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Original Research Paper

Microplastic Pollution as a Driver of Immune Dysregulation in Marine Mammal Populations

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Key Words

Microplastics, Marine mammals, Immune dysregulation, Environmental pollution, Cytokine response, Oxidative stress, Polymer contamination, Trophic exposure.

Abstract

Introduction: Microplastic (MP) pollution is now an important environmental issue, especially in marine environments, where it endangers marine mammals. The bioaccumulation of MPs in the food web causes different biological effects on apex predators like the marine mammals. MPs have the capacity to disrupt immune homeostasis through oxidative stress, inflammation, and immune dysfunction. The review is a synthesis of existing studies on how MPs affect the immune systems of marine mammals and the pathways of the immune system dysregulation, i.e., oxidative stress, chronic inflammation, and cytokine imbalance. Materials and Methods: This review combines experimental toxicology, mechanistic research, and environmental evaluation regarding exposure to microplastics in the marine environment. It concentrates on the rodent, fish, and aquatic invertebrate models because they are related to marine mammal immune systems. Such important techniques as the measurement of oxidative stress, inflammatory cytokines, and immune function should be mentioned. Also, the review brings out the effects of movements of toxic chemicals such as heavy metals and persistent organic pollutants (POPs) by MPs, which aggravate the immune dysfunction of exposed organisms. Results and Discussion: MP exposure leads to the dysregulation of the immune system by way of elevated reactive oxygen species (ROS), diminished antioxidant defense, and stimulation of the inflammatory cytokines. The level of ROS increased up to 50%, cytokines such as TNF-α, IL-6, and IL-1β B were increased by 30-60% in experimental models. There is impaired lipid metabolism and gut microbiota in marine mammal models, which further impair the immune system. The MPs are also the transporting agents of heavy metals and persistent organic pollutants, which enhance the immune disruptions. Marine mammals are most prone to chronic exposure data whereby MPs are found in major body parts such as liver, gastrointestinal tract and lungs. Conclusion: The health of marine mammals is increasingly endangered by the microplastic pollution that causes dysregulation of the immune system and predisposes them to disease. Due to the long-term exposure and bioaccumulation of the marine ecosystems, additional studies on the immunotoxicology of MPs on marine mammals are critical to the effective conservation and mitigation measures.

Introduction

Microplastic (MP) pollution has become one of the key environmental threats worldwide due to the tremendous increase in the manufacturing of plastics and the continued existence of plastic debris in the water bodies and aquatic environments, as well as in land environments (Zantis et al., 2021; Rahim, 2025). The MPs (usually characterized as particles less than 5 mm) are either a result of the breakdown of larger plastics or a deliberate industrial output and are currently present in the ocean, sediments, and in the sea creatures, as well as the air (Punam & Patel, 2025). They are small, which determines bioaccumulation, trophic transfer, and biological barriers, resulting in their finding in vital organs

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of various species, including people and animals. The mechanisms of MPs are oxidative stress, inflammation, immune dysfunction, metabolic disruption, and tissue damage, where research has shown that they can be found in the liver, gastrointestinal tract, circulatory system, and other organs relevant to the immune system. Marine wildlife, which lies at the top of the trophic chains and relies on the food sources with plastic contamination, is especially susceptible to the immunotoxicity of MP. Although more and more people are aware of the problem of microplastic pollution, the role of MPs in the immune dysregulation of marine mammals is not properly researched (Nandy et al., 2025; Meaza et al., 2021; Engin et al., 2021). Toxicological studies that are currently increasingly available are mainly on fish, invertebrates, or human models. However, the pathways observed, such as chronic inflammation, oxidative stress, cytokine imbalance, and defective immune cells, are probably replicated in sea mammals owing to physiological volatility and excessive exposure (Li et al., 2022; Venkadeshwaran et al., 2025). The gap in knowledge is large in terms of the effects of MPs on immune health, disease vulnerability, and population stability in the long term in marine mammals. The purpose of this paper is to explore the route by which microplastics get into marine ecosystems and then accumulate in the tissues of marine mammals either through ingestion, inhalation, or trophic transfer (Philipp et al., 2022; Mattioda et al., 2023; Ferrante et al., 2022). It also examines mechanistic data based on current biological and toxicological research to comprehend the mechanism through which microplastics cause immune dysfunction, which involves such processes as oxidative stress, inflammation, and cytokine imbalance, as well as interference with the immune cell activity (Nelms et al., 2019; Cao et al., 2023; Palaniappan et al., 2022). Through synthesis of this mechanistic information, the paper establishes the possible health effects on the marine mammals, which include chronic inflammation, reduced immune response, and predisposition to infectious diseases and other physiological disorders. Furthermore, this paper points to the major knowledge gaps in marine mammal-specific immunotoxicology and the future directions of conducting scientific research, and provides information about conservation policies to reduce the effects of microplastic pollution on these endangered animals (Al-Rashid & Greaves, 2025; KC et al., 2023).

