to identify the sources, sinks, and governing mechanisms that control the spatial distribution and ecological accumulation of microplastics (μPs) in marine environments.

Sources of Microplastics

Primary Microplastics

Primary microplastics are intentionally manufactured particles designed for specific applications. These include microbeads in personal care products, industrial abrasives, resin pellets (nurdles), and plastic-based glitter.

Microbeads

Several cosmetic and personal care products, including facial cleansers, toothpastes, and exfoliating formulations, incorporate microbeads composed of synthetic polymers such as polyethylene, polylactic acid (PLA), polypropylene, polystyrene, and polyethylene terephthalate (PET). These plastic microbeads have largely replaced natural exfoliating materials, including ground almond shells, walnut shells, cellulose, oatmeal, and pumice. In addition to personal care products, microplastics are also utilized as abrasive agents in certain industrial cleaning applications [7]. Following consumer use, microbeads are discharged directly into domestic wastewater systems and are insufficiently removed during conventional wastewater treatment processes, allowing them to enter rivers, lakes, and marine environments. Consequently, microbeads represent a direct and significant source of microplastic pollution in aquatic ecosystems. It has been estimated that a single tube of exfoliating facial cleanser can release more than 350,000 microbeads into the environment. On a larger scale, Rochman *et al.* (2015) reported that wastewater treatment plants in the United States collectively discharge approximately 8 trillion microbeads into aquatic systems each day [8]. Similarly, Murphy *et al.* demonstrated that an individual wastewater treatment facility in Scotland may release up to 65 million microbeads daily, underscoring the substantial and continuous contribution of these particles to environmental microplastic accumulation.

Nurdles

Nurdles, also known as plastic resin pellets or colloquially as "mermaid tears," are small spherical or cylindrical plastic particles typically ranging from 1 to 5 mm in diameter. They serve as the primary raw material for the manufacture of most plastic products. Despite their industrial importance, nurdles are frequently released into the environment at multiple stages of the plastic production chain, including manufacturing, storage, transportation, and processing into finished goods [9].

Environmental accumulation of nurdles has been ongoing since the expansion of large-scale plastic production in the 1940s; however, their ecological significance did not receive substantial scientific attention until the 1970s. Global estimates indicate that approximately 230,000 metric tons of nurdles are unintentionally released into the environment each year, highlighting their widespread and persistent nature (Sherrington, 2016). Localized pollution events can result in particularly severe contamination. For instance, surveys conducted in September 2018 reported densities ranging from 300,000 to over one million nurdles per mile along Mustang Island and North Padre Island, Texas. These exceptionally high concentrations were attributed to offshore nurdle spills during transportation, illustrating the substantial environmental risks associated with pellet loss during industrial handling.

Plastic based Glitters (PBG)

Plastic-based glitter consists of microscopic, highly reflective particles that are typically brightly colored and visually lustrous. Although decorative glitter has been used in cosmetics and art since ancient times—historically derived from natural materials such as mica flakes and mineral pigments, including those used in early cave paintings—synthetic plastic-based glitter is a relatively recent innovation. It was first developed in 1934 by Henry Ruschmann [10]. Modern plastic glitter is manufactured by coating a thin aluminum layer onto a polymer substrate, most commonly biaxially oriented polyethylene terephthalate (BoPET), followed by the application of color coatings. The characteristic iridescence of glitter is achieved through controlled deposition of titanium dioxide (TiO_2) layers of varying thicknesses, which selectively reflect light to produce a wide spectrum of colors. Glitter particles are typically as small as 0.15 mm and are produced in diverse shapes, sizes, and color variations.

The widespread adoption of plastic-based glitter accelerated during World War II, when it replaced traditional glass-based glitter due to its lower cost, enhanced durability, and ease of production. Since then, its use has expanded substantially across numerous sectors, including cosmetics, printing inks, adhesives, textiles, fashion accessories, footwear, jewellery, and craft materials. The growing popularity of these applications has led to a continuous increase in the production and environmental release of plastic-based glitter, raising concerns regarding its contribution to microplastic pollution.

Sources of Secondary Microplastics

Secondary microplastics are generated through the fragmentation and degradation of larger plastic debris in the environment.

Table 1: Categories of plastic particles

Particle Category	Diameter range (mm = millimetres)
Nanoplastics	< 0.0001 mm (0.1µm)
Small microplastics	0.33 – 1 mm
Large microplastics	1.01– 4.75 mm
Mesoplastics	4.76 – 200 mm
Macroplastics	>200 mm

Eriksen (2014) investigated this process in marine ecosystems and classified plastic particles into four distinct size categories (Table 1). By examining the progressive breakdown of macroplastic items into smaller fragments, the study provided a detailed framework for understanding the fragmentation pathways and size distribution of secondary microplastics (Figure)

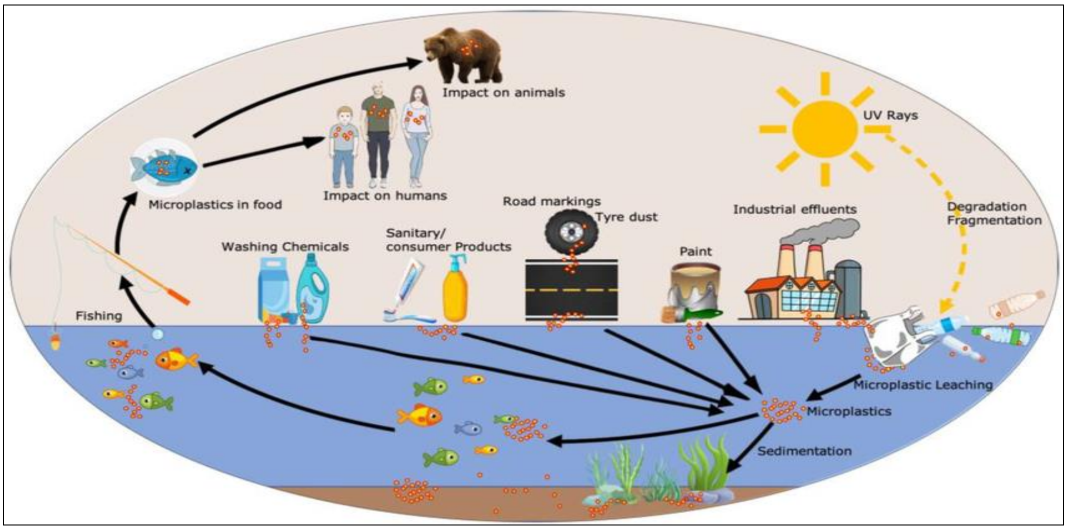

Fig 1: Pathways and Sources of Microplastic Pollution: From Environmental Release to Bioaccumulation in the Food Chain

