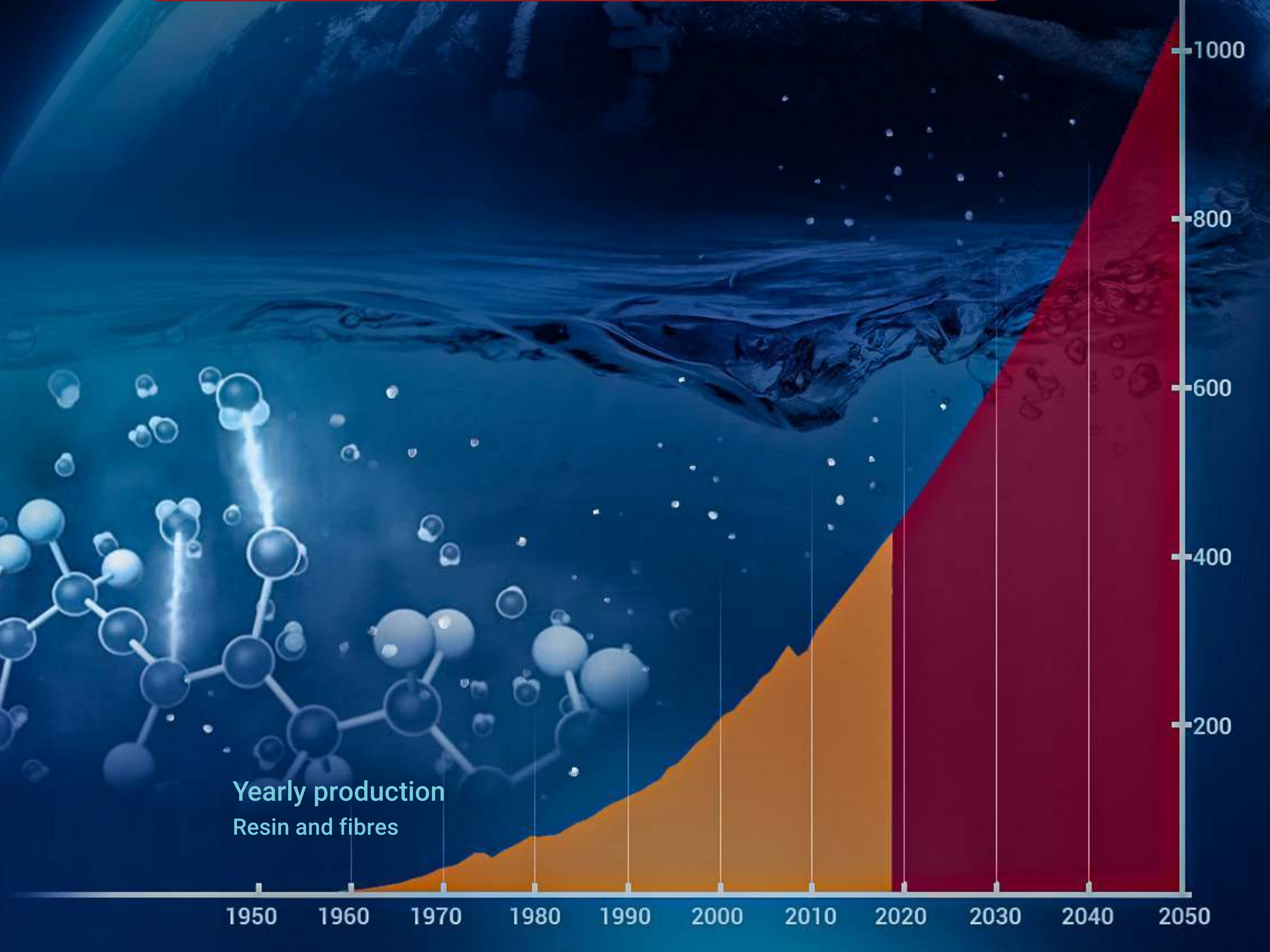
REPORT

NANOPLASTICS IN THE BIOSPHERE

FROM MOLECULAR IMPACT TO PLANETARY CRISIS



REPORT

NANOPLASTICS IN THE BIOSPHERE

FROM MOLECULAR IMPACT TO PLANETARY CRISIS

AUTHORS

ALLATRA International Public Movement

INSTITUTIONAL REVIEW
Academic Collaboration

Bolivian Catholic University "San Pablo" - UCB
Faculty of Environmental Engineering and Research

Juan Misael Saracho Autonomous University - UAJMS
Department of Research, Science and Technology

SCIENTIFIC COLLABORATOR

Creative Society International Project

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ABSTRACT

If Earth were keeping a diary, the last century would be inked in black with the title: "The Plastic Age." From microscopic particles infiltrating cells of living organisms to colossal garbage patches drifting in the oceans, plastics have become etched into the planet's geological record. But at what cost?

Every year, the world generates more than 400 million tons of plastic waste, with an estimated 11 million tons entering the world's oceans. To date, over 200 million tons have accumulated in marine environments. Surface water samples reveal that plastics now outweigh zooplankton by a factor of six. If current trends continue, by 2050 the mass of plastics in the oceans will surpass the mass of all fish.

Although plastics take hundreds or even thousands of years to degrade, they break down under the influence of waves, salt water, and ultraviolet radiation into tiny fragments known as micro- and nanoplastics. These particles can travel thousands of miles through marine air and precipitation, crossing borders, continents, and oceans. They accumulate in forests and are found in our food and drinking water. Microplastics have been detected in some of the most remote locations on Earth, from the Mariana Trench to the summit of Mount Everest.

This report presents a comprehensive analytical assessment of the impact of plastic pollution on the environment, human health, and the resilience of society's critical systems. It examines the behavior of micro- and nanoplastics that carry static charges and toxic chemical compounds, and their effects on ecosystems. Particular attention is given to their role in ocean acidification, destabilization of food chains, and threats to biodiversity. The report suggests a hypothesis linking micro- and nanoplastics to changes in water properties, which may accelerate ocean warming and intensify natural disasters.

One of the most urgent and troubling issues discussed in this report is the impact of micro- and nanoplastics (MNPs) on human health. Due to their minute size, these particles can bypass biological barriers, triggering oxidative stress, DNA damage, inflammatory responses, and cellular dysfunction. The report highlights a possible correlation between MNP exposure and the rising prevalence of neurodegenerative and neuropsychiatric disorders. It shows that exposure to MNPs during prenatal and postnatal development can impair cognitive function and mental health in children, posing a serious threat to future generations.

The growing incidence of MNP-related diseases is already diminishing the quality of life, particularly in regions with high levels of plastic pollution. The report identifies regions currently facing heightened risk as well as those that so far remain relatively unaffected. If the situation continues to deteriorate and effective protective measures remain unavailable, populations may be forced to migrate in search of safer living conditions. This can lead to waves of uncontrolled migration, heightening social tension, straining urban infrastructure, and destabilizing economies.

In this way, the environmental challenge of plastic pollution will gradually evolve into a macroeconomic and geopolitical challenge.

The report underscores the urgent need to address MNP pollution, offering a new perspective on distribution, impact, and effects of MNPs. The report is unique as it is based on an interdisciplinary approach that integrates physical, chemical, and biological data on plastic pollution. This makes the report relevant to scientists across a broad range of fields, who are committed to developing sustainable solutions for a safer future for the planet and humanity.

CONSEQUENCES OF PLASTIC POLLUTION: MICRO- AND NANOPLASTICS (MNPS) AS A NEW DRIVER OF THE PLANETARY CRISIS

Plastics have become an inseparable part of present-day life. Packaging and utensils, clothing and footwear, hygiene products and medicine, transportation and communication — most everyday items are made of plastics. However, plastics do not just exist in the form of large visible objects: they also break down into microscopic particles known as microplastics and nanoplastics. Microplastics are defined as particles smaller than 5 mm, often visible to the naked eye. Nanoplastics, on the other hand, measure less than one micrometer (one-millionth of a meter), and most of them are invisible even under a standard microscope.

Plastic materials come in a variety of types, but all are composed of polymers — natural or synthetic substances built from long molecular chains. Polymers possess unique chemical properties that make them highly durable and resistant to degradation in the environment.

Thus, thanks to their durability, versatility, and low production cost, plastics have become a major material of choice for mass manufacturing, especially for single-use items.[1] However, improper waste management has turned plastics into the world's most voluminous pollutants by mass.

Quantitative Estimates and Trends in Global Plastic Waste Production

Since the 1950s, the world has produced approximately 9,200 million metric tons of plastics. Of that, about 2,900 million tons are still in use today, including 2,700 million tons of virgin plastics and roughly 200 million tons of recycled materials. Around 5,300 million tons have ended up in landfills, while 1,000 million tons have been incinerated. An additional 1,750 to 2,500 million tons are classified as "mismanaged," meaning they may have entered the environment through uncontrolled channels (Fig. 1).

To date, nearly 640 million tons of chemical additives have been incorporated into plastic products.[2]

According to the United Nations Environment Programme (UNEP),[3] the world now produces more than 400 million tons of plastic waste annually.

[1] Karlsruhe Institute of Technology. Blind spots in the monitoring of plastic waste https://www.kit.edu/kit/english/pi_2022_097_blind-spots-in-the-monitoring-of-plastic-waste.php (accessed: 1 May 2025)
[2] Schmidt, C. et al. A multidisciplinary perspective on the role of plastic pollution in the triple planetary crisis. Environment International 193, 109059 (2024). https://doi.org/10.1016/j.envint.2024.109059
[3] United Nations Environment Programme (UNEP) Beat plastic pollution https://www.unep.org/interactives/beat-plastic-pollution (accessed: 1 May 2025)

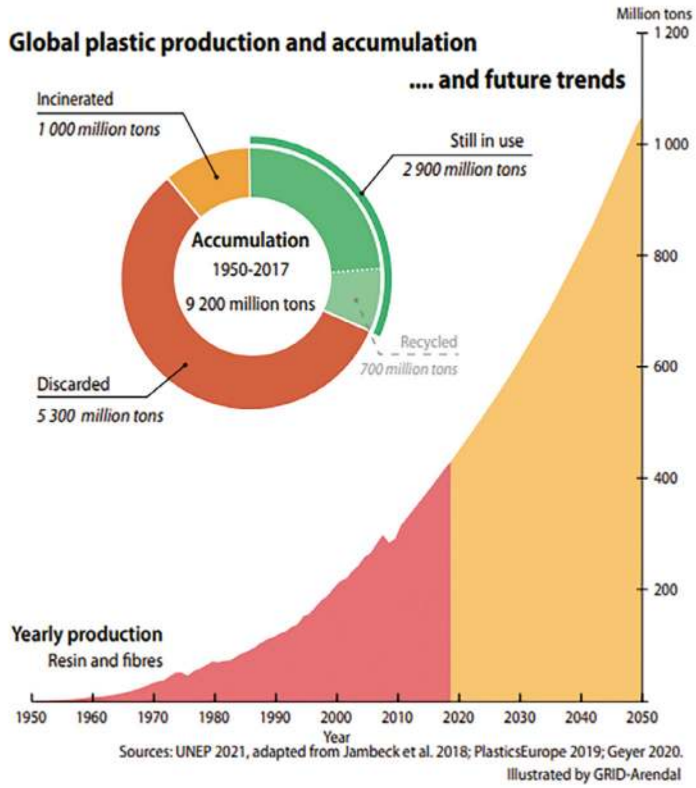

Figure 1: Global plastic production, accumulation, and future trends

Source: UNEP 2021, adapted from Jambeck et al. 2018; PlasticsEurope 2019; Geyer 2020. Illustrated by GRID-Arendal https://malaysia.un.org/sites/default/files/2022-02/POLSOLSum_1.pdf

Only about 9% of plastic waste is recycled, 19% is incinerated, and the rest remains in the environment, including landfills and oceans[4] (Fig. 2).

Disposal Method	Share (Global, 2023)
Recycled	9%
Incinerated	19%
Mismanaged	22%
Landfilled	49%

Figure 2: Annual plastic waste by disposal method, World, 2000 to 2023
Source: Our World in Data https://ourworldindata.org/grapher/plastic-fate

Every year, approximately 11 million tons of plastics enter the world's oceans,[5] which is equivalent to more than one garbage truck of plastics being dumped into the ocean every minute.

[4] How Much of the World's Plastic Waste Actually Gets Recycled? https://www.visualcapitalist.com/how-much-plastic-gets-recycled (accessed: 1 May 2025)
[5] Jenna R. Jambeck et al., Plastic waste inputs from land into the ocean. Science 347, 768-771 (2015). https://doi.org/10.1126/science.1260352

Currently, over 200 million tons of big plastic waste (macroplastics) and approximately 35,540 tons of microplastics have accumulated in the oceans.[6] Estimates of annual plastic waste entering aquatic ecosystems from land sources vary depending on analytical methods. Under a "business-as-usual" (BAU) scenario without intervention, these levels can nearly triple — from 9–14 million tons in 2016 to 23–37 million tons a year by 2040.

Another methodology projects an almost doubling of ocean-bound plastic waste — from 19–23 million tons in 2016 to 53 million tons by 2030.[7]

As indicated by research, if current trends persist, by 2050 the ocean will hold as much as 12,000 million tons of plastics,[8] rivaling the total biomass of marine fish estimated at roughly 10,000 million tons.[9]

Depending on the type, plastics take between 100 and 1,000 years to decompose (Fig. 3). In marine environments, especially in the cold and dark depths of the ocean, plastics break down even more slowly.[10]

Figure 3: Estimated decomposition time for various types of plastic waste dumped in the sea

[6]Eriksen, M. et al. Plastic Pollution in the World's Oceans: More than 5 Trillion Plastic Pieces Weighing over 250,000 Tons Afloat at Sea. PLoS ONE 9, e111913 (2014). https://doi.org/10.1371/journal.pone.0111913)

[7]United Nations Environment Programme (2021). From Pollution to Solution: A global assessment of marine litter and plastic pollution. Nairobi. https://www.unep.org/resources/pollution-solution-global-assessment-marine-litter-and-plastic-pollution

[8]Geyer, R., Jambeck, J. R. & Law, K. L. Production, use, and fate of all plastics ever made. Sci. Adv. 3, e1700782 (2017). https://doi.org/10.1126/sciadv.1700782

[9]Irigoien, X. et al. Large mesopelagic fishes biomass and trophic efficiency in the open ocean. Nat Commun 5, 3271 (2014). https://doi.org/10.1038/ncomms4271

[10]Barnes, D. K. A., Galgani, F., Thompson, R. C. & Barlaz, M. Accumulation and fragmentation of plastic debris in global environments. Phil. Trans. R. Soc. B 364, 1985–1998 (2009). https://doi.org/10.1098/rstb.2008.0205

Except for the portion that has been incinerated, virtually all plastics ever introduced into the environment still exist today either as intact objects or in fragmented form.[11] This waste doesn't disappear and keeps accumulating. The situation is akin to a trash bin that is constantly being filled but never emptied. The question of what that bin might look like after a month indicates the scale of the problem of global plastic waste accumulation.

The Great Pacific Garbage Patch

Plastic waste accumulated in the ocean water and floating on its surface is captured by ocean currents and carried into central gyres, forming massive clusters known as "garbage patches."

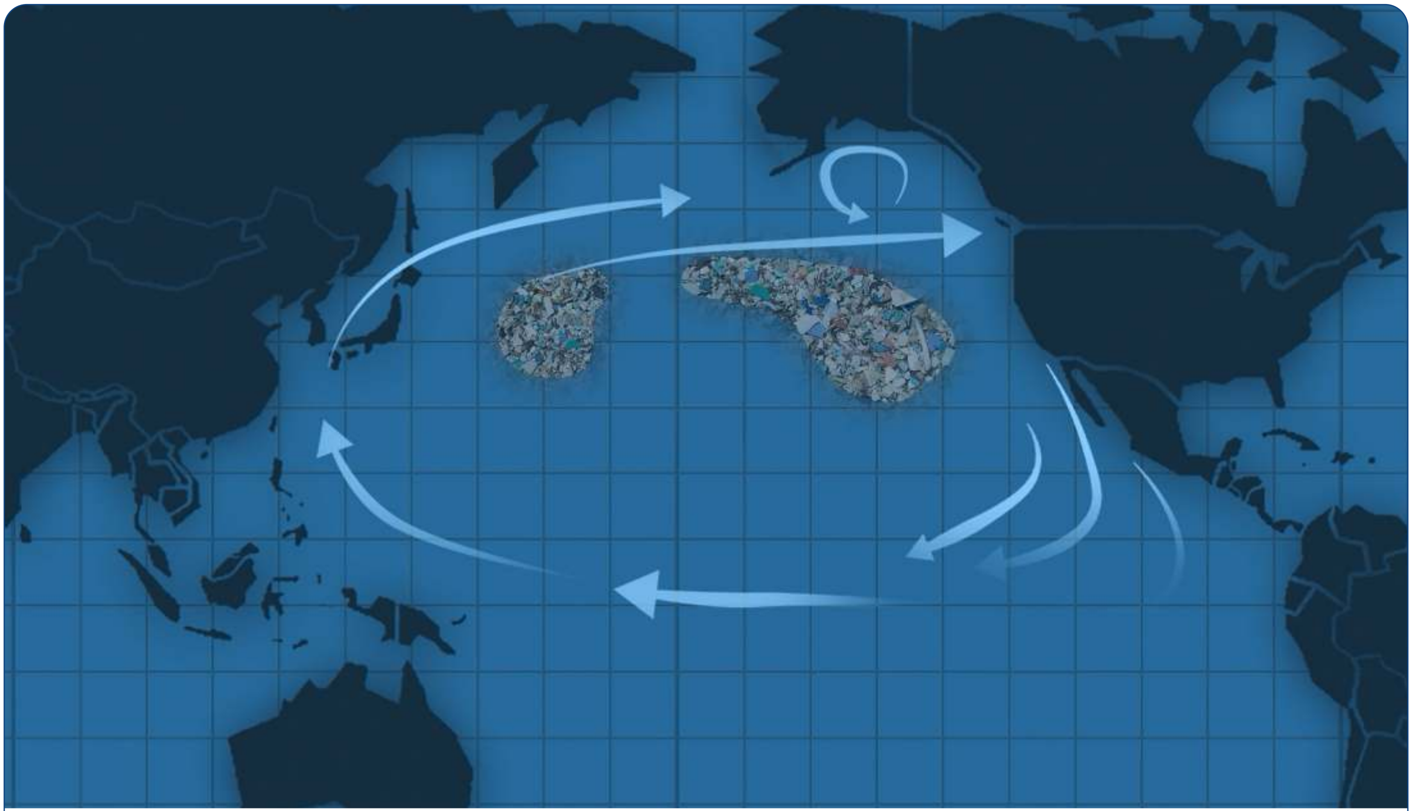

Figure 4: Diagram of plastic accumulation in the Pacific Ocean

[11]Barnes, D. K. A., Galgani, F., Thompson, R. C. & Barlaz, M. Accumulation and fragmentation of plastic debris in global environments. Phil. Trans. R. Soc. B 364, 1985–1998 (2009). https://doi.org/10.1098/rstb.2008.0205

The Great Pacific Garbage Patch is the largest concentration of plastics on the planet, and it exhibits steady growth (Fig. 4). The garbage patch spans a vast area between North America and Japan. Observations indicate that in 2018, its surface area measured about 618 thousand square miles,[12] although this figure is subject to fluctuation due to ocean currents and seasonal variability.

Studies indicate that up to 80 %[13] of the material in the garbage patches consists of plastics.[14] The patch contains at least 80,000 metric tons of plastic waste.[15] Yet, that's just the visible portion of the problem. An estimated 94 % of ocean plastic sinks to the seabed[16] where vast amounts of waste may remain hidden and continue to accumulate.

The full extent of the Great Pacific Garbage Patch is still unknown, partly because the North Pacific Subtropical Gyre is so vast that it defies comprehensive scientific mapping with current technology.

Dynamics of Plastics Accumulation in the Ocean

Instrument-based measurements show an exponential increase in the size of the Great Pacific Garbage Patch. Between 2015 and 2022, the average mass of plastic waste in this region grew fivefold.[17] Of particular concern is the tenfold increase in small plastic fragments over the same period, evidencing rapid degradation of larger plastic debris.

The Great Pacific Garbage Patch has effectively formed a seventh "continent" on Earth. However, it is important to note that this phenomenon is not unique. To date, scientists have identified five major garbage patches in the world's oceans[18]: two in the Atlantic, two in the Pacific, and one in the Indian Ocean[19] (Fig. 5).

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[12] Lebreton, L., Slat, B., Ferrari, F. et al. Evidence that the Great Pacific Garbage Patch is rapidly accumulating plastic. Sci Rep 8, 4666 (2018). https://doi.org/10.1038/s41598-018-22939-w

[13] Derraik, J. G. B. The pollution of the marine environment by plastic debris: a review. Marine Pollution Bulletin 44, 842–852 (2002). https://doi.org/10.1016/S0025-326X(02)00220-5

[14] Morishige, C., Donohue, M. J., Flint, E., Swenson, C. & Woolaway, C. Factors affecting marine debris deposition at French Frigate Shoals, Northwestern Hawaiian Islands Marine National Monument, 1990–2006. Marine Pollution Bulletin 54, 1162–1169 (2007). https://doi.org/10.1016/j.marpolbul.2007.04.014

[15] Lebreton, L., Slat, B., Ferrari, F. et al. Evidence that the Great Pacific Garbage Patch is rapidly accumulating plastic. Sci Rep 8, 4666 (2018). https://doi.org/10.1038/s41598-018-22939-w

[16] Eunomia. Plastics in the Marine Environment. https://eunomia.eco/reports/plastics-in-the-marine-environment (accessed: 1 May 2025)

[17] Lebreton, L. et al. Seven years into the North Pacific garbage patch: legacy plastic fragments rising disproportionally faster than larger floating objects. Environ. Res. Lett. 19, 124054 (2024). https://doi.org/10.1088/1748-9326/ad78ed

[18] Van Sebille, E., England, M. H. & Froyland, G. Origin, dynamics and evolution of ocean garbage patches from observed surface drifters. Environ. Res. Lett. 7, 044040 (2012). https://doi.org/10.1088/1748-9326/7/4/044040

[19] Garbage Patches. Marine Debris Program. NOAAA https://marinedebris.noaa.gov/discover-marine-debris/garbage-patches (accessed: 1 May 2025)

Figure 5: Schematic representation of the five major garbage patches in the world's oceans: two in the Atlantic, two in the Pacific, and one in the Indian Ocean.

Millions of tons of plastics and other human-generated waste are circulating in the oceans. These garbage patches are growing at an alarming rate.

How Micro- and Nanoplastic Particles Are Formed

Plastic waste is highly resistant to biodegradation, however, under the influence of waves, saltwater, and sunlight, it gradually breaks down into smaller particles — micro- and nanoplastics[20] that are often invisible to the naked eye. These particles retain their polymer structure,[21] and the degradation process continues down to the nanoscale (Figs. 6–7). As a result, having bypassed natural degradation mechanisms, plastic waste becomes a permanent component of the planet's ecosystems.

Moreover, micro- and nanoplastics contain hazardous chemicals that are added during plastic manufacturing.

"We now know that plastics contain roughly 16,000 chemicals. Of these, it is known that over 4,200 are persistent in the environment, accumulate in living organisms, are transported over long distances or pose a potential hazard," says Annika Jahnke, author and environmental chemist at the Helmholtz Centre for Environmental Research (UFZ).[22]

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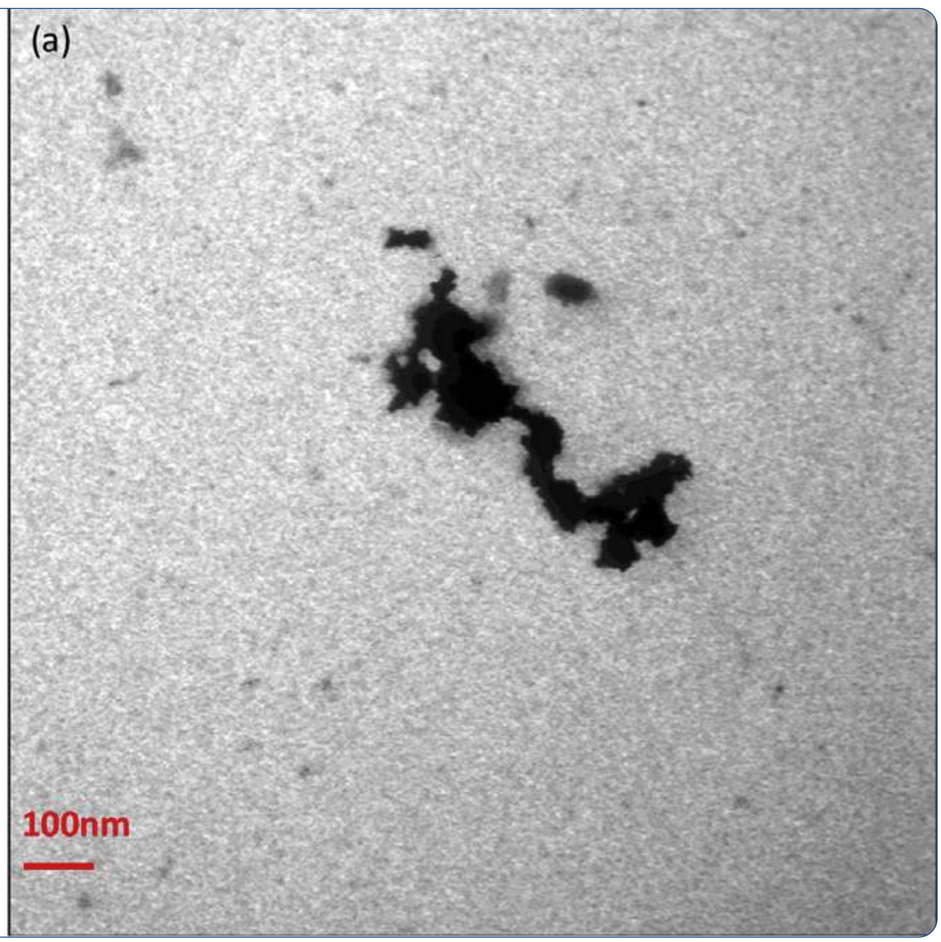
[20] Yu, R.-S. & Singh, S. Microplastic Pollution: Threats and Impacts on Global Marine Ecosystems. Sustainability 15, 13252 (2023). https://doi.org/10.3390/su151713252
[21] Barnes, D. K. A., Galgani, F., Thompson, R. C. & Barlaz, M. Accumulation and fragmentation of plastic debris in global environments. Phil. Trans. R. Soc. B 364, 1985–1998 (2009). https://doi.org/10.1098/rstb.2008.0205
[22] Helmholtz Centre for Environmental Research - UFZ. Environmental Impacts of Plastics: Moving beyond the perspective on waste. https://www.ufz.de/index.php?en=36336&webc_pm=44/2024 (accessed: 1 May 2025)

Figure 6: Fragmentation of plastic particles to nanoparticles while maintaining their polymer structure

Figure 7: Transmission electron microscopy of environmentally relevant nanoplastics of polyethylene degraded by UV from aged-microplastics sampled in the North Atlantic Ocean

Source: Gigault, J. et al. Current opinion: What is a nanoplastic? Environmental Pollution 235, 1030–1034 (2018). https://doi.org/10.1016/j.envpol.2018.01.024



Spread of Micro- and Nanoplastics in the Ocean

The highest concentrations of plastics are found in the regions of garbage patches. Those oceanic dumps function like industrial plants where micro- and nanoplastics are continuously generated. Much like a virus spreads through the body via the bloodstream, microplastics are transported by ocean currents throughout the world's oceans, underscoring the global scale of the issue.

Despite technical challenges in detecting microplastics, which complicate their accurate quantification in the oceans, theoretical models make it possible to estimate the magnitude of the problem.

Microplastics are found in nearly every sample of ocean water, while in some regions, concentrations are dozens of times higher than the global average.

Oceanic gyres contribute to the widespread distribution of microplastics, reaching even remote regions such as the Arctic. Studies of ice cores have shown that microplastic pollution levels in the Arctic Ocean are 100 times higher than those in the waters north of Scotland or the North Pacific Subtropical Gyre.[23] These findings point to both the severity and transboundary nature of the problem.

Most global studies on plastic pollution in marine environments focus on the ocean's surface layer. According to estimates, in 2019 the surface layer of the ocean contained between 82 and 358 trillion plastic particles.[24]

However, there is mounting evidence that in deep-sea zones and bottom sediments, the number of microplastic particles may reach uncountable trillions.[25]

Lightweight plastics tend to float, while denser plastics or those colonized by marine organisms sink to the ocean floor.[26] Estimates suggest that about 50% of urban plastic waste is denser than seawater, allowing it to settle quickly. Once on the seafloor, it is transported by deep-sea currents and accumulates in trenches and depressions. Microplastics have even been found at the bottom of the Mariana Trench — the deepest known point in the ocean (Figs. 8–9).[27]

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[23] Obbard, R. W. et al. Global warming releases microplastic legacy frozen in Arctic Sea ice. Earth's Future 2, 315–320 (2014). https://doi.org/10.1002/2014EF000240
[24] Eriksen, M. et al. A growing plastic smog, now estimated to be over 170 trillion plastic particles afloat in the world's oceans—Urgent solutions required. PLoS ONE 18, e0281596 (2023). https://doi.org/10.1371/journal.pone.0281596
[25] Eunomia. Plastics in the Marine Environment. https://eunomia.eco/reports/plastics-in-the-marine-environment (accessed: 1 May 2025)
[26] Lusher, A. (2015). Microplastics in the Marine Environment: Distribution, Interactions and Effects. In: Bergmann, M., Gutow, L., Klages, M. (eds) Marine Anthropogenic Litter. Springer, Cham. https://doi.org/10.1007/978-3-319-16510-3_10
[27] Peng, X. et al. Microplastics contaminate the deepest part of the world's ocean. Geochem. Persp. Let. 9, 1–5 (2018). https://doi.org/10.7185/geochemlet.1829

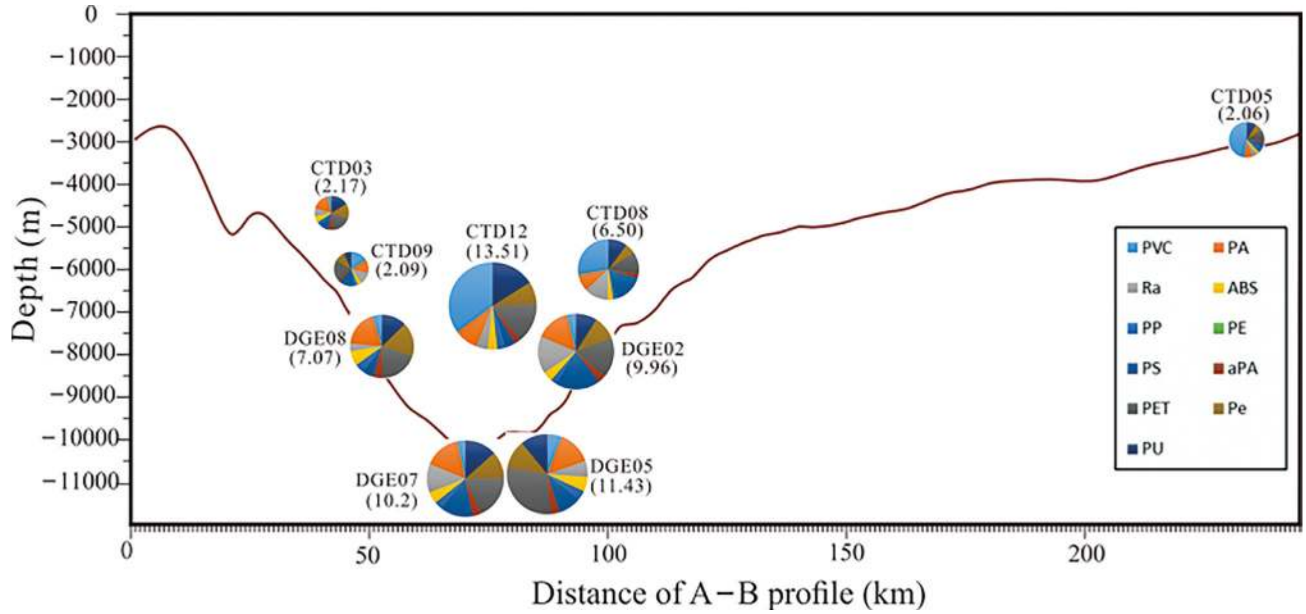

Figure 8: Profile of microplastic abundances and compositions in water samples from Mariana Trench. Pie charts represent the microplastic compositions and numbers in the bracket are the microplastic abundances with units of pieces per litre. PVC-polyvinyl chloride, PA-polyamide, Ra-rayon, ABS-acrylonitrile butadiene styrene, PP-polypropylene, PE-polyethylene, PS-polystyrene, aPA-aromatic polyamide, PET-polyethylene terephthalate, Pe-polyester, PU-polyurethane. The X-axis corresponds to the crossline from point A (12 ºN, 142.5 ºE) to point B (9.8 ºN, 141.43 ºE).
Source: Peng, X. et al. Microplastics contaminate the deepest part of the world's ocean. Geochem. Persp. Let. 9, 1–5 (2018). https://doi.org/10.7185/geochemlet.1829

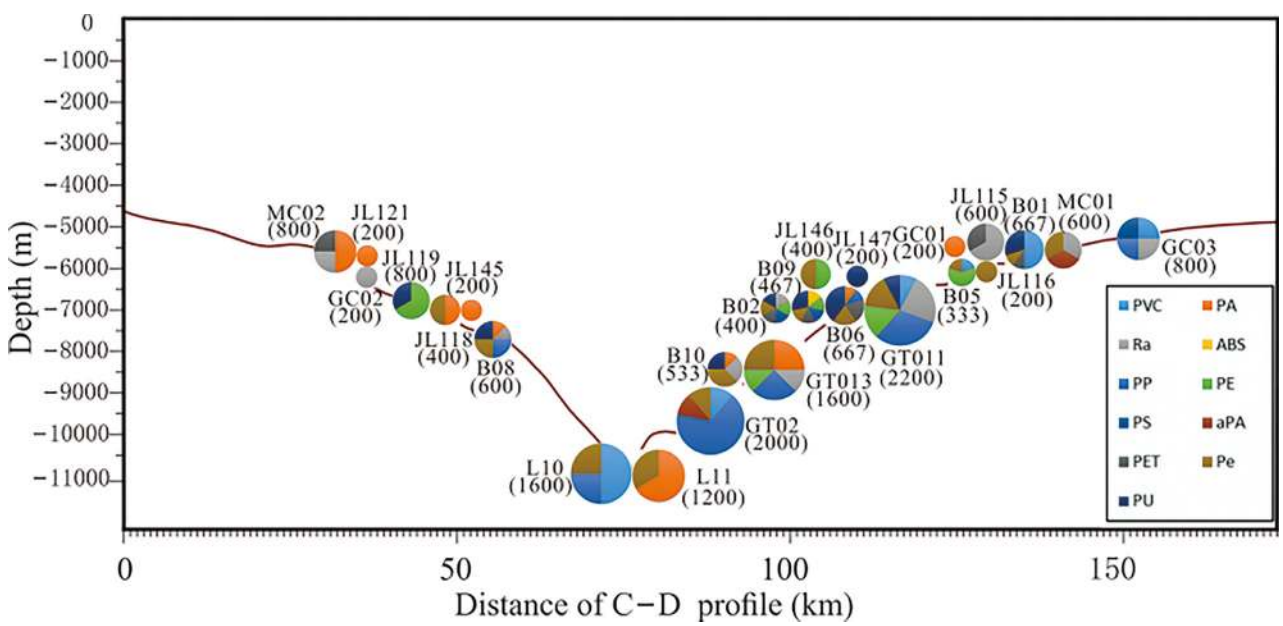

Figure 9: Profile of microplastic abundances and compositions in sediment samples from Mariana Trench. Pie charts represent the microplastic compositions and numbers in the bracket are the microplastic abundances with units of pieces per litre. PVC-polyvinyl chloride, PA-polyamide, Ra-rayon, ABS-acrylonitrile butadiene styrene, PP-polypropylene, PE-polyethylene, PS-polystyrene, aPA-aromatic polyamide, PET-polyethylene terephthalate, Pe-polyester, PU-polyurethane. The X-axis corresponds to the crossline from point C (12 ºN, 141.9 ºE) to point D (10.5 ºN, 141.3 ºE).
Source: Peng, X. et al. Microplastics contaminate the deepest part of the world's ocean. Geochem. Persp. Let. 9, 1–5 (2018). https://doi.org/10.7185/geochemlet.1829

In fact, the primary site of microplastics accumulation is not the ocean surface, but the deep-sea floor. Gradually, the entire ocean floor is becoming covered with a layer of plastics. However, data on microplastic pollution in the ocean is likely underestimated, and the actual situation may be significantly worse. "Not everyone has access to very sophisticated and expensive instruments and sampling tools," explains Melanie Bergmann, a biologist at the Alfred Wegener Institute in Germany. She says that as much as 80-90% of marine microplastic particles may be missed by standard sampling techniques because they are too small to be detected (Fig. 10).[28]