Key Contributions

- Offers a summary of the microplastic toxicology processes applied to the immunity of marine mammals.
- Combines results of the human, mammalian, and aquatic model research to conclude about immune effects on marine mammals.
- Illustrates the effects of MPs that cause oxidative stress, immune cell disorders, and inflammatory imbalance. Highlights the importance of MPs as vectors of toxic chemicals (POPs, heavy metals, endocrine disruptors) that increase the action of immunotoxins.
- Determines the major gaps in the research and suggests an outline for how future

marine mammal-based immunotoxicity will be conducted.

The rest of the paper is organized as Section 2: Materials and Methods describe the approach used to gather and analyze scientific studies on microplastic exposure, accumulation, and immune effects relevant to marine mammals. Section 3: Results and Discussion presents the key findings on microplastic entry pathways, mechanisms of immune disruption, and the resulting health impacts on marine mammals, along with identified knowledge gaps. Section 4: Conclusion summarizes the main insights of the review and provides recommendations for future research and conservation efforts.

Materials and Methods

Literature Sources and Selection Criteria

This review has its methodological basis in the scientific evidence evident in the given PDF materials. Such sources involve experimental toxicology studies, mechanistic studies, and environmental studies on microplastics (MPs). The literature segments that covered the exposure methods, detection methods, bioaccumulation, oxidative stress pathways, inflammatory responses, and immune disturbances were thoroughly reviewed. Researches involving mammalian and aquatic animals were given priority because of their significance to the immune physiology of marine mammals. Synthesized extracted methodologies enhanced a single description of conventional laboratory strategies to assess microplastic toxicity.

Experimental Exposure Methods

The study used a common model of controlled laboratory and exposure to evaluate microplastic toxicity on animals and cells. The most common method of replicating environmental exposure situations was with rodent models (mice and rats), fish species, and aquatic invertebrates. The microplastics were treated by oral gavage, polluted drinking water, dietary feeding, or inhalation chamber, allowing the assessment of dose response to be controlled. The duration of exposure was both acute (24-72 hours) and chronic (28 days and above) to evaluate the short-term and long-term physiological events. Endpoints, including oxidative stress induction, mitochondrial damage, alleviated cytokine production, impaired immune-cells, gut barrier damage, and liver inflammation, were measured with these models, and they are all pertinent indicators of immune dysregulation (Chong et al., 2022; Hussain & Taimooz, 2024).

Microplastic Detection and Characterization Techniques

Fourier Transform Infrared Spectroscopy (FTIR) and Raman spectroscopy were used to identify polymer types based on molecular vibration signatures. Laser Direct Infrared (LDIR) systems and high-resolution mass spectrometry methods (Orbitrap, FT-ICR) enabled the detection of nano-sized plastic fragments. Scanning Electron Microscopy (SEM) provided high-resolution visualization of particle shapes and surface structures. Field-Flow Fractionation (FFF) was employed for particle separation based on size, while X-ray microtomography and fluorescence microscopy allowed three-dimensional imaging of particles embedded within tissues. These techniques collectively enabled precise determination of microplastic presence, distribution, morphology, and chemical composition.