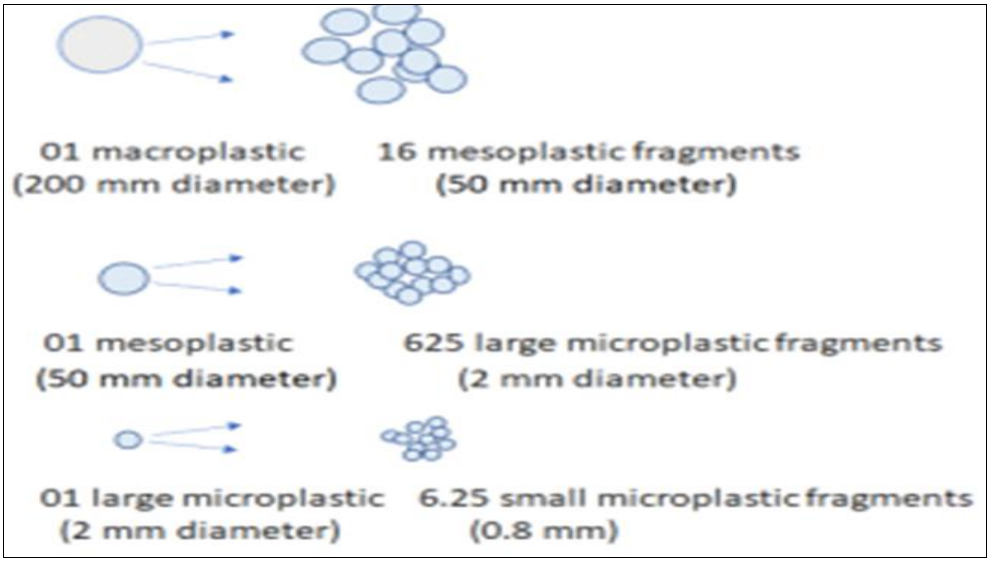

Fig 2: Fragmentation of Macroplastics into Microplastics: Size Reduction Pathways and Processes

Synthetic Textile

In 2004, Thompson *et al*. reported the presence of fibrous microplastics approximately 20 µm in diameter in marine environments, providing early evidence of microfiber contamination in the oceans. Subsequent research by Napper and Thompson (2016) [18] demonstrated that the laundering of synthetic textiles, including polyester and nylon fleece garments, releases substantial quantities of microplastic fibers into wastewater systems. Their findings indicated that up to 1,900 microfibers can be shed during a single washing cycle, many of which ultimately enter rivers and marine environments [11]. These textile-derived microfibers are predominantly composed of synthetic polymers such as polyester, polyethylene, acrylic, elastane, and polyamide.

Wear and tear of vehicle tiers and brake wear

Tire wear particles are generated through the mechanical abrasion of vehicle tires against road surfaces during normal use. The chemical composition of these particles varies according to the formulation of the original tire materials, which include complex mixtures of synthetic rubbers and additives. Due to their widespread release and persistence, tire wear particles have been described as omnipresent microplastics in the environment. Emissions arise from multiple transportation sources, including passenger vehicles, heavy-duty trucks, and aircraft, and are further compounded by brake wear, collectively constituting a major source of environmental microplastic pollution [12]. Global estimates suggest that approximately six million metric tons of tire wear particles are generated annually, underscoring their substantial contribution to overall microplastic emissions. Evidence of their long-range environmental transport is supported by the detection of synthetic rubber and styrene–butadiene rubber residues in surface waters of Jinhae Bay, South Korea, as well as in marine sediments from Terra Nova Bay, Antarctica. Despite growing recognition of their environmental prevalence, the mechanisms governing the transport pathways of tire-derived microplastics from road surfaces into freshwater and marine systems remain insufficiently understood and are the subject of ongoing research.

Degradation of plastics

Human activities, the shape of the land, and how water moves around all play a part in how microplastics (MPs) travel. These tiny plastics don't just float around harmlessly they pick up toxic chemicals, both inorganic and organic, and carry them through the environment. When those chemicals finally leach out, they make the plastics even more dangerous for living things. Depending on their size and what they absorb, these broken-down plastic bits can float on the surface, drift through the water, cling to marine snow, or sink all the way to the sea floor. That means almost every creature in the water can end up exposed to them, and in the end, these plastics creep into food systems and hit human health too. Most of the time, sunlight specifically UV rays drives the breakdown of plastic waste in nature [13]. UV light triggers photooxidation, which breaks plastics into smaller and smaller pieces by releasing monomers and oligomers. So, plastic pollution doesn't just stick around; it keeps breaking down and spreading, becoming harder to deal with over time. Smaller pol break down more easily, so they're more likely to biodegrade [14]. Here's what happens: plastic polymers first break apart into their monomer, those monomers eventually get mineralized.

Microplastics (MPs) pile up from all sorts of places, but in the end, most of them land in the ocean. Plastics from land or rivers wash downstream, and the ocean ends up as the final dumping ground. Most common plastics like polyethylene (PE), polypropylene (PP), polystyrene (PS), PET, PVC, polycarbonate, and so on aren't just pure polymer. Manufacturers mix in additives like bisphenol A (BPA), phthalates, and PBDEs. These additives don't actually bond with the plastic at the molecular level, so when the plastic breaks down, they leach out. This constant mix of polymers and free-floating additives picks up all kinds of organic materials and contaminants from the environment, creating what's called an "eco-corona." Basically, it's a complex layer that forms between MPs and whatever organic stuff is around. This layer changes how toxic and available these plastics are to living things. The eco-corona also affects how bacteria stick to the surface. It helps form a thin film a biofilm on the plastic. That changes how the plastics interact with everything else in the water. How quickly MPs and NPs settle really comes down to biofouling and what kind of polymers they're made from. Out in the ocean, plastics break down thanks to physical, chemical, and biological forces. For plastics, oxygen and sunlight do most of the heavy lifting photodegradation works best [15]. That's why beaches, with all that sun and exposure, see plastics break down the fastest. Floating plastics in the ocean don't degrade as quickly as those on land. A big reason? Marine organisms build a thin film on the surface, blocking sunlight. Plus, the water's cooler than land, which slows things down even more [15]. Dive deeper into the ocean, and it gets worse: colder temperatures and a lack of UV rays mean plastics degrade at a crawl.