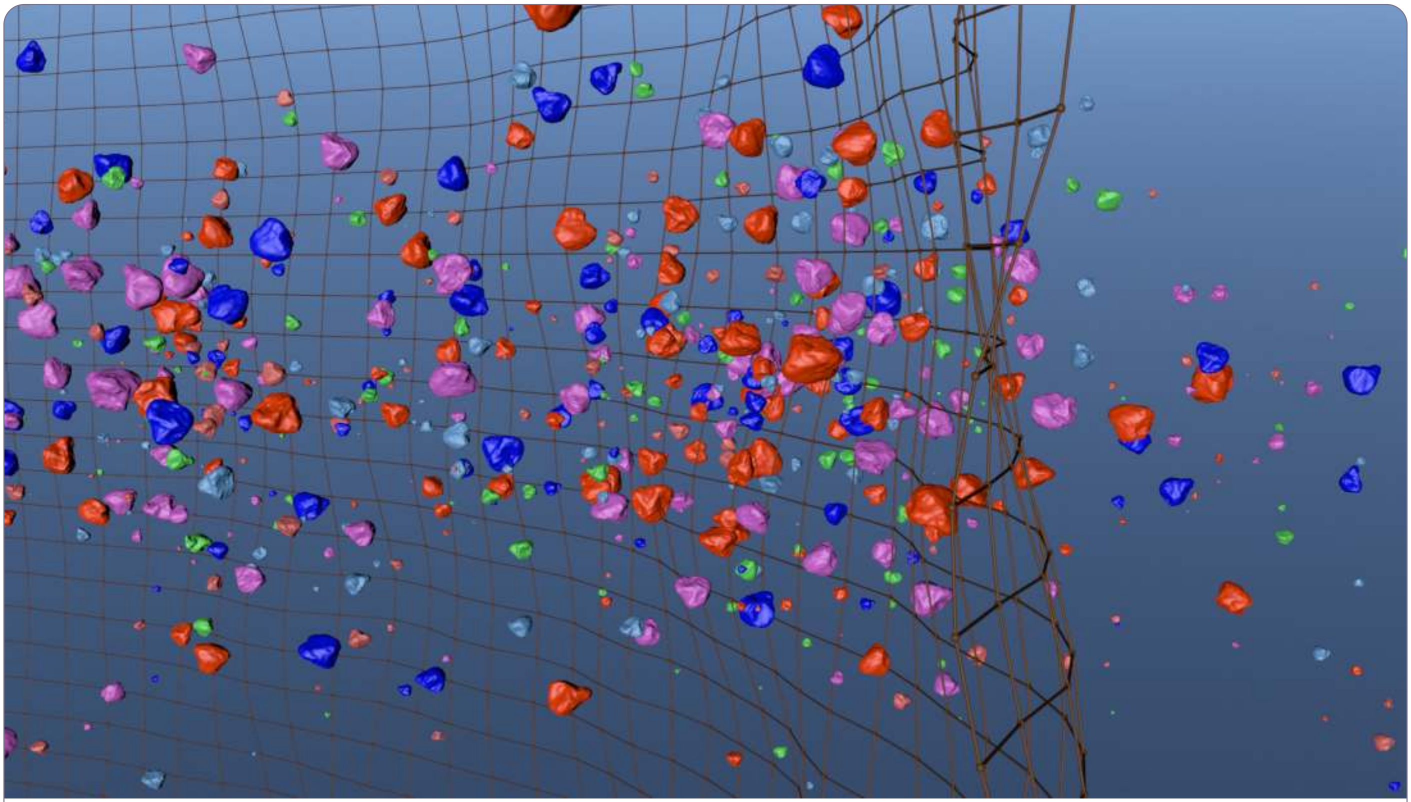

Figure 10: Schematic representation of imperfect analytical methods of micro- and nanoplastics capture

[28]Microplastics pose risk to ocean plankton, climate, other key Earth systems. Mongabay. https://news.mongabay.com/2023/10/microplastics-pose-risk-to-ocean-plankton-climate-other-key-earth-systems (accessed: 1 May 2025)

Figure 11: Schematic representation of the surface and bottom layers of micro- and nanoplastic pollution

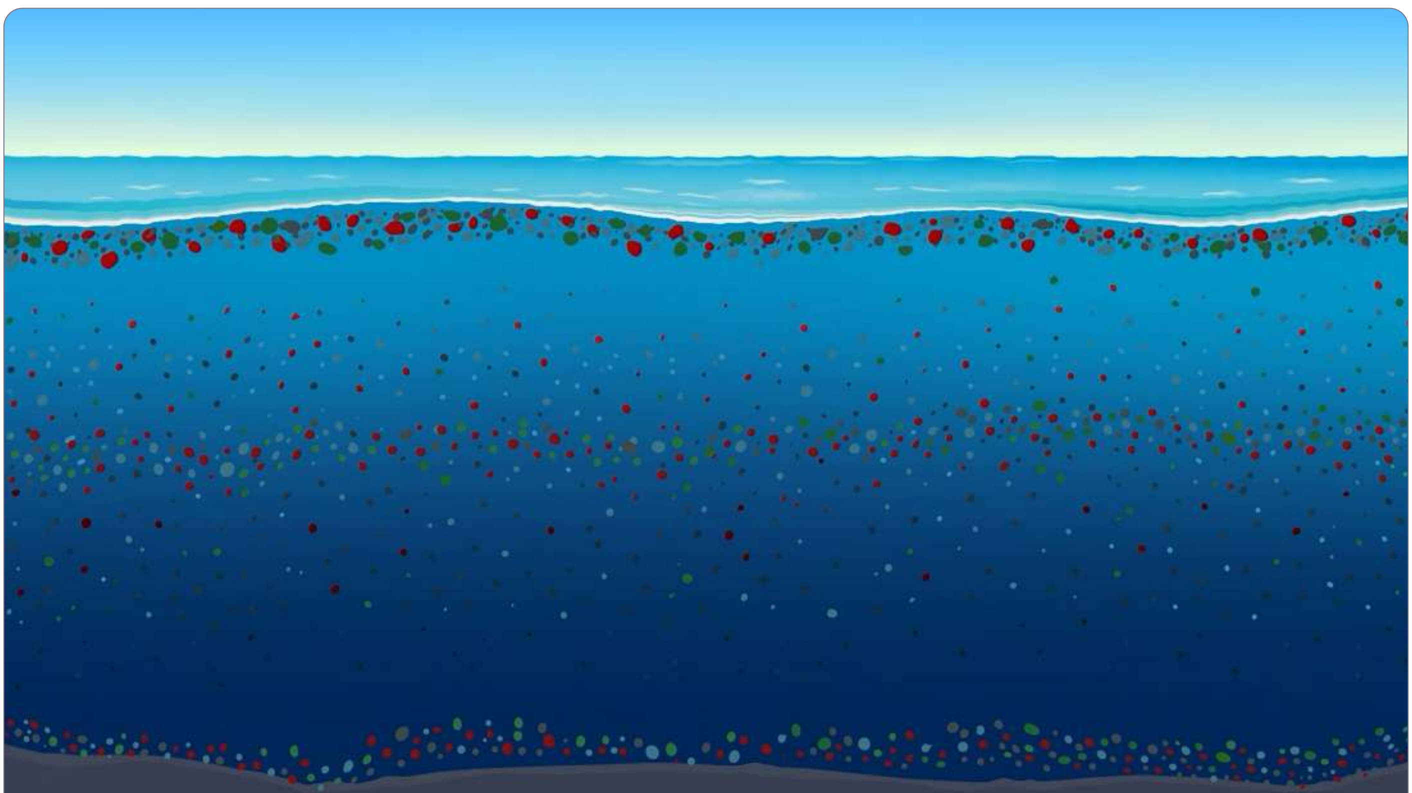

Figure 12: Schematic representation of micro- and nanoplastics location in the surface, bottom, and thermocline layers

In addition to surface and bottom layer pollution (Fig. 11), the concentrations of micro- and nanoplastics increase significantly in the thermocline zone[29] (Fig. 12) — a layer of water characterized by a sharp temperature change. The steep density gradient in this layer causes plastic particles to become trapped for extended periods. The ocean can be visualized as a layered cake, where each layer has a unique temperature and density, and microplastics accumulate at the boundaries between those layers.

Furthermore, microplastics are dispersed throughout the ocean via living organisms that ingest, digest, and excrete them.[30]

Spread of MNPs in the Environment

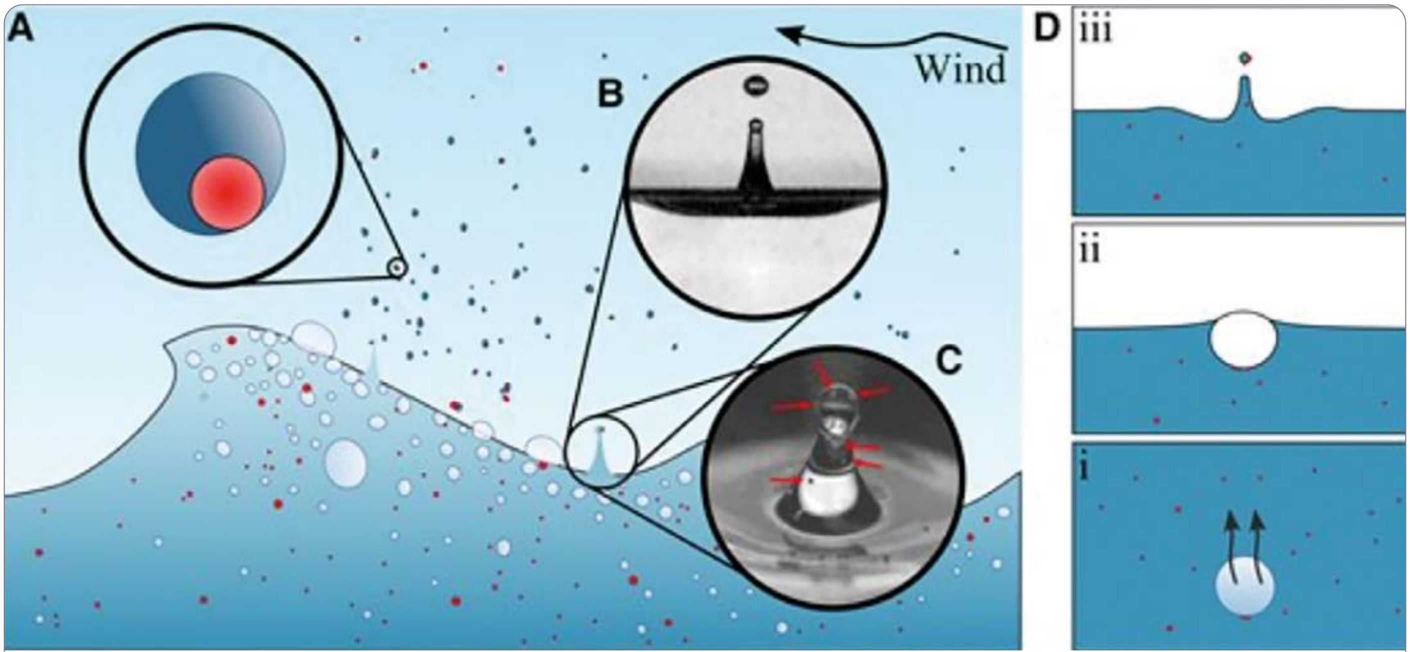

Figure 13: Sketch of the relevant processes ejecting microplastic out of the ocean adapted from Refs. (4, 16).
A) Microplastic (red/darker color) in the ocean is transported into the atmosphere by sea spray drops.
B) Bursting bubbles create small drops or aerosols such as jet drops.
C) Microplastics present in the liquid can be carried up into the jet drops produced. The arrows point to 100 μм microplastic pieces. Drops produced can be picked up by wind and carry microplastic material up into the atmosphere. The liquid eventually evaporates leaving behind microplastic pieces.
D) The relevant physical processes for bubble-bursting ejection of microplastic start with the scavenging of particles as the bubble rises
Di). After arriving at the surface
Dii), the bubble eventually settles into its equilibrium shape which—upon bursting—focuses capillary waves at its base to form jet drops
Diii) which carry microplastic material.

Source: Shaw, D. B., Li, Q., Nunes, J. K. & Deike, L. Ocean emission of microplastic. PNAS Nexus 2, pgad296 (2023). https://doi.org/10.1093/pnasnexus/pgad296

[29] Tikhonova, D. A., Karetnikov, S. G., Ivanova, E. V. & Shalunova, E. P. The Vertical Distribution of Microplastics in the Water Column of Lake Ladoga. Water Resour 51, 146–153 (2024). https://doi.org/10.1134/S009780782370063X
[30] Dawson, A. L. et al. Turning microplastics into nanoplastics through digestive fragmentation by Antarctic krill. Nat Commun 9, 1001 (2018). https://doi.org/10.1038/s41467-018-03465-9

When water evaporates,[31] microplastics rise into the atmosphere from the surface of the ocean.[32] Additionally, a combination of sea spray, wind, and waves creates air bubbles in the water that contain microplastics. When the bubbles burst, the particles are released into the atmosphere (Fig. 13). Each year, around 136,000 tons of microplastic[33] is transported to coastal areas by sea breezes alone. Up to 25 million metric tons of micro- and nanoplastic is transported annually for thousands of kilometers by marine air, spray, snow, and fog, crossing countries, continents, and oceans.

> *"Air is a much more dynamic medium than water,"* says co-author Dr. Melanie Bergmann from AWI. *"As a result, micro- and nanoplastics can reach the most remote and so far largely untouched regions of our planet much more quickly."*

Once there, the particles may affect surface climate and the health of local ecosystems.[34]

Microplastics have been found in various places — from the sea surface to deep-sea sediments, from agricultural lands to our highest mountains, as well as in sea ice, lakes, and rivers. They have been detected in 1,300 aquatic and terrestrial species, from invertebrates at the base of the food chain to top predators, with evidence of impact at all levels of biological organization, from the cellular to the ecosystem level. Microplastics are widespread in the food we eat, the water we drink, and the air we breathe (Fig. 14). They have been found in many human tissues and organs, and evidence of their potential effect is beginning to emerge.[35]

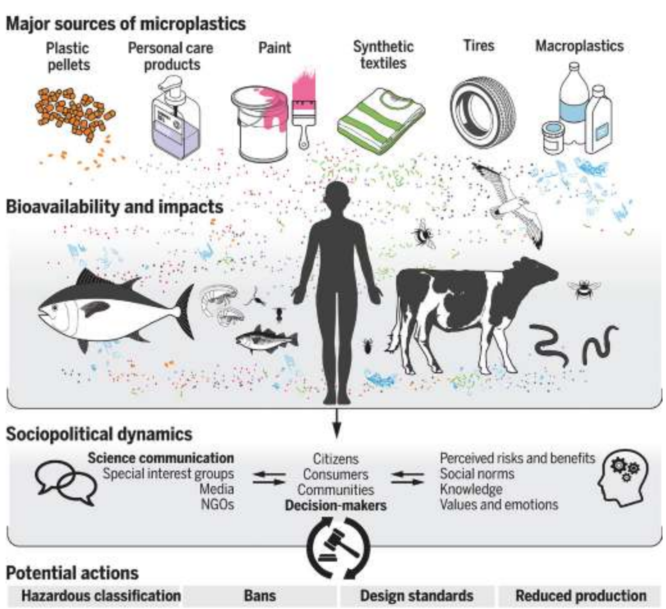

Figure 14: Ubiquitous presence of microplastic in food, water, and air

Source: https://www.science.org/doi/10.1126/science.adl2746

[31]Shaw, D. B., Li, Q., Nunes, J. K. & Deike, L. Ocean emission of microplastic. PNAS Nexus 2, pgad296 (2023). https://doi.org/10.1093/pnasnexus/pgad296

[32]Deike, L., Reichl, B. G. & Paulot, F. A Mechanistic Sea Spray Generation Function Based on the Sea State and the Physics of Bubble Bursting. AGU Advances 3, e2022AV000750 (2022). https://doi.org/10.1029/2022AV000750

[33]Allen, S. et al. Examination of the ocean as a source for atmospheric microplastics. PLoS ONE 15, e0232746 (2020). https://doi.org/10.1371/journal.pone.0232746

[34]Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research. Micro- and nanoplastic from the atmosphere is polluting the ocean. https://www.awi.de/en/about-us/service/press/single-view/mikro-und-nanoplastik-aus-der-atmosphaere-belastet-meere.html (accessed: 1 May 2025)

[35]Thompson, R. C. et al. Twenty years of microplastic pollution research—what have we learned? Science 386, eadl2746 (2024). https://doi.org/10.1126/science.adl2746

Thus, the transport of microplastics to remote and even polar regions may be due to a combination of atmospheric and marine pathways.

Therefore, it is important to understand the interaction between the atmosphere and the ocean in order to determine which particle sizes are being transported and in what quantities.

For example, a group of researchers recently discovered plastic granules with hydrophilic (water-attracting) surfaces[36] in clouds atop mountains in Japan.

They then analyzed the samples and concluded that lower-altitude and denser clouds contain higher amounts of microplastics.

The presence of polymers, acting as condensation nuclei, plays a key role in rapid cloud formation, which may ultimately influence the overall climate.[36]

Plastic particles in clouds help retain more water, delaying rainfall. When rain finally occurs, it becomes more intense, as more water has accumulated in the clouds.

In addition, microplastics that had been exposed to ultraviolet light and filtered water from clouds have a rougher surface, which promotes the accumulation of more lead, mercury, and oxygen-containing groups[37] on their surface.

The atmosphere primarily transports small microplastic particles, making it a much faster transport pathway that can result in significant deposition across a wide range of ecosystems.

Research data shows that forests act as barriers to windborne microplastics. Leaves, branches, and trunks trap microplastic particles, which settle on their surfaces. This causes microplastic particles carried by wind and precipitation to remain on the plants or settle on the ground.

Limited airflow beneath the dense forest canopy promotes the sustained accumulation of these particles within forested areas. The canopy leaves serve as a long-term reservoir for airborne microplastics.[38]

Studies have shown that from autumn 2017 to summer 2019, more than 1,000 tons of plastic particles fell with precipitation across 11 national parks and reserves in the western United States. This amount is enough to produce 120 million plastic bottles.[39]

A similar situation is observed in other regions of the world. For example, *Quercus serrata* forests in Japan, covering an area of about 32,500 km², annually capture approximately 420 trillion airborne microplastic particles[40] in their canopies.

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[36]Wang, Y., Okochi, H., Tani, Y. et al. Airborne hydrophilic microplastics in cloud water at high altitudes and their role in cloud formation. Environ Chem Lett 21, 3055–3062 (2023). https://doi.org/10.1007/s10311-023-01626-x

[37]Busse, H. L., Ariyasena, D. D., Orris, J. & Freedman, M. A. Pristine and Aged Microplastics Can Nucleate Ice through Immersion Freezing. ACS EST Air 1, 1579–1588 (2024). https://doi.org/10.1021/acsestair.4c00146

[38]Sunaga, N., Okochi, H., Niida, Y. et al. Alkaline extraction yields a higher number of microplastics in forest canopy leaves: implication for microplastic storage. Environ Chem Lett 22, 1599–1606 (2024). https://doi.org/10.1007/s10311-024-01725-3

[39]Brahney, J., Hallerud, M., Heim, E., Hahnenberger, M. & Sukumaran, S. Plastic rain in protected areas of the United States. Science 368, 1257–1260 (2020). https://doi.org/10.1126/science.aaz5819

[40]Sunaga, N., Okochi, H., Niida, Y. & Miyazaki, A. Alkaline extraction yields a higher number of microplastics in forest canopy leaves: implication for microplastic storage. Environ Chem Lett 22, 1599–1606 (2024). https://doi.org/10.1007/s10311-024-01725-3

Unlike forests, in the cities there is better deposition of micro- and nanoplastics because of better ventilation and the presence of heavier particulates from vehicle exhaust and industrial smog. Today, the air in forests is more saturated with nanoplastic than in megacities.

The world has changed! Now, when people swim in the ocean, sunbathe on the beach, jog along the coast or in the park, or walk in the forest for their health, they are, in fact, exposing their bodies to additional microplastic contamination.

Microplastics from Africa and North America have been found in remote and seemingly untouched places, such as the French Pyrenees. This indicates the global distribution of microplastic, which is carried by air currents and precipitation across vast distances.

Micro- and nanoplastics enter urban water bodies through stormwater runoff, industrial discharge, and rainwater, which captures particles from the atmosphere. For example, a single wash of synthetic fabrics can release up to 1.5 million microplastic[41] particles into wastewater. Once in the, these particles eventually flow into rivers and oceans, where they are ingested by fish and other aquatic organisms.

By analyzing waste found in rivers and surrounding landscapes, researchers estimated that just 10 river systems transport between 88% and 95% of the plastic that flows from rivers into the ocean.[42]

In another study, scientists reassessed commonly accepted assumptions about plastic transport in rivers and concluded that the actual amount of plastic waste in rivers could be 90% higher than previously thought.[43]

Plastic is also present in most of the world's large lakes. In fact, the density of plastic waste in lakes may even exceed that in the largest oceanic garbage patches, and even lakes located in pristine areas contain significant amounts of debris. This was confirmed by a major international study led by Barbara Leoni and Veronica Nava from the University of Milano-Bicocca.[44]

According to the 2021 report by the United Nations Environment Programme (UNEP), microplastic was found in all freshwater bodies studied - including rivers, lakes, and reservoirs.[45] For example, researchers found that nearly 10,000 metric tons - or 22 million pounds - of plastic waste enter the Great Lakes from the United States and Canada every year.[46]

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[41] De Falco, F., Di Pace, E., Cocca, M. & Avella, M. The contribution of washing processes of synthetic clothes to microplastic pollution. Sci Rep 9, 6633 (2019). https://doi.org/10.1038/s41598-019-43023-x

[42] Schmidt, C., Krauth, T. & Wagner, S. Export of Plastic Debris by Rivers into the Sea. Environ. Sci. Technol. 51, 12246–12253 (2017). https://doi.org/10.1021/acs.est.7b02368

[43] Valero, D., Belay, B. S., Moreno-Rodenas, A., Kramer, M. & Franca, M. J. The key role of surface tension in the transport and quantification of plastic pollution in rivers. Water Research 226, 119078 (2022). https://doi.org/10.1016/j.watres.2022.119078

[44] Nava, V., Chandra, S., Aherne, J. et al. Plastic debris in lakes and reservoirs. Nature 619, 317–322 (2023). https://doi.org/10.1038/s41586-023-06168-4

[45] United Nations Environment Programme. Monitoring Plastics in Rivers and Lakes: Guidelines for the Harmonization of Methodologies. (2020) https://www.unep.org/resources/report/monitoring-plastics-rivers-and-lakes-guidelines-harmonization-methodologies

[46] Hoffman, M. J. & Hittinger, E. Inventory and transport of plastic debris in the Laurentian Great Lakes. Marine Pollution Bulletin 115, 273–281 (2017). https://doi.org/10.1016/j.marpolbul.2016.11.061

Eventually, microplastic returns to humans through the consumption of fish and seafood.

Italian scientists have also discovered that fruits and vegetables contain millions of microplastic particles. High concentrations were found in apples, pears, carrots, potatoes, lettuce, and broccoli. Notably, fruit contained 2–3 times more microplastic particles than vegetables—ranging from 52,000 particles per gram in lettuce to 223,000 particles per gram in apples.[47]

A study found that 81% of 159 tap water samples from around the world contained microplastics.[48] Other research supports these findings, also detecting microplastic particles in bottled mineral water. Interestingly, the number of particles was roughly the same in both glass and polyethylene terephthalate (PET) bottles, with concentrations reaching 6,292 particles per liter.[49, 50, 51]

Researchers from the University of Newcastle (Australia) conducted a study[52] to estimate how much plastic the average person consumes. Their results showed that a person ingests about 250 grams of plastic per year, equivalent to 50 plastic bags.[53]

[47] Oliveri Conti, G. et al. Micro- and nano-plastics in edible fruit and vegetables. The first diet risks assessment for the general population. Environmental Research 187, 109677 (2020). https://doi.org/10.1016/j.envres.2020.109677
[48] Kosuth, M., Mason, S. A. & Wattenberg, E. V. Anthropogenic contamination of tap water, beer, and sea salt. PLoS ONE 13, e0194970 (2018). https://doi.org/10.1371/journal.pone.0194970
[49] Schymanski, D., Goldbeck, C., Humpf, H.-U. & Fürst, P. Analysis of microplastics in water by micro-Raman spectroscopy: Release of plastic particles from different packaging into mineral water. Water Research 129, 154–162 (2018). https://doi.org/10.1016/j.watres.2017.11.011
[50] Oßmann, B. E. et al. Small-sized microplastics and pigmented particles in bottled mineral water. Water Research 141, 307–316 (2018). https://doi.org/10.1016/j.watres.2018.05.027
[51] Winiarska, E., Jutel, M. & Zemelka-Wiacek, M. The potential impact of nano- and microplastics on human health: Understanding human health risks. Environmental Research 251, 118535 (2024). https://doi.org/10.1016/j.envres.2024.118535
[52] University of Newcastle. Plastic ingestion by people could be equating to a credit card a week. https://www.newcastle.edu.au/newsroom/featured/plastic-ingestion-by-people-could-be-equating-to-a-credit-card-a-week (accessed: 1 May 2025)
[53] Senathirajah, K. et al. Estimation of the mass of microplastics ingested – A pivotal first step towards human health risk assessment. Journal of Hazardous Materials 404, 124004 (2021). https://doi.org/10.1016/j.jhazmat.2020.124004

ENVIRONMENTAL AND CLIMATE CONSEQUENCES OF MICRO- AND NANOPLASTIC POLLUTION

How MNPs Disrupt Ecosystems at the Molecular Level

Plastic waste is found everywhere — from oceans and rivers to soil, air, and even glaciers.[54]

Long-term observations confirm that, unlike organic plant and animal matter, plastic does not undergo active natural decomposition. It persists in the environment without participating in natural biodegradation cycles.[55] Engineered to resist breakdown, plastic has become a permanent fixture in the global ecosystem. What was once hailed as a technological triumph has now become a source of significant ecological disruption.

More than 13,000 chemical substances are used in the production of plastics. Of these, over 3,200—including monomers, additives, and processing aids—are potentially hazardous due to their toxic properties.[56]

Impact of MNPs on Soil Properties and Ecosystems Degradation

Studies show that microplastic pollution in terrestrial ecosystems—particularly agricultural soils—may exceed levels in oceanic environments by 4 to 23 times,[57] indicating significant plastic accumulation in soils. Plastics enter soil through various pathways, including wastewater treatment facilities, mulching practices, atmospheric deposition, and everyday consumer products. The widespread use of single-use plastic items is closely tied to serious contamination of soils with microplastics (MP) and nanoplastics (NP). Both natural and human-driven factors enable[58] these tiny plastic particles to infiltrate soil layers, disrupting critical environmental processes.[59]

Observations confirm the harmful effects of microplastics on ecosystems, impacting the structure and function of microorganisms, plants, and soils (Fig. 15).

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[54]Hale, R. C., Seeley, M. E., La Guardia, M. J., Mai, L. & Zeng, E. Y. A Global Perspective on Microplastics. Journal of Geophysical Research: Oceans 125, e2018JC014719 (2020). https://doi.org/10.1029/2018JC014719

[55]Huang, S. et al. Plastic Waste Management Strategies and Their Environmental Aspects: A Scientometric Analysis and Comprehensive Review. IJERPH 19, 4556 (2022). https://doi.org/10.3390/ijerph19084556

[56]United Nations Environment Programme. Chemicals in Plastics - A Technical Report (2023). https://www.unep.org/resources/report/chemicals-plastics-technical-report (accessed: 1 May 2025)

[57]Yu, H., Zhang, Y., Tan, W. & Zhang, Z. Microplastics as an Emerging Environmental Pollutant in Agricultural Soils: Effects on Ecosystems and Human Health. Front. Environ. Sci. 10, 855292 (2022). https://doi.org/10.3389/fenvs.2022.855292

[58]Rillig, M. C., Ingraffia, R. & De Souza Machado, A. A. Microplastic Incorporation into Soil in Agroecosystems. Front. Plant Sci. 8, 1805 (2017). https://doi.org/10.3389/fpls.2017.01805

[59]Shafea, L. et al. Microplastics in agroecosystems: A review of effects on soil biota and key soil functions. J. Plant Nutr. Soil Sci. 186, 5–22 (2023). https://doi.org/10.1002/jpln.202200136

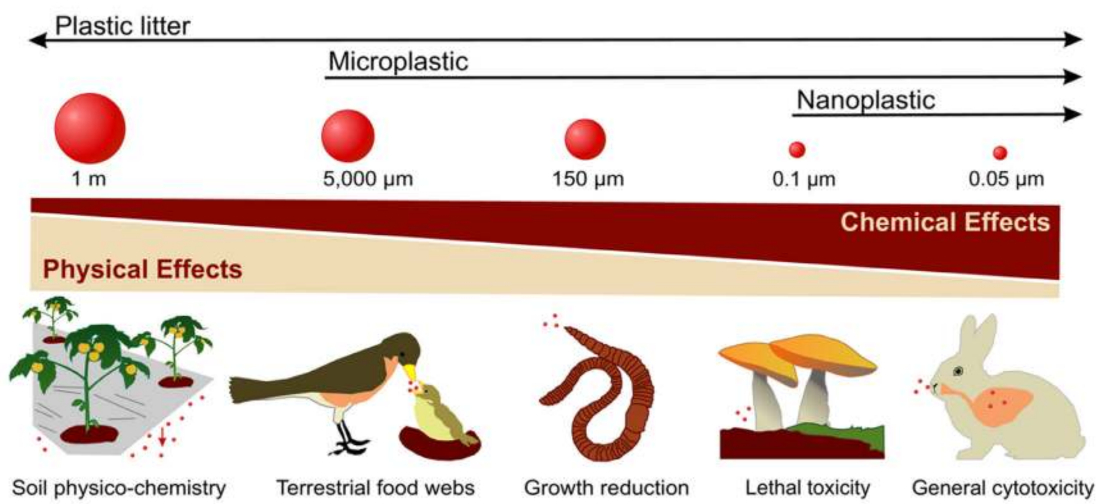

Figure 15: Microplastics as a trigger for combined physical and chemical effects.

Soil biogeochemistry related to agricultural mulching (Steinmetz et al., 2016), ingestion by terrestrial and continental birds (Gil-Delgado et al., 2017; Holland et al., 2016; Zhao et al., 2016), reduction in growth of earthworms (Lwanga et al., 2016), lethal toxicity to fungi (Miyazaki et al., 2014, 2015; Nomura et al., 2016), mammal lung inflammation (Hamoir et al., 2003; Oberdorster, 2000; Schmid & Stoeger, 2016) and broad cytotoxicity (Forte et al., 2016; Kato et al., 2003) of nanoplastics.

Adapted from: de Souza Machado AA, Kloas W, Zarfl C, Hempel S, Rillig MC. Microplastics as an emerging threat to terrestrial ecosystems. Glob Change Biol. 2018; 24: 1405–1416. https://doi.org/10.1111/gcb.14020

Research conducted by the Chinese Academy of Sciences found that the presence of plastic film particles of various sizes in soil significantly increases the rate of water evaporation. The effect is especially pronounced with the addition of 2-millimeter particles. Larger plastic fragments (5–10 mm) cause soil cracking, disrupting its structural integrity. These findings suggest that plastic pollution interferes with the water cycle in soils, which may exacerbate soil water shortages and affect the vertical transport of pollutants[60] (Fig. 16, 17).

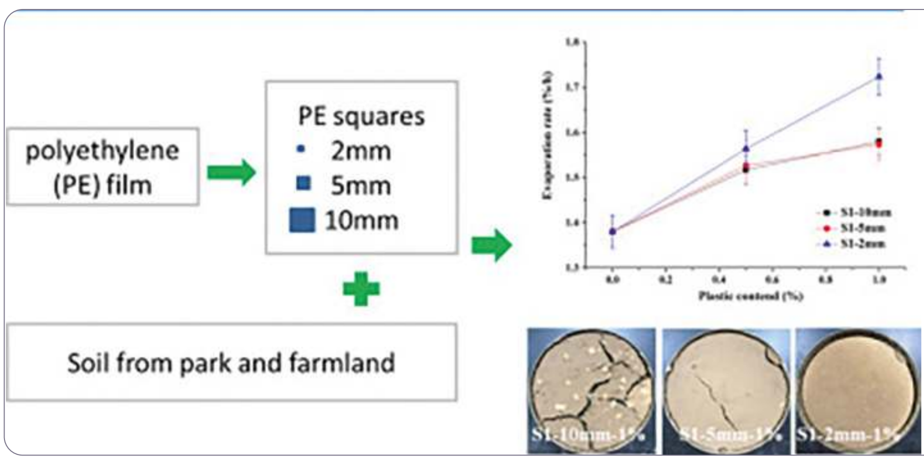

Figure 16: Disruption of soil structural integrity caused by microplastics
Source: Wan, Y., Wu, C., Xue, Q. & Hui, X. Effects of plastic contamination on water evaporation and desiccation cracking in soil. Science of The Total Environment 654, 576–582 (2019). https://doi.org/10.1016/j.scitotenv.2018.11.123

[60] Wan, Y., Wu, C., Xue, Q. & Hui, X. Effects of plastic contamination on water evaporation and desiccation cracking in soil. Science of The Total Environment 654, 576–582 (2019). https://doi.org/10.1016/j.scitotenv.2018.11.123

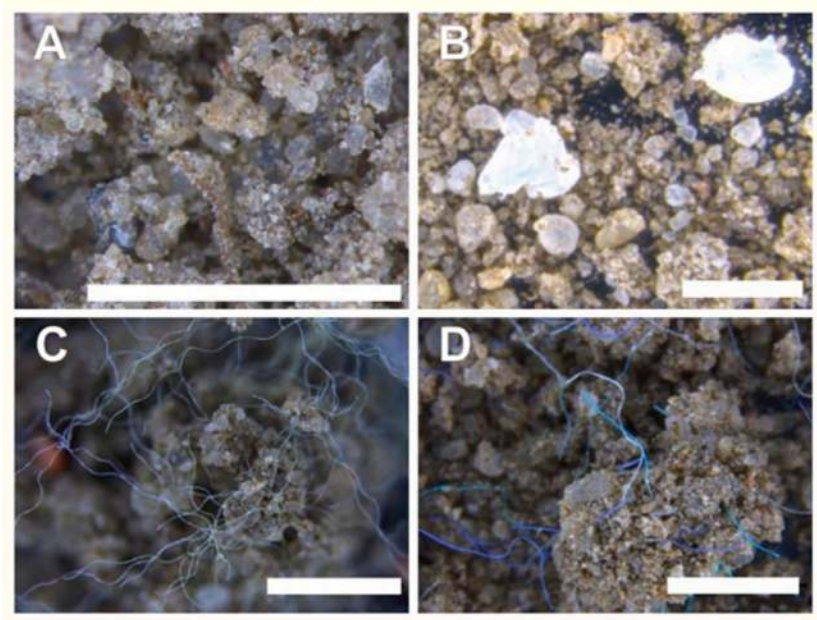

Figure 17: Integration of microplastic particles into the soil's biophysical environment

Structure of control soil (A) was not visually distinct under the stereomicroscope from soil contaminated with polyamide beads (SI S1D). Polyethylene fragments (B), and polyester (C) or polyacrylic fibers (D) resulted in visually apparent soil features. The white bar in each panel represents 1 mm size.

Source: De Souza Machado, A. A. et al. Impacts of Microplastics on the Soil Biophysical Environment. Environmental Science & Technology, 52, 9656–9665 (2018). https://doi.org/10.1021/acs.est.8b02212

Studies also confirm the adverse effects of plastics on soil biota—a diverse community that includes microorganisms (such as bacteria and fungi) and fauna (both microscopic and macroscopic animals). These organisms interact with each other, with plant roots, and with the surrounding environment to form soil food chains (Fig. 18), which are essential for nutrient cycling and plant health.

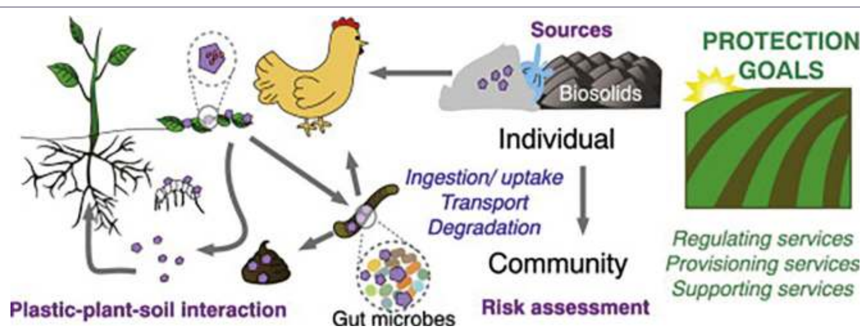

Figure 18: Schematic illustration of soil food chain formation.