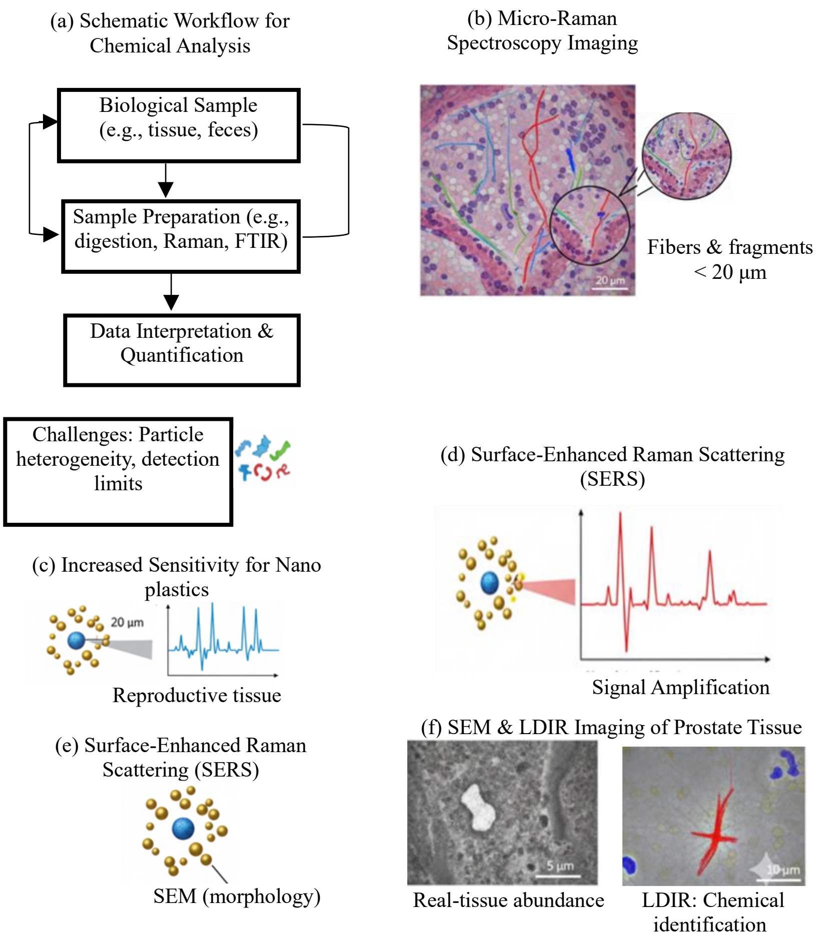

Figure 1: Analytical Techniques Used for Microplastic Detection

The key methods of the detection and characterization of microplastics in biological and environmental samples are presented in Figure 1. The first panel represents the typical workflow of an analytical process that starts with the digestion and filtration of the sample and continues with the chemical identification of the sample by FTIR or Raman spectroscopy. The second panel shows micro-Raman imaging applied as a method of identifying microplastic pieces in tissues. The third panel points out the use of Surface-Enhanced Raman Scattering (SERS) in the detection of nanoscale plastics. The last panel displays SEM and LDIR images displaying morphology of the particles and making sure polymer type in the human tissue specimens. Figure 1 explains the manner in which contemporary measurement tools can allow the proper identification of microplastics at both micro- and nano-scales. Chemical composition is determined using spectroscopic techniques, whereas structural details and visualization of interactions of particles with tissues are achieved with the help of microscopic and imaging methods. These are essential capabilities of bioaccumulation patterns, tissue penetration mechanisms, and potential immune-related effects of microplastics in marine mammals.

Biological and Immunological Assays

The toxicological experiments used in the PDFs used various assays to measure the biological reactions with exposure to microplastics. Oxidative stress was determined by reactive oxygen species (ROS) testing, lipid peroxidation testing, and antioxidant enzyme (SOD, CAT, and GPx) testing. The presence of inflammatory cytokines, such as TNF- a, IL- 6, and IL -1b, was measured by means of ELISA or gene-expression. The structural abnormalities due to MP accumulation were found in histopathological analysis of the liver, gut, and spleen, among others. Other tests were metabolomic profiling, gut microbiome sequencing, and the apoptosis or pyroptosis pathway. All these assays gave an understanding of immune activations, tissue damage, and systemic disturbances of the inflammatory system.

Data Integration and Interpretation

The information obtained about the methodologies employed to examine microplastic-induced immune effects was synthesized to formulate a consistent assessment of the methodologies. Despite the fact that the studies studied different species, the similarity of the mechanistic patterns was found among models, which included oxidative stress, chronic inflammation, dysfunction of immune cells, and pathology at the organ level. Conserved responses give a good basis for how similar mechanisms could occur in marine mammals exposed to microplastics in their natural habitats.