Sources of Microplastics in Aquatic Environments

Microplastic pollution originates from a wide range of manufactured materials and enters aquatic environments through both direct and indirect pathways. In some cases, plastics are deliberately or accidentally discharged directly into rivers, lakes, and marine systems. More commonly, microplastics are transported via surface runoff, stormwater drains, wastewater effluents, and atmospheric deposition, collectively contributing to what is commonly referred to as marine debris or litter. Microplastics entering aquatic environments are generally classified into two categories: primary and secondary sources. Primary microplastics include microbeads, microfibers, and resin pellets that are intentionally produced at microscopic sizes or unintentionally released during industrial processes [16]. These originate from industrial discharges as well as the degradation of consumer products such as plastic boards, tires, and wheels. Secondary microplastics, in contrast, are generated through the progressive fragmentation of larger plastic items under the influence of biophysical and biochemical processes, including biodegradation, thermal stress, oxidation, ultraviolet radiation, and mechanical abrasion.

A substantial proportion of microplastics entering marine environments originate from land-based activities. These include improperly managed coastal waste, untreated sewage discharges, agricultural runoff, tourism-related litter, and recreational beach activities. In regions lacking adequate waste management infrastructure, a diverse array of materials—including plastics, glass, metals, paper, rubber, and textiles—are frequently discarded into coastal and marine environments. As coastal populations and tourism increase, the volume of waste entering the marine environment correspondingly escalates. Many synthetic polymers exhibit low densities and remain buoyant, enabling them to float, disperse with ocean currents, and periodically re-strand along shorelines [17]. Marine-based sources also contribute significantly to microplastic pollution. These include discarded, lost, or abandoned fishing gear, waste generated by shipping activities, and accidental releases during maritime transport. With approximately 600,000 shipping containers transporting goods globally, the potential for plastic loss during shipping operations remains substantial. The issue is particularly pronounced in developing countries, where insufficient waste collection and treatment infrastructure leads to increased plastic leakage into aquatic systems.

In addition to anthropogenic activities, natural events play a critical role in transporting plastic debris into marine environments. Extreme weather events such as storms, floods, heavy rainfall, and tsunamis can mobilize vast quantities of land-based plastic waste and deliver it to the ocean. The 2011 Japanese tsunami, for example, released an estimated five million metric tons of debris into the marine environment in a single event. The accumulation of plastic debris in aquatic systems has far-reaching socioeconomic consequences, including the degradation of fisheries, losses in tourism revenue, and reduced access to natural resources for coastal communities [18]. Furthermore, cleanup efforts impose substantial financial burdens, with governments and local communities spending millions annually on waste removal, while the degradation of marine ecosystem services results in economic losses amounting to billions of dollars globally.

Distribution processes

1. Biofouling

Biofouling is what happens when layers of organisms start piling up on things underwater, like shown in Fig.3.The whole process really depends on the type of polymer, the size and roughness of the microplastic (μP) particles, and even the energy of their surface. Where the plastic sits in the water column and how productive the surrounding seawater is also playing a big role. On plastics floating at the surface, biofouling kicks in pretty quickly just a few days or weeks. But if the plastics are deeper underwater, the buildup takes longer. At first, the μP particles get coated with dissolved organic molecules, bacteria, algae, larvae, and spores. All this form a sticky biofilm, sometimes called a 'conditioning film' [19], which then attracts more life things like invertebrates and microalgae, including tubeworms, hydroids, and mussels. As more stuff piles on, the particles get heavier. Once they're denser than seawater, they sink.

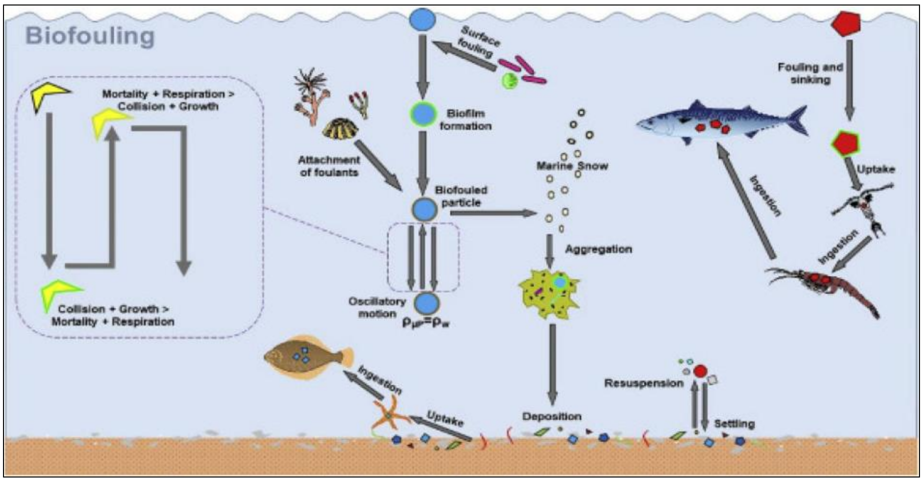

Fig 3: Schematic Representation of Microplastic (μP) Biofouling and Its Environmental Interactions

Seawater density increases with depth in the ocean, causing sinking particles to accumulate at depths where their density equals that of the surrounding water column [20]. When the density of a microplastic particle differs from ambient seawater, it undergoes vertical oscillatory movement. This motion is strongly influenced by biological processes occurring on the particle surface, particularly the growth, collision, mortality, and respiration rates of attached microorganisms [20].

Observational and experimental studies indicate that microplastic particles tend to reach their maximum sinking depth around midday, when microbial growth and collision rates exceed mortality and respiration. During nighttime, the balance shifts, with increased microbial mortality and respiration leading to a reduction in particle density and subsequent upward movement. Incubation experiments further demonstrate that prolonged exposure of initially buoyant microplastics to biofouling accelerates their sinking velocity over time. These findings underscore the critical role of biofouling in controlling the vertical transport and sinking behavior of microplastics, largely independent of polymer type.