Source: Ng, E.-L. et al. An overview of microplastic and nanoplastic pollution in agroecosystems. Science of The Total Environment, 627, 1377–1388 (2018). https://doi.org/10.1016/j.scitotenv.2018.01.341

Various types of terrestrial biota serve as bioindicators of microplastic pollution. All samples analyzed contained microplastic particles and potentially toxic elements (Sb, As, Fe, Al, Se, Zn) in varying concentrations, indicating[61] the possible toxicity of microplastics.[62]

Research has shown that polystyrene beads can be ingested by the soil-dwelling nematode Caenorhabditis elegans (Fig. 19); this also suggests that polystyrene particles may accumulate within the soil food chain.[63]

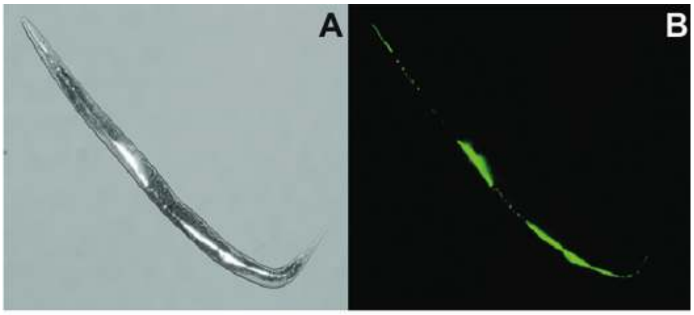

Figure 19: Bright field (A) and fluorescence (B) images of a Caenorhabditis elegans adult worm that accumulated 0.5 μm microspheres of yellow-green fluorescence for 15 min at 20°. The photographs were taken at ×100 magnification.
Source: Kiyama, Y., Miyahara, K. & Ohshima, Y. Active uptake of artificial particles in the nematode Caenorhabditis elegans. Journal of Experimental Biology 215, 1178–1183 (2012). https://doi.org/10.1242/jeb.067199

Soil biota is more than just the "biological engine of the Earth"—it is a multifunctional system upon which all terrestrial ecosystems depend. Its role in sustaining life on the planet is comparable to that of the oceans and atmosphere, as confirmed by research in soil science, ecology, and climate studies. Any disruption caused by toxicity can therefore impact numerous critical processes within the soil and its food chain, leading to ecological imbalance.[64]

Findings show that microplastics can quickly adsorb to soil surfaces due to their small size, high specific surface area, strong hydrophobicity, and resistance to biodegradation.[65] These properties facilitate easy uptake and accumulation in organisms, posing a potential threat to human health. This process is not limited to the soil layer—it extends to plants, where microplastics continue to exert harmful effects.

MNPs in Food Products

Anthropogenic pollutants can significantly impact ecosystems, especially when they enter plant systems. Microplastics have been confirmed to be absorbed and translocated into various parts of plants.

Research shows that microplastics accumulate in plant systems through multiple pathways, exerting harmful effects on vegetation, agricultural crops, and food products.

[61]Ng, E.-L. et al. An overview of microplastic and nanoplastic pollution in agroecosystems. Science of The Total Environment 627, 1377–1388 (2018). https://doi.org/10.1016/j.scitotenv.2018.01.341

[62]Al Malki, J. S., Hussien, N. A., Tantawy, E. M., Khattab, Y. & Mohammadein, A. Terrestrial Biota as Bioindicators for Microplastics and Potentially Toxic Elements. Coatings 11, 1152 (2021). https://doi.org/10.3390/coatings11101152

[63]Kiyama, Y., Miyahara, K. & Ohshima, Y. Active uptake of artificial particles in the nematode Caenorhabditis elegans. Journal of Experimental Biology 215, 1178–1183 (2012). https://doi.org/10.1242/jeb.067199

Due to their extremely tiny size, nanoplastics can directly penetrate plant tissue.[66] Plants absorb nanoplastics from nutrient media, after which they are transported to aboveground parts through the xylem—the vascular system responsible for transporting water and nutrients from roots to stems and leaves.

Microplastics that settle on leaves can enter through stomata and may then move downward to the roots via vascular bundles. Both micro- and nanoplastics exhibit toxic effects on the physiological processes and enzymatic activity of agricultural plants (Fig. 20).[67]

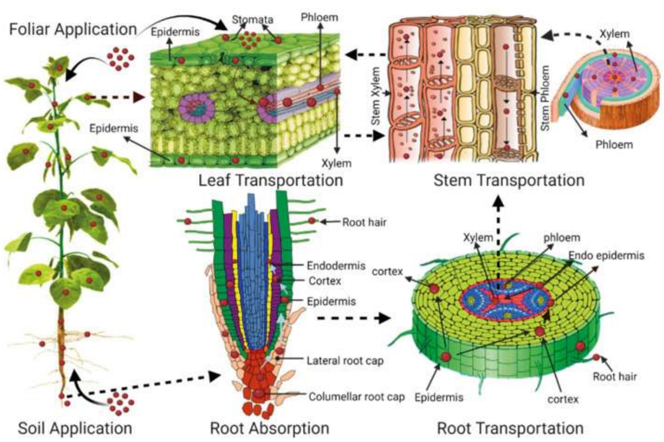

Figure 20: Mechanisms of micro- and nanoplastic uptake in plants.
Plant uptake mechanism of plastic by soil application via root absorption and transport pathways from root to stem and stem transport to leaf and fruits. Foliar application reveals the entry of plastic to leaf stomata and later transfer to other parts of the plant. Cure arrow indicates the availability of plastic to plant and the dashed arrow indicates transportation within the plant.

Source: Azeem, I. et al. Uptake and Accumulation of Nano/Microplastics in Plants: A Critical Review. Nanomaterials 11, 2935 (2021). https://doi.org/10.3390/nano11112935

The plant water transport system can rapidly carry nanoplastics to stems, leaves, and possibly fruits. Research on tobacco plants (Nicotiana tabacum) shows that while 100-nanometer nanoplastics do not enter plant cells, smaller particles—20 to 40 nanometers in size—are successfully absorbed.[68]

Additionally, some plastic particles carry surface charges, which can enhance their adsorption to plant roots through electrostatic attraction. This interaction may affect nutrient immobilization or interfere with photosynthesis.[69] Negatively charged microplastics are more likely to enter the root cortex.[70]

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[64]Al Malki, J. S., Hussien, N. A., Tantawy, E. M., Khattab, Y. & Mohammadein, A. Terrestrial Biota as Bioindicators for Microplastics and Potentially Toxic Elements. Coatings 11, 1152 (2021). https://doi.org/10.3390/coatings11101152
[65]Sajjad, M. et al. Microplastics in the soil environment: A critical review. Environmental Technology & Innovation 27, 102408 (2022). https://doi.org/10.1016/j.eti.2022.102408
[66]Hasan, M. M. et al. Impact of microplastics on terrestrial ecosystems: A plant-centric perspective. Environmental Pollution and Management 1, 223–234 (2024). https://doi.org/10.1016/j.epm.2024.11.002
[67]Azeem, I. et al. Uptake and Accumulation of Nano/Microplastics in Plants: A Critical Review. Nanomaterials 11, 2935 (2021). https://doi.org/10.3390/nano11112935
[68]Bandmann, V., Müller, J. D., Köhler, T. & Homann, U. Uptake of fluorescent nano beads into BY2-cells involves clathrin-dependent and clathrin-independent endocytosis. FEBS Letters 586, 3626–3632 (2012). https://doi.org/10.1016/j.febslet.2012.08.008
[69]Lian, J. et al. Do polystyrene nanoplastics affect the toxicity of cadmium to wheat (Triticum aestivum L.)? Environmental Pollution 263, 114498 (2020). https://doi.org/10.1016/j.envpol.2020.114498
[70]Li, W. et al. Uptake and effect of carboxyl-modified polystyrene microplastics on cotton plants. Journal of Hazardous Materials 466, 133581 (2024). https://doi.org/10.1016/j.jhazmat.2024.133581

In agroecosystems heavily contaminated with these particles, studies report stunted plant growth,[71] as well as short-term and transient effects on seed germination and root development.[72]

Studies confirm the presence of microplastics in commercially available honey, produced both industrially and locally. Further analysis revealed the widespread presence of microplastics in the inflorescences of various plant species.[73, 74]

In recent years, the state of global bee populations has seen a sharp decline. Research suggests that one of the underestimated contributors may be environmental contamination from microplastics and nanoplastics. Studies indicate that bees "collect" microplastics from the air, water, plants, and soil, then carrying them back to their hives. Bees gather nectar and pollen from flowers, and they collect water from natural sources — all of which already contain microplastic particles. The fine hairs covering bees' bodies act as natural "traps" for these particles. Plastic particles also accumulate on their legs, particularly in the joints and between segments, as they come into contact with plant surfaces, soil, water, and even the hive itself.

> *"The honeybee is a very good biological indicator of environmental contamination because it is ubiquitous, covered by hairs that capture contaminants and particles present in the air, sensitive to pollutants, and has great mobility and wide flying range, among others"*[75]
>
> *Source: https://www.sciencedirect.com/science/article/abs/pii/S0269749123000805*

Micro- and nanoplastics also enter the bee's body through the cuticle—the outer layer of its exoskeleton. Once inside, plastic particles reach the brain within just three days, causing impairments in memory, spatial orientation, and cognitive functions that are critical for foraging and navigation.[76] The impact of microplastics on the brain also reduces the bee's ability to restore memory. This is particularly concerning, as bees navigate using familiar environmental landmarks. Nanoplastics in the bee brain further impair their ability to remember nectar sources, reduce responsiveness to floral scents, and disrupt their ability to find their way back to the hive. Such cognitive dysfunctions directly decrease pollination efficiency and may destabilize the entire colony.[76]

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[71]Azeem, I. et al. Uptake and Accumulation of Nano/Microplastics in Plants: A Critical Review. Nanomaterials 11, 2935 (2021). https://doi.org/10.3390/nano11112935
[72]Bosker, T., Bouwman, L. J., Brun, N. R., Behrens, P. & Vijver, M. G. Microplastics accumulate on pores in seed capsule and delay germination and root growth of the terrestrial vascular plant Lepidium sativum. Chemosphere 226, 774–781 (2019). https://doi.org/10.1016/j.chemosphere.2019.03.163
[73]Liebezeit, G. & and Liebezeit, E. Non-pollen particulates in honey and sugar. Food Additives & Contaminants: Part A 30, 2136–2140 (2013). https://doi.org/10.1080/19440049.2013.843025
[74]Basaran, B. et al. Microplastics in honey from Türkiye: Occurrence, characteristic, human exposure, and risk assessment. Journal of Food Composition and Analysis 135, 106646 (2024). https://doi.org/10.1016/j.jfca.2024.106646
[75]Alma, A. M., de Groot, G. S. & Buteler, M. Microplastics incorporated by honeybees from food are transferred to honey, wax and larvae. Environmental Pollution 320, 121078 (2023). https://doi.org/10.1016/j.envpol.2023.121078
[76]Pasquini, E. et al. Microplastics reach the brain and interfere with honey bee cognition. Science of The Total Environment 912, 169362 (2024). https://doi.org/10.1016/j.scitotenv.2023.169362
[77]Sheng, D., Jing, S., He, X. et al. Plastic pollution in agricultural landscapes: an overlooked threat to pollination, biocontrol and food security. Nature Communications 15, 8413 (2024). https://doi.org/10.1038/s41467-024-52734-3
[78]Al Naggar, Y. et al. Chronic exposure to polystyrene microplastic fragments has no effect on honey bee survival, but reduces feeding rate and body weight. Toxics 11, 100 (2023). https://doi.org/10.3390/toxics11020100

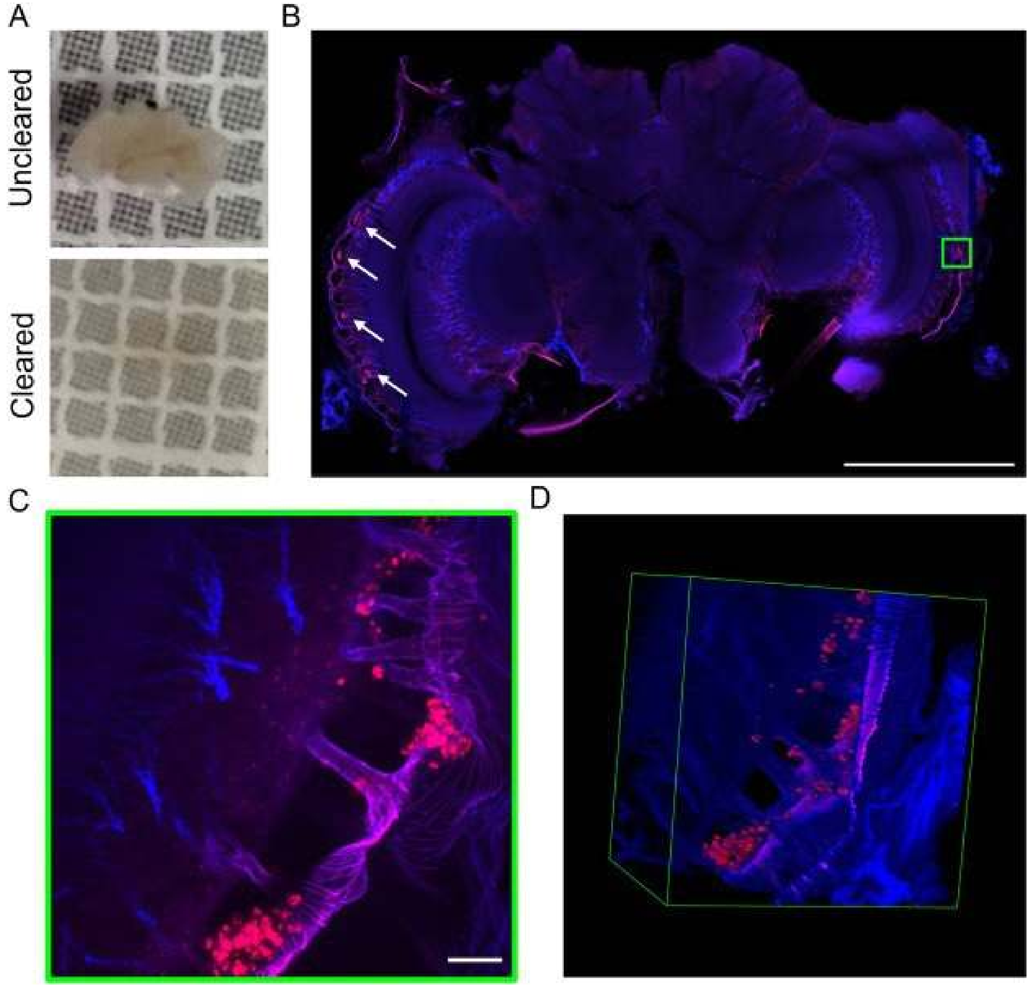

Figure 21. Detection of significant amounts of microplastics in honeybee brain.

A) Photos of a dissected brain before and after the iDISCO clearing.
B) Single plane (depth ~ 200 μm) of a 3D reconstruction obtained with TPFM of the whole brain with a 10× objective, resolution of 0.51 × 0.51 × 2 μm3. In blue = autofluorescence signal of the tissue; in red = red fluorescence MPs (pointed with white arrows). Scale bar = 1000 μm.
C) High-resolution inset of the green region of interest in B acquired with a 63× objective. The image is the maximum intensity projection of a 150 μm depth stack quired with a resolution of 0.17 × 0.17 × 1 μm3. Scale bar = 20 μm.
D) 3D rendering of the stack in C. Dimensions = 170 × 170 × 150 μm3.

Source: Pasquini, E. et al. Microplastics reach the brain and interfere with honey bee cognition. Science of The Total Environment 912, 169362 (2024). https://doi.org/10.1016/j.scitotenv.2023.169362

Once inside the bee's body, nanoplastics also cause intestinal damage, weaken the immune system, and increase susceptibility to viral infections—factors that can lead to bee mortality even in the absence of acute plastic toxicity.[75, 77] In addition, plastic fragments accumulate not only in bees themselves but also in honey, wax, and larvae, creating a closed cycle of plastic contamination within the hive.[75]

[75]Alma, A. M., de Groot, G. S. & Buteler, M. Microplastics incorporated by honeybees from food are transferred to honey, wax and larvae. Environmental Pollution 320, 121078 (2023). https://doi.org/10.1016/j.envpol.2023.121078
[77]Sheng, D., Jing, S., He, X. et al. Plastic pollution in agricultural landscapes: an overlooked threat to pollination, biocontrol and food security. Nature Communications 15, 8413 (2024). https://doi.org/10.1038/s41467-024-52734-3

This poses potentially serious implications not only for bee populations but also for global food security. Bees are key pollinators, and their decline directly affects agricultural yields.

Brain damage, reduced body mass, and suppressed immunity lead to a decrease in pollination activity, which researchers warn could exacerbate the crisis in global food production.[77] Bees function as active bioindicators of environmental pollution, and microplastics have already been detected in significant quantities in honey, regardless of the country of origin.[78]

Microplastic exposure reduces overall chlorophyll content by 5.63–17.42%, leading to global losses in rice, wheat, and corn production. These losses account for 4.11–13.52% of the total annual global yield of these staple crops—an impact with serious implications for food security (Figure 22).[79]

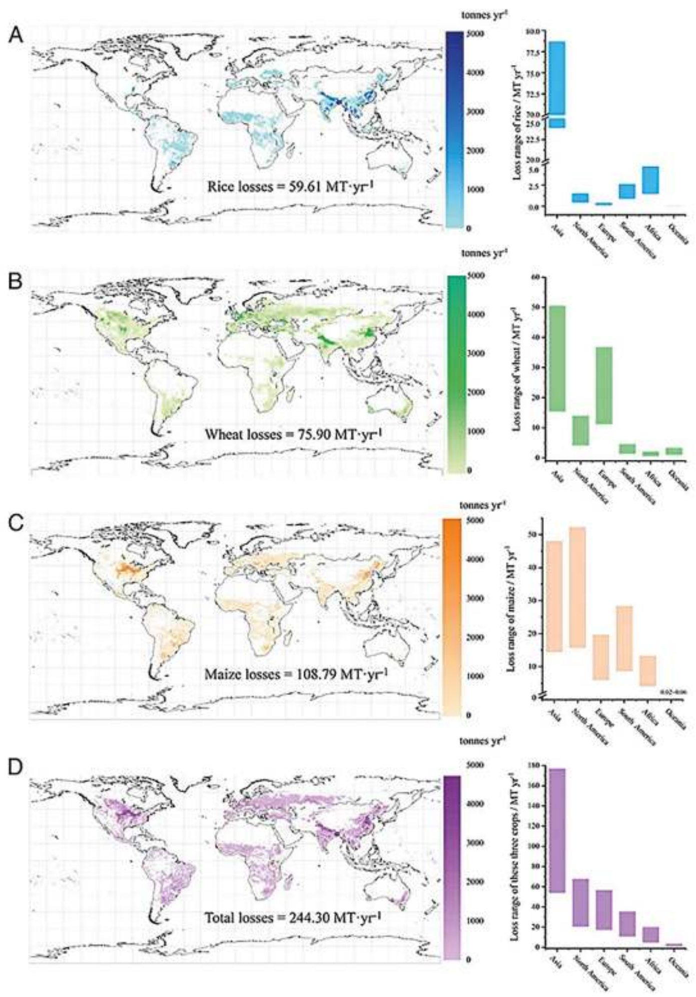

Figure 22: Global maps of annual production losses for three main food crops.
(A) Rice; (B) Wheat; (C) Corn; (D) All three crops combined.

The maps on the left display the median predicted annual yield losses due to microplastic pollution, while the floating bar charts on the right illustrate the range of annual production losses for each corresponding crop. Crop production data (2020 version) were sourced from the Spatial Production Allocation Model (SPAM) database.

Source: Zhu, R. et al. A global estimate of multiecosystem photosynthesis losses under microplastic pollution. Proceedings of the National Academy of Sciences, 122, e2423957122 (2025). https://doi.org/10.1073/pnas.2423957122

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Forests as Global Accumulators of Microplastics

Analyses have revealed the presence of nanoplastics in roots, stems, leaves, and needles across all examined concentrations and time intervals. Nanoplastic concentrations in roots exceeded those in aboveground parts by at least a factor of 10.

Plastic pollution negatively affects the functioning of both evergreen conifers and deciduous tree species by inducing oxidative stress and reducing photosynthetic efficiency, potentially leading to growth inhibition or even plant death.

Studies indicate that disruptions in photosynthetic stages cause the accumulation of excess light energy. When this energy is not converted into chemical energy, it leads to photooxidative stress and tissue damage. To mitigate this, plants activate photoprotective mechanisms, in which carotenoids dissipate the excess energy as heat.[80]

By impairing photosynthesis, inducing oxidative stress, and lowering plant physiological activity, plastic pollution increases ecosystem vulnerability to climate change. These findings underscore the broad-scale impact of plastic contamination on plant communities and, by extension, raise concerns about its consequences for terrestrial animals that depend on these ecosystems.

How Nanoplastics Destroy Fauna

Numerous studies indicate that the accumulation of micro- and nanoplastics in the environment, including in plants, affects livestock production[81] by disrupting food chains and impacting animal health. Observations from a dairy farm in Italy showed that all samples of ryegrass hay contained microplastics.[82] A study conducted in India found polyethylene terephthalate microplastic contamination in 100% of dairy cattle feed samples, with concentrations ranging from 89 to 326 g/kg.[83]

Analysis confirmed the presence of microplastics in the follicular fluid of cattle,[84] in milk,[85] in sheep feces,[86] in beef, and in blood,[87] pointing to significant impacts on ruminants.

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According to available data, 50–60% of foreign objects retrieved from slaughtered livestock[88]—including small ruminants such as goats and sheep—consisted of plastic materials. In addition, microplastics have been detected in the internal tissues of urban dogs and cats,[89] in the intestines of domestic ducks,[90] and in the lung tissue of pigs.[91] Research findings confirm that microplastics harm animals not only directly, but also through the additives used in their production and the pollutants they absorb from the surrounding environment, causing damage of varying severity.[92] Observations indicate that microplastics trigger toxic effects in animals, including oxidative stress, intestinal damage, immunotoxicity, as well as reproductive and neurotoxicity (Fig. 23).[93]

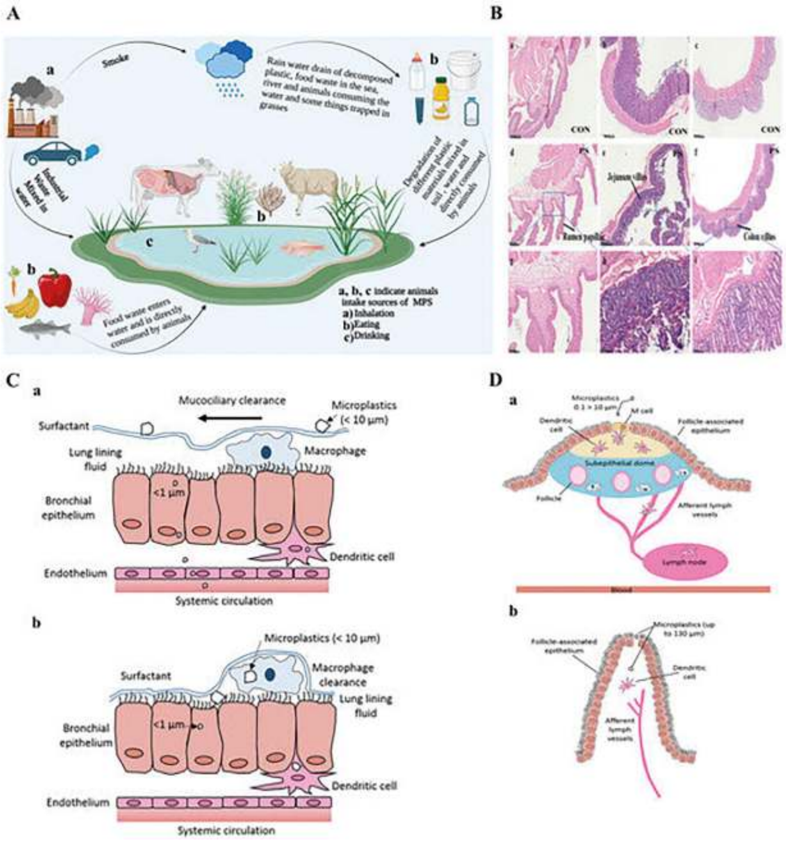

Figure 23: Schematic diagram of the pathways of animal ingestion of MPs and the effects of MPs on the gastrointestinal tract.
(A) Pathways of MP intake by animals.
(B) PS gastrointestinal section before and after exposure: H&E images of the rumen (a), jejunum (b), and colon (c) in the CON group;
(d) rumen H&E map of S-PS group;
(e) L-PS group jejunum H&E map;
(f) colon H&E map of L-PS group;
and (g–i) are locally enlarged images corresponding to (d–f), respectively.
(C) Potential uptake and clearance mechanisms of MPs (0.1 > 10 μm) in the lungs:
(a) There is a reduced chance of lung fluids (surfactants and mucus) causing microplastic displacement in the upper respiratory tract (central lung) where the lung membrane is thicker. The ciliary mucosa with particles >1 μm was cleared. Particles <1 μm can be ingested through the epithelium.
(b) If the aerodynamic diameter of the microplastic allows deposition deep in the lung, it may penetrate the thinner lung fluid and contact the epithelium, metastasizing through diffusion or active cell uptake.
(D) Predicted pathways for uptake of MPs from the gastrointestinal tract (GIT):
(a) MPs uptake from GIT lumen by M cells of Pyle's collecting lymph nodes through endocytosis (0.1 > 10 μm). M cells sample and transport particles from the intestinal lumen to mucosal lymphoid tissue.
(b) MPs are absorbed from the GIT lumen by paracellular absorption. Non-degradable particles, such as MPs, can be mechanically pinched into the underlying tissue through loose connections in the single-celled upper layer. Dendritic cells are able to devour these particles, transporting them to lymph vessels and veins below. They may be distributed to secondary tissues, including the liver, muscles, and brain
Source: Su, M. et al. (2025). Toxicity Mechanisms of Microplastic and Its Effects on Ruminant Production: A Review. Biomolecules, 15, 462. https://doi.org/10.3390/biom15040462

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Moreover, microplastics act as carriers for contaminants such as heavy metals, antibiotics, persistent organic compounds, and pesticides—further amplifying potential risks to ecosystems, animal health, and human health.[94]

Observational data indicate that wild animals often mistake plastic waste for food, leading to its accumulation in their intestines. In Zimbabwe[95] and Sri Lanka[96], elephants that fed at open dumps died from ingesting indigestible plastic. In Japan's Nara Park, wild deer died from complications caused by swallowing plastic waste left by tourists[97]. A study of over 30,000 camels near Dubai in the United Arab Emirates found that approximately 1% of the animals likely died due to plastic accumulated in their digestive systems.[98]

Scientists coined the term "polybezoar" to describe a dense mass of indigestible materials—such as plastic, rope, trash, and salt deposits—forming a stone-like concretion in the stomach or intestines, especially in ruminants. The term combines “poly” (synthetic material) and “bezoar” (a hardened mass). Observations confirm that polybezoars cause gastrointestinal blockages, sepsis from bacterial growth, dehydration, and malnutrition (Fig. 24).

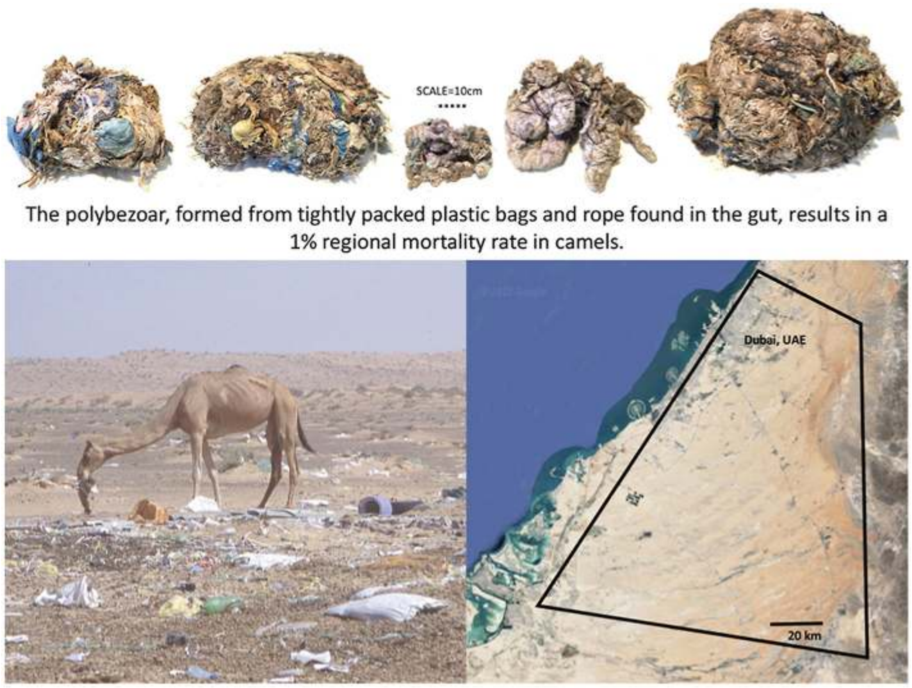

Figure 24: Polybezoars found inside dead camels in the desert near Dubai.
The largest one analyzed in the new study weighed nearly 64 kilograms (141 pounds).
Source: Eriksen, M., Lusher, A., Nixon, M. & Wernery, U. (2021). The plight of camels eating plastic waste. Journal of Arid Environments, 185, 104374. https://doi.org/10.1016/j.jaridenv.2020.104374

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Transfer of MNPs Via Food Chains From Plankton to Humans

The accumulation of plastics in the ocean has a significant negative impact on marine ecosystems. Scientific observations over the past four decades have revealed microplastics in nearly all marine habitats worldwide.[99] Studies confirm that plastic debris affects marine biodiversity across a wide spectrum of habitats. At least 690 marine species have been affected by plastic pollution globally, including cetaceans, pinnipeds, seabirds, turtles, fish, and crustaceans.[100] Ingesting plastic debris can also expose the animal to an additional source of toxins. The chemical components can leach into the body following ingestion, with pollutants transferred from prey to predator within food chains. The effects of entanglement or ingestion can be lethal or sublethal in nature, and lead to a range of issues such as compromised feeding capacity and digestion problems leading to malnutrition, disease, reduced reproductive output, reduced growth rates, and shorter lifespan.[101]

Due to their small sizes, microplastics are ingested by plankton — a key component of marine food chains. Plankton is consumed by many marine species, and those that do not feed on it directly eat organisms that have already ingested it. In this way, microplastics become integrated into food chains (Figs. 25–26).

In 1999, an analysis of surface water samples in the North Pacific Subtropical Gyre revealed that the mass of plastic exceeded the mass of zooplankton — the primary food source of the ecosystem — by six times[102], highlighting the dominance of plastic over living organisms in the ocean.

Estimates based on observational data indicate that the concentration of microplastics increases with fish size.

Data show that the largest animal — the whale — ingests up to 43.6 kg of plastics daily, with 98.5 % of this volume coming from prey, not directly from the water, since microplastics are already present in the food it consumes.[103]

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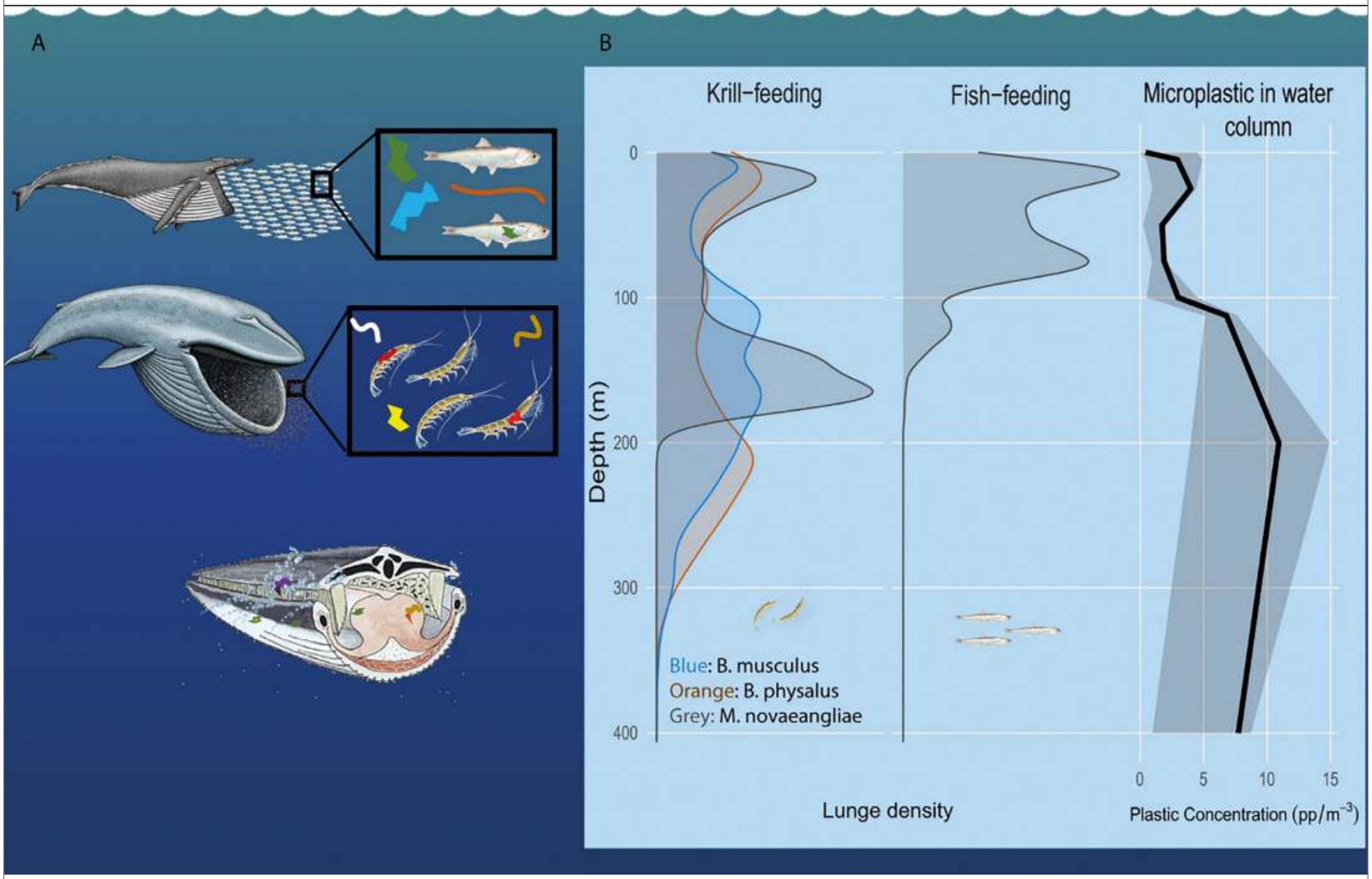

Figure 25: a — Plastics ingested by whales per day, modeled as the sum of (i) plastics filtered from water per day and (ii) plastics consumed in prey per day. We created three scenarios to capture the range of possible exposure risk of plastic ingestion: low, medium, and high, since some of the variables lack comprehensive data; b — Lunge depths from deployments in Monterey Bay aligned with the depth profile of plastic concentration in Monterey Bay. Whales and prey items were illustrated by Alex Boersma, and the cut-away filtration diagram was illustrated by Scott Landry at Center for Coastal Studies. Source data has been provided as a source data file.

Source: Kahane-Rapport, S. R. et al. Field measurements reveal exposure risk to microplastic ingestion by filter-feeding megafauna. Nat Commun 13, 6327 (2022). https://doi.org/10.1038/s41467-022-33334-5

Figure 26: Schematic representation of plastics penetration into food chains

Plastics Kill Marine Organisms

Every year, around 1 million seabirds and 100,000 marine mammals die due to pollution.[104] Observations confirm a link between ingested debris and seabird mortality. A study of 1,733 seabirds of 51 species found that 557 (32.1 %) had ingested marine debris, ranging from 1–40 items, with a maximum weight of 3,440 mg and volume of 3,621 mm^3.[105]

Some data also show that certain plastics release dimethyl sulfide — a chemical compound that mimics the olfactory signal used by seabirds to identify food.[106] New research has also established that plastics ingestion causes kidney, liver, and stomach damage in chicks, as well as brain lesions similar to Alzheimer's disease. This highlights the destructive impact of plastic pollution on marine fauna.[107] Plastic particles were found in every individual of all seven species of turtles across three oceanic basins (Fig. 27).[108]

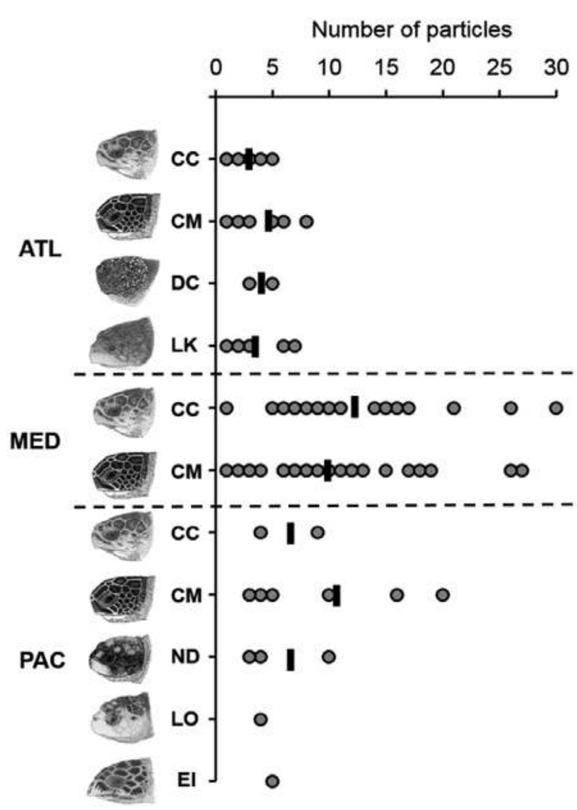

Figure 27: Synthetic microparticle ingestion in all species of marine turtles from three ocean basins. Total number of particles identified in each 100 ml subsample per species per ocean basin.
Black line = mean number of particles.