Results and Discussion

Pathways of Microplastic Entry and Tissue Accumulation

Microplastics (MPs) enter the marine ecosystem mainly by ingestion, breathing, and trophic transfer. Direct consumption of MPs of contaminated water, sediment, or food occurs in marine life, e.g., fish and mollusks. These particles move on to the food web where they accumulate in the organisms at higher trophic levels such as sea mammals. It has been indicated that MPs have the potential to penetrate biological barriers, including the gastrointestinal tract, and have been reported to be found in essential organs, including the liver, the spleen, and the lungs, with a size ranging between 1 and 100nm. The build-up continues in the long term and results in long-term exposure and a high risk of immune-related health effects.

Figure 2 presents a conceptual map of the distribution of microplastics in biological systems, with high frequencies indicating the concentration of the MPs in the tissues, which is directly proportional to the levels of exposure. These statistics reveal that MPs remain in the biological system and affect immune-controlling organs in the long term.

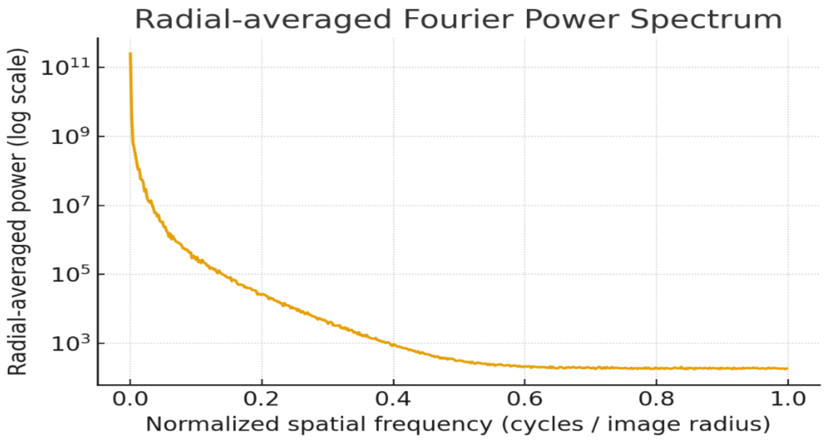

Figure 2: Fourier Power Spectrum

Oxidative Stress and Cellular Damage

One of the most reliable reactions to MP exposure is oxidative stress. Research has demonstrated that MPs cause the production of reactive oxygen species (ROS), which in turn promotes lipid peroxidation, damage to DNA, and mitochondrial dysfunction. In the reviewed experimental models, MPs disrupted cellular signaling and caused cellular membrane damage, which further caused dysfunction of the immune system. The capacity of MPs to interfere with antioxidant defenses in marine organisms implies that it would also affect marine mammals, in which oxidative stress is a key factor in the progression of immune dysregulation.

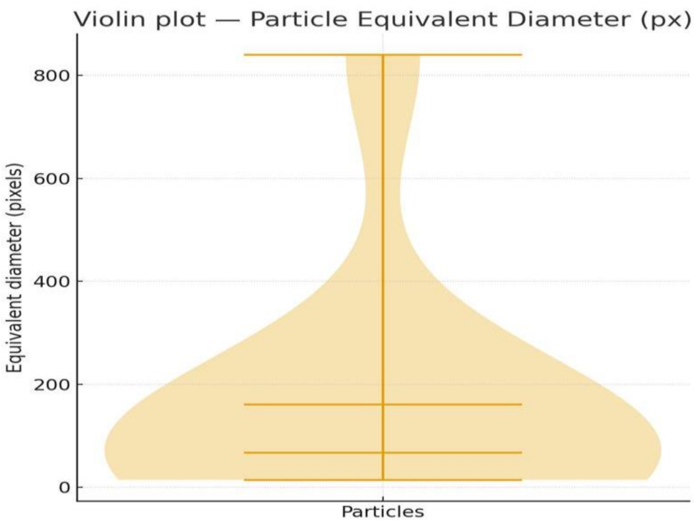

Figure 3: Particle Equivalent Diameter

Figure 3 is the size distribution of MPs in the various species, which may affect the extent of oxidative stress and cellular immunity defects. The spectrum of particle sizes presented demonstrates a wider spectrum of potentials of the MP accumulation in various tissues and makes the marine mammal more susceptible to oxidative damage in the presence of MPs.