2. Aggregation

Oxygenated marine aggregates, composed of fecal pellets, phytoplankton, microorganisms, and particulate organic matter, are ubiquitous in oceanic environments. Concentrations of these aggregates can reach up to approximately 5,300 particles per litre of seawater [21]. They play a crucial role in the vertical transport of both inorganic and organic materials from surface waters to deeper ocean layers and significantly influence the sinking behavior, bioavailability, transport pathways, and ultimate fate of microplastics (μPs) in marine systems.The aggregation of μPs is illustrated in Fig.4.Aggregation refers to the process by which particles—including microplastics, living cells, detrital organic matter, and mineral particles—collide and adhere to one another, forming larger composite structures. A key mediator of this process is the presence of Transparent Exopolymer Particles (TEPs), which are gel-like substances formed through the coagulation of extracellular polymeric substances (EPSs). These EPSs are primarily produced by microorganisms such as phytoplankton, algae, and bacteria and exhibit strong adhesive properties that facilitate aggregation [22]. Microorganisms involved in EPS production frequently colonize microplastic surfaces during biofouling, thereby linking biofouling and aggregation processes. Although microplastics may aggregate due to hydrophobic interactions, this mechanism is relatively limited under natural conditions, as natural colloids are far more abundant than microplastics and therefore dominate aggregation dynamics in marine environments.

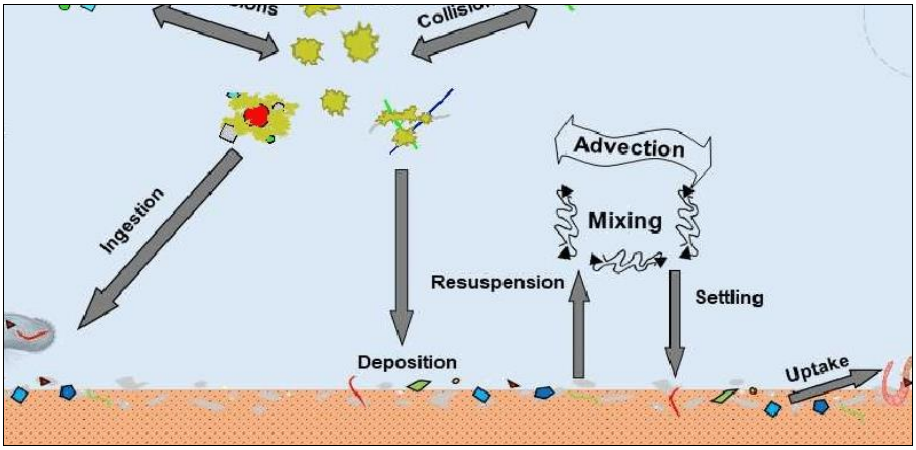

Fig 4: Schematic Illustration of Microplastic (μP) Aggregation Processes in Aquatic Environments

Marine aggregates readily incorporate microplastics, with studies indicating that approximately 73% of sampled aggregates contain microplastic particles [23]. Sinking experiments have demonstrated that these aggregates are highly effective in transporting microplastics through the water column, including buoyant polymers such as polypropylene and polyethylene, to deeper ocean layers and the seafloor. Transport via aggregation occurs at significantly higher rates compared to the sinking of individual microplastic particles or transport driven solely by biofouling processes. This enhanced downward transport is attributed to the substantially greater density of aggregates relative to individual microplastic particles, resulting in sinking velocities that can reach several hundred meters per day.

Effects of exposure to microplastics

Relatively few studies have comprehensively evaluated the toxicity of microplastics to aquatic organisms, and significant uncertainties remain regarding the underlying mechanisms of their effects [24]. The extent of biological impact is influenced by several factors, including the degree of microplastic accumulation within organisms, the specific tissues or organs involved, the efficiency of elimination processes, and the potential for trophic transfer through the food web.

1. Effects of microplastic ingestion

Despite increasing evidence that numerous aquatic organisms are capable of ingesting microplastics, the effects of microplastic exposure on aquatic biota remain only partially understood. It is still unclear whether microplastics exert effects on small aquatic organisms comparable to those caused by macroplastics in larger species, such as physical obstruction, entanglement, or internal tissue damage. Consequently, considerable uncertainty persists regarding the ecological consequences of microplastic ingestion at lower trophic levels. Recent research has increasingly focused on primary producers, particularly microalgae, due to their fundamental role in aquatic ecosystems. Experimental exposure of Scenedesmus obliquus to polystyrene nanoparticles (nano-PS) for 72 hours resulted in inhibited growth and a significant reduction in chlorophyll-a content [25]. Similarly, the adhesion of microplastics to algal species such as Chlorella and Scenedesmus has been shown to impair photosynthetic activity and increase the production of reactive oxygen species, likely as a result of reduced light penetration and interference with carbon dioxide and nutrient uptake.

Furthermore, trophic transfer studies indicate that when microplastic-exposed algae are consumed by higher organisms, reductions in algal growth and chlorophyll content are further amplified, suggesting potential cascading effects within aquatic food webs. Although such impacts on algal populations may be advantageous in systems experiencing algal overgrowth, adverse effects on primary producers can disrupt energy flow and nutrient cycling, ultimately destabilizing aquatic food chains.

2. Microplastic-associated contaminants

Plastics often contain a variety of additives, with phthalates—commonly associated with PVC—being among the most prevalent. The exchange of contaminants or additives between microplastic particles and the surrounding water depends on several factors: the concentration gradient, the type of medium the microplastics are in, the chemical and physical characteristics of the plastic, and the degree of degradation over time. Smaller additives tend to leach out quickly from plastics [26]. Regarding chemicals, they typically adhere to the softer, non-crystalline regions of the plastic. One study reported that phenanthrene and 4,4'-DDT reached their sorption capacity on plastics in less than 24 hours. Interestingly, when new plastic pellets were deployed in the environment, they absorbed fewer contaminants such as PCBs, DDE, and nonylphenols over six days compared to older, weathered pellets from the same location. Aged plastics tend to retain more pollutants. In addition to the additives incorporated during production, microplastics can also adsorb other environmental pollutants. Due to their large surface area and hydrophobic nature, microplastics readily accumulate organic contaminants, including dichlorodiphenyltrichloroethane (DDT), polycyclic aromatic hydrocarbons (PAHs), polybrominated diphenyl ethers (PBDEs), and polychlorinated biphenyls (PCBs). These persistent organic pollutants (POPs) can adsorb onto microplastics at concentrations several orders of magnitude higher than in the surrounding water, thereby increasing exposure for aquatic organisms.