Note that 100 ml was analysed per animal irrespective of size, so the number of particles per animal should not be over-interpreted. ATL = Atlantic (North Carolina, USA) loggerhead turtle (*Caretta caretta*, n = 8), green turtle (*Chelonia mydas*, n = 10), leatherback turtle (Dermochelys coriacea, n = 2), Kemp›s ridley turtle (*Lepidochelys kempii*, n = 10). MED = Mediterranean (Northern Cyprus) loggerhead turtle (n = 22), green turtle (n = 34). PAC = Pacific (Queensland, Australia) loggerhead turtle (n = 3), green turtle (n = 7), flatback turtle (*Natator depressus*, n = 4), hawksbill turtle (*Eretmochelys imbricata*, n = 1) and olive ridley turtle (*Lepidochelys olivacea*, n = 1). Sea turtle skull figures used with permission of WIDECAST; original artwork by Tom McFarland

Source: Duncan, E. M. et al. Microplastic ingestion ubiquitous in marine turtles. Global Change Biology 25, 744–752 (2019). https://doi.org/10.1111/gcb.14519

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Studies of 171,774 individuals from 555 species of marine fish show that 386 species, including 210 commercially important species, consume plastic debris[109]. The incidence rate of plastic ingested by fish was 26 %, doubling over the last decade (Fig. 28). Analysis revealed a positive correlation between the abundance of plastic in surface waters (Fig. 29) and its consumption by marine organisms (Fig. 30).

Laboratory studies show that compounds from plastic, when absorbed into fish tissues, reduce activity, impair liver function, damage the brain, and also delay growth and worsen reproductive fitness.[109, 106, 107]

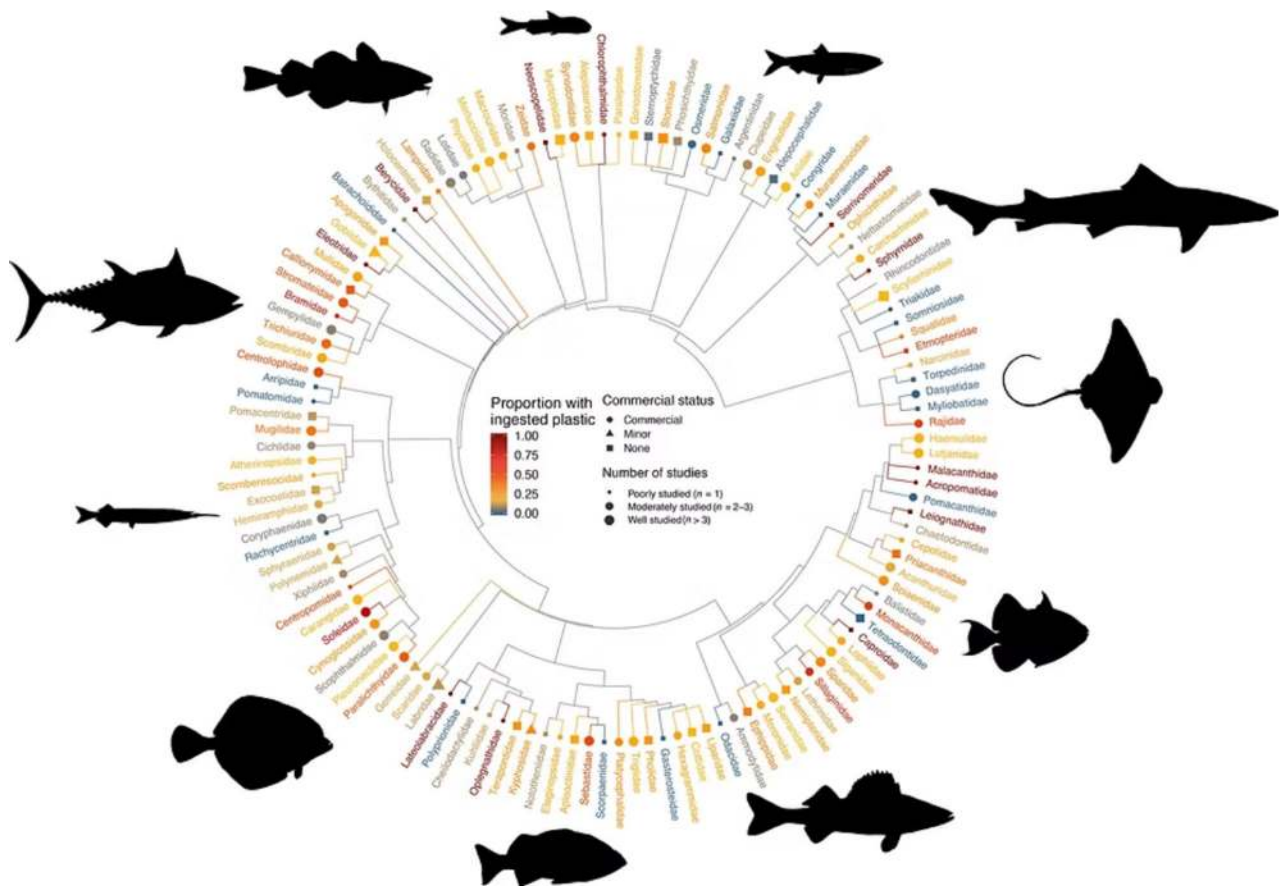

Figure 28: Fish families and plastic ingestion. Phylogenetic relationships of marine fish families (n = 131) colored by their incidence of plastic ingestion. Shapes of each tip denote the proportion of species within the family in the dataset that are commercially harvested (0 = no species targeted commercially; minor = 0%–25% of species targeted commercially; commercial = >25% of species targeted commercially). The size of the tip point indicates the number of studies conducted on species in that family. This highlights 15 families that are well sampled (n > 10 individuals, >2 species) with a high incidence of plastic ingestion (FO plastic > 0.25); 67 of these families with records of plastic ingestion are also commercial.

Source: Savoca, M. S., McInturf, A. G. & Hazen, E. L. "Plastic ingestion by marine fish is widespread and increasing." Global Change Biology 27, 2188–2199 (2021). DOI

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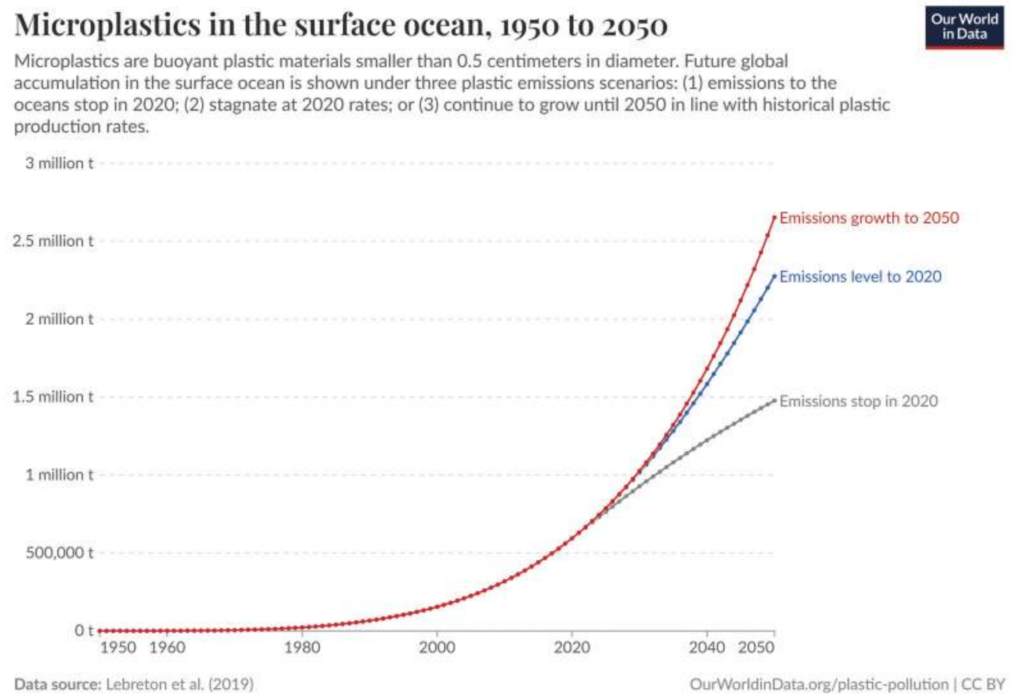

Figure 29:
Microplastics in the surface ocean, 1950 to 2050
Source: Our World in Data. Link (accessed on: May 1, 2025)
Source: Lebreton, L., Egger, M. & Slat, B. "A global mass budget for positively buoyant macroplastic debris in the ocean." Sci Rep 9, 12922 (2019). DOI

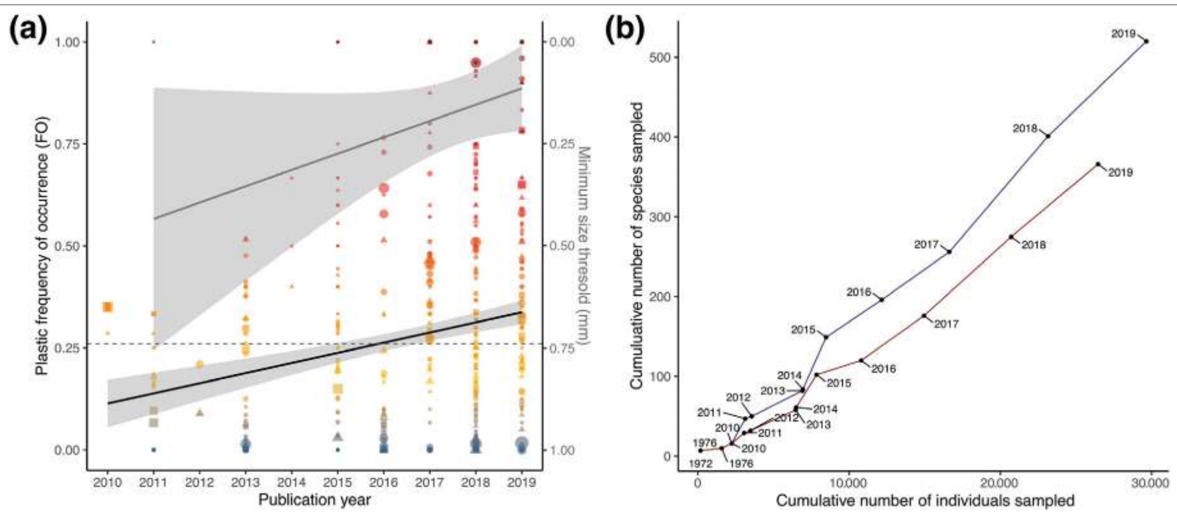

Figure 30: Temporal trends of plastics ingestion by fish. (a) The upper gray line indicates that since 2011 there has been a trend for detecting increasingly smaller particles. The lower black line shows an increasing plastic frequency of occurrence (FO) across all fish species from 2010 to 2019. During this period, plastic ingestion incidence increased significantly at a rate of 2.4% a year. The horizontal dashed line represents an FO of 0.26, the average plastic ingestion incidence in fish globally. (b) Species accumulation curve where the blue line indicates the cumulative number of species studied over time including species found with and without ingested plastic, and the red line depicts only species with plastic ingestion. The lack of an asymptote in the red line indicates a high likelihood that there will continue to be additional species to ingest plastic in the coming years
Source: Savoca, M. S., McInturf, A. G. & Hazen, E. L. Plastic ingestion by marine fish is widespread and increasing. Global Change Biology, 27, 2188–2199 (2021). DOI

Corals Under Threat: A Micro Threat of Global Scale

Plastic pollution poses a growing threat to coral reefs by entering their food chains, exacerbating the spread of diseases, and contributing to the degradation of reef communities. Analysis has identified anthropogenic debris on 77 out of 84 surveyed reefs, including isolated atolls in the central Pacific Ocean.[112] Negative health impacts, such as bleaching and tissue necrosis,[113] have been recorded in five out of six studied species[114] (Fig. 31).

Larger plastic fragments facilitate the transmission of diseases and physical damage, increasing coral vulnerability to pathogens.[115] These effects also impact the skeletal microbiome, which plays a crucial role in maintaining the health of coral colonies[116] (Fig. 32). Research further reveals that biofilms on microplastics, known as "plastispheres,"[114] can induce microbiome dysbiosis in corals.[117]

When in contact with plastics, the risk of coral disease increases from 4 % to 89 % (Fig. 33). The death of coral reefs significantly impacts biodiversity loss, as reefs provide habitat for a quarter of marine species.[115]

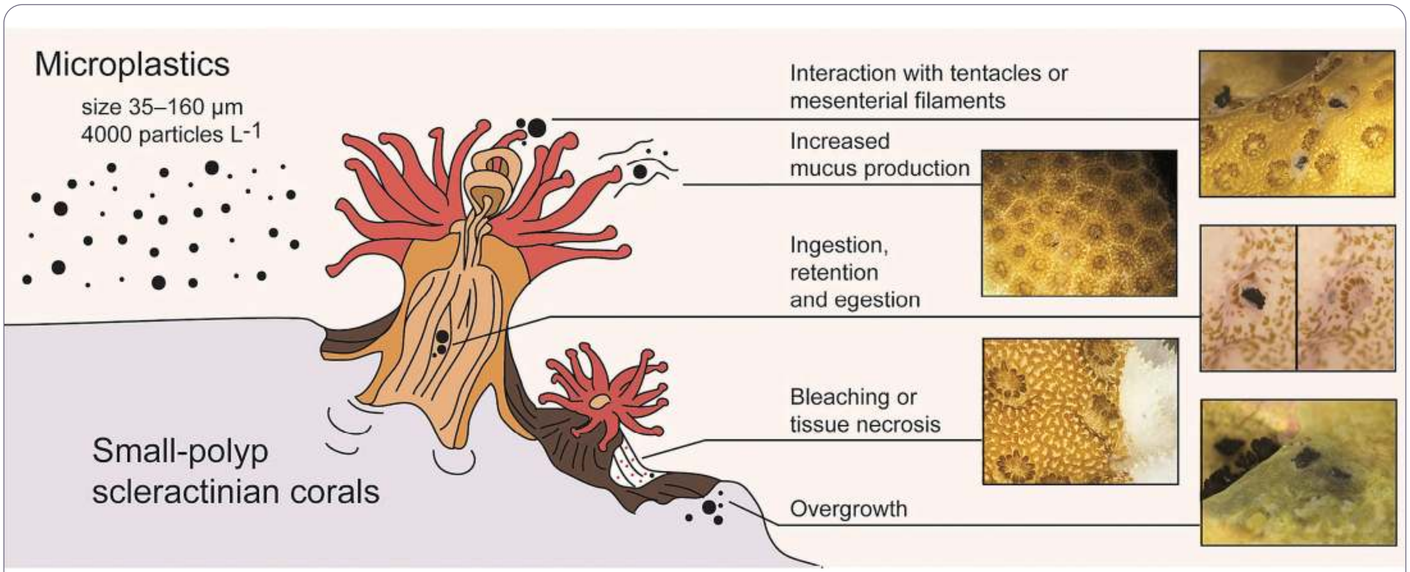

Figure 31: Impact of plastics on coral reef health
Corals can respond with a variety of cleaning mechanisms (e.g., ciliary action, mucus production, or tissue expansion), retention of particles through overgrowing, or egestion of mistakenly ingested particles.
Source: Reichert, J., Schellenberg, J., Schubert, P. & Wilke, T. Responses of reef-building corals to microplastic exposure. Environmental Pollution 237, 955–960 (2018). DOI: 10.1016/j.envpol.2017.11.006

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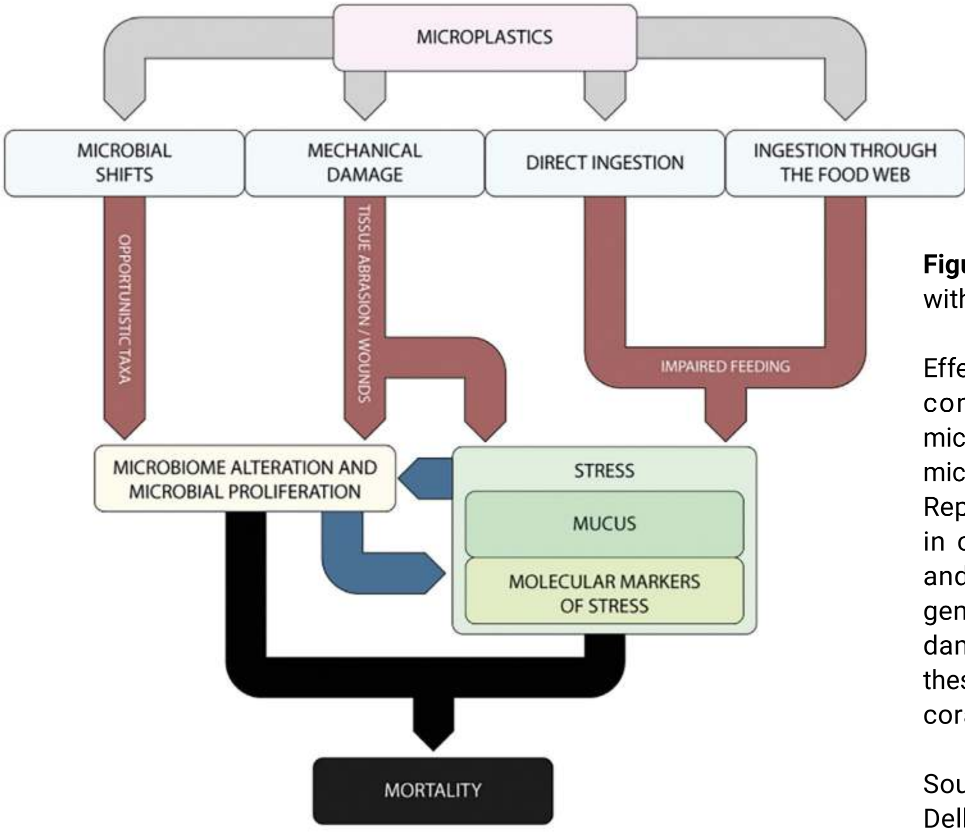

Figure 32: Effects caused by contact with plastics

Effects induced by ingestion, physical contact with coral tissue and microbial response to the presence of microplastic particles in the seawater. Reported are the consequent shifts in coral microbiome composition and stress in terms of changes in gene expression and DNA oxidative damage. The combination of all of these processes can ultimately cause coral mortality.

Source: Corinaldesi, C., Canensi, S., Dell'Anno, A. et al. Multiple impacts of microplastics can threaten marine habitat-forming species. Commun Biol 4, 431 (2021). DOI: 10.1038/s42003-021-01961-1

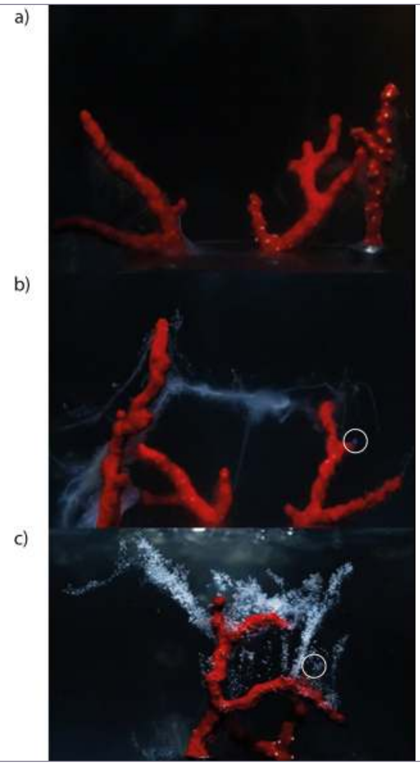

Figure 33: Mucus release increases with increasing microplastic particles concentration
a — low, b — medium, and c — high concentrations of microplastic particles. Mucus release increases with increasing microplastic particles concentration. White circles indicate microplastic items trapped by mucus (polyethylene particles).

Source: Corinaldesi, C., Canensi, S., Dell'Anno, A. et al. Multiple impacts of microplastics can threaten marine habitat-forming species. Commun Biol 4, 431 (2021). DOI: 10.1038/s42003-021-01961-1

Impact of MNPs on the Oxygen Balance in Ecosystems

Observations show that plastics in the environment primarily degrade due to solar radiation. This process alters their chemical composition and structure. Research confirms that reactions triggered by sunlight enhance the leaching of dissolved organic compounds, which impacts the biogeochemistry of seawater and stimulates the growth of heterotrophic bacteria[118] (Fig. 34).

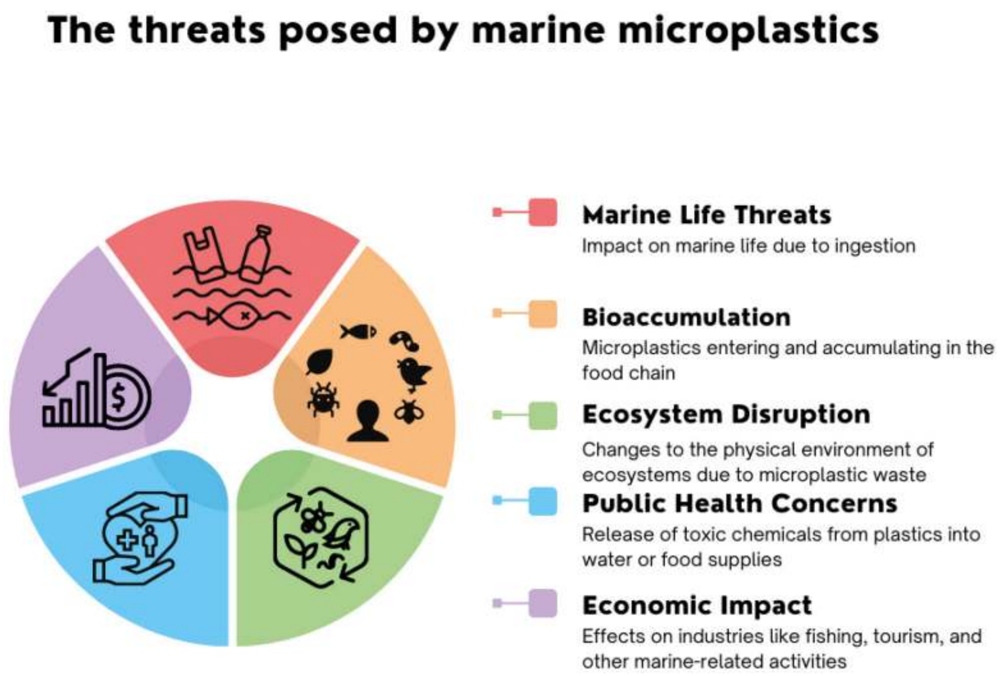

Figure 34: Threats posed by marine microplastics
Source: Yu, R.-S. & Singh, S. Microplastic Pollution: Threats and Impacts on Global Marine Ecosystems. Sustainability 15, 13252 (2023). DOI: 10.3390/su151713252

Long-term studies show that the chemical compounds released by plastics into seawater during their degradation originate either from the material itself or from additives used to provide color or stability to the polymer. Some of the compounds are organic acids, which explains their role in reducing pH. Therefore, plastics contribute to intensification of ocean acidification (Fig. 35), which, in turn, can significantly disrupt the functioning of Earth's natural systems.[119]

[118]Yu, R.-S. & Singh, S. Microplastic Pollution: Threats and Impacts on Global Marine Ecosystems. Sustainability 15, 13252 (2023). https://doi.org/10.3390/su151713252
[119]Romera-Castillo, C. et al. Abiotic plastic leaching contributes to ocean acidification. Science of The Total Environment 854, 158683 (2023). https://doi.org/10.1016/j.scitotenv.2022.158683

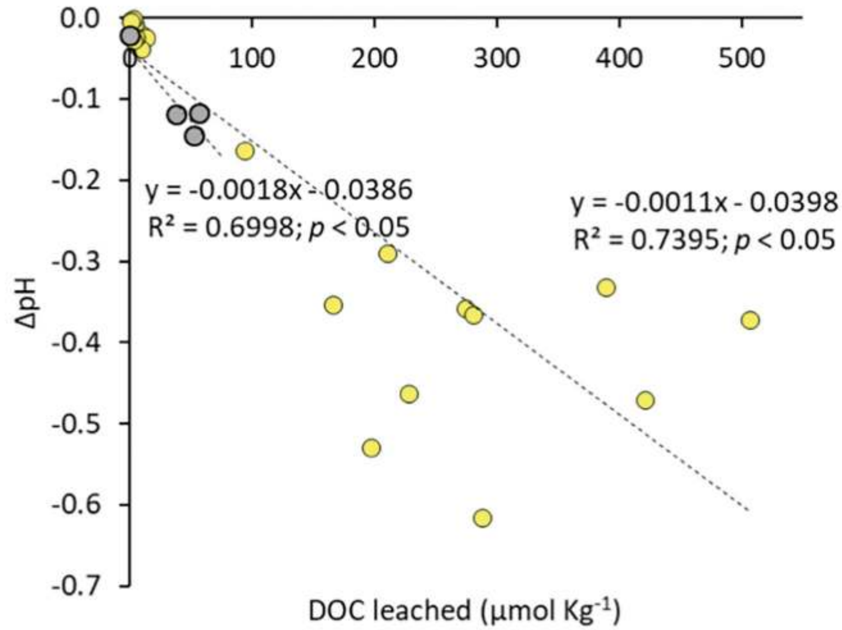

Figure 35: Relationships between the variation of pH vs DOC leached from plastic plotted for every individual replicate sample of all experiments. Controls without plastic for each experiment are also included. Yellow dots correspond to irradiated treatments and grey dots to dark treatments.

Source: Romera-Castillo, C. et al. Abiotic plastic leaching contributes to ocean acidification. Science of The Total Environment 854, 158683 (2023). DOI: 10.1016/j.scitotenv.2022.158683

"Thanks to this study we have been able to prove that in highly plastic-polluted ocean surface areas, plastic degradation will lead to a drop of up to 0.5 pH units, which is comparable to the pH drop estimated in the worst anthropogenic emissions scenarios for the end of the 21st century," points out Cristina Romera-Castillo, ICM-CSIC researcher and first author of the study which has been published this week in the journal Science of the Total Environment (Fig. 36).[120]

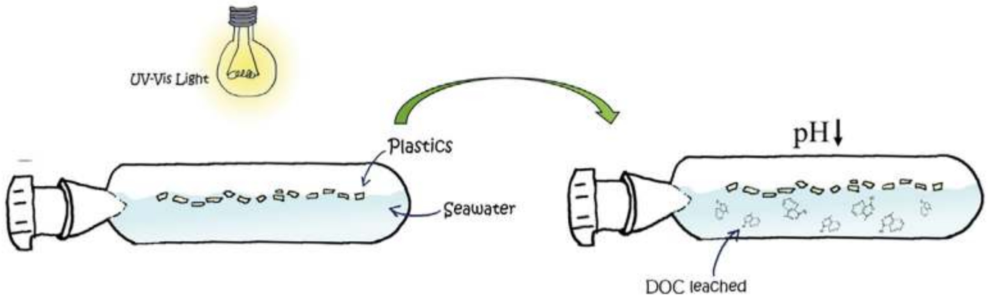

Figure 36: Plastics leaching can lead to a decrease in seawater pH by up to 0.5 units
Source: Romera-Castillo, C. et al. Abiotic plastic leaching contributes to ocean acidification. Science of The Total Environment 854, 158683 (2023). DOI: 10.1016/j.scitotenv.2022.158683

[120]Institute of Marine Sciences (ICM-CSIC). Plastic degradation in the ocean contributes to its acidification. https://www.icm.csic.es/en/news/plastic-degradation-ocean-contributes-its-acidification (accessed: 1 May 2025)

Ocean acidification is a disruption of marine conditions, creating persistent and growing environmental pressure.[121] The consequences for ecosystems unfold over decades, centuries, and longer. Observations confirm a reduction in biodiversity in coastal systems due to a decrease in pH.[122, 123]This lowers ecosystem resilience and threatens essential functions, including habitat provision, nutrient cycling, and carbon storage.[123]

Research indicates that with ocean acidification, mussels (Mytilus edulis) grow slower and have reduced survival rates (Fig. 37). This decreases their population, which in turn reduces their ability to filter water and maintain coastal ecosystem quality.[124]

Current ocean surface pH levels are unprecedented at least for the past 26,000 years.[125] This process has a significant impact on coral reefs, deep-sea ecosystems, and high-latitude ecosystems, which rely on unique species. Those species play an irreplaceable role, and their extinction disrupts key ecosystem functions, as there are no equivalents capable of replacing them.[126]

Figure 37: Slime acts as a barrier, preventing harmful substances, microorganisms, or parasites from entering the organism. It can capture and expel potentially dangerous particles, including microplastics, from the gills and digestive system.
Oysters and mussels show a noticeable decline in population along gradients of decreasing carbonate saturation. Ocean acidification may lead to a reduction in oyster populations and the ecosystem services they provide in the wild; it may also degrade their quality as seafood.
Source: https://www.nationalgeographic.com/magazine/article/ocean-acidification

[121]Scott C. Doney, D. Shallin Busch, Sarah R. Cooley and Kristy J. Kroeker. The Impacts of Ocean Acidification on Marine Ecosystems and Reliant Human Communities. Annual Review of Environment and Resources 45, 83–112 (2020). https://doi.org/10.1146/annurev-environ-012320-083019
[122]Hall-Spencer, J. M. & Harvey, B. P. Ocean acidification impacts on coastal ecosystem services due to habitat degradation. Emerging Topics in Life Sciences 3, 197–206 (2019). https://doi.org/10.1042/ETLS20180117
[123]James P. Barry, Stephen Widdicombe, and Jason M. Hall-Spencer. Effects of ocean acidification on marine biodiversity and ecosystem function. Ocean acidification, edited by Jean-Pierre Gattuso, Lina Hansson. Oxford, Oxford University Press, 2011. https://books.google.com.ua/books?id=8yjNFxkALjIC&pg=PA192
[124]Broszeit, S., Hattam, C. & Beaumont, N. Bioremediation of waste under ocean acidification: Reviewing the role of Mytilus edulis. Marine Pollution Bulletin 103, 5–14 (2016). https://doi.org/10.1016/j.marpolbul.2015.12.040
[125]The Intergovernmental Panel on Climate Change (IPCC). Climate Change 2021: The Physical Science Basis. https://www.ipcc.ch/report/ar6/wg1
[126]James P. Barry, Stephen Widdicombe, and Jason M. Hall-Spencer. Effects of ocean acidification on marine biodiversity and ecosystem function. Ocean acidification, edited by Jean-Pierre Gattuso, Lina Hansson. Oxford, Oxford University Press, 2011. https://books.google.com.ua/books?id=8yjNFxkALjIC&pg=PA192

Research confirms that microplastics have considerable negative effects on biological parameters like growth[127], chlorophyll content, photosynthesis activity and reactive oxygen species (ROS) of microalgae.[128, 129]

Data points and reveal that MP exposure leads to a global reduction in photosynthesis of 7.05 to 12.12% in terrestrial plants, marine algae, and freshwater algae.[130] Photosynthesis is known to be the primary process on Earth that produces molecular oxygen (O_2), which is released into the atmosphere.

Microplastics in marine sediments alter microbial communities and disrupt nitrogen cycling, potentially magnifying human-caused problems like toxic algal blooms. Changes in plankton communities at the ocean surface could exacerbate deoxygenation driven by climate change, starving marine organisms of oxygen.[131]

Data shows that from 1960 to 2010, the ocean lost 2 % of its dissolved oxygen due to rising water temperatures and the accumulation of pollutants, including industrial, household, and agricultural runoff.[132] The decrease in oxygen leads to the formation of dead zones — areas of the ocean where marine flora and fauna have almost completely disappeared. Observations indicate that in the 1960s, there were 45 dead zones in the world's oceans, whereas by 2011, their number had increased to around 700.[133] According to data published on the UNDP website, the number of dead zones has been doubling every decade since the 1960s. Based on this trend, it is highly likely that the number could reach 1,500 by 2025.[134] Plastic pollution impacts many processes in the Earth's system. According to research, it may exacerbate critical environmental issues such as biodiversity loss and climate change.[135]

[127] Nanthini devi, K., Raju, P., Santhanam, P. & Perumal, P. Impacts of microplastics on marine organisms: Present perspectives and the way forward. Egyptian Journal of Aquatic Research 48, 205–209 (2022). https://doi.org/10.1016/j.ejar.2022.03.001

[128] Wu, Y. et al. Effect of microplastics exposure on the photosynthesis system of freshwater algae. Journal of Hazardous Materials 374, 219–227 (2019). https://doi.org/10.1016/j.jhazmat.2019.04.039

[129] Sarkar, P., Xavier, K. A. M., Shukla, S. P. & Rathi Bhuvaneswari, G. Nanoplastic exposure inhibits growth, photosynthetic pigment synthesis and oxidative enzymes in microalgae: A new threat to primary producers in aquatic environment. Journal of Hazardous Materials Advances 17, 100613 (2025). https://doi.org/10.1016/j.hazadv.2025.100613

[130] Zhu, R. et al. A global estimate of multiecosystem photosynthesis losses under microplastic pollution. Proceedings of the National Academy of Sciences 122, e2423957122 (2025). https://doi.org/10.1073/pnas.2423957122

[131] Microplastics pose risk to ocean plankton, climate, other key Earth systems. Mongabay. (2023) https://news.mongabay.com/2023/10/microplastics-pose-risk-to-ocean-plankton-climate-other-key-earth-systems

[132] Bhuiyan, M. M. U. et al. Oxygen declination in the coastal ocean over the twenty-first century: Driving forces, trends, and impacts. Case Studies in Chemical and Environmental Engineering 9, 100621 (2024). https://doi.org/10.1016/j.cscee.2024.100621

[133] The International Union for Conservation of Nature (IUCN). Ocean deoxygenation. https://iucn.org/resources/issues-brief/ocean-deoxygenation

[134] United Nations Development Programme. Ocean hypoxia: Dead zones. https://www.undp.org/publications/issue-brief-ocean-hypoxia-dead-zones

[135] Villarrubia-Gómez, P., Carney Almroth, B., Eriksen, M., Ryberg, M. & Cornell., S. E. Plastics pollution exacerbates the impacts of all planetary boundaries. One Earth 7, 2119–2138 (2024). https://doi.org/10.1016/j.oneear.2024.10.017

IMPACT OF MICRO- AND NANOPLASTICS ON THE CLIMATE

Ocean Functions

The ocean plays a key role in maintaining the planet's climate balance, functioning as a natural "air conditioner." Its unique ability to absorb and gradually release heat helps moderate temperature fluctuations on Earth. Just a ten-meter layer of ocean water can absorb more heat than the entire Earth's atmosphere (Fig. 38). This reduces temperature swings both during the day and night (Fig. 39), as well as between seasons — summer and winter.