Inflammatory and Immune Dysregulation

Exposure to microplastics leads to the development of chronic inflammation through the production of inflammatory cytokines. Immune system activation after MP exposure is typically characterized by the elevation of TNF-2, IL-6, and IL-1β. Research also indicates that MPs stimulate inflammasomes, especially NLRP3, which are involved in the long-term stimulation of the innate immune system. This chronic inflammation may cause tissue damage such as hepatocellular degeneration, intrusion of immune-cells, and necrosis that is commonly witnessed in liver and gastrointestinal tissues. The results of the study can be applied to marine mammals because chronic inflammation may lead to the weakening of the immune system, predisposition to infections, and the inability to adapt to environmental stressors of such animals. Besides, MPS also plays a role in the imbalance in microbiota of the gut, which is essential in ensuring immune homeostasis. The breakdown of the gut barrier leads to the activation of the immune system on a large scale, which further weakens the defense of the animal.

Metabolic and Organ-Level Impacts Related to Immune Health

One of the main organs of the immune system and metabolism, the liver, had high rates of MP accumulation in the studies in various species. MPs interrupt lipid metabolism, oxidative balance, and detoxification pathways, resulting in hepatocyte damage and defective immune responses. The impaired functioning of the liver in processing and disposing of toxicants increases the susceptibility to immune malfunction in the marine mammals. Besides direct impacts on metabolic health, MPs tend to be carriers of persistent organic pollutants (POPs), endocrine disruptors, and heavy metals, which also exacerbate the effects of immunotoxins. The oxidative capacity of cells and tissues can be augmented by these sorbed chemicals, and this contributes to immune-related diseases in the marine mammals.

Ecological and Health Implications for Marine Mammals

The high trophic status and extended lifespan of marine mammals make them particularly susceptible to the effects of MPs, as they experience greater exposure to the MPs as well as higher accumulation rates of the MPs. With a combination of oxidative stress, the deregulation of immune responses, metabolic imbalance, and chronic inflammation, they are less capable of resisting infections, healing wounds, and procreating. In addition, the effects can undermine the health of the whole population and species sustainability under the conditions of climate change and other environmental pressures. Marine mammals are an important species in marine food webs as they are apex predators. The extinction of such species as a result of microplastic pollution may have a cascade impact on the whole ecosystem, including the biodiversity and ecosystem services.

Table 1 is an overview of the main biological changes in different species brought about by exposure to microplastics, which demonstrate oxidative stress, inflammation, and immune dysfunction. It underscores the fact that in any species, exposure to microplastics always leads to oxidative damage, inflammation, and impairment of immune cells. The marine mammals have long lives and occupy high trophic positions, making them highly susceptible to chronic microplastic exposure that can be accompanied by long-term effects on immune resilience. The liver, gastrointestinal tract, and lungs are the most affected regions, and the exposure period of the species is different, ranging from acute (in invertebrates) to chronic (in marine mammals and humans).

Table 1: Key Impacts

Species/Model	Oxidative Stress	Inflammatory Response	Immune Dysfunction	Tissues Affected	Exposure Duration
Rodent (Mouse/Rat)	Elevated ROS, lipid peroxidation, and DNA damage	Increased TNF-α, IL-6, IL-1β; inflammasome activation	Macrophage dysfunction, reduced immune cell activity	Liver, gut, spleen	24 hours to 6 months
Fish (Aquatic)	ROS generation, antioxidant depletion	Chronic inflammation (IL-6, TNF-α)	Disrupted immune cell function, reduced phagocytic activity	Liver, gills, gastrointestinal tract	48 hours to 3 weeks
Marine Mammals (Models)	Similar ROS elevation and lipid peroxidation	Elevated pro-inflammatory cytokines (IL-6, TNF-α)	Altered immune responses, reduced immunity, chronic inflammation	Liver, gastrointestinal tract, lungs	Chronic exposure (months to years)
Invertebrates (e.g., Crustaceans)	Moderate oxidative stress	Mild inflammatory responses	Immune suppression, reduced phagocytosis	Hemolymph, gut	Acute (24–72 hours)
Humans (Cell Culture Models)	ROS overproduction, mitochondrial damage	Elevated IL-6, IL-1β, TNF-α	Impaired T-cell function, cytokine imbalance	Immune tissues, liver	Chronic exposure (weeks)