Because microplastics have a higher surface area-to-volume ratio than larger plastic fragments, they preferentially bind organic pollutants [27]. This property has led to the use of plastics as passive sampling tools for assessing POP concentrations in water, sediment, and biota. Low- and high-density polyethylene (PE), PVC, and polypropylene (PP) have all been employed as passive samplers due to their ability to concentrate hydrophobic contaminants. Sorption rates, however, depend on both the type of plastic and the specific contaminant. For instance, DDT has been shown to outcompete phenanthrene for adsorption onto PVC and PE. Studies comparing the sorption capacities of polystyrene (PS), PE, and PP for PAHs, hexachlorohexanes, and chlorinated benzenes found that their capacities are generally within one order of magnitude for most compounds. Notably, PS adsorbs most chemicals more effectively than PE or PP, except for highly hydrophobic PAHs. Among PAHs and benzenes, PE retains more than PP, whereas PP outperforms PE for hexachlorohexanes [28]. Another study revealed that nano-PS exhibits strong adsorption for planar PCBs, with 17 different PCBs binding more to nano-PS than to micro-PE or organic matter in sediments. Salinity typically does not significantly affect the adsorption of most POPs onto plastics; however, for some contaminants, it can influence both the rate and extent of sorption. For example, increasing salinity was found to enhance the uptake of PCBs by nano-PS and micro-PE, while the binding of these compounds to sediment organic matter decreased.

3. Adverse effects on human health

Humans are primarily exposed to microplastics through inhalation, ingestion of contaminated food and water, or skin contact. While most microplastics cannot penetrate the skin, very small particles may enter through hair follicles or sweat glands [29]. In the case of skin exposure, the concern is generally more about chemicals such as BPA and phthalates that leach from everyday plastics rather than the microplastic particles themselves. Seafood is another major source of exposure. Consumption of mussels, oysters, and even sea salt can introduce microplastics into the human body, raising significant food safety concerns [29]. Microplastics can impact human health in several ways: through the particles themselves, via the chemicals they carry, or by serving as carriers for bacteria and parasites. Although the full extent of their interactions with the human body is still under investigation, current studies indicate potential harm to the lungs and gastrointestinal tract.

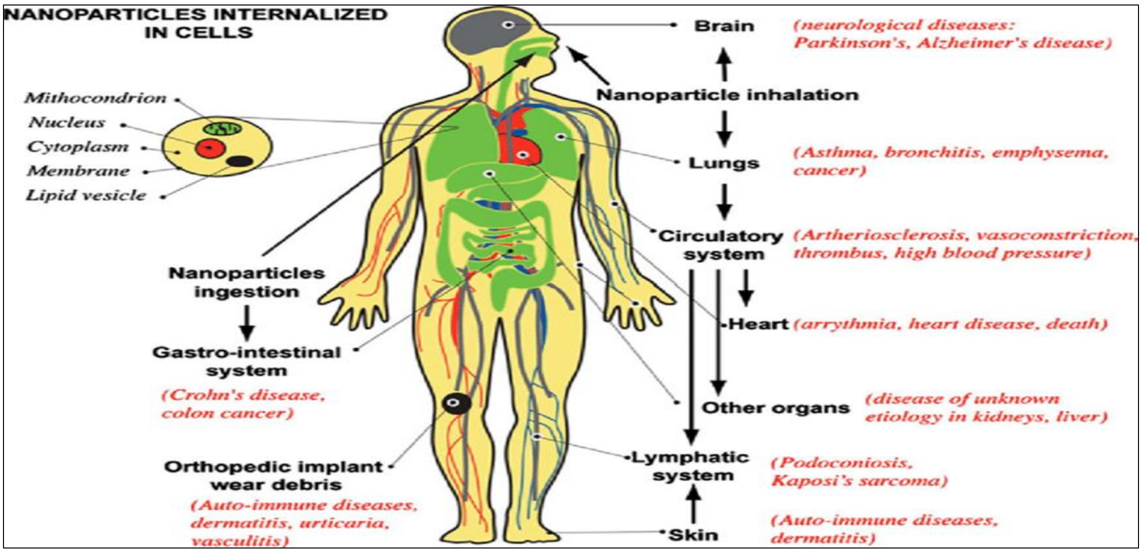

Fig 5: Circulation Pathways of Micro- and Nanoplastic Particles within the Human Body

The smallest microplastic particles are capable of crossing cell membranes, penetrating the blood-brain barrier, and even reaching the placenta. Once inside the body, they can induce oxidative stress, inflammation, cellular damage, and disrupt normal energy metabolism [30]. Garrett and colleagues have mapped the circulation of nano-sized particles throughout the body, providing insight into their distribution, although much remains to be understood. When ingested, microplastics follow a relatively specific path through the body (see Fig. 5). They are absorbed from the gut into the bloodstream primarily via microfold cells located in the gut-associated lymphatic tissue. Once in circulation, the particles can accumulate in organs such as the liver and gallbladder and may be returned to the intestines through bile. Notably, microfibers, due to their elongated shape, can pose greater risks than other forms of microplastics, as their behavior in the body differs from that of spherical particles.

Inhaled microplastic particles interact with immune cells in the respiratory system, triggering inflammatory responses through oxidative stress and the activation of proteases and cytokines [30]. Prolonged inflammation may damage DNA and contribute to carcinogenesis by promoting malignant cell formation. Additionally, tiny plastic particles often carry various chemicals that can penetrate cell membranes, facilitating the entry of these substances into cells in a manner analogous to nano-sized drug delivery systems. Bisphenol A (BPA), a common chemical in polycarbonate plastics and protective coatings of food containers, is a notable concern. BPA is an endocrine disruptor that interferes with hormone signaling [31]. Studies by Acharya and others have shown that BPA alters alpha- and beta-adrenergic receptor activity in adipose tissue, disrupting fat metabolism and increasing the risk of metabolic disorders such as heart disease and diabetes. BPA also affects the cardiovascular system and inhibits estrogen receptor function at both the genetic and cellular levels, weakening estrogen's protective effects against colon cancer. Consequently, women exposed to BPA have a higher risk of developing colon cancer, and BPA exposure has been linked to increased risks of breast and prostate cancers. Microfibers can also serve as carriers for harmful microorganisms and parasites. In wastewater, pathogens form resilient biofilms on the surfaces of these fibres. When these microfibers enter water bodies, they can release the pathogens, increasing the risk of human exposure through bathing or drinking water. Despite these concerns, there is still a lack of comprehensive studies, and the full health risks of ingesting or inhaling microplastic particles remain incompletely understood.