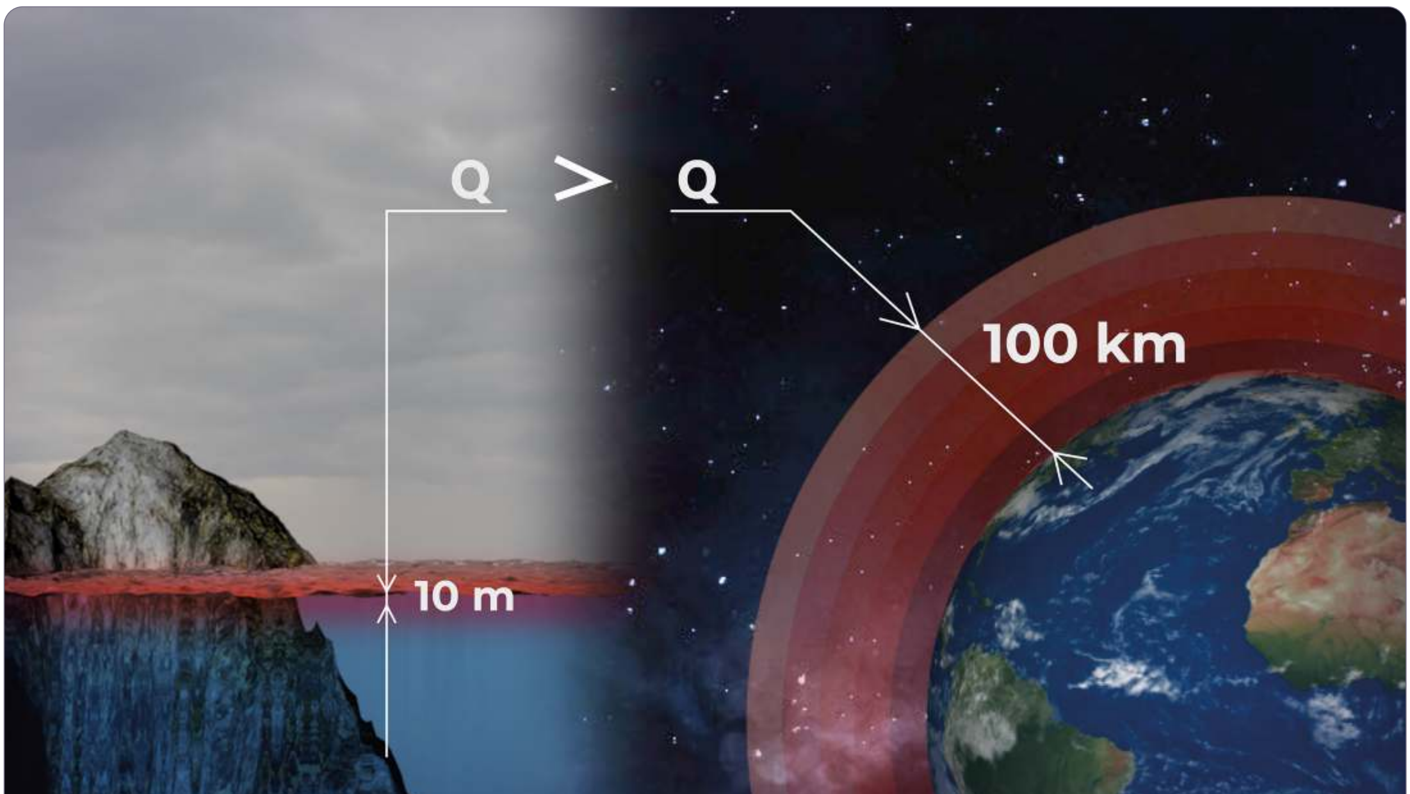

Figure 38: Comparative heat capacity of the ocean and the atmosphere: despite a lower mass of air, the ocean is able to accumulate and retain tens of times more heat, playing a key role in regulating Earth's climate

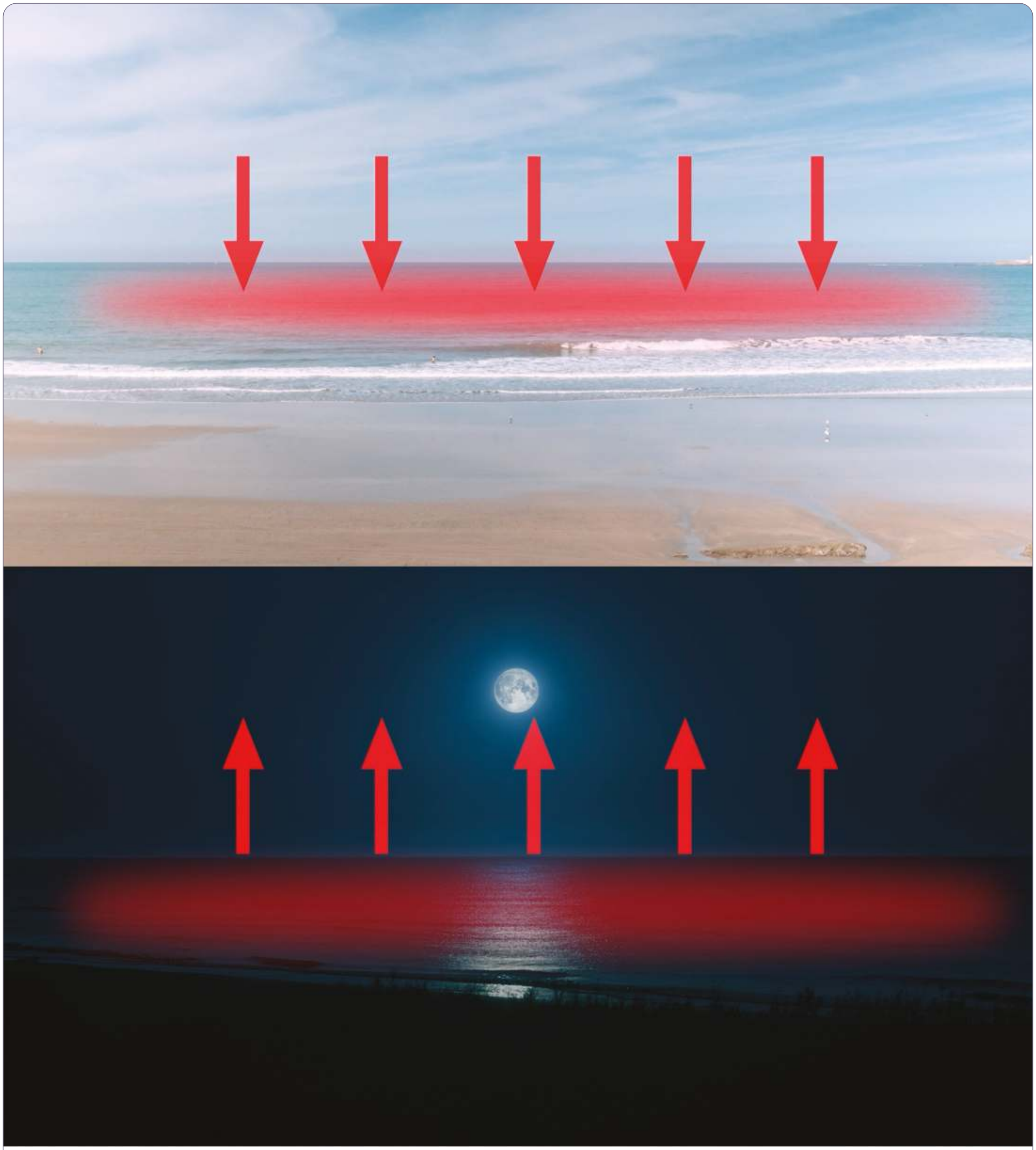

Figure 39: Schematic representation of daily heat exchange: the ocean absorbs heat during the day and releases it at night, smoothing out temperature fluctuations

Ocean currents carry warm water from the tropics to colder regions, such as the northern latitudes. This helps moderate the climate in coastal areas. Cold currents, in turn, return cooled water back toward the equator. In this way, the ocean regulates the planet's climate.

The ocean has a major impact on atmospheric processes and plays a key role in the formation of clouds and precipitation. Every day, a vast amount of water evaporates from its surface, later condensing into clouds and falling back to Earth as rain or snow. This process is vital for replenishing freshwater resources in rivers, lakes, and soil.

Microscopic algae in the ocean, such as phytoplankton (Fig. 40), produce more than 50% of the oxygen.[136] Many ocean chemistry and biology models predict that as the ocean surface warms in response to increasing greenhouse gases in the atmosphere, phytoplankton productivity will decline (Fig. 41).[137, 138]

Figure 40: Phytoplankton are extremely diverse, varying from photosynthesizing bacteria (cyanobacteria) to plant-like diatoms, to armor-plated coccolithophores (drawings not to scale). (Collage adapted from drawings and micrographs by Sally Bensusen, NASA EOS Project Science Office.)

Source: NASA. What are Phytoplankton? https://earthobservatory.nasa.gov/features/Phytoplankton

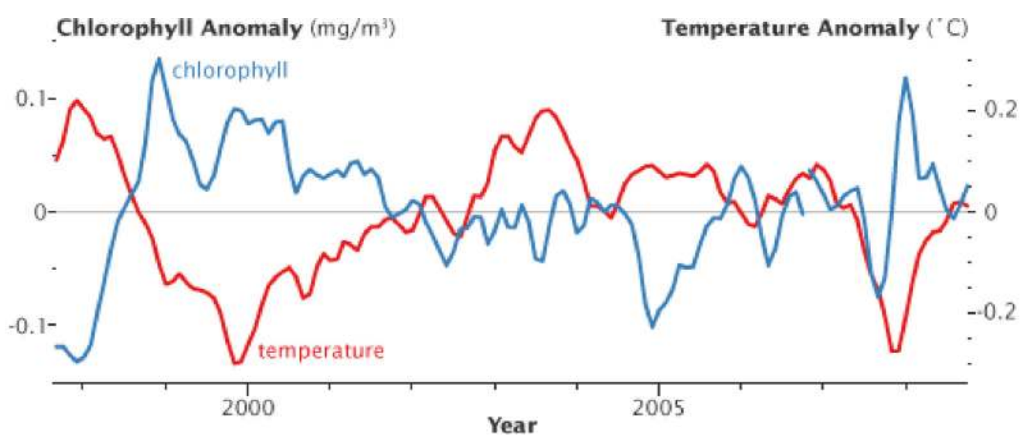

Figure 41: About 70% of the ocean is permanently stratified into layers that don't mix well. Between late 1997 and mid-2008, satellites observed that warmer-than-average temperatures (red line) led to below-average chlorophyll concentrations (blue line) in these areas. (Graph adapted from Behrenfeld et al. 2009 by Robert Simmon)
Source: https://earthobservatory.nasa.gov/features/Phytoplankton

[136]NOAA. How much oxygen comes from the ocean? https://oceanservice.noaa.gov/facts/ocean-oxygen.html
[137]Boyce, D. G., Lewis, M. R. & Worm, B. Global phytoplankton decline over the past century. Nature 466, 591–596 (2010). https://doi.org/10.1038/nature09268
[138]Bopp, L. et al. Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models. Biogeosciences 10, 6225–6245 (2013). https://doi.org/10.5194/bg-10-6225-2013

Changing Ocean Temperature Patterns

The State of the Global Ocean Report 2024 demonstrates a troubling picture — an unprecedented ocean heating trend.

Studies show that between 1960 and 1986, ocean temperatures rose at a steady rate. However, in recent decades, this process has accelerated twofold (Fig. 41).[139]

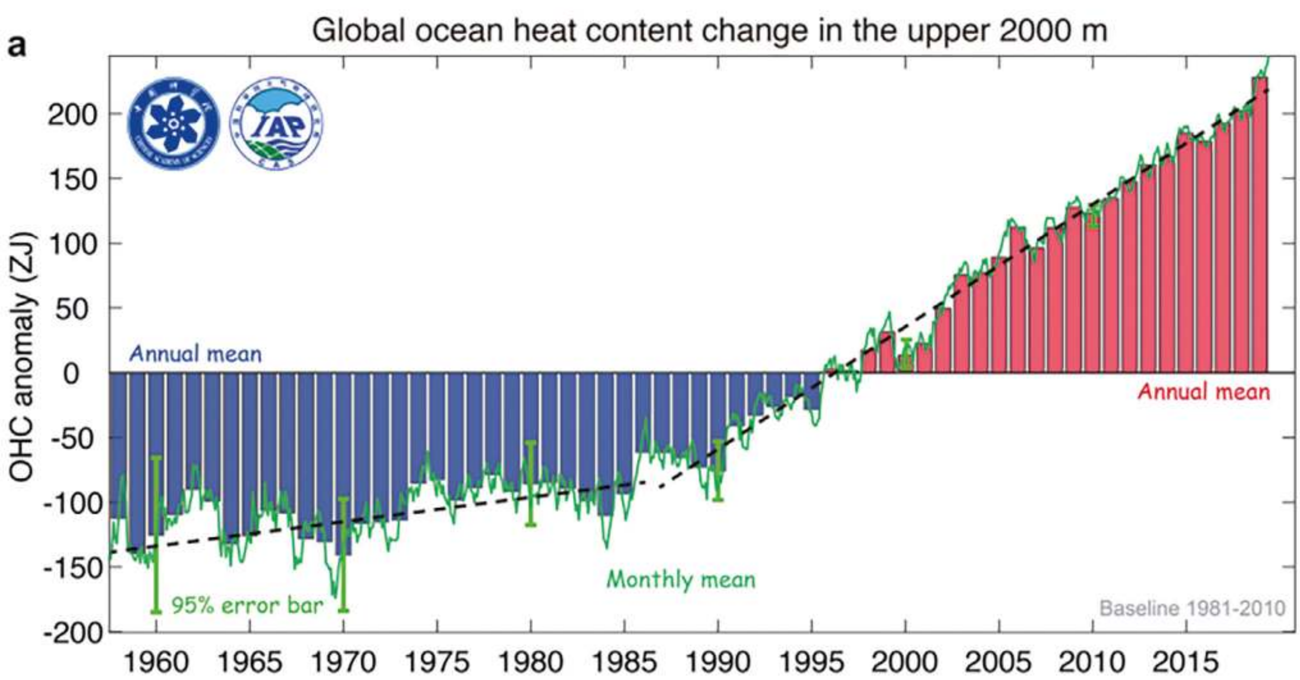

Figure 42: Change of heat content in the upper 2,000-meter layer of the World Ocean

Source: Cheng, L., Abraham, J., Zhu, J., Trenberth, K. E., Fasullo, J., Boyer, T., Locarnini, R., Zhang, B., Yu, F., Wan, L., Chen, X., Song, X., Liu, Y., & Mann, M. E. (2020). Record-Setting Ocean Warmth Continued in 2019. Advances in Atmospheric Sciences, 37(2), 137–142. https://doi.org/10.1007/s00376-020-9283-7

The year 2023 became the warmest year on record, surpassing the previous high set in 2016. An all-time record for sea surface temperature (SST) was also observed.[140] This trend continued, and the year 2024 broke the records of 2023 (Fig. 43), making it the hottest year in recorded history.[141] During this period, sea surface temperatures remained at record monthly values for 15 consecutive months, highlighting the persistence of the warming trend.

[139]Cheng, L., Abraham, J., Zhu, J. et al. Record-Setting Ocean Warmth Continued in 2019. Adv. Atmos. Sci. 37, 137–142 (2020). https://doi.org/10.1007/s00376-020-9283-7
[140]NOAA. Earth had its warmest year on record; Upper-ocean heat content was record high while Antarctic sea ice was record low. https://www.ncei.noaa.gov/news/global-climate-202312 (accessed: 1 May 2025)
[141]World Meteorological Organization (WMO) confirms 2024 as warmest year on record at about 1.55°C above pre-industrial level. https://wmo.int/news/media-centre/wmo-confirms-2024-warmest-year-record-about-155degc-above-pre-industrial-level (accessed: 1 May 2025)

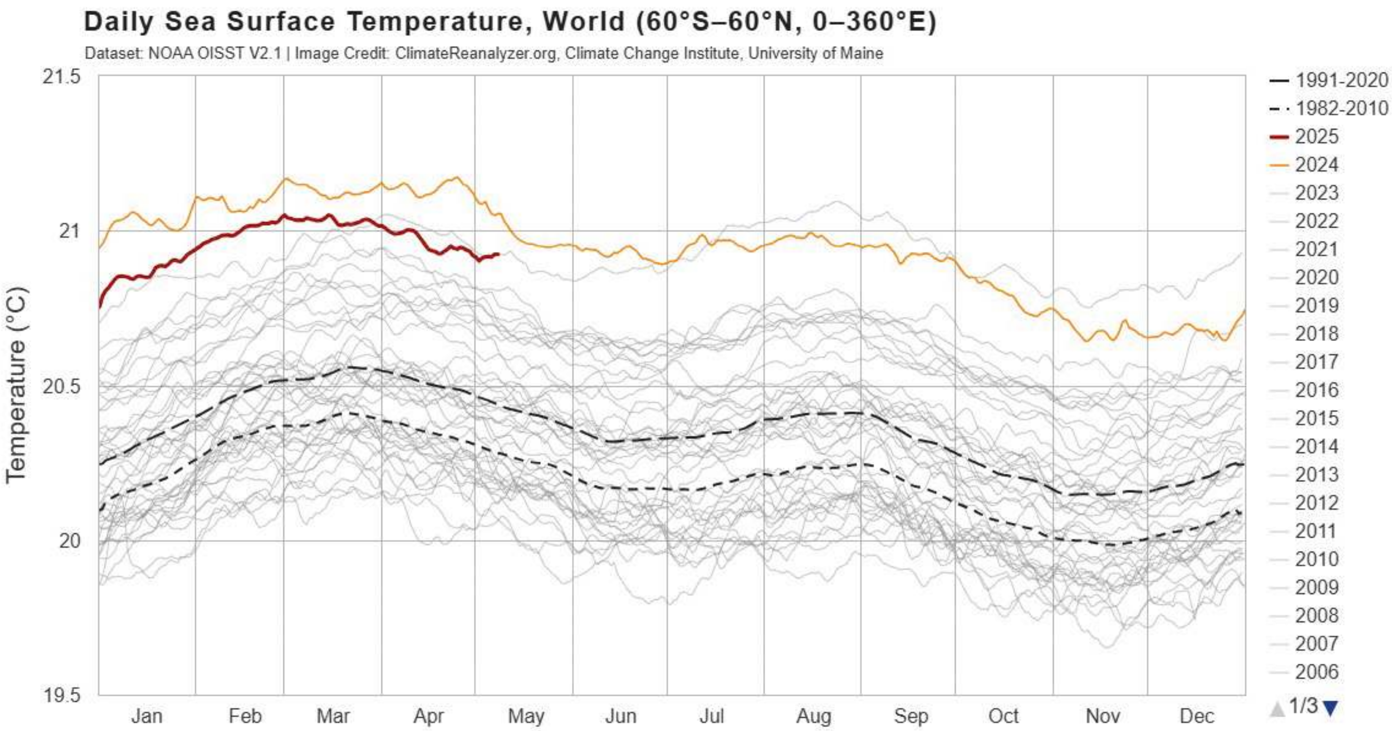

Figure 43: Daily sea surface temperature: graphic representation of changes in the upper ocean layer temperature, reflecting seasonal fluctuations by years
Source: NOAA OISST V2.11 Image Credit: Climate Reanalyzer.org, Climate Change Institute. University of Maine

For the first time on record, the global average surface temperature was 1.5 °C above the pre-industrial level[142](Fig. 44). According to experts, this is a critical threshold: beyond it, humanity will face large-scale climate catastrophes.[143]

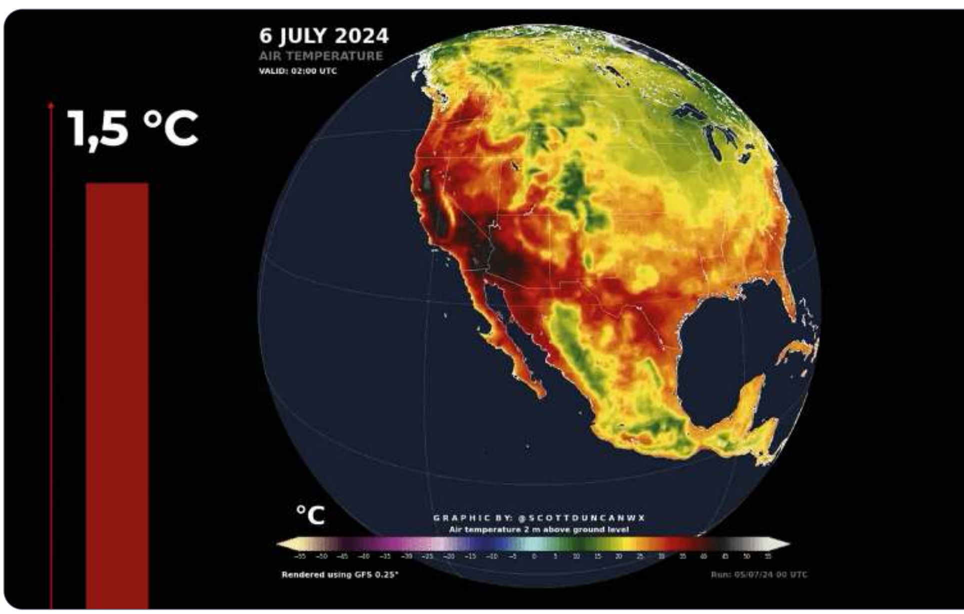

Figure 44: Schematic representation of the climate milestone: in 2024, the average annual global temperature for the first time exceeded the 1.5 °C threshold compared to preindustrial levels

[142]World Meteorological Organization (WMO). State of the Global Climate 2024. https://wmo.int/publication-series/state-of-global-climate-2024 (accessed: 1 May 2025)
[143]IPCC. Global Warming of 1.5°C. (Cambridge University Press, 2022). https://doi.org/10.1017/9781009157940 (accessed: 1 May 2025)

Such a temperature increase was expected by the mid-21st century,[144] yet this threshold has already been crossed.

According to UN estimates, if current trends proceed, global temperatures could rise by nearly 3°C this century.[144]

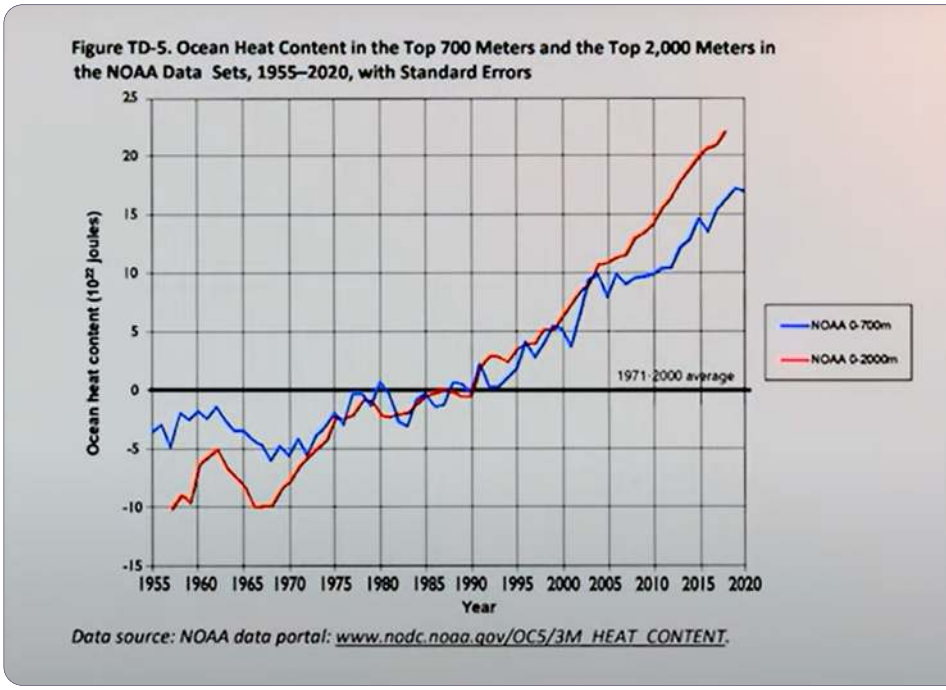

Figure 45: Ocean heat content in the layers of 0–700 and 0–2,000 meters. NOAA data sets, 1955-2020, standard. Source: NOAA data portal www.nodc.noaa.gov/OC5/3M_HEAT_CONTENT

Figure 46: This figure shows changes in heat content of the top 700 meters of the world's oceans between 1955 and 2023. Ocean heat content is measured in joules, a unit of energy, and compared against the 1971–2000 average, which is set at zero for reference. Choosing a different baseline period would not change the shape of the data over time. The lines were independently calculated using different methods by government organizations in four countries: the United States' National Oceanic and Atmospheric Administration (NOAA), Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO), China's Institute of Atmospheric Physics (IAP), and the Japan Meteorological Agency's Meteorological Research Institute (MRI/JMA).

Source: CSIRO, 2024;5 IAP, 2024;6 MRI/JMA, 2024;7 NOAA, 20248

[144] The Intergovernmental Panel on Climate Change (IPCC). Climate Change 2021: The Physical Science Basis https://www.ipcc.ch/report/ar6/wg1/

The middle depths of a part of the Pacific Ocean have warmed 15 times faster in the past 60 years than they did during the previous 10,000 years (Figs. 45–46).[145] This indicates that the processes of global warming affect not only the upper ocean layers, but also deeper regions where sunlight does not reach. Heating water at such depths requires an enormous amount of energy, underscoring the scale of the problem. According to scientists, for the ocean to warm at its current rate, it would take an energy release equivalent to the explosion of 7 atomic bombs every second for an entire year[146] — staggering figures that raise a question: where is this energy coming from?

Rising ocean temperatures inevitably lead to sea level rise, threatening to engulf entire coastlines. Over the past two centuries, the global mean sea level has risen by 21 centimeters (8.3 inches), and in the last 30 years alone — by 10.1 centimeters (3.98 inches).[147] The current rate of increase is 2.5 times higher than before, and this trend is expected to continue. If the situation doesn't change, millions of people will become climate refugees, forced to leave their homes and seek shelter far from the coasts.

"The rise we saw in 2024 was higher than we expected," said Josh Willis, a sea level researcher at NASA's Jet Propulsion Laboratory in Southern California. "Every year is a little bit different, but what's clear is that the ocean continues to rise, and the rate of rise is getting faster and faster."[148] (Fig. 47).

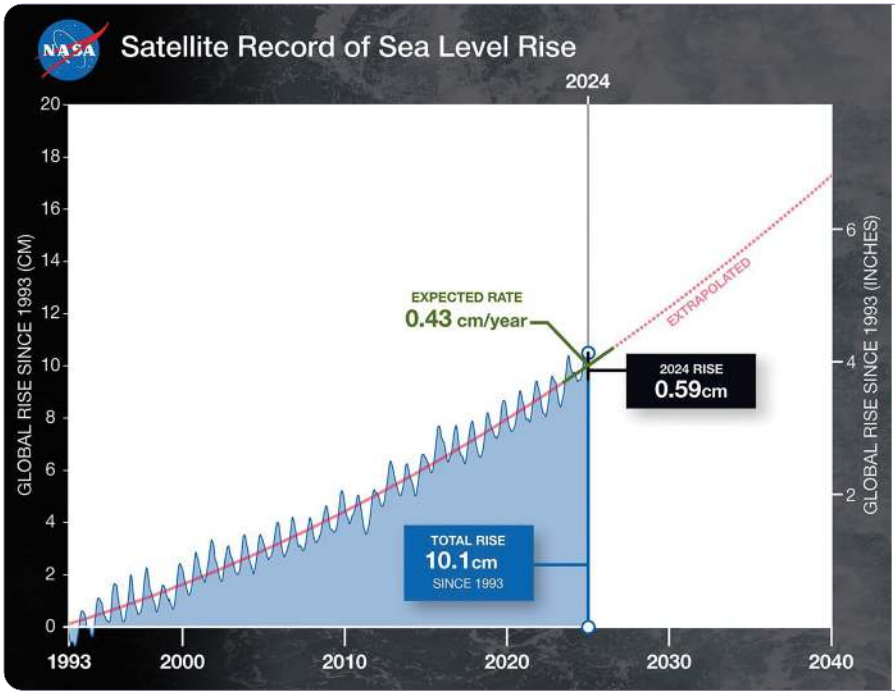

Figure 47: This graph shows global mean sea level (in blue) since 1993 as measured by a series of five satellites. The solid red line indicates the trajectory of this increase, which has more than doubled over the past three decades. The dotted red line projects future sea level rise. Credit: NASA/JPL-Caltech

Source: NASA. NASA Analysis Shows Unexpected Amount of Sea Level Rise in 2024 https://sealevel.nasa.gov/news/282/nasa-analysis-shows-unexpected-amount-of-sea-level-rise-in-2024

Ocean warming also contributes to more frequent and intense extreme weather events, such as floods, typhoons, and abnormal precipitation. These changes threaten the planet's ecosystems and the lives of billions of people, and with each passing year, their impact becomes more evident.

[145]Rosenthal, Y., Linsley, B. K., & Oppo, D. W. (2013). Pacific Ocean Heat Content During the Past 10,000 Years. Science, 342(6158), 617–621. https://doi.org/10.1126/science.1240837; Oppo, D. (2013, October 31). Is Global Heating Hiding Out in the Oceans? https://www.earth.columbia.edu/articles/view/3130
[146]Cheng, L. et al. Another Year of Record Heat for the Oceans. Adv. Atmos. Sci. 40, 963–974 (2023). https://doi.org/10.1007/s00376-023-2385-2
[147]NASA. Tracking 30 Years of Sea Level Rise https://earthobservatory.nasa.gov/images/150192/tracking-30-years-of-sea-level-rise (accessed: 1 May 2025)
[148]NASA. NASA Analysis Shows Unexpected Amount of Sea Level Rise in 2024 https://sealevel.nasa.gov/news/282/nasa-analysis-shows-unexpected-amount-of-sea-level-rise-in-2024 (accessed: 1 May 2025)

Why is the Ocean Warming? Hypothesis

The main widely recognized factors contributing to ocean warming are greenhouse gases, such as CO_2, which trap heat in the atmosphere and increase the temperature of the ocean's upper layers. However, there are other factors that may also have a significant impact on this process. One additional factor influencing ocean warming will be discussed in the chapter "X Factor."

Since the second half of the 20th century, there has been a sharp increase in the amount of plastics in the oceans, coinciding with a period of rapid industrial development and the mass production of plastic goods (Fig. 48).

Between 1960 and 2019, a change in ocean temperature has also been observed. The chart (Fig. 49) shows a parallel increase in the mean sea surface temperature, which has likewise been recorded since the mid-20th century.

When comparing the two charts (Figs. 48–49), a correlation can be observed between the rise in oceanic plastics concentrations and the warming of ocean waters. This suggests that plastic pollution in the oceans may be one of the significant, yet insufficiently studied, factors contributing to the heating of ocean waters.

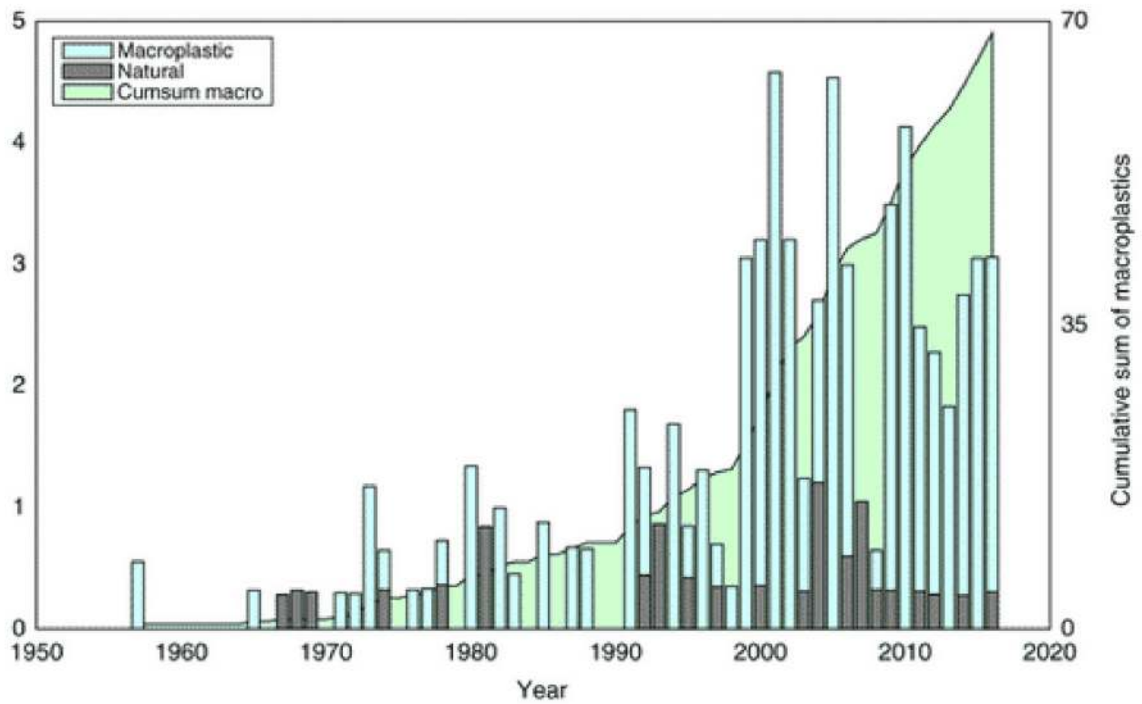

Figure 48: Chart showing the rise in plastics concentration in the oceans over recent decades. Cumulative amount of macroplastics in the ocean and annual values
Source: Ostle, C., Thompson, R.C., Broughton, D. et al. The rise in ocean plastics evidenced from a 60-year time series. Nature Communications, 10, 1622 (2019). https://doi.org/10.1038/s41467-019-09506-1

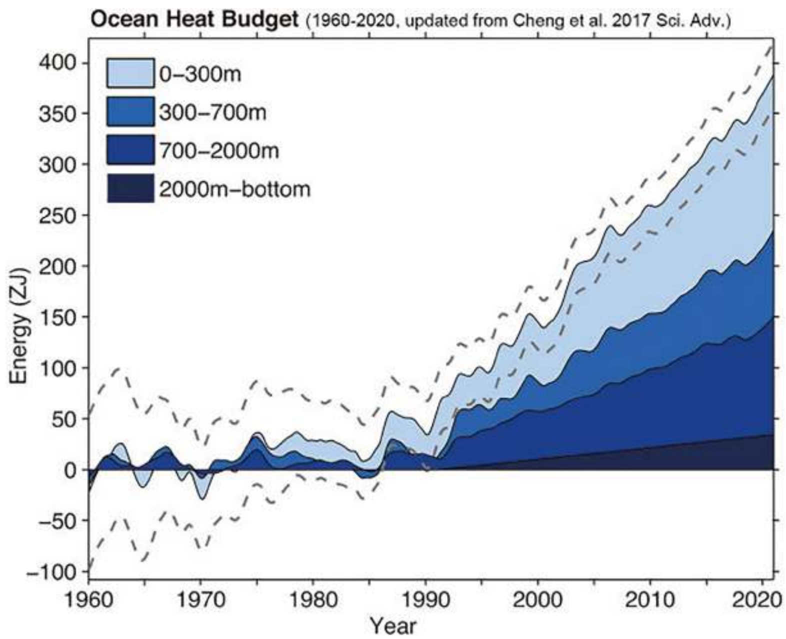

Figure 49: Graph of global ocean temperature changes over the same period (1960–2019)

Source: (Purkey and Johnson, 2010; with data update Cheng и др., 2017) Cheng, L. et al. Record-Setting Ocean Warmth Continued in 2019. Adv. Atmos. Sci. 37, 137–142 (2020). https://doi.org/10.1007/s00376-020-9283-7

To further explore this issue, it is important to understand whether plastics can affect the physical properties of ocean water, such as thermal conductivity and heat capacity. And can these changes contribute to rising ocean temperatures? To gain a better understanding of these processes, let's examine the fundamental properties of water and how it interacts with pollutants.

Fundamental Properties of Water

A water molecule has a symmetrical V-shape, with two hydrogen atoms positioned on one side relative to the larger oxygen atom (Fig. 50).

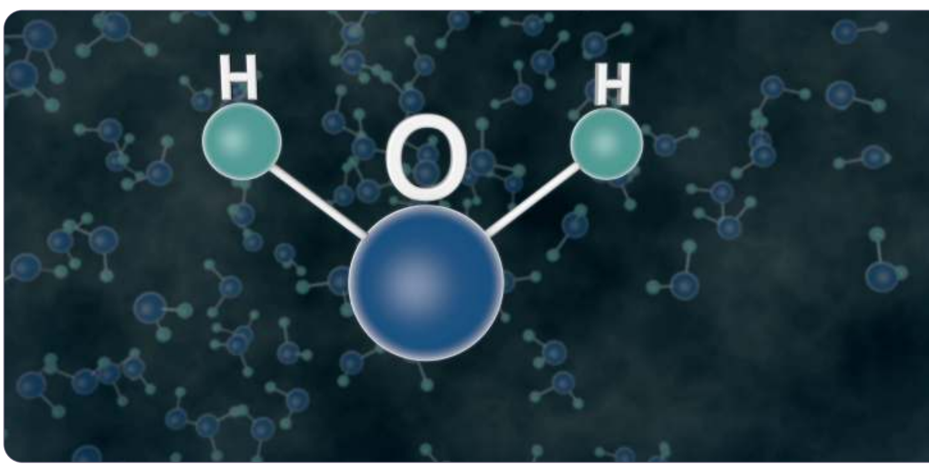

Figure 50:
Schematic representation of a water molecule: two hydrogen (H) atoms are connected to one oxygen (O) atom at an angle of ~104.5°, forming a dipole with a positive and a negative charge

This structure differs from linear molecules, such as CO_2, where all atoms are arranged in a straight line. The unique shape of the water molecule makes it vital for numerous processes on Earth.

The specific properties of water molecules allow water to remain in a liquid state at temperatures that would typically cause other triatomic molecules to become gases (Fig. 51).

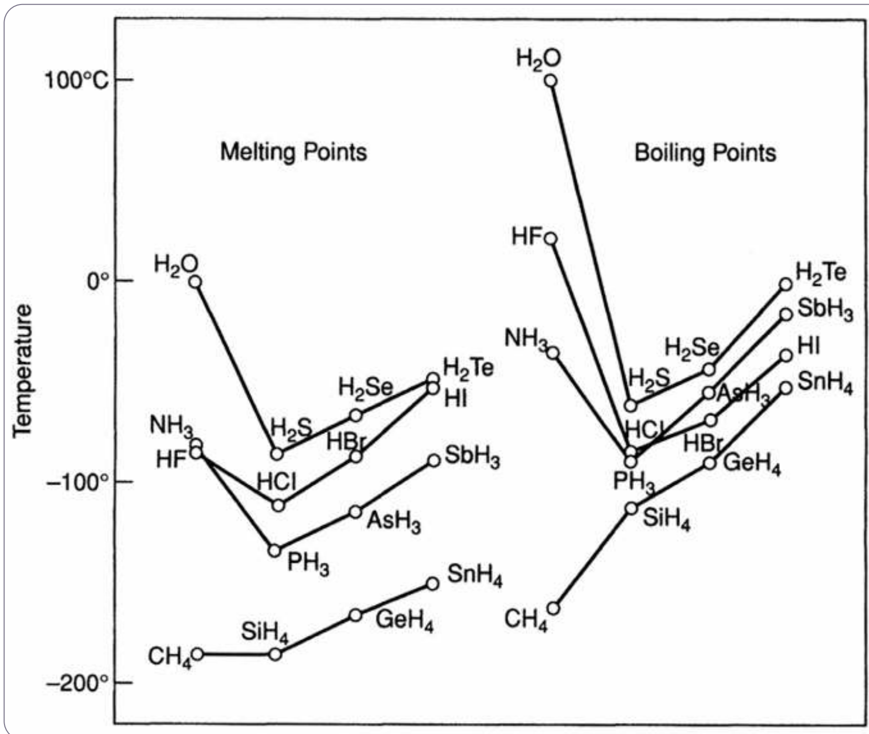

Figure 51: The melting points (left) and boiling points (right) of isoelectronic sequences of hydride molecules. The temperatures for water are significantly higher than expected when extrapolating the data for similar compounds.