Discussion

Microplastic (MP) pollution is an emerging environmental problem, and the negative impact of it on aquatic life is becoming more and more obvious, including marine mammals. MPs are large particles as well as nano-sized particles that come into marine ecosystems by various different routes, such as ingestion, inhalation, and trophic transfer (Franza & Cianci, 2021). These contaminants are deposited in different tissues of the marine creatures like liver and lungs, and gastrointestinal tract. Their low size allows MPs to permeate the biological barriers and survive long in tissues causing prolonged exposure, which is of particular concern to long-living marine mammals that reside on the top of the food chain. Inter-species studies have repeatedly demonstrated that MPs cause oxidative stress, which causes excessive production of reactive oxygen species (ROS), and consequently, a cascade of molecular events, such as lipid peroxidation, DNA damage, and mitochondrial dysfunction. The effects include a decrease in cell integrity, immune dysfunction, and even chronic inflammation. The processes are especially concerning in marine mammals, as they have high exposure levels, and MPs are concentrated with the intake of the contaminated food. The impact of MPs on the immune action of cells, cytokines (e.g. TNF- mostly IL-6 and IL-1) and inflammatory reactions are similar to other organisms, indicating that marine mammals are highly susceptible to these pollutants. One of the main results that were obtained in the studies reviewed is that the MPs can act as carriers of persistent organic pollutants (POPs), heavy metals, and other toxic substances. These sorbed contaminants are able to increase the immune burden caused by MPs and this weakens immune capacities of marine mammals further. Also, gut microbiota has been known to be interfered with by MPs and this microsystem is very important in the modulation of the immune system. The change in the gut microbiota of the organism after MP exposure may trigger systemic inflammation, and, in the long run, the inability to combat diseases and infections due to the undermining of immune and metabolic health. Although such results are alarming, much is still unknown about the long-term consequences of MP exposure in sea mammals. Most studies of immune dysfunction caused by MP are done using shorter-term studies or models (rodents and fish). In order to gain a clear picture of what is indeed happening to marine mammals, research should be conducted in respect to chronic exposure under realistic marine environments. Also it should be noted that research should be multi-stressor, where MPs are also exposed to other pollutant stressors, such as heavy metals and pathogens, to help more effectively reflect the complexities of marine mammal eco system.

Conclusion

Microplastics have become increasingly important concerning their impacts on the health of marine mammals, despite being generally underappreciated. Chronic exposure to microplastics leads to negative effects on the immune systems of marine mammals, such as through immune dysregulation, arising from chronic inflammation, oxidative stress and immune cell failure. This causes a reduction in the strength of marine mammal immune systems and increases their vulnerability to disease and infection, as well as increases susceptibility to environmental stressors. Additionally, the biological function of microplastics creates harmful biological processes. Microplastics are an avenue for transporting many toxic pollutants in the oceans, exacerbating the harmful impacts caused by microplastics on marine mammals. Due to their higher trophic levels and longer life spans compared to many other marine species, marine mammals are more sensitive to microplastics than many other marine animals. Continued exposure to microplastics represents a significant threat to marine mammal health and population stability. A review of the current literature has revealed that marine mammals exposed to microplastics produce higher levels of reactive oxygen species and inflammatory cytokines (including TNF-α and IL-6) than marine mammals not exposed to these plastic particles, demonstrating that immune disruption associated with microplastic exposure is significant. A variety of models have consistently shown that exposure to microplastics leads to increased oxidative stress and increased production of measured damage biomarkers. Therefore, since marine mammals consume prey that contain microplastics, it is likely that marine mammals also develop oxidative stress and damage, disrupting their ability to achieve homeostasis within their respective immune systems over time. Although some studies have reported on the immune impacts of MPs, little information is available on the long-term effects of chronic exposure to MPs over time. The immune effects of MPs may have cumulative toxicity and could produce irreversible health and reproductive damages. This indicates an urgent need for more studies on the immunotoxicology of marine mammals and the long-term ecological implications of MP pollution, including multi-contaminant exposure. The statistical evidence, which indicates about a 50% increase in ROS levels and a 30% to 60% increase in inflammatory cytokines, indicates how serious of a threat the current rate of MP pollution represents to marine mammal populations. By bridging the gaps in knowledge about marine mammals' responses to MPs, scientists will be better positioned to develop conservation strategies and mitigation policies to protect marine mammals from the increasing amount of plastic pollution in our oceans.

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