4. Impacts of Microplastics on the Environment

Microplastics are a real problem for marine life and other ecosystems. Tiny creatures and big ones alike end up eating these bits of plastic, mistaking them for food. Once inside, the particles pile up and start causing trouble blocking digestive tracts, damaging organs, and making animals feel full without giving them any real nutrition. That kind of constant "fake fullness" can leave them malnourished. It doesn't stop there. Microplastics mess with reproduction, too, so populations start to drop. There's even evidence that these plastics change how animals behave and function some can't swim as well, and they get picked off by predators more easily. But it's not just the oceans. Microplastics get into soil as well. When they do, they mess with how the soil holds water and disrupt the way nutrients move around [32]. So, the problem spreads far beyond the sea. Microplastics are causing real trouble in freshwater ecosystems. They mess with the food web and put aquatic life at risk. The problem doesn't stop with fish and other animals these tiny plastics can end up in the food chain, so people who eat seafood or drink contaminated water can be exposed too. There's even some evidence that microplastics affect air quality, though honestly, scientists still have a lot to figure out there. What's clear is that microplastics are hitting ocean life and other environments harder than ever. We need to do more to stop them from getting into the water in the first place, and we've got to find better ways to clean them up. It's not just the environment that pays the price. The fishing and tourism industries take a hit too. As microplastics build up in fish and shellfish, their quality drops, which drags down their value at the market. People start worrying about the safety of seafood, and that makes things even tougher for folks who depend on fishing for a living. Tourism takes a hit from microplastics too, not just the fishing industry [33]. Think about it coastal tourism depends on clean beaches and healthy oceans. When microplastics show up, they mess with the natural beauty and even the ecosystem itself. No one wants to vacation on a polluted beach, right? That means fewer tourists and less money for local businesses. Honestly, it's time to step up our game. Cutting down on plastic waste and fixing how we manage trash goes a long way in keeping microplastics out of the ocean. There's also some real progress with new tech that pulls microplastics out of the water. All of this helps protect jobs and communities that count on fishing and tourism. The stakes are high, and we can't afford to ignore the problem or put off solutions any longer.

Governance Approaches and Management Practices for Microplastics' Pollution

Microplastic pollution is now ubiquitous in the world's oceans, posing significant challenges for management and mitigation [34]. These small plastic particles not only disrupt marine ecosystems and habitats but also threaten the resources that coastal communities rely on. The issue transcends national boundaries, evolving into a global concern that demands urgent and coordinated action. Addressing it effectively requires collaboration among nations, organizations, and stakeholders worldwide.

1. Governance Approaches to Microplastics' Pollution

Numerous strategies exist to reduce plastic use and prevent it from contaminating our oceans. In recent years, microplastics have garnered increasing attention from both scientists and the public. However, there remains a significant gap in comprehensive policies and coordinated action to address the issue. Current global efforts have often been fragmented and insufficient. To achieve meaningful progress in sustainable ocean governance and meet the 2030 Sustainable Development Goals, urgent and focused action on microplastics is essential. The United Nations Environment Assembly recognizes the severity of the problem and has called for stronger measures to prevent microplastic pollution, encouraging countries to implement robust national and regional strategies for managing marine litter. The Sustainable Development Goals emphasize that microplastic pollution is not merely an environmental issue—it is an environmental justice concern [35]. Microplastics threaten biodiversity, disrupt livelihoods, and compromise critical resources that communities rely on worldwide. Addressing this challenge effectively requires coordinated policy action, as it is fundamental to protecting both life and fairness on a global scale.

2. Management of Microplastics and Plastic Debris

Efforts to improve the production and use of plastics are ongoing, with the goal of reducing pollution in our oceans. A widely recognized approach is the "3Rs": reduce, reuse, and recycle. Though simple, this concept has become a cornerstone in managing plastic waste. Conventional plastics, with their long, resilient carbon chains, resist natural degradation, making the 3Rs even more critical [36]. Lohr and colleagues describe this as a "circular economy," which moves away from the traditional linear model of "make, use, dispose" toward a system that keeps materials in continuous use. Upcycling—reusing materials to create products of higher value—is a key aspect of this approach. Product redesign and extended producer responsibility are also increasingly emphasized. Yet, challenges remain: open landfills and unmanaged dumpsites continue to accumulate plastic, much of which eventually enters the oceans during rainfall events. Recycling and reusing plastics are therefore essential to mitigating this flow of waste.

In recent years, chemical recycling has gained attention. This process breaks down used plastics into their chemical components, which can then be repurposed into new plastics with the same properties as the originals, without relying on virgin resources. Researchers are exploring multiple chemical recycling methods to optimize yield and create useful products from old plastics [67]. Another focus is the development of "green plastics," which are designed to degrade over time. Sustainable production strategies include replacing fossil-fuel-based feedstocks with plant-derived alternatives. Plant-based monomers can either replicate conventional polymers or serve as entirely new, biodegradable plastics. Substituting traditional plasticizers with bio-based chemicals, such as citrates, also reduces the chemical load in plastic production.

Zeolites have emerged as important catalysts in this context, facilitating the conversion of biological feedstocks into plastics. For instance, zeolites can convert lactic acid into lactide, a key precursor for polylactic acid (PLA) plastics, which are biodegradable [37]. The reaction's efficiency and selectivity depend heavily on the zeolite's internal pore structure, highlighting the importance of continued research and innovation. Addressing microplastic pollution effectively requires a combination of technological advancement, informed consumer behaviour, and strong policy frameworks. Public awareness and education are crucial: understanding the impacts of plastic pollution motivates better practices among manufacturers, policymakers, and consumers. Educational programs targeting children, as well as community workshops and beach clean-up events, can foster environmental stewardship from an early age [69]. Practical measures are equally important. Proper recycling programs for fishing nets and waste management at ports and harbours reduce contributions from commercial activities [38]. Regional initiatives to recover lost or abandoned fishing gear benefit both the economy and marine ecosystems by preventing bycatch and protecting wildlife [39]. Ultimately, everyone—from governments and businesses to local communities—must recognize the consequences of mismanaged plastic and microplastic waste and take coordinated action to address it.