Source: Pauling, L. The Nature of the Chemical Bond, 3rd ed., Chapter 12-2, Cornell Univ. Press, 1960.

This is due to hydrogen bonds[149] that connect water molecules, forming a strong and orderly structure.

Most hydrogen bonds are weak attractions, with bond strength approximately one-tenth that of a typical covalent bond. Nonetheless, they are extremely important. Without them, all wooden structures would collapse, cement would crumble, oceans would evaporate, and all living matter would disintegrate into inanimate substances.[150]

That is why water has the ability to form clusters, which explains many of its anomalous properties (Figs. 52–53). Water clusters can cover over 95% of hydrogen bond network, among which some clusters maximally encompass thousands of molecules extending beyond 3.0 nanometers.[151]

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[149] Pauling, L. The Nature of the Chemical Bond, 3rd edn, Chapter 12-2 (Cornell Univ. Press, 1960).
[150] Jeffrey, G. A. An Introduction to Hydrogen Bonding (Oxford University Press, New York, 1997). https://books.google.com/books?vid=ISBN0195095499
[151] Gao, Y., Fang, H., Ni, K. & Feng, Y. Water clusters and density fluctuations in liquid water based on extended hierarchical clustering methods. Sci Rep 12, 8036 (2022). https://doi.org/10.1038/s41598-022-11947-6

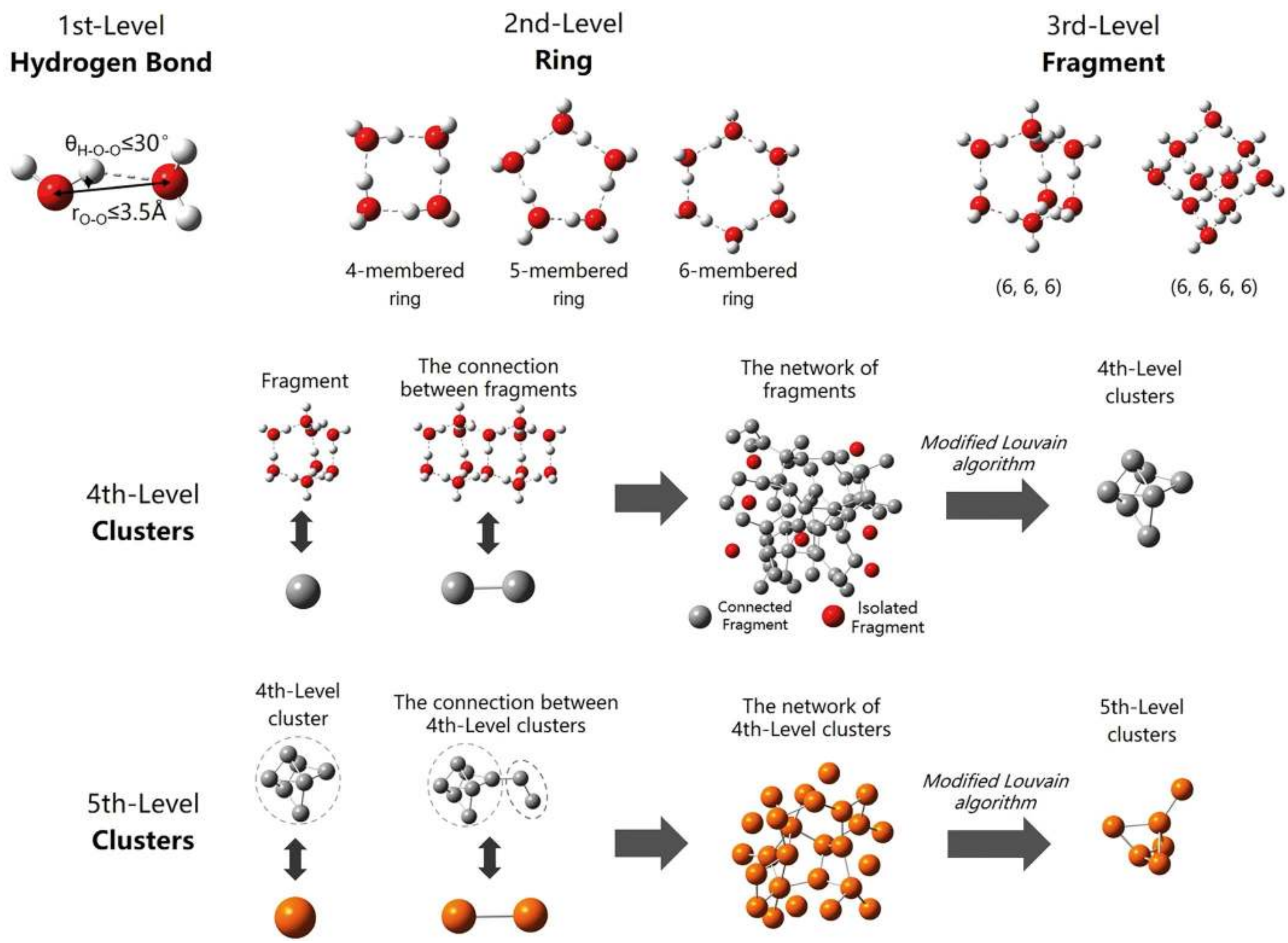

Figure 52: Schematics of hierarchical clustering method proposed in this study. Hydrogen bonds, rings and fragments are considered as 1st-, 2nd-, and 3rd-level structures which are ball-and-stick models from a chemical perspective and the red and white balls denote oxygen and hydrogen atoms, respectively. The full and dotted sticks denote O–H covalent bonds and hydrogen bonds, respectively. The 4th- and 5th-level clusters are illustrated by topological perspective. The balls represent the structure of last levels. Note that the structures in the figure are only a selection among the considered ones by the clustering algorithm.

Source: Gao, Y., Fang, H. & Ni, K. A hierarchical clustering method of hydrogen bond networks in liquid water undergoing shear flow. Sci Rep 11, 9542 (2021). https://doi.org/10.1038/s41598-021-88810-7

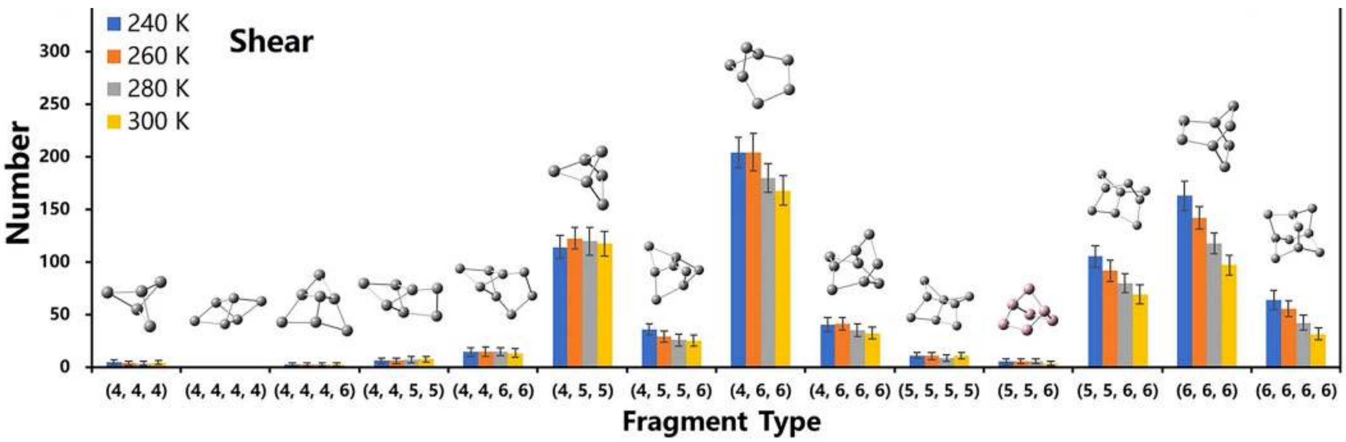

Figure 53: The distribution of hierarchical structures at the 1st, 2nd and 3rd levels in the network in various cases. (a) The distribution of hydrogen bonds (1st-level structures) at various temperatures. (b) The distribution of rings (2nd-level structures) at various temperatures. (c) The distribution of fragments (3rd-level structures) at various temperatures. Note that (4, 4, 4) denotes a symbol of a fragment including three 4-membered rings.

Source: Gao, Y., Fang, H. & Ni, K. A hierarchical clustering method of hydrogen bond networks in liquid water undergoing shear flow. Sci Rep 11, 9542 (2021). https://doi.org/10.1038/s41598-021-88810-7

Heat Capacity, Thermal Conductivity, and Density of Water, and Their Functional Significance

1. High Heat Capacity of Water

Water has the highest specific heat capacity of any liquid or solid under normal conditions, second only to a few gases such as hydrogen.[152] This means water can absorb, retain, and transfer large amounts of heat energy while undergoing only a relatively small change in its own temperature.

Water's heat capacity is calculated as the amount of heat required to raise the temperature of 1 gram of water by 1 degree Celsius and is approximately 4.18 J/(g·°C) under standard conditions. This property is one of the key factors in climate regulation: ocean water accumulates heat during the day and gradually releases it at night. In summer, the ocean absorbs excess heat, whereas in winter, it slowly releases it, acting as a giant thermostat and reducing temperature fluctuations across the planet.

2. Thermal Conductivity of Water

Water has relatively low thermal conductivity compared to metals, but it is higher than that of many other liquids. Thermal conductivity reflects a substance's ability to transfer heat from one its part to another without the movement of the substance itself. Under standard conditions (25 °C), water's thermal conductivity is approximately 0.6 W/(m·K), which makes it an efficient conductor of heat in natural processes such as heat distribution in oceans and other water bodies.

[152] Lide, D. R. (ed.) CRC Handbook of Chemistry and Physics, 85th edn (CRC Press, 2004).

Studies show that the thermal conductivity of water increases with rising temperature, up to a certain point.[152] In addition, this value can vary in the presence of impurities or dissolved substances.[153, 154] These characteristics influence the way heat is distributed in water, which is critical to understanding the interactions between the ocean and the atmosphere.

3. Anomalous Behavior of Water Density

Unlike that of most substances, the density of water behaves unusually as temperature changes. When water cools down to 4 °C, its density increases, but when cooled further (from 4 °C to 0 °C), its density begins to decrease (Fig. 54). When water freezes, its density drops by about 8–9 %. This explains why ice floats instead of sinking. This phenomenon is critically important for life in water bodies because ice protects the underlying water and living organisms from freezing and prevents water from freezing solid all the way to the bottom.

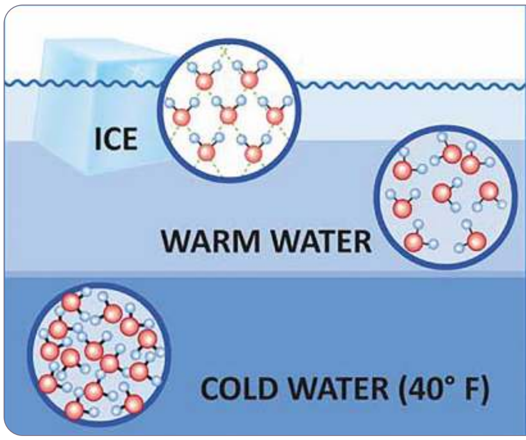

Figure 54: Schematic representation of the change in water density during cooling: As water cools, the molecules come closer together (increasing density) to a point. Water is most dense at about 40 degrees F (4° C). As water cools further, the hydrogens push against each other, aligning in a certain way as ice crystals form, expanding and making ice about 10 percent less dense than liquid water.

Source: https://askascientistblog.wordpress.com/2015/11/04/if-molecules-in-colder-things-get-denser-why-does-ice-float/

Influence of Water Properties on Climate and Ecosystems

Changes in water temperature can significantly affect the thermal balance of the World Ocean and its ability to retain and transfer heat. This, in turn, will impact Earth's climate system.

Thus, the physicochemical properties of water, especially its heat capacity and thermal conductivity, play a vital role in maintaining environmental balance on the planet and regulating climate processes (Fig. 55).

[152] Lide, D. R. (ed.) CRC Handbook of Chemistry and Physics, 85th edn (CRC Press, 2004).
[153] Sharqawy, M. H., Lienhard, J. H. & Zubair, S. M. Thermophysical properties of seawater: a review of existing correlations and data. Desalination and Water Treatment 16, 354–380 (2010). https://doi.org/10.5004/dwt.2010.1079
[154] Jamieson, D. T. & Tudhope, J. S. Physical properties of sea water solutions: thermal conductivity. Desalination 8, 393–401 (1970). https://doi.org/10.1016/S0011-9164(00)80240-4

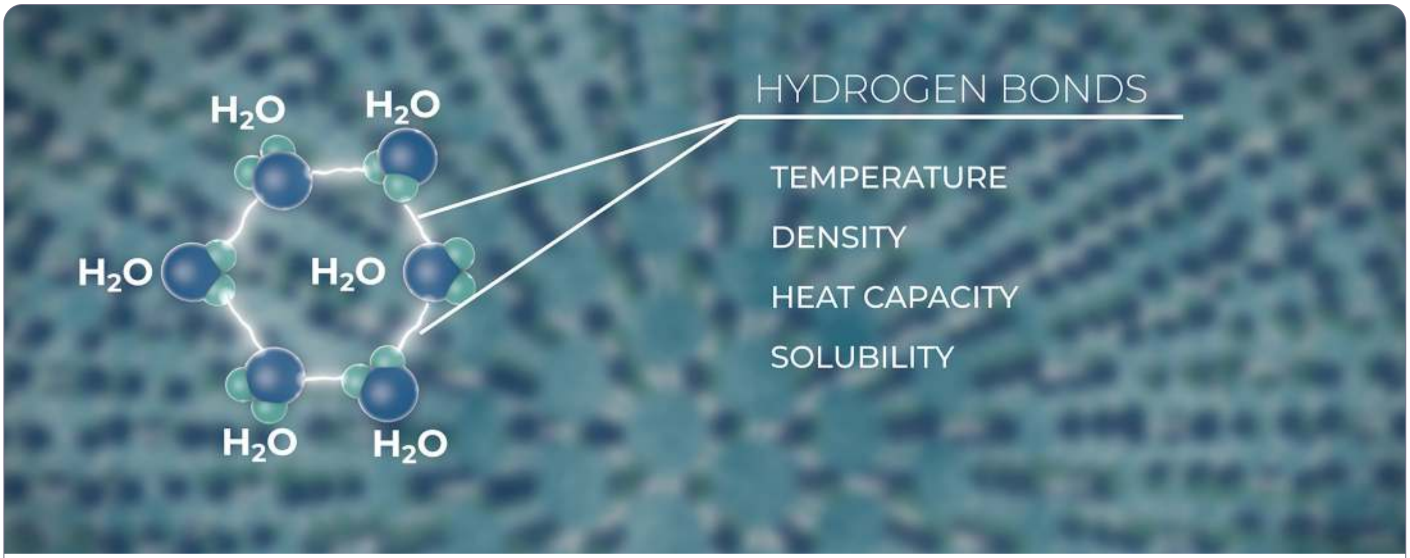

Figure 55: Schematic representation of hydrogen bonds in water molecules and their impact on key properties of water: Hydrogen bonds contribute to water's high heat capacity, allowing it to efficiently absorb and retain heat. These bonds also determine water's density—maximal at 4°C—as well as its ability to dissolve polar and ionic substances, making water a universal solvent.

Role of MNPs in Altering Seawater's Physical Properties

As products of the petrochemical industry, plastics do not biodegrade in nature. Instead, they break down into smaller particles, such as micro- and nanoplastics.[155] Those particles, especially nanoplastics, can significantly affect the physical and chemical properties of water, which in turn can influence ecosystems and climate processes.

Nanoplastics are particles measured in nanometers, meaning they are smaller than a virus (Fig. 56).

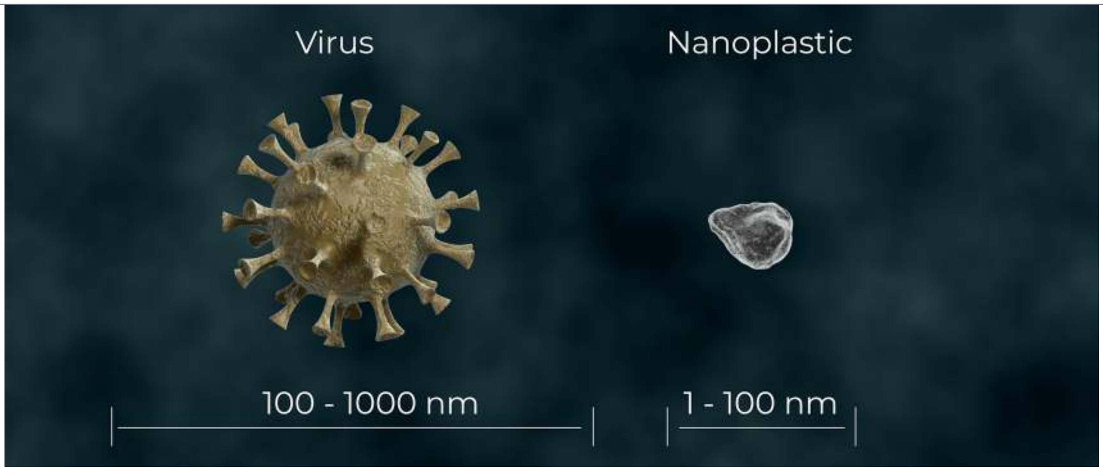

Figure 56: Schematic comparison of sizes of a virus and a nanoplastic particle

[155] Yu, R.-S. & Singh, S. Microplastic Pollution: Threats and Impacts on Global Marine Ecosystems. Sustainability 15, 13252 (2023). https://doi.org/10.3390/su151713252

For instance, nylon (polyamide) nanoplastics, which contain nitrogen and oxygen, can form hydrogen bonds with water.[156] When nanoplastic particles enter water, they disrupt the ordered structure of hydrogen bonds between water molecules. This can alter the water's physicochemical properties (Fig. 57). In particular, the mobility of water molecules decreases, which reduces their ability to efficiently participate in heat exchange processes. Moreover, in aqueous solutions containing various substances, plastic nanoparticles may acquire an electric charge.[157]

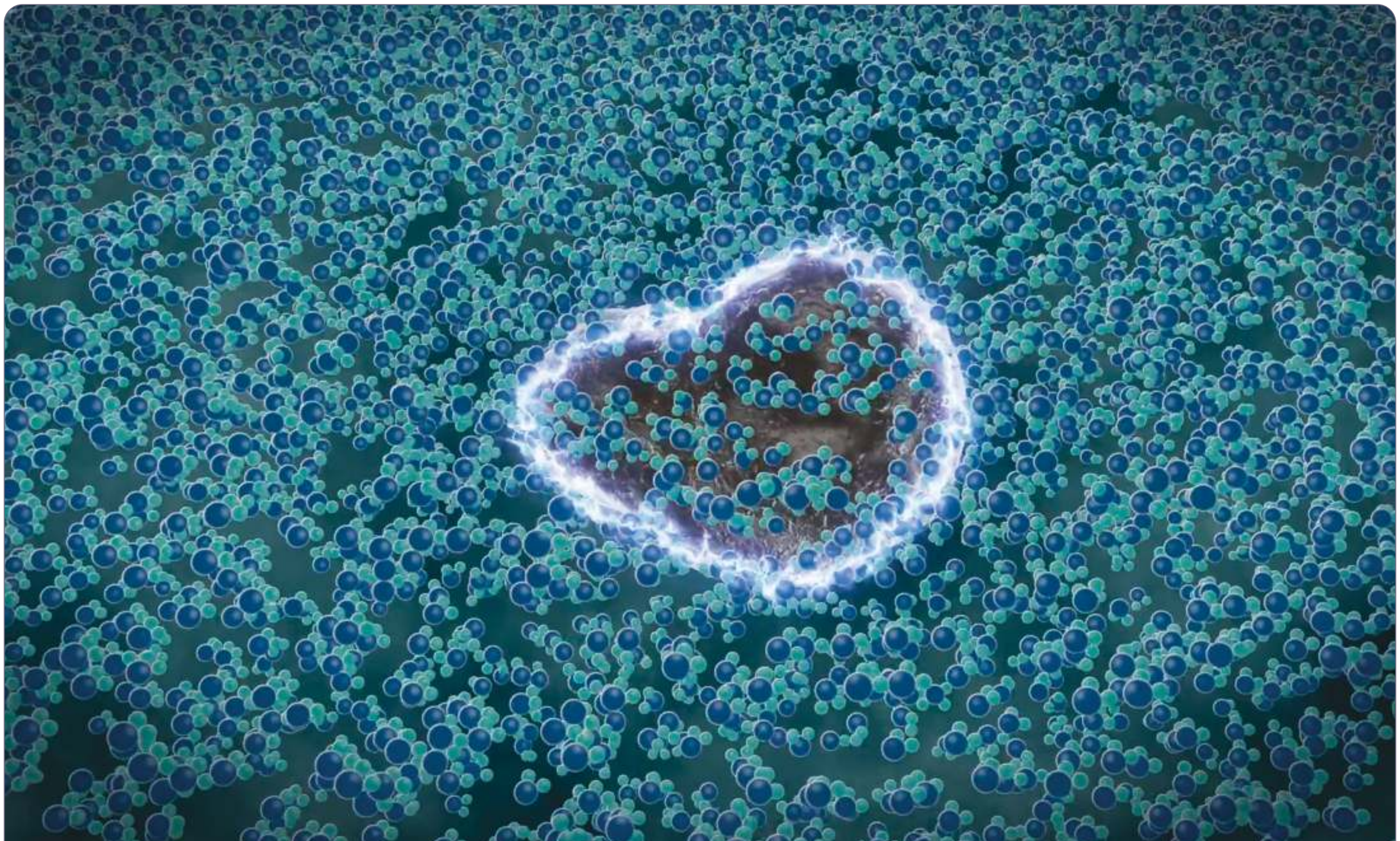

Figure 57: Schematic representation of charged plastic nanoparticles in water: when exposed to unstable water conditions, such as the presence of organic or synthetic impurities, changes in pH, temperature, or salinity, the surface of nanoplastics becomes potentially active and capable of generating electric charges in the aquatic environment.

Source: Rahman, A. M. N. A. A. et al. A review of microplastic surface interactions in water and potential capturing methods. Water Science and Engineering 17, 361–370 (2024). https://doi.org/10.1016/j.wse.2023.11.008

This is due to chemical changes on their surface, such as oxidation and adsorption of ions, e.g., sodium (Na^+) and chlorine (Cl^-), in seawater. Charged plastic nanoparticles surrounded by ions attract water molecules and form a hydrate shell around them[158] (Fig. 58).

[156] Ivleva, N. P. Chemical Analysis of Microplastics and Nanoplastics: Challenges, Advanced Methods, and Perspectives. Chem. Rev. 121, 11886–11936 (2021). https://doi.org/10.1021/acs.chemrev.1c00178

[157] Rahman, A. M. N. A. A. et al. A review of microplastic surface interactions in water and potential capturing methods. Water Science and Engineering 17, 361–370 (2024). https://doi.org/10.1016/j.wse.2023.11.008

[158] Chen, Y. et al. Electrolytes induce long-range orientational order and free energy changes in the H-bond network of bulk water. Sci. Adv. 2, e1501891 (2016). https://doi.org/10.1126/sciadv.1501891

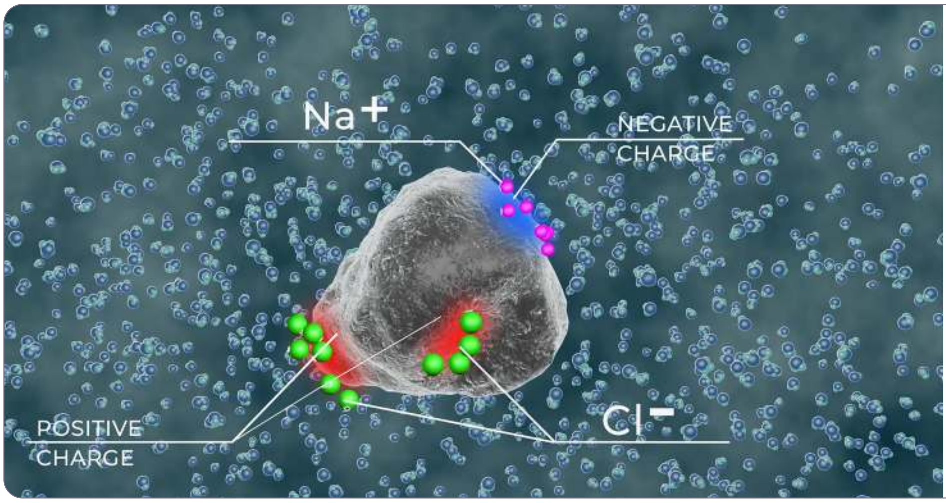

Figure 58: Schematic representation of a hydrate shell forming around charged plastic nanoparticles: in this process, charged nanoparticles attract ions, contributing to formation of water molecules around them and creating a protective hydrate shell. Source: Chen, Y. et al. Electrolytes induce long-range orientational order and free energy changes in the H-bond network of bulk water. Source: Sci. Adv. 2, e1501891 (2016). https://doi/10.1126/sciadv.1501891

Researchers from the Polytechnic School of Lausanne (EPFL) decided to find out the size of this hydrate shell of ions, that is, how many water molecules react to an ion. It turned out that one ion can influence about a million water molecules around it. This effect is enhanced if a particle has a large surface charge and a high concentration of adsorbed ions. Therefore, a single nanoplastic particle can change the properties of millions of water molecules[158] (Fig. 59). The molecules bound in a hydrate shell are less mobile.[159] As a result, the total heat capacity of the water is reduced.[160, 161]

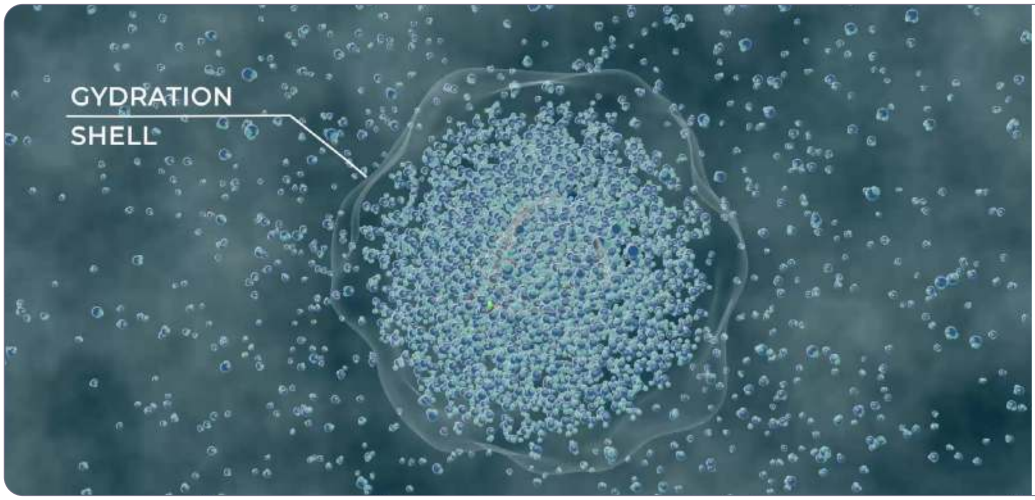

Figure 59: Schematic illustration of the hydrate shell around a nanoplastic particle

Disruption of hydrogen bond structures also leads to a decrease in thermal conductivity.[162] Consequently, water may remain heated near nanoplastics, as it loses its ability to effectively transfer heat.

[158]Chen, Y. et al. Electrolytes induce long-range orientational order and free energy changes in the H-bond network of bulk water. Sci. Adv. 2, e1501891 (2016). https://doi.org/10.1126/sciadv.1501891
[159]Laage, D., Elsaesser, T. & Hynes, J. T. Water Dynamics in the Hydration Shells of Biomolecules. Chem. Rev. 117, 10694–10725 (2017). https://doi.org/10.1021/acs.chemrev.6b00765
[160]Chew, T., Daik, R. & Hamid, M. Thermal Conductivity and Specific Heat Capacity of Dodecylbenzenesulfonic Acid-Doped Polyaniline Particles—Water Based Nanofluid. Polymers 7, 1221–1231 (2015). https://doi.org/10.3390/polym7071221
[161]Riazi, H. et al. Specific heat control of nanofluids: A critical review. International Journal of Thermal Sciences 107, 25–38 (2016). https://doi.org/10.1016/j.ijthermalsci.2016.03.024
[162]Berger Bioucas, F. E. et al. Effective Thermal Conductivity of Nanofluids: Measurement and Prediction. Int J Thermophys 41, 55 (2020). https://doi.org/10.1007/s10765-020-2621-2

Areas of Micro- and Nanoplastics Concentration in the Ocean

Micro- and nanoplastics can be dispersed throughout the ocean by currents, while denser particles or contaminated plastics can settle on the ocean floor. Accumulation of nanoplastics is also observed in the thermocline areas — transitional layers between warm surface waters and colder deep waters[163] (Fig. 60).

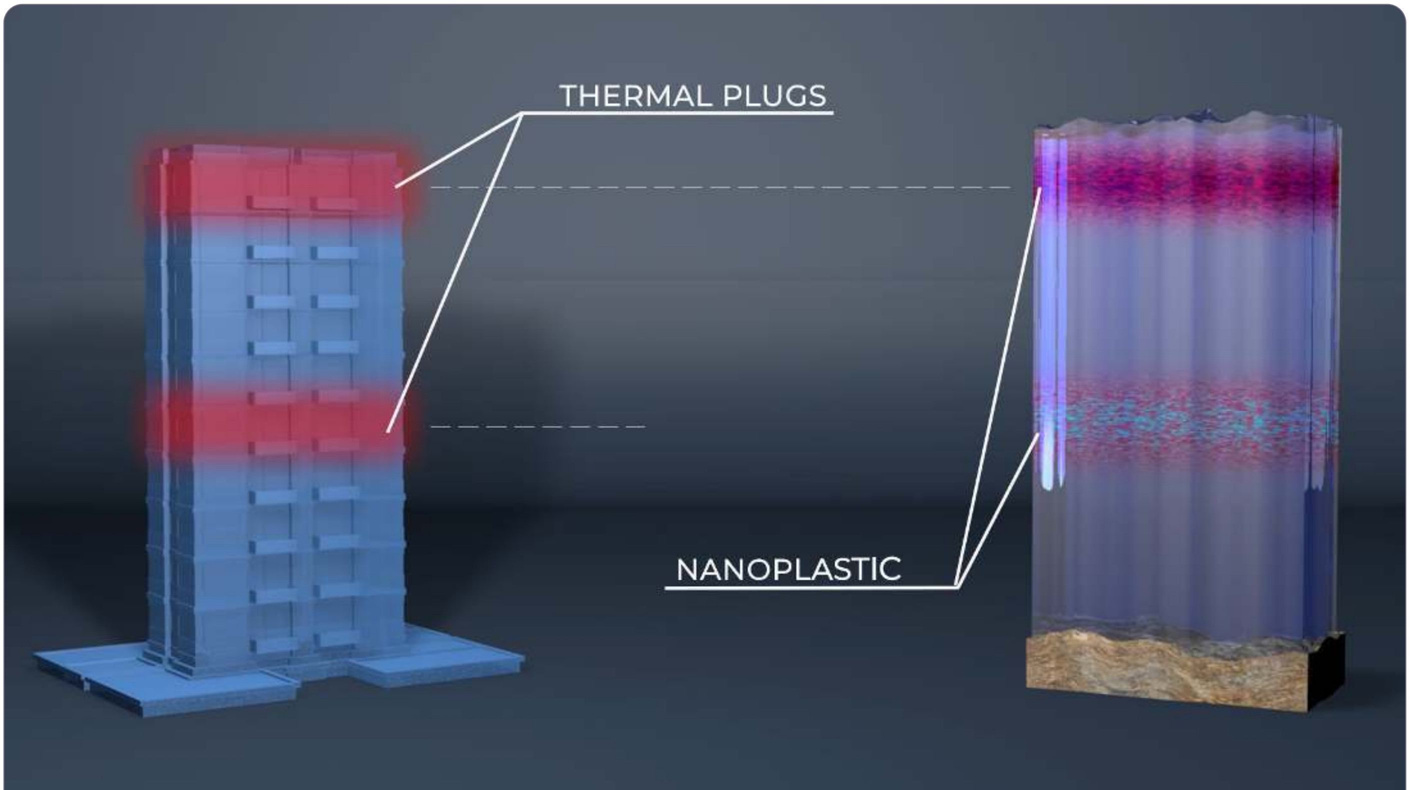

Figure 60: The image illustrates a figurative comparison between areas of micro- and nanoplastic concentration in the ocean and a multistory building with thermal blockages on the 5th and 10th floors. The blockages hinder normal heat exchange, causing heat to accumulate on these floors instead of being evenly distributed. A thermal camera would show that the temperature inside the building is significantly higher than in a similar building without blockages. Similarly, nanoplastics disrupt natural heat exchange mechanisms in water, creating "thermal blockages" in the ocean.

Increased concentrations of nanoplastics in the oceans can cause changes in the global heat balance. This can influence the rise in ocean temperatures, potentially causing climate change. It's important to note that even a small amount of nanoplastic can have a significant impact on ecosystems. A rise in ocean surface temperature accelerates fragmentation of plastic waste into micro- and nanoplastics (Fig. 61). Consequently, the number of these particles increases, and they enter the atmosphere along with water vapor. The presence of micro- and nanoplastics in the atmosphere contributes to further warming, which in turn intensifies the warming of the ocean. Thus, a feedback loop is formed, where the processes mutually reinforce each other.

[163]Tikhonova, D. A., Karetnikov, S. G., Ivanova, E. V. & Shalunova, E. P. The Vertical Distribution of Microplastics in the Water Column of Lake Ladoga. Water Resour 51, 146–153 (2024). https://doi.org/10.1134/S009780782370063X

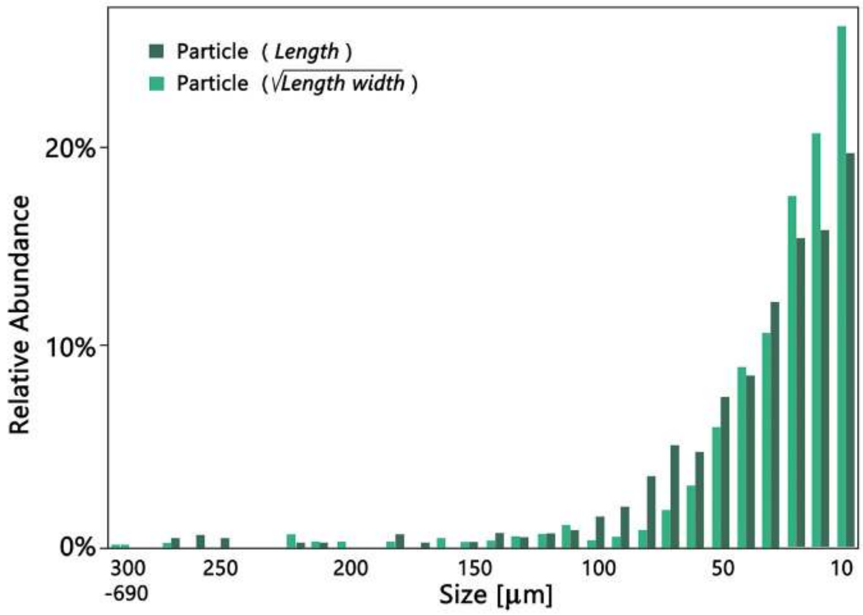

Figure 61: Relative distribution of microplastic particles by sizes at all the analysed stations (np = 543). Images show the smallest (left) and largest (right) MP particles found and confirmed via Raman spectroscopy.

Source: Enders, K., Lenz, R., Stedmon, C. A. & Nielsen, T. G. Abundance, size and polymer composition of marine microplastics ≥ 10 μm in the Atlantic Ocean and their modelled vertical distribution. Marine Pollution Bulletin 100, 70–81 (2015). https://doi.org/10.1016/j.marpolbul.2015.09.027

Link Between the MNP Electrostatic Charge and Atmospheric Phenomena

Micro- and nanoplastics enter the atmosphere through various pathways. Water vapor evaporating from the surface of oceans and other water bodies carries microparticles into the air.[164] On land, the primary sources of atmospheric plastics include factories, waste incineration plants, and landfills. Additionally, microplastics are lifted into the air when agricultural fertilizers and plastic mulch dry out and are dispersed by winds. Microplastic particles are also released through the friction of automobile tires.

These and many other sources contribute significantly to atmospheric pollution. These processes promote accumulation and spread of microplastics in the atmosphere, creating serious environmental and climate-related threats. Once in the atmosphere, micro- and nanoplastic particles can serve as condensation nuclei for water vapor. The greater the number of such nuclei, the faster the condensation of water vapor into droplets occurs. Airborne microplastics have been found in cloud water samples collected from mountaintops in Japan[165] (Fig. 62).

[164]Shaw, D. B., Li, Q., Nunes, J. K. & Deike, L. Ocean emission of microplastic. PNAS Nexus 2, pgad296 (2023). https://doi.org/10.1093/pnasnexus/pgad296
[165]Wang, Y. et al. Airborne hydrophilic microplastics in cloud water at high altitudes and their role in cloud formation. Environ Chem Lett 21, 3055–3062 (2023). https://doi.org/10.1007/s10311-023-01626-x

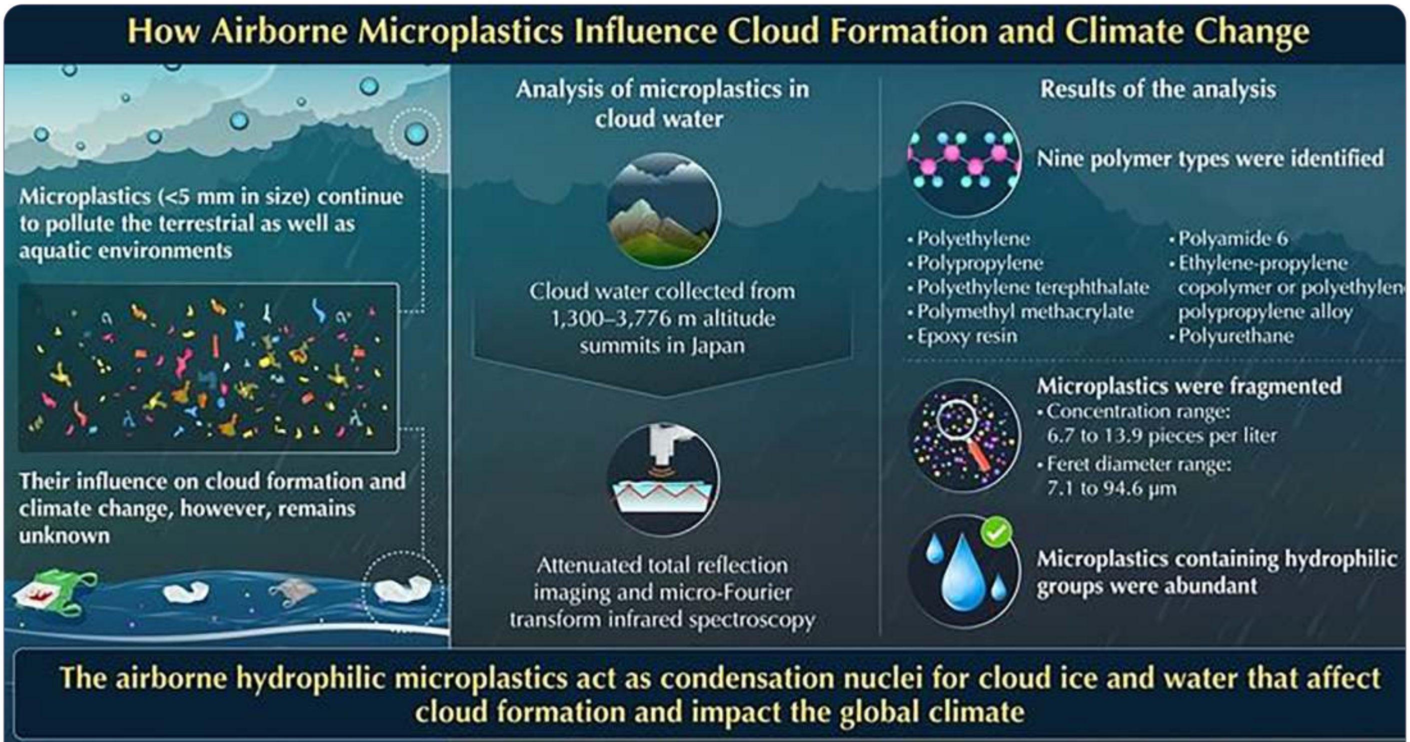

Figure 62: Airborne hydrophilic microplastics in cloud water at high altitudes and their role in cloud formation

Source: Hiroshi Okochi from Waseda University
https://www.sustainableplastics.com/news/scientists-find-microplastics-clouds-above-mount-fuji

"In a polluted environment with many more aerosol particles, like microplastics, you are distributing the available water among many more aerosol particles, forming smaller droplets around each of those particles. When you have more droplets, you get less rain, but because droplets only rain once they get large enough, you collect more total water in the cloud before the droplets are large enough to fall and, as a result, you get heavier rainfall when it comes," said Miriam Friedman, Professor of Chemistry of Penn State's Department of Meteorology and Atmospheric Science.[166]

This explains why anomalous precipitation has been observed in various regions in recent years.

[166] The Pennsylvania State University Research. Microplastics impact cloud formation, likely affecting weather and climate. (2024) (accessed: 1 May 2025) https://www.psu.edu/news/research/story/microplastics-impact-cloud-formation-likely-affecting-weather-and-climate) (accessed: 1 May 2025)

Electric Charges in Clouds

Earth's atmosphere is a complex electrical system in which water molecules play a vital role. Since 1752, when Benjamin Franklin first demonstrated that the atmosphere is electrified and thunderstorms have an electrical nature, it has become clear that water, in the form of vapor, liquid, and ice, plays a key role in these processes. While pure water is electrically neutral, during phase changes such as melting and freezing, as well as during collisions between molecules, it can transfer ions to other particles. This leads to a buildup of electric charges and contributes to atmospheric electrical phenomena.

In the atmosphere, collisions between ice crystals, supercooled water droplets, and other particles, especially in the presence of natural electric fields, cause separation of charges. This process plays a key role in the development of atmospheric electricity, including formation of thunderclouds. It is also essential to formation of clouds and precipitation. Electrically charged droplets are drawn towards each other, accelerating their coalescence into larger drops. This ultimately leads to the formation of clouds capable of producing precipitation such as rain, snow, or hail.

> *"Charges are really important, and in cloud formation, charges are practically everything. And what we found is that charges are critical,"* said Gerald H. Pollack, PhD, professor of bioengineering at the University of Washington, editor-in-chief and founder of the interdisciplinary research journal WATER.[167]

In 1843, Michael Faraday discovered that electricity can be generated when water droplets rub against metal surfaces, effectively charging the water. This finding sparked further research into how water becomes electrically charged through friction, phase transitions and contact electrification, and even resulted in efforts to harness this effect for new energy sources.

It is known that humid air can neutralize surface charges by forming a thin water film that allows ions to move and dissipate built-up charge. However, in some cases, surfaces that absorb water can actually accumulate charge from a moist atmosphere, which also influences the surrounding electrical environment.[168] Research has also shown that heavy metals can easily bind to microplastics, and this combination may pose serious risks to global ecosystems.

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[167] AllatRa TV. Anthropogenic factor in the oceans' demise: Popular science film. Time 55:00, (2025). https://allatra.tv/en/video/anthropogenic-factor-in-the-oceans-demise-popular-science-film (accessed 1 May 2025).

[168] Lax, J. Y., Price, C. & Saaroni, H. On the Spontaneous Build-Up of Voltage between Dissimilar Metals Under High Relative Humidity Conditions. Sci Rep 10, 7642 (2020). https://doi.org/10.1038/s41598-020-64409-2

Moreover, microplastics and the mix of substances on their surface can not only stick to other pollutants, but also interact with each other, altering their chemical properties.[169] When micro- and nanoplastic particles enter the atmosphere, they can disrupt the delicate balance of atmospheric processes. Plastic particles may carry a charge, enhancing the attraction of polar water molecules and promoting the formation of droplets. Unlike typical condensation nuclei such as pollen, sea salt, or soot, plastic particles can gather droplets more efficiently than neutral particles.[170]

This means that water droplets begin to form more quickly around charged particles, which affects cloud structure and may lead to the formation of larger droplets and even abnormally large ice crystals.[171] For instance, a recent study by a group of researchers found plastic pellets with water-attracting surfaces in clouds at mountain peaks in Japan.[172]

Impact on Cloud Formation and Precipitation

Microplastics can influence the nature of precipitation, weather forecasting, climate modeling, and even flight safety by affecting how atmospheric ice crystals form clouds.

A study[173] has shown that water droplets containing microplastics freeze at temperatures 4–10 °C higher than droplets without them, meaning they freeze at lower altitudes. Typically, a water droplet without any impurities freezes at around –38°C. However, in the case of microplastics, 50 % of the droplets froze at –18 to –24 degrees Celsius, depending on the type of plastic.

Water droplets containing microplastics freeze faster, forming larger ice particles. Those particles are carried upwards by air currents, repeatedly coated with layers of ice, and then fall to the ground. This kind of phenomenon can lead to an increase in the size of hailstones (Figs. 63–64), intensifying their destructive impact and accelerating the formation of ice clouds. As a result, the frequency and intensity of precipitation, including rain and snow, may change. This can trigger cascading effects that impact the climate, the hydrological cycle, and ecosystems.

When nanoplastic particles are present in the atmosphere, clouds begin to form at lower altitudes — typically below 6,500 feet. This causes clouds to become less mobile, which disrupts normal precipitation patterns. Consequently, some areas may experience drought, while others receive excessive rainfall.

[169] Ho, W.-K. et al. Sorption Behavior, Speciation, and Toxicity of Microplastic-Bound Chromium in Multisolute Systems. Environ. Sci. Technol. Lett. 10, 27–32 (2023). https://doi.org/10.1021/acs.estlett.2c00689

[170] Harrison, R. G. Atmospheric electricity and cloud microphysics https://cds.cern.ch/record/557170/files/p75.pdf (accessed: 1 May 2025)

[171] The Pennsylvania State University News. Microplastics impact cloud formation, likely affecting weather and climate. (2024) https://www.psu.edu/news/research/story/microplastics-impact-cloud-formation-likely-affecting-weather-and-climate (accessed: 1 May 2025)

[172] Wang, Y., Okochi, H., Tani, Y. et al. Airborne hydrophilic microplastics in cloud water at high altitudes and their role in cloud formation. Environ Chem Lett 21, 3055–3062 (2023). https://doi.org/10.1007/s10311-023-01626-x

[173] Busse, H. L., Ariyasena, D. Dh., Orris J. & Freedman, M. Ar. Pristine and Aged Microplastics Can Nucleate Ice through Immersion Freezing. ACS ES&T Air 1, 1579-1588 (2024). https://doi.org/10.1021/acsestair.4c00146

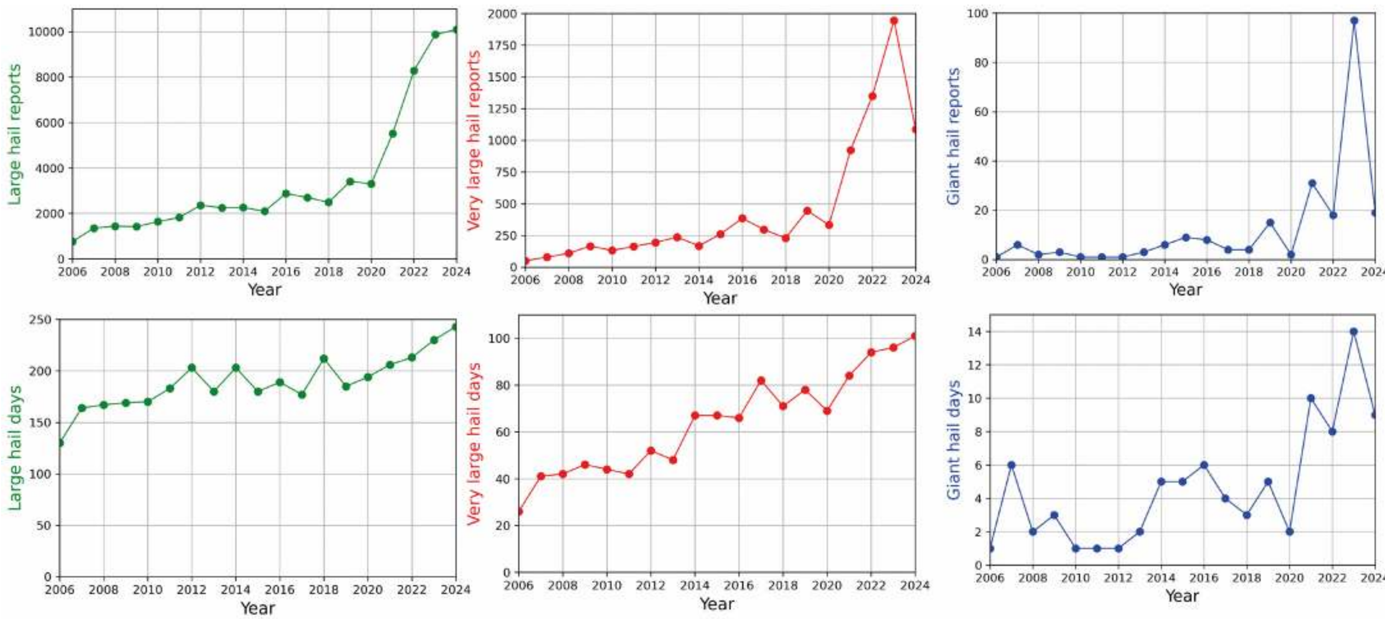

Figure 63: Number of reports and days with (0.8+ inches), very large (2+ inches), and giant (4+ inches) hail from 2006 to 2024

Source: European Severe Storms Laboratory. Hailstorms of 2024
https://www.essl.org/cms/hailstorms-of-2024/

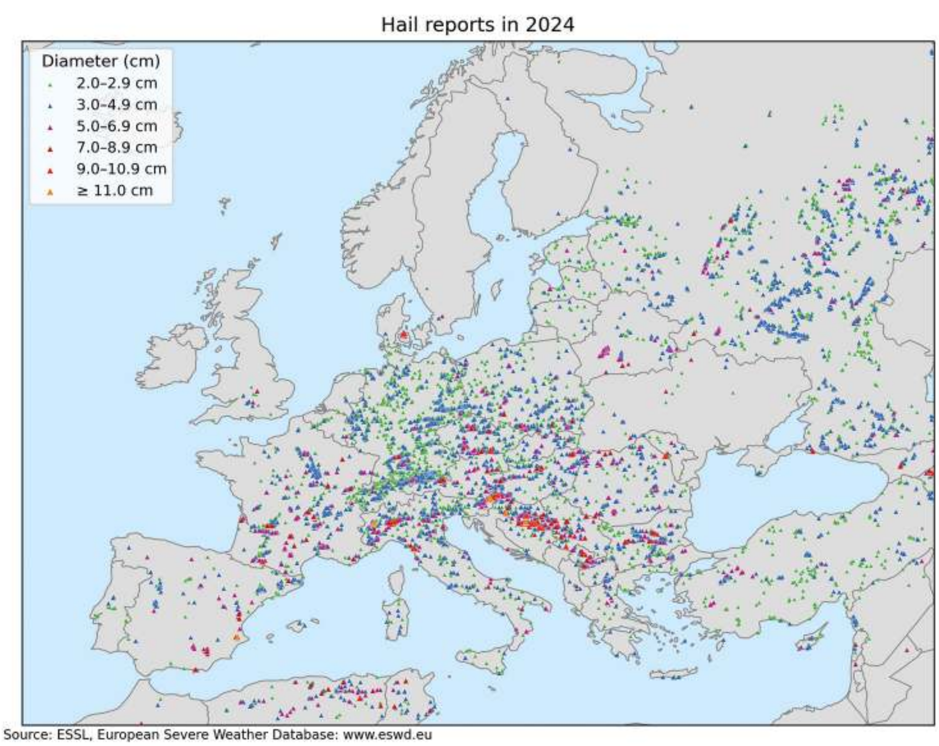

Figure 64: Spatial distribution of large hail reports across Europe and surrounding regions in 2024

Source: European Severe Storms Laboratory. Hailstorms of 2024
https://www.essl.org/cms/hailstorms-of-2024/

Role of MNPs in Disrupting Earth's Climate Balance

Denser clouds begin to trap heat in lower layers of the atmosphere, acting like a blanket by absorbing and re-radiating thermal energy back toward Earth's surface. This reduces the amount of heat escaping into space and contributes to atmospheric warming. Rising temperatures lead to increased evaporation from the oceans, while more moisture in the air further amplifies the warming, creating a self-reinforcing cycle. Notably, for every 1 °C (1.8 °F) increase in temperature, the amount of moisture in the atmosphere rises by approximately 7 %,[174] and the frequency of lightning strikes increases by about 12 %.[175]

> As noted by Kevin Trenberth, a distinguished climatologist at the U.S. National Center for Atmospheric Research (NCAR) and a lead author of IPCC reports, *"Those two ingredients, the increased temperature and the increased water vapor, lead to increased instability of the atmosphere. And what that leads to is more convection, more storms, some of which, the more severe ones, become thunderstorms. And there's a greater risk of strong thunderstorms as a result. And if the thunderstorms get together and cooperate, as they do in a tropical storm, you can end up with stronger hurricanes as well. And so, all of those things are adding together. And there's an increased risk of the kinds of storms, the severe thunderstorms, the supercell storms especially that produce the hail and also can in some places in the right conditions, produce tornadoes."*

Thus, extreme ocean heating along with excess electricity and heat in the atmosphere is worsening the climate situation, causing more destructive weather events such as severe thunderstorms, hurricanes, lightning, and sprites.

In the atmosphere, plastics do not just pollute the environment, but also disrupt climate processes by influencing cloud formation and precipitation. They enhance electrostatic charge in the atmosphere, accelerate condensation of water vapor, and affect cloud density — factors that can increase the intensity of storms, thunderstorms, and other extreme weather events. We are on the brink of understanding the full scale of this impact on the climate, underscoring the urgent need for comprehensive action to reduce plastic particle pollution in both the oceans and the atmosphere.

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[174] NASA. Steamy relationships: How atmospheric water vapor amplifies Earth's greenhouse effect. (2022) https://science.nasa.gov/earth/climate-change/steamy-relationships-how-atmospheric-water-vapor-amplifies-earths-greenhouse-effect (accessed: 1 May 2025)

[175] Romps, D. M., Seeley, J. T., Vollaro, D. & Molinari, J. Projected increase in lightning strikes in the United States due to global warming. Science 346, 851–854 (2014). https://doi.org/10.1126/science.1259100

Interaction Between the Ocean and Earth's Magnetic Field

The oceans cover about 70 % of Earth's surface and are far more than vast reservoirs of water: they play a crucial role in the planet's complex electrical systems. They interact with Earth's magnetic field and actively participate in its electromagnetic processes.

Earth's magnetic field acts as a natural shield, protecting the planet's surface from solar wind and cosmic radiation. Without it, our atmosphere would be stripped away. This geomagnetic field is generated deep within the planet where the liquid outer core, composed of metals, moves around the solid inner core, creating a natural generator through a process known as geodynamo (Fig. 65).

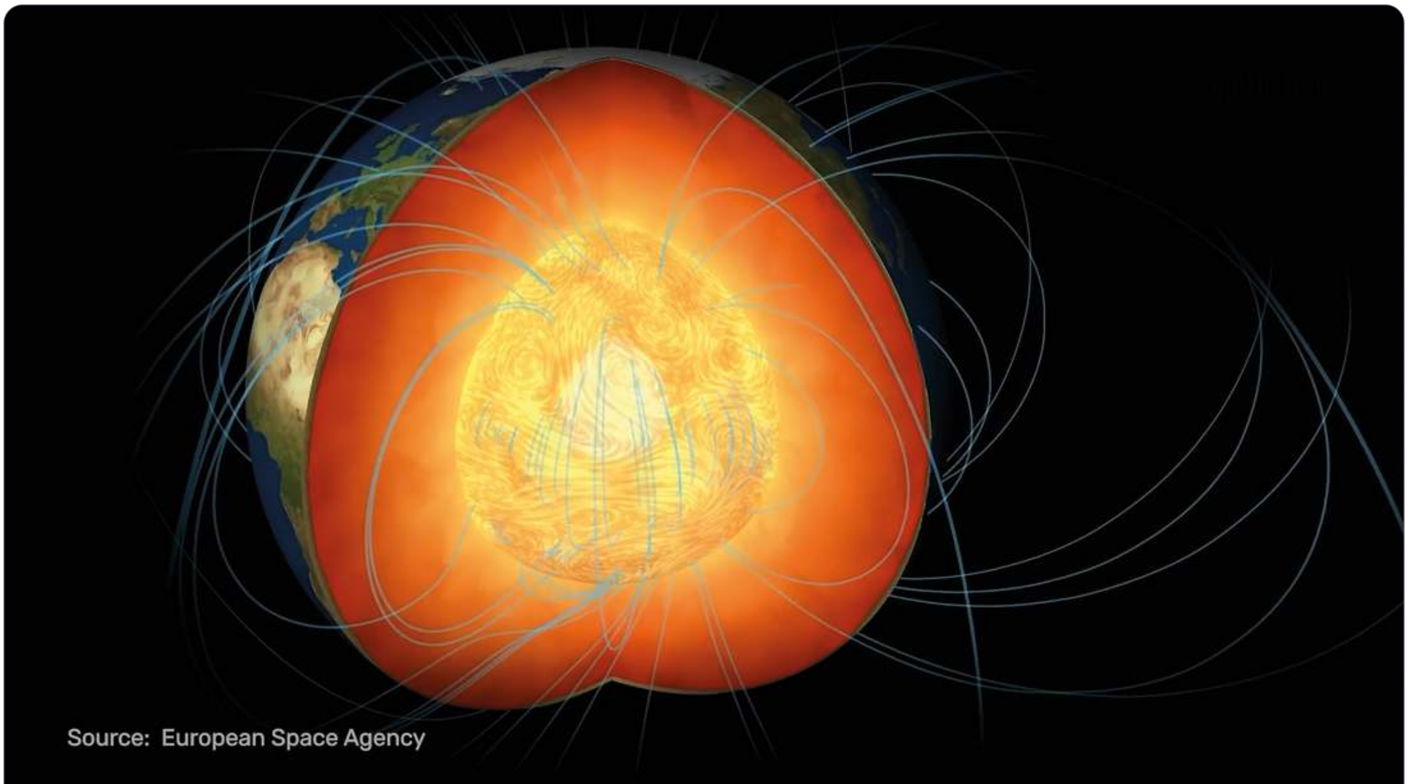

Figure 65: Schematic illustration of the geomagnetic field formation process: Earth's liquid outer core spins around its solid inner core, acting like a natural generator known as geodynamo that produces the planet's magnetic field.

Source: European Space Agency (ESA) – https://www.esa.int

Earth's magnetic field interacts with electrical phenomena in both the oceans and the atmosphere. Seawater, rich in salts and dissolved ions, is highly conductive and capable of carrying electric currents. Those currents, in turn, interact with the planet's magnetic field, generating complex electromagnetic processes that influence the dynamics of Earth's geomagnetic system.

As previously discussed, ocean pollution, particularly from micro- and nanoplastics, can alter the chemical and electrical properties of seawater. The higher the concentration of pollutants, the more natural electromagnetic processes are disrupted. When polluted water evaporates, it can carry with it metals, microplastics, and other substances, potentially influencing atmospheric processes.

During evaporation, microscopic droplets and aerosols can transport micro- and nanoplastics, heavy metals[176], and other contaminants into the atmosphere, where they may affect local electromagnetic conditions. This process is somewhat analogous to placing a metallic object near a magnet: it distorts the magnetic field and weakens its strength in specific areas.

The impact of ocean pollution on Earth's magnetic field requires further research, especially in the context of global climate change. A deeper understanding of these processes can help scientists assess their potential effects on the planet's climate system and ecosystems.

[176] Ho, W.-K. et al. Sorption Behavior, Speciation, and Toxicity of Microplastic-Bound Chromium in Multisolute Systems. Environ. Sci. Technol. Lett. 10, 27–32 (2023). https://doi.org/10.1021/acs.estlett.2c00689

IMPACT OF MICRO- AND NANOPLASTICS ON HUMAN HEALTH

> *"Not only are plastics polluting our oceans and waterways and killing marine life - it's in all of us and we can't escape consuming plastics. Global action is urgent and essential to tackling this crisis."*
>
> Marco Lambertini
> Director General of WWF International

Micro- and Nanoplastics as Emerging Risk Factors in the 21st-Century Epidemics

Over the past 30 years, there has been a steady rise in heart attacks, strokes, cancer, diabetes, allergies, and inflammatory bowel diseases. A decline in immune function is being observed in both children and adults worldwide. Infertility is becoming more widespread. Even though data on the number of infertile individuals and couples remains limited, the World Health Organization estimates that around 17.5 % of the adult population[177] — roughly 1 in 6 worldwide — experience infertility.

Since 2010, a decline in intellectual abilities has been observed. Even in developed countries, 25% of adults struggle with basic math problems; in the United States, this figure reaches 35%. Attention span, logical thinking, and the ability to solve simple tasks are deteriorating. The prevalence of various forms of dementia and cognitive impairment is growing.[178]

The rise in mental health disorders has overtaken the growth of physical illnesses.[179] Anxiety disorders, autism, depression, bipolar disorder, and attention deficit hyperactivity disorder (ADHD) are reaching pandemic levels.

There is growing evidence that micro- and nanoplastics play a role in the development of these health conditions.

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[177] World Health Organization. 1 in 6 people globally affected by infertility. (2023) https://www.who.int/news/item/04-04-2023-1-in-6-people-globally-affected-by-infertility (accessed 1 May 2025).
[178] Financial Times. Have humans passed peak brain power? https://www.ft.com/content/a8016c64-63b7-458b-a371-e0e1c54a13fc (accessed 1 May 2025).
[179] Ipsos. Ipsos Health Service Report 2024: Mental Health seen as the biggest Health issue. (2024) https://www.ipsos.com/en/ipsos-health-service-report (accessed 1 May 2025)

Molecular Mechanisms of MNP Toxicity: Destruction of DNA, Mitochondria, and Cell Membranes

Micro- and nanoplastics (MNPs) are among the most widespread forms of anthropogenic pollution in the environment. Due to their physical and chemical properties, plastic particles can travel long distances, crossing both geographic and ecological barriers. The main pathways through which micro- and nanoplastics enter the human body are ingestion (through water and food), inhalation (from the air), and absorption through the skin (Fig. 66).[180]

As mentioned in Part 1: **"Plastics in the Environment: Scale of the Problem,"** the marine environment serves as a major source of secondary microplastics. According to estimates, marine breezes carry about 136,000 tons of microplastics to coastal areas each year. Additionally, open bodies of water in urban areas — including wastewater and stormwater systems — have become significant centers for the accumulation and further spread of plastic particles, with concentrations that may exceed previous estimates by up to 90%.

Food products represent a major pathway for MNPs to enter the human body. Plants are capable of accumulating nanoplastics through their root systems: during irrigation or rainfall, particles enter the soil and are absorbed with water, moving through the xylem and accumulating in leaf and fruit tissues.[181]

The highest concentrations of plastic particles have been found in crops such as apples, pears, carrots, and broccoli.

Seafood is another route for the transfer of MNPs. The ingestion of microplastics by marine organisms has been recorded at all trophic levels. According to research by Newcastle University, the average person may consume up to 250 grams of microplastics per year — approximately 5 grams per week, or the weight of one plastic credit card. Moreover, when plastic containers — including baby food packaging — are heated in microwave ovens, more than 2 billion nanoparticles and 4 million microparticles of plastic can be released into the food per square centimeter of surface area.

Microplastics are widespread in drinking water. Studies show that up to 90% of tap water samples in the United States contain MNPs. Major sources of contamination include wastewater runoff, industrial emissions, and atmospheric deposition of airborne plastics. When contaminated water evaporates, plastic particles can rise into the atmosphere and later fall with rain or snow. A study conducted across 11 U.S. national parks recorded more than 1,000 tons of plastic particles falling with precipitation over just 14 months — enough to produce 120 million plastic bottles.

[180]Bora, S. S. et al. Microplastics and human health: unveiling the gut microbiome disruption and chronic disease risks. Front. Cell. Infect. Microbiol. 14, 1492759 (2024). https://doi.org/10.3389/fcimb.2024.1492759

[181]Azeem, I. et al. Uptake and Accumulation of Nano/Microplastics in Plants: A Critical Review. Nanomaterials 11, 2935 (2021). https://doi.org/10.3390/nano11112935

Aerosol transmission of MNPs is considered one of the most dangerous exposure pathways for humans. Plastic particles are lifted from the surfaces of oceans and bodies of water, transported by air currents, and become part of atmospheric aerosols. Estimates suggest that in a major city, an adult can inhale up to 106,000 microplastic particles during a two-hour walk. In areas near bodies of water, this figure can be ten times higher.

A new study presented at the American College of Cardiology conference (ACC.25) revealed that higher exposure to microplastics — which can be unintentionally ingested or inhaled — is associated with an increased prevalence of chronic non-communicable diseases. The research found that communities located along the East and West Coasts, the Gulf Coast, and certain lakeshores in the U.S. showed higher concentrations of microplastics in the environment, which correlated with greater rates of chronic conditions such as hypertension, diabetes, and stroke.

> *"This study provides initial evidence that microplastics exposure has an impact on cardiovascular health, especially chronic, noncommunicable conditions like high blood pressure, diabetes and stroke,"* said Sai Rahul Ponnana, MA, a research data scientist at Case Western Reserve School of Medicine in Ohio and the study's lead author. *"When we included 154 different socioeconomic and environmental features in our analysis, we didn't expect microplastics to rank in the top 10 for predicting chronic noncommunicable disease prevalence."*[182]

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[182] American College of Cardiology. New evidence links microplastics with chronic disease. (2025) https://www.acc.org/About-ACC/Press-Releases/2025/03/25/10/19/New-Evidence-Links-Microplastics-with-Chronic-Disease (accessed 1 May 2025).

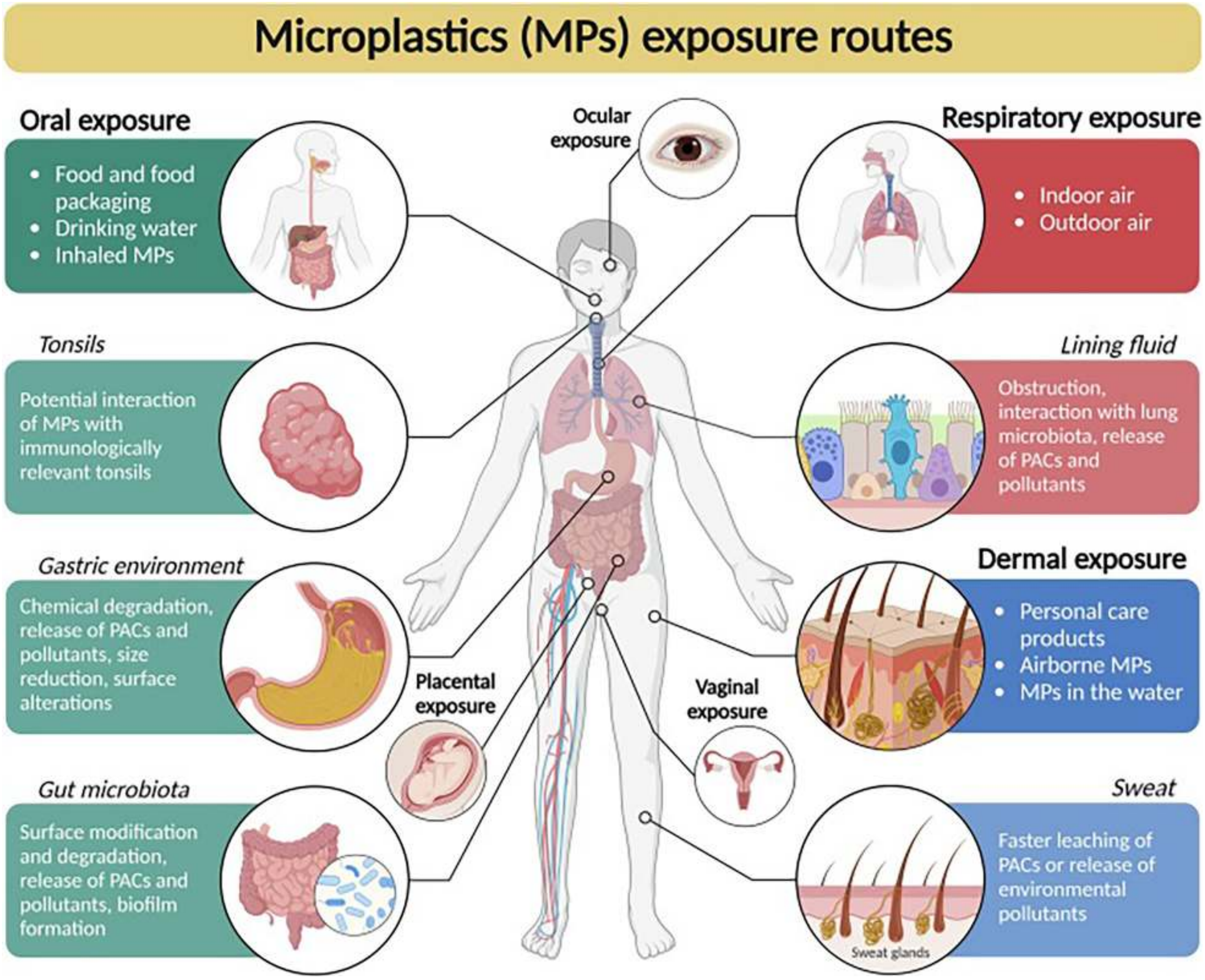

Figure 66: An overview of the human exposure routes to microplastics (MPs) and common events that may shape effects of MP particles, plastic-associated chemicals (PACs), and adsorbed environmental pollutants on human health.

Source: Alijagic, A. et al. The triple exposure nexus of microplastic particles, plastic-associated chemicals, and environmental pollutants from a human health perspective. Environment International 188, 108736 (2024). https://doi.org/10.1016/j.envint.2024.108736

Micro- and nanoplastics have been found capable of penetrating and crossing biological barriers, including those of the intestine, lungs, brain, and placenta.[183] Microplastics exposed to fresh or marine water more easily penetrate cells (Fig. 67) due to the accumulation of biomolecules on their surface. These biomolecules form a coating (eco-corona) that helps microplastics pass through the digestive tract and integrate into tissues. This coating acts as a facilitator, enhancing the particles' internalization into cells much like a "Trojan horse."[184]

[183]Alqahtani, S., Alqahtani, S., Saquib, Q. & Mohiddin, F. Toxicological impact of microplastics and nanoplastics on humans: understanding the mechanistic aspect of the interaction. Front. Toxicol. 5, 1193386 (2023). https://doi.org/10.3389/ftox.2023.1193386

[184]Ramsperger, A. F. R. M. et al. Environmental exposure enhances the internalization of microplastic particles into cells. Sci. Adv. 6, eabd1211 (2020). https://doi.org/10.1126/sciadv.abd1211

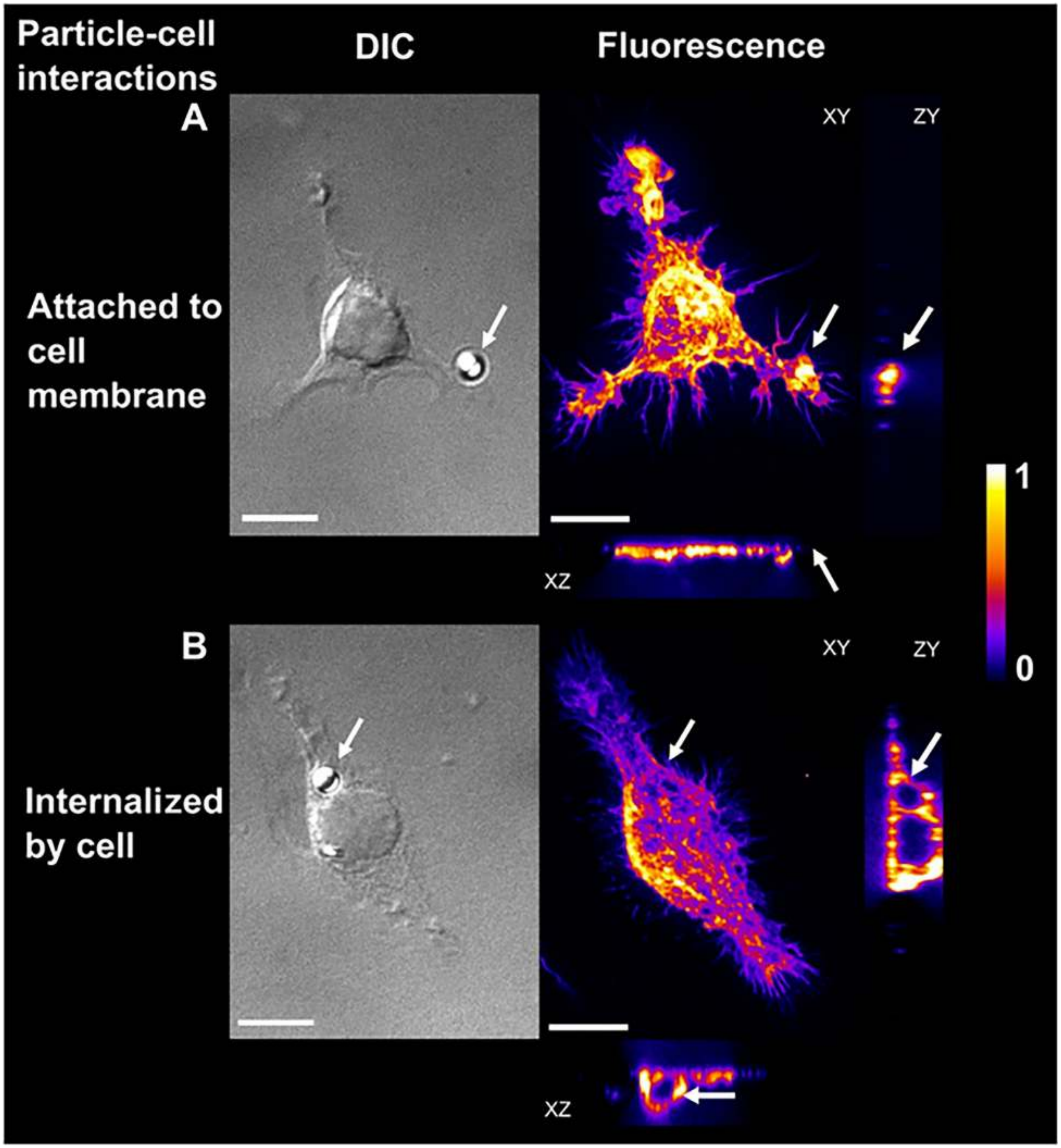

Figure 67: Images of particle-cell interactions of microplastic particles exposed to fresh water for 2 weeks. DIC: Differential interference contrast microscopy images of particle-cell interactions. Fluorescence: Spinning disc confocal images of the cells with fluorescently labeled filamentous actin (false color image, maximum intensity projection showing arbitrary units). XY, YZ, and XZ projections of three-dimensional confocal images allow the differentiation of microplastic particles (A) attached to cell membranes or (B) internalized microplastic particles. Arrows indicate microplastic particle position. Scale bars, 10 μm.