Mitigation and remediation strategies

1. Policy and regulatory frameworks

Microplastics pose a significant threat not only to the environment but also to human health. Scientists and policymakers continue to explore strategies to reduce their prevalence [40]. European guidelines on plastic particles in cosmetics were established in response to growing concerns raised across multiple countries. This movement has expanded beyond Europe, with initiatives to eliminate microbeads gaining traction in South Africa, India, New Zealand, South Korea, France, and the United Kingdom [41]. However, microbeads in personal care products represent only a small portion of the broader microplastics issue. In January 2019, the European Chemicals Agency proposed a comprehensive ban on microplastics in products sold throughout the EU and EEA. Following years of studies, consultations, and expert reviews, the European Commission formally approved the regulation in April 2023. This legislation is now incorporated into the EU's REACH framework, aiming to reduce environmental microplastic pollution by restricting their use across a wide range of consumer and industrial products. China has also taken steps to address plastic pollution, banning most non-biodegradable plastic bags and limiting the import of foreign plastic waste, particularly in major urban areas.

2. Strategies pertaining to Technological solutions

Various strategies have been explored to remove microplastics from soil and water, including advanced oxidation processes (Table 2), photocatalysis, microwave-assisted degradation, and bioremediation [42]. For instance, in photocatalysis, plastic particles degrade and create hollow spaces around the catalyst, promoting oxidation. This process generates carbonyl and carboxyl groups, which subsequently undergo photooxidation to form volatile organic compounds, carbon dioxide, and water [43]. When an iron-based catalyst is combined with microwave treatment of shredded plastics, the process can produce hydrogen and predominantly carbon nanotubes within 30 to 90 seconds. Alternatively, photocatalysis using Nb_2O_5 can fully convert plastic waste into carbon dioxide while also generating acetic acid (CH_3COOH), simulating natural degradation pathways. Another approach, carbocatalytic oxidation using carbon nanotubes paired with hydrothermal hydrolysis, produces highly reactive radicals that effectively break down microplastics into harmless organic compounds. These compounds can then serve as carbon sources for algae, enabling complete mineralization of microplastics from water [44]. Membrane technologies are also employed to filter microplastics and nanoplastics from water. However, significant challenges remain, particularly in removing particles smaller than 100 micrometers, underscoring the need for more advanced and efficient remediation techniques.

Table 2: MP degradation by different AOPs

Type of AOPs	Parameters	MP type	Degradation rate
Photo-Fenton reaction	pH: 2; room temperature PS	PS	>99%
Photocatalytic degradation	pH: 3–10	HDPE, PE, PA, PP, and POM	NA
Persulfate-based AOPs	Temperature 160 °C	Facial cleaner MPs	Up to 50 wt%
Fenton reaction	pH: 3	PA6 and PS	25% for PA6, 22% for PS
Fenton, Photo-Fenton	pH: 3–7	LDPE, PP, PVC	LDPE degradation is 25 times higher than the mass of iron; PVC degradation is 11 and 15 time
UV-C/H2O2 and UV-C/ S2O8 2−	pH: 4–10	PS, PVC	NA

3. Microplastic remediation

Researchers have tried all sorts of ways to get rid of microplastics in soil and water things like advanced oxidation, photocatalysis, microwaves, and bioremediation (Fig:6.) Take photocatalysis, for example. In this process, plastic particles break down around the catalyst, which kicks off oxidation. First, you get carbonyl and carboxyl groups, which break down into volatile organics, CO_2, and water when exposed to light. It works well. If you switch to a microwave-assisted catalytic process and use an iron-based catalyst, you can turn shredded plastic into hydrogen and mostly carbon nanotubes in just half a minute to a minute and a half [45]. That's seriously quick. Photocatalysis with Nb_2O_5 goes a step further and can completely break down some plastics. There's a lot of talk about biodegradable plastics being safer than synthetic ones. Microorganisms find them easier to break down, so switching to biodegradable plastics and using microbes to degrade waste looks promising for tackling micro- and nanoplastic pollution. People have also pointed out that biodegradable microbeads, like chito-beads used in cosmetics, clean better than the usual polyethylene beads. Plus, they break down completely in soil, turning into CO_2, water, and biomass, and they don't harm plants. So, making better biodegradable plastics and engineering microbes to break down both regular and biodegradable plastics could really help clean up microplastic and nanoplastic pollution. It's a big step toward an environmentally friendly solution. Fig. 6 shows a possible way to remove these pollutants from the environment and support a biobased circular economy without losing the benefits that plastics bring. Plants both on land and in water pull microplastics and nanoplastics straight from their surroundings. Microbes aren't just bystanders either; they break these tiny plastic pieces down into things like carbon dioxide, water, and methane.

Some of these breakdown products actually end up feeding the plants. So, if we combine bioremediation with growing non-edible crops on land and algae in water, then use that plant material to make biodegradable plastics, we've got a solid approach to getting rid of microplastics and nanoplastics. People see biodegradable plastics as safer than the regular synthetic stuff. Microbes break them down more easily, so switching to these materials and letting microbes do their thing with plastic waste takes us another step closer to cleaning up microplastic pollution. There's more: biodegradable microbeads made from chitosan, used in cosmetics, actually clean better than the usual polyethylene beads. They also break down completely in soil, turning into harmless stuff like CO_2 and water, without hurting plants. In the end, the real game-changer is developing biodegradable plastics and engineering microbes that can quickly turn both traditional and biodegradable plastics into harmless minerals [46]. That's the key to dealing with microplastics and nanoplastics for good, making the whole process a lot friendlier for the environment. There's even a diagram Fig. 7 that lays out this whole cycle, showing how we can get rid of these pollutants and keep the benefits of plastics, all while pushing forward a bio-based circular economy. Microorganisms break down MPs and NPs into things like CO_2, H_2O, and CH_4. Plants actually use some of these byproducts. So, if we combine bioremediation with growing non-edible plants on land and algae in water, then use that biomass to make biodegradable plastic, we get a real shot at cleaning up MP and NP pollution.

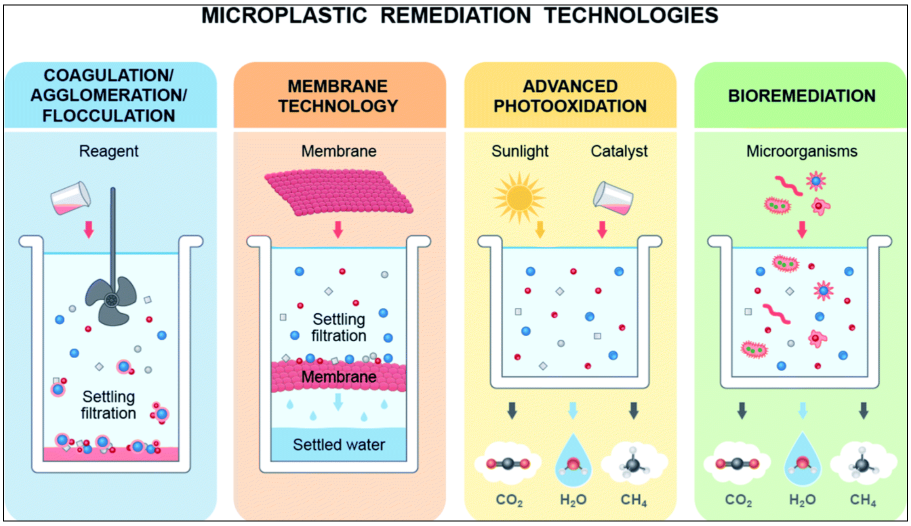

Fig 6: Overview of Current Technologies for Microplastic Remediation in Soil and Water

Kang and his team found a way to turn plastic waste into CO_2 in a lab setup that mimics nature, and they managed to make CH_3COOH without using a sacrificial agent. They noticed that when they combined carbocatalytic oxidation and hydrothermal hydrolysis on carbon nanotubes, it created really reactive radicals that broke down microplastics into harmless organic compounds. These compounds can actually feed algae, which then helps fully break down microplastics in water. People have tried using membrane technologies to tackle microplastic and nanoplastic pollution in water, but honestly, these methods still need work especially when it comes to filtering out particles smaller than 100 micrometers. Agglomeration and coagulation are other tricks to clump small plastics into bigger ones so they're easier to remove, but how well this works really depends on the size of the microplastics in the first place. Catalytic processes can turn plastics into nanocarbons or hydrocarbons, and while these methods help, they don't really solve the problem for microplastics and nanoplastics that are already spread throughout the environment in all shapes and sizes [47]. Here's something hopeful: scientists have found that microbes can clear out microplastics and nanoplastics from soil and water, no matter if the plastics are synthetic or biodegradable. The clean-up happens in four steps biodeterioration, biofragmentation, assimilation, and mineralization. First, exoenzymes like oxygenases chop up those long plastic chains and add oxygen, which turns them into things like alcohols, peroxyls, and carboxylic compounds. After that, microbes' step in and break down what's left, finally turning everything into harmless minerals.

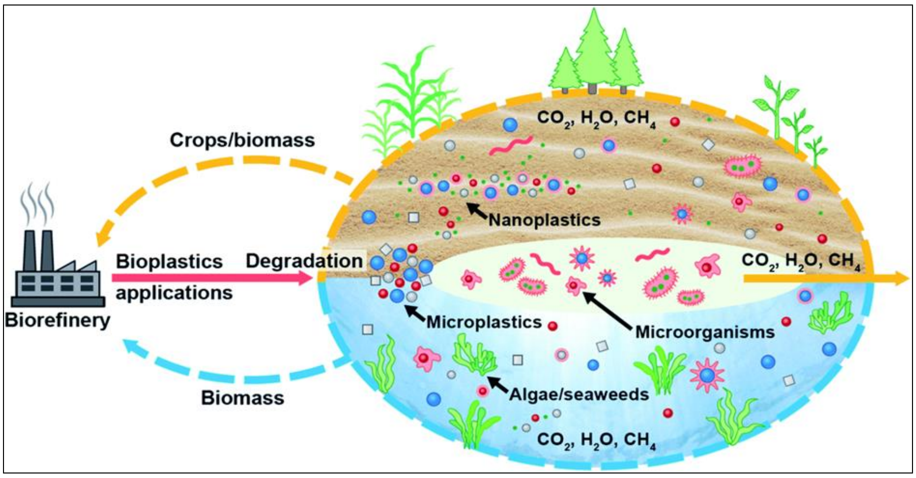

Fig 7: Potential Pathways for Microplastic Remediation and Recovery from Natural Ecosystems

Research has shown that earthworms, particularly Lumbricus terrestris, can contribute to the degradation of low-density polyethylene (LDPE). When these worms ingest LDPE, the size of microplastic particles decreases within just four weeks, demonstrating that earthworms can accelerate plastic breakdown. Biodegradable plastics are generally considered safer than conventional plastics because they are more readily degraded by microbes. Transitioning to biodegradable plastics and leveraging microbial degradation offers a promising approach to addressing microplastic and nanoplastic pollution [48]. For example, biodegradable microbeads such as chito-beads, used in cosmetics, perform cleaning functions more effectively than polyethylene microbeads and fully degrade in soil into CO_2, water, and biomass without harming plants. This highlights the potential of developing more biodegradable plastics and engineering microbes capable of breaking down both conventional and biodegradable plastics. Such strategies could transform plastic waste into harmless substances, contributing to environmental cleanup. Fig. 7 illustrates one approach for removing microplastics and nanoplastics from the environment while supporting a bio-based circular economy, maintaining the functional benefits of plastics. Plants in terrestrial and aquatic systems can absorb these tiny particles, while microbes convert them into CO_2, water, and methane, some of which can be utilized by the plants [49]. By integrating bioremediation with non-edible crops on land and algae in water, and subsequently producing biodegradable plastics from this biomass [50], it may be possible to significantly reduce microplastic and nanoplastic pollution in the environment.

Conclusions

Upon critical review it is observed that the density of polymers plays a key role in the initial distribution of microplastics in the ocean: lighter particles tend to float, while heavier ones sink. However, the presence of microplastics in deeper ocean layers is largely influenced by their interactions with marine organisms. Once released into the environment—whether clean, coated in biofilms, or incorporated into marine aggregates—it is crucial to quantify their abundance in each state and monitor their transitions over time. Microplastics are highly persistent and pervasive, accumulating at an accelerating rate. Their environmental impact is exacerbated by the adsorption of chemical pollutants, which become concentrated on their surfaces. Marine organisms, including fish, inadvertently ingest these particles, allowing both surface-bound contaminants and plastic additives to leach into their tissues. These chemicals can biomagnify through the food chain, ultimately reaching humans. Given the severity of this threat, coordinated global action is essential. However, strategies to address microplastic and nanoplastic pollution must be carefully evaluated for sustainability. Implementing solutions without thorough assessment risks causing unintended environmental harm and compromising long-term investments.

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