Source: Ramsperger, A. F. R. M. et al. Environmental exposure enhances the internalization of microplastic particles into cells. Sci. Adv. 6, eabd1211 (2020). https://doi.org/10.1126/sciadv.abd1211

There are many factors that may influence the toxicity of microplastics, including size, shape, surface charge, weathering/aging process, adsorption, etc.[185] Smaller particles penetrate cells more easily and cause more pronounced oxidative stress. The surface charge of microplastics is a key factor in determining how efficiently they are taken up by cells, as it affects adhesion. In addition, microplastics are composed of polymers and various chemical additives, which further increase their harmful effects.[183]

Micro- and nanoplastic particles, the chemical compounds used in plastics, and pollutants from the surrounding environment that plastics absorb — all act together in a complex[186] and harmful way, posing a significant threat to human health (Fig. 68).

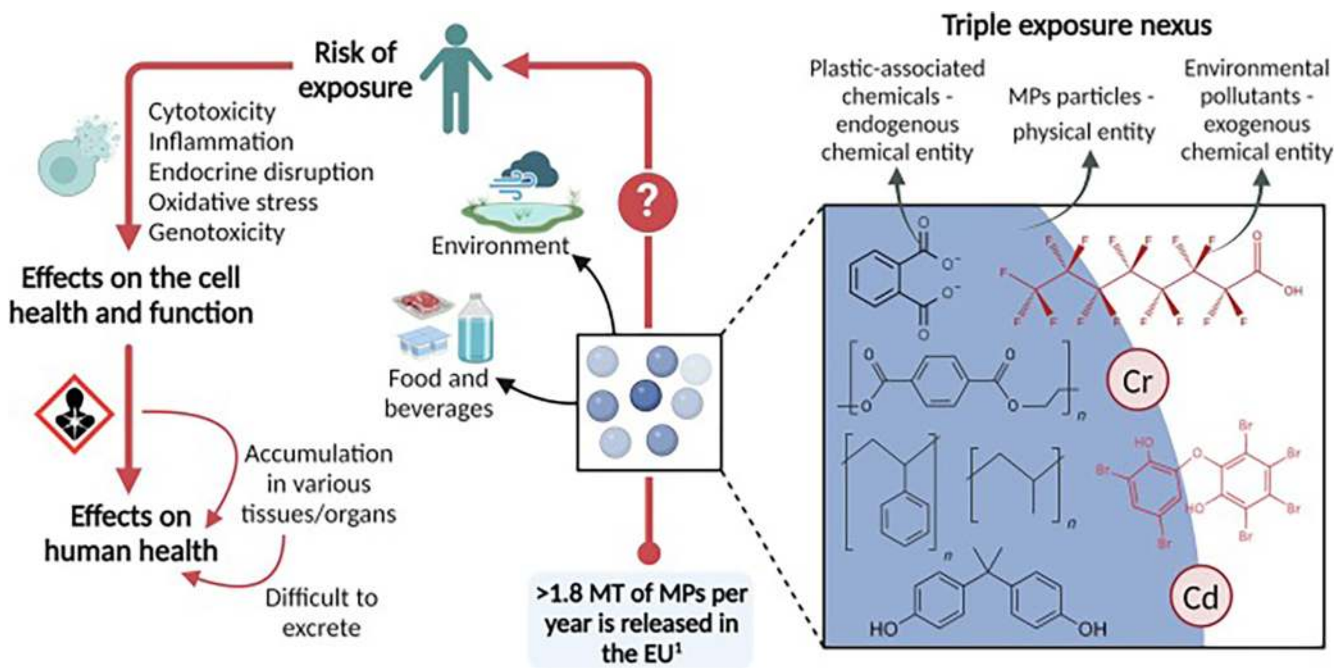

Figure 68: A triple exposure nexus between microplastic (MP) particles, plastic-associated chemicals, and environmental pollutants and its potential impacts on human health and well-being
MT = million tons
Source: Alijagic, A. et al. The triple exposure nexus of microplastic particles, plastic-associated chemicals, and environmental pollutants from a human health perspective. Environment International 188, 108736 (2024). https://doi.org/10.1016/j.envint.2024.108736

[183]Alqahtani, S., Alqahtani, S., Saquib, Q. & Mohiddin, F. Toxicological impact of microplastics and nanoplastics on humans: understanding the mechanistic aspect of the interaction. Front. Toxicol. 5, 1193386 (2023). https://doi.org/10.3389/ftox.2023.1193386
[185]Li, Y. et al. Potential Health Impact of Microplastics: A Review of Environmental Distribution, Human Exposure, and Toxic Effects. Environ. Health 1, 249–257 (2023). https://doi.org/10.1021/envhealth.3c00052
[186]Alijagic, A. et al. The triple exposure nexus of microplastic particles, plastic-associated chemicals, and environmental pollutants from a human health perspective. Environment International 188, 108736 (2024). https://doi.org/10.1016/j.envint.2024.108736

Just one gram of microplastic can contain up to 24,000 nanograms of persistent organic pollutants.[187] These substances are highly toxic, accumulate in organisms, and can cause harm even in small concentrations.

Microplastics can also make other contaminants more dangerous,[188] since both the plastic itself and the chemical mixture on its surface can not only stick to other pollutants but also interact with them — altering their chemical properties.

Studies show that exposure to micro- and nanoplastics cause serious toxicity to various biological organisms including:

- **Macromolecules:** DNA & gene damage, affected gene expression, and altered protein transcription.
- **Organelle cells:** Altered cellular division, cellular toxicity, apoptosis, oxidative stress reaction, metabolism, increased calcium ions.
- **Tissues:** Inflammation, fibrosis, and bone tissue osteolysis.
- **Organs:** Immune responses, organ dysfunction, neurotoxicity, carcinogenesis, altered feeding, changed metabolic demand, and energy reserves redistribution.
- **Animal and Human Populations:** Reduced fertility, slower growth, and reduced population.

These effects highlight the multilevel impact of micro- and nanoplastics on biological systems.[189]

1. Disruption of Cellular Function

The destruction of the human body under the influence of micro- and nanoplastics begins at the cellular level.[190] MNPs interact with cell membranes through various bonds (e.g., hydrogen, halogen) or hydrophobic, van der Waals, and electrostatic forces.

Acting as a destabilizing factor, MNPs disrupt the integrity and function of cellular membranes (Fig. 69).

[187] Shanwei Government. Content on environmental health. Microplastics found in the human body for the first time, are they harmful to health? Here's the answer. https://www.shanwei.gov.cn/swhbj/467/503/content/post_550539.html (accessed 1 May 2025).
[188] Ho, W.-K. et al. Sorption Behavior, Speciation, and Toxicity of Microplastic-Bound Chromium in Multisolute Systems. Environ. Sci. Technol. Lett. 10, 27–32 (2023). https://doi.org/10.1021/acs.estlett.2c00689
[189] Kaushik, A., Singh, A., Kumar Gupta, V. & Mishra, Y. K. Nano/micro-plastic, an invisible threat getting into the brain. Chemosphere 361, 142380 (2024). https://doi.org/10.1016/j.chemosphere.2024.142380
[190] Khan, A. & Jia, Z. Recent insights into uptake, toxicity, and molecular targets of microplastics and nanoplastics relevant to human health impacts. iScience 26, 106061 (2023). https://doi.org/10.1016/j.isci.2023.106061

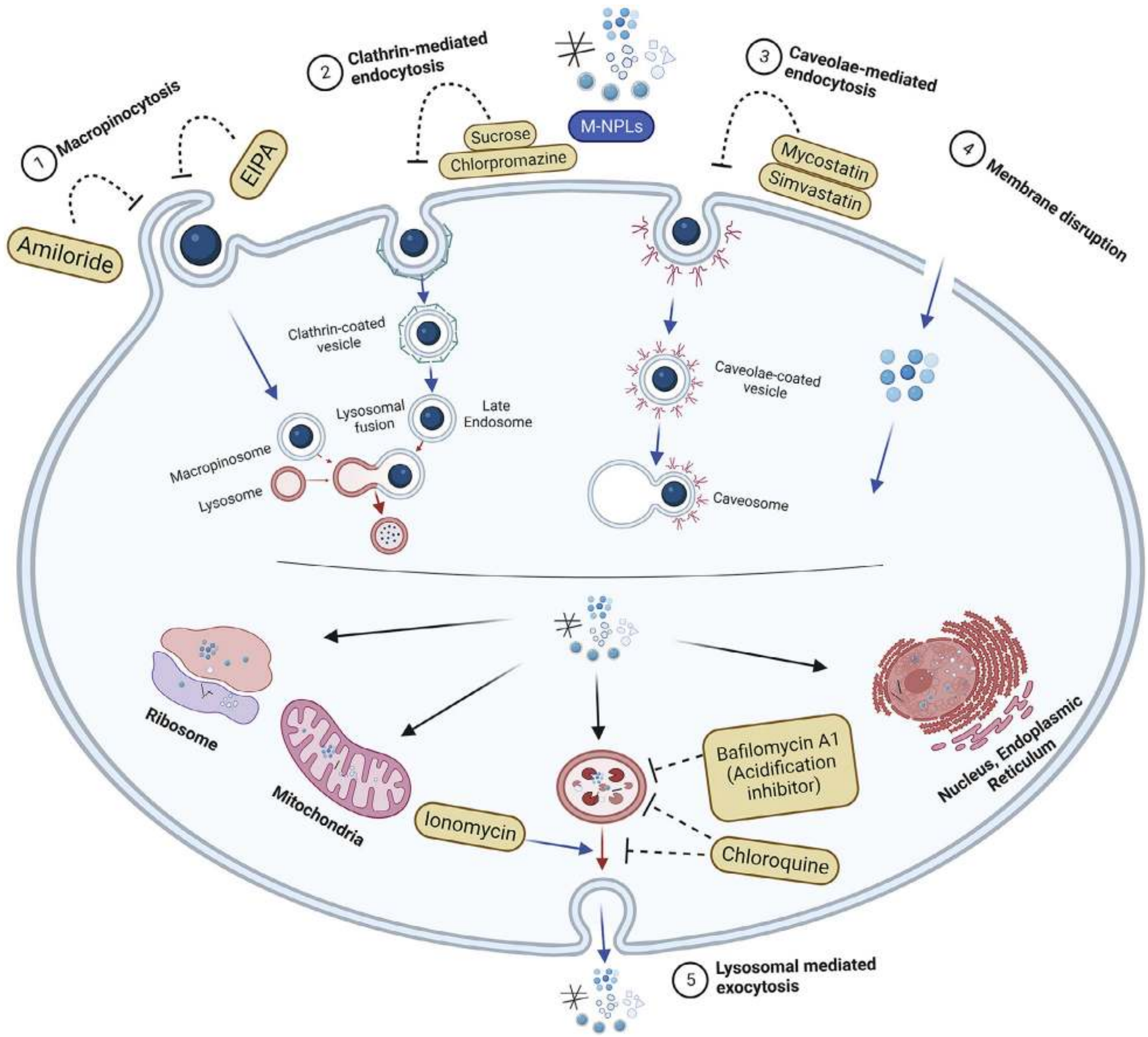

Figure 69: Cellular uptake and release of M-NPLs. M-NPLs utilize various types of endocytosis.

(1) Macropinocytosis, (2) Clathrin-mediated endocytosis, (3) Caveolae-mediated endocytosis, and disruption of cellular membrane to get internalized. M-NPLs are released from the cells by 4) lysosomal-mediated endocytosis.

Source: Khan, A. & Jia, Z. Recent insights into uptake, toxicity, and molecular targets of microplastics and nanoplastics relevant to human health impacts. iScience 26, 106061 (2023). https://doi.org/10.1016/j.isci.2023.106061

Due to their small size, MNPs can easily penetrate human cells (Fig. 70). Their tiny dimensions and accumulated electrostatic charge enable MNPs to exert a systemic impact on the human body.[191]

[191]Casella, C. & Ballaz, S. J. Genotoxic and neurotoxic potential of intracellular nanoplastics: A review. Journal of Applied Toxicology 44, 1657–1678 (2024). https://doi.org/10.1002/jat.4598

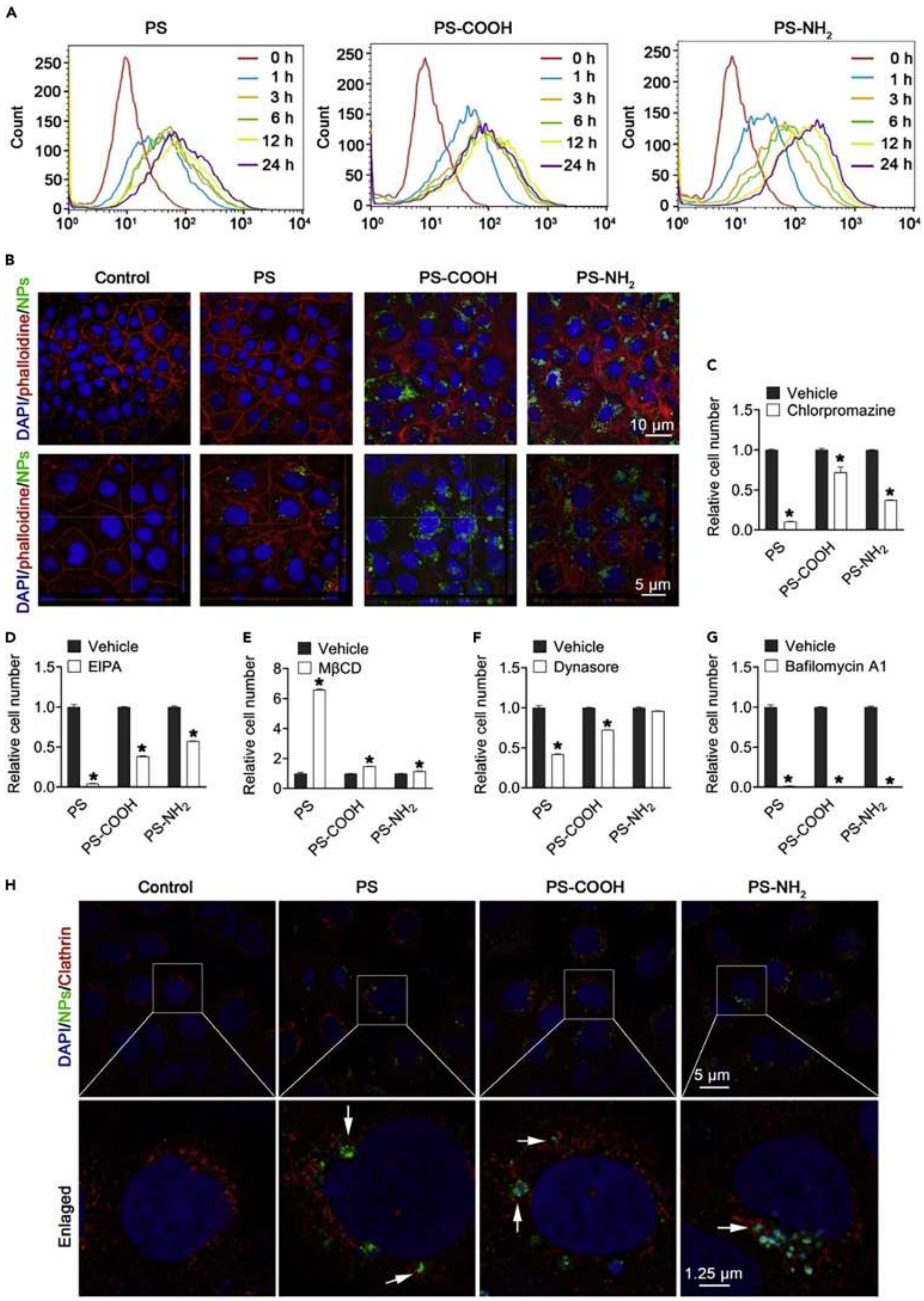

Figure 70: Caco-2 cells internalizing NPLs

(A–G) Analysis of NPLs internalization by Caco-2 cells using flow cytometry (A) and Confocal microscopy (B). Flow cytometry analysis of Caco-2 cells pre-treated for 1 h with chlorpromazine (C), EIPA (D), MβCD (E), dynasore (F), and bafilomycin A1 (G) followed by posttreatment with NPLs for 24 h. Localization of NPLs in Clathrin-mediated vesicle examined with confocal microscopy (H). Adopted with permission from Elsevier.

Source: Khan, A. & Jia, Z. Recent insights into uptake, toxicity, and molecular targets of microplastics and nanoplastics relevant to human health impacts. iScience 26, 106061 (2023).
https://doi.org/10.1016/j.isci.2023.106061

A key aspect of their destructive action at the cellular level is the damage to cell membranes, mitochondria, and the destruction of DNA.

Electrostatically charged micro- and nanoplastic particles can destabilize the membrane potential of cells — especially neurons — leading to spontaneous electrical signals, failures in intercellular communication, or cell death.

Inside the cell, the main target of nanoplastics' destructive effect is the mitochondria — the essential organelles responsible for the cell's survival and recovery (Fig. 71). Beyond acting as the cell's "powerhouses," mitochondria perform multifunctional roles, influencing overall health, resistance to stress, the development of chronic diseases, and the aging process.

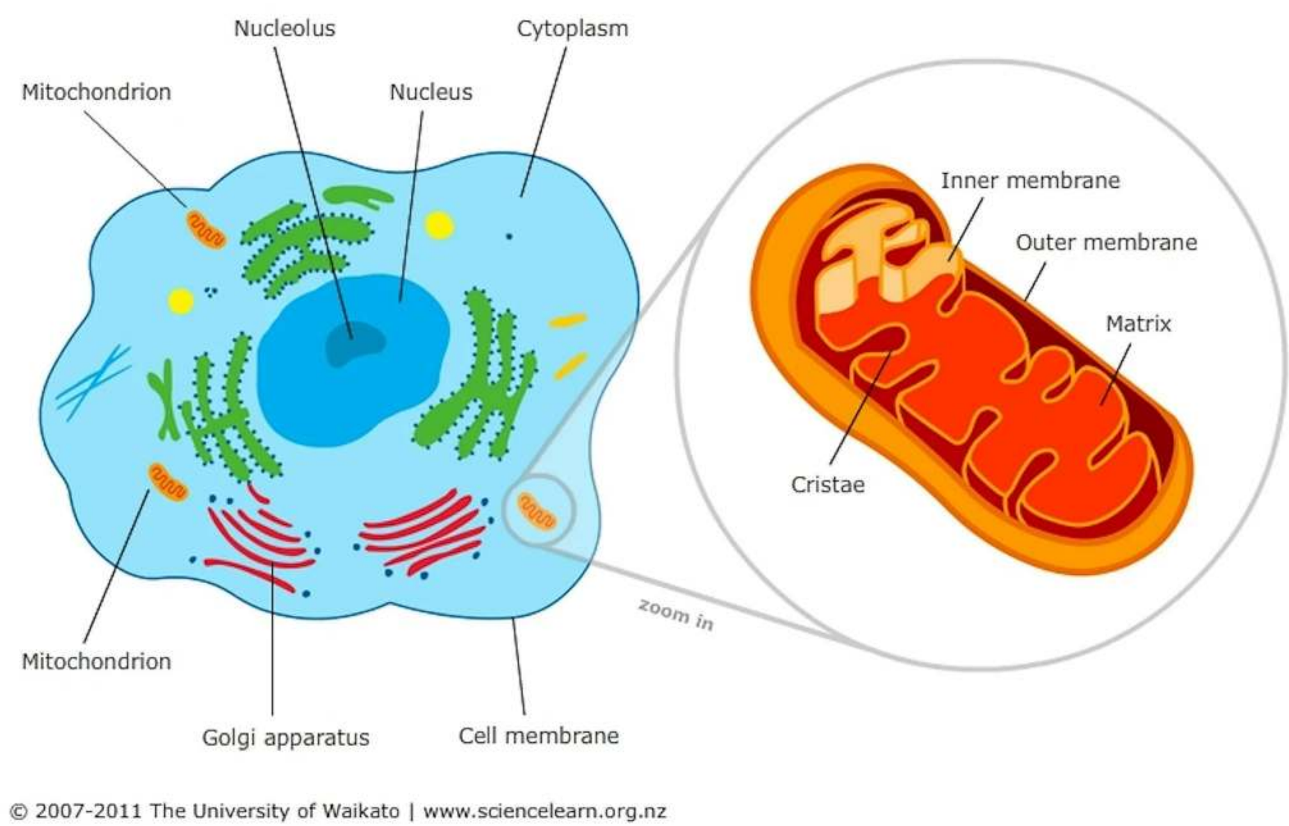

Figure 71: Schematic illustration of a cell and its mitochondria

Proper mitochondrial function is vital for cell survival, homeostasis, and energy production. The structure and functionality of mitochondria are maintained by the mitochondrial quality control system, which includes mitochondrial biogenesis, dynamics (fusion and fission), mitophagy, and the mitochondrial unfolded protein response (UPR^{mt}). Mitochondrial dysfunction or damage has been linked to the onset and progression of numerous human diseases, including neurodegenerative disorders, cardiovascular conditions, age-related illnesses, diabetes, and cancer. Environmental stress and pollutants can heighten mitochondrial vulnerability, triggering dysfunction.

Growing evidence points to the impact of micro- and nanoplastics (MNPs) on mitochondrial health. MNPs have been shown to induce oxidative stress and increase the production of reactive oxygen species, ultimately disrupting the mitochondrial membrane potential. These particles can cross biological barriers in the human body and be absorbed by cells, potentially altering mitochondrial dynamics, bioenergetics, and signaling pathways — thereby affecting cellular metabolism and function.

Given the mitochondria's critical role in both cellular and overall health, MNPs represent a serious threat to mitochondrial integrity. Current findings emphasize the urgent need to address the widespread issue of MNP pollution — not only to protect the environment but also to safeguard human health.[192]

Mitochondria synthesize ATP — the universal energy molecule that powers all biological processes, from muscle contraction and nerve impulse transmission to hormone production and cell division. They are involved in the metabolism of carbohydrates, fats, and amino acids, helping to maintain the body's metabolic balance.

Mitochondria also regulate cell death, or apoptosis — a critically important process that prevents the accumulation of damaged or potentially dangerous cells. Disruptions in this system are linked to the development of cancer, autoimmune disorders, and neurodegenerative diseases.

Additionally, mitochondria play a key role in antioxidant defense by regulating levels of reactive oxygen species (ROS). When this system fails, cellular damage accumulates, aging accelerates, and the risk of chronic inflammation and disease increases (Fig. 72).

[192]Yöntem, F. D. & Ahbab, M. A. Mitochondria as a target of micro- and nanoplastic toxicity. Cambridge Prisms: Plastics 2, e6 (2024). https://doi.org/10.1017/plc.2024.6

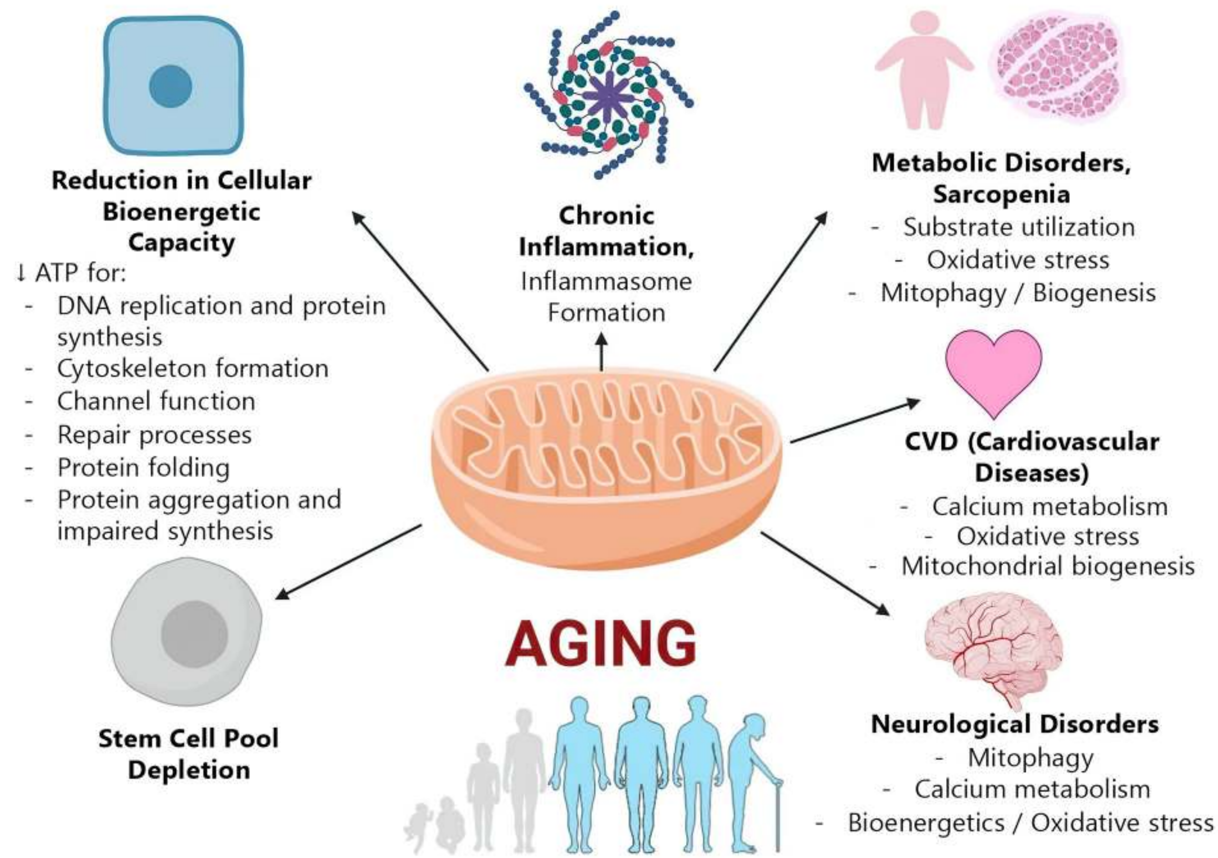

Figure 72: Mitochondrial dysfunction caused by environmental pollution may lead to various diseases

Source: Borisova, O. Mitochondria medicine. Open Longevity. (2019) https://openlongevity.org/mitochondria_medicine_1 (accessed 1 May 2025).

Mitochondria contain their own DNA, which is inherited maternally, making them unique contributors to genetic diseases. They regulate the activity of nuclear genes and help cells adapt to changes in their external environment. Mitochondria also plays a role in the synthesis of steroid hormones — including cortisol, estrogens, and testosterone.

Disruption of mitochondrial function due to exposure to nanoplastics lies at the core of a cascade of pathological processes. These can lead to serious and potentially irreversible consequences — not only in individual organs and systems, but in the body as a whole (Table 1).

Neurological diseases	Parkinson's disease, Alzheimer's disease, Amyotrophic lateral sclerosis (ALS), Epilepsy, Migraines, Mitochondrial encephalomyopathies (such as MELAS syndrome)
Cardiovascular diseases	Cardiomyopathies, Heart failure, Atherosclerosis (through oxidative stress)
Immune and inflammatory diseases	Autoimmune diseases (e.g., systemic lupus erythematosus), Chronic inflammatory conditions (through dysfunction of ROS and cytokine signaling)
Metabolic disorders	Type 2 diabetes, Obesity, Metabolic syndrome, Fatty acid and lactate metabolism disorders
Oncological diseases	Mitochondrial dysfunction leads to an increased risk of mutations and malignant cell transformation
Muscle disorders	Mitochondrial myopathies, Chronic muscle weakness and fatigue
Sense organ diseases	Retinitis pigmentosa, Leber hereditary optic neuropathy (inherited disease that causes vision loss)
Genetic mitochondrial disorders	Leigh syndrome, Kearns–Sayre syndrome, Barth syndrome

Table 1. Overview of Selected Diseases Associated with Mitochondrial Dysfunction

Role of MNPs in Premature Aging and Cancer Development

Exposure to nanoplastics can trigger premature aging by interfering with mitochondrial function and disrupting the body's genetic programs. Mitochondrial damage leads to excessive production of reactive oxygen species (ROS), causing oxidative stress. This, in turn, damages DNA, undermines genetic stability, triggers inflammation, and accelerates tissue aging. Additionally, nanoplastics contribute to the shortening of telomeres, limiting the cell's ability to divide.

> *"We also were able to show in humans how a single nucleotide change in mitochondrial DNA that's specifically associated with poor function of mitochondria and causing pediatric mitochondrial disorders can accelerate aging,"* said Taosheng Huang, MD, PhD, Professor and Chief of Genetics in the Department of Pediatrics at the Jacobs School of Medicine and Biomedical Sciences at UB. *"We found that reactive oxygen species due to poor function of mitochondria leads to increased DNA damage over time."*[193]

Epigenetic aging refers to changes in gene regulation that occur through modifications at the DNA level (switching genes on or off), without altering the DNA itself. It's a subtle "molecular clock" that can be measured, and it may run faster or slower than chronological aging. High mitochondrial DNA activity is linked to accelerated epigenetic aging. In some individuals, even in their 20s and 30s, the biological age of cells can significantly surpass their chronological age, meaning their bodies age faster than expected.

People with mitochondrial dysfunction often develop age-related diseases at an early age, including dementia, cardiovascular diseases, arrhythmias, and heart failure.

Scottish researchers have found that the later a person was born, the greater their risk of illness by age 50. For example, those born between 1956 and 60 have higher disease scores than the 1951–55 or 1946–50 cohorts at the same age (Fig. 73).[194]

[193]Medindia. Study unravels how mitochondrial dysfunction leads to premature aging. (2022) https://www.medindia.net/news/study-unravels-how-mitochondrial-dysfunction-leads-to-premature-aging-208364-1.htm (accessed 1 May 2025).
[194]Ribe, E., Cezard, G. I., Marshall, A. & Keenan, K. Younger but sicker? Cohort trends in disease accumulation among middle-aged and older adults in Scotland using health-linked data from the Scottish Longitudinal Study. European Journal of Public Health 34, 696–703 (2024). https://doi.org/10.1093/eurpub/ckae062

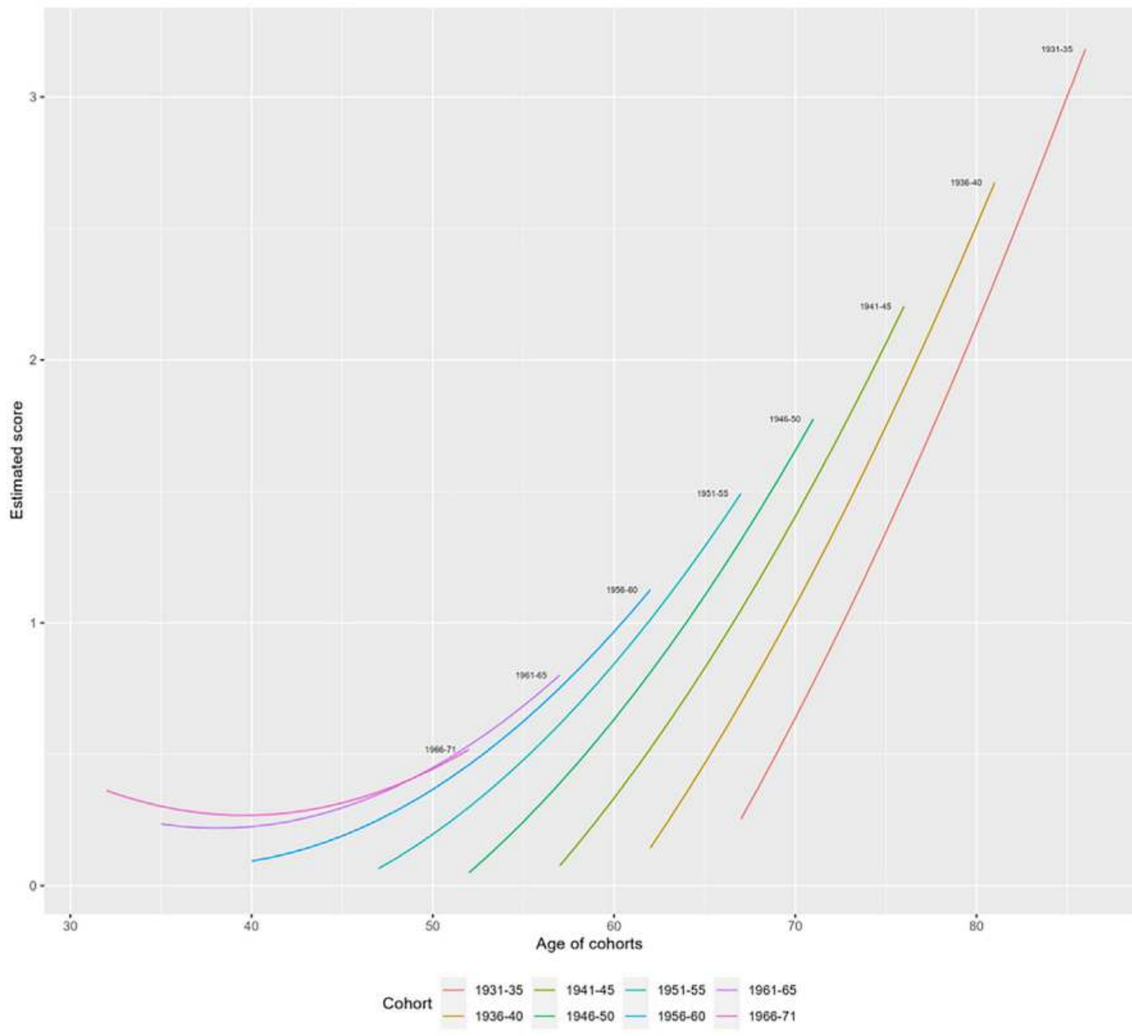

Figure 73: Predicted multimorbidity scores by cohort and age

Source: Scottish Longitudinal Study. Source: Scottish Longitudinal Study.
Ribe, E., Cezard, G. I., Marshall, A. & Keenan, K. Younger but sicker? Cohort trends in disease accumulation among middle-aged and older adults in Scotland using health-linked data from the Scottish Longitudinal Study. European Journal of Public Health 34, 696–703 (2024). https://doi.org/10.1093/eurpub/ckae062

Mitochondrial DNA Mutations in Aging and Cancer

The key mechanisms underlying aging and cancer development share many common features. A central factor in both processes is mitochondrial dysfunction — disruption of the cell organelles responsible for energy production. With age, mutations in mitochondrial DNA (mtDNA) accumulate in human tissues, and similar mutations have long been observed in various forms of cancer.[195]

When a mutation occurs in a cell, it can alter the cell's behavior. For example, the mutated cell may begin to grow and divide more rapidly, resist cell death even when it should occur, become "invisible" to the immune system, or tolerate a lack of oxygen or nutrients more effectively.

Such mutated cells gain a competitive advantage over normal cells as they live longer, divide more frequently, occupy increasing space, and eventually dominate surrounding tissues. Once these abnormal cells accumulate in sufficient numbers, tumor growth may begin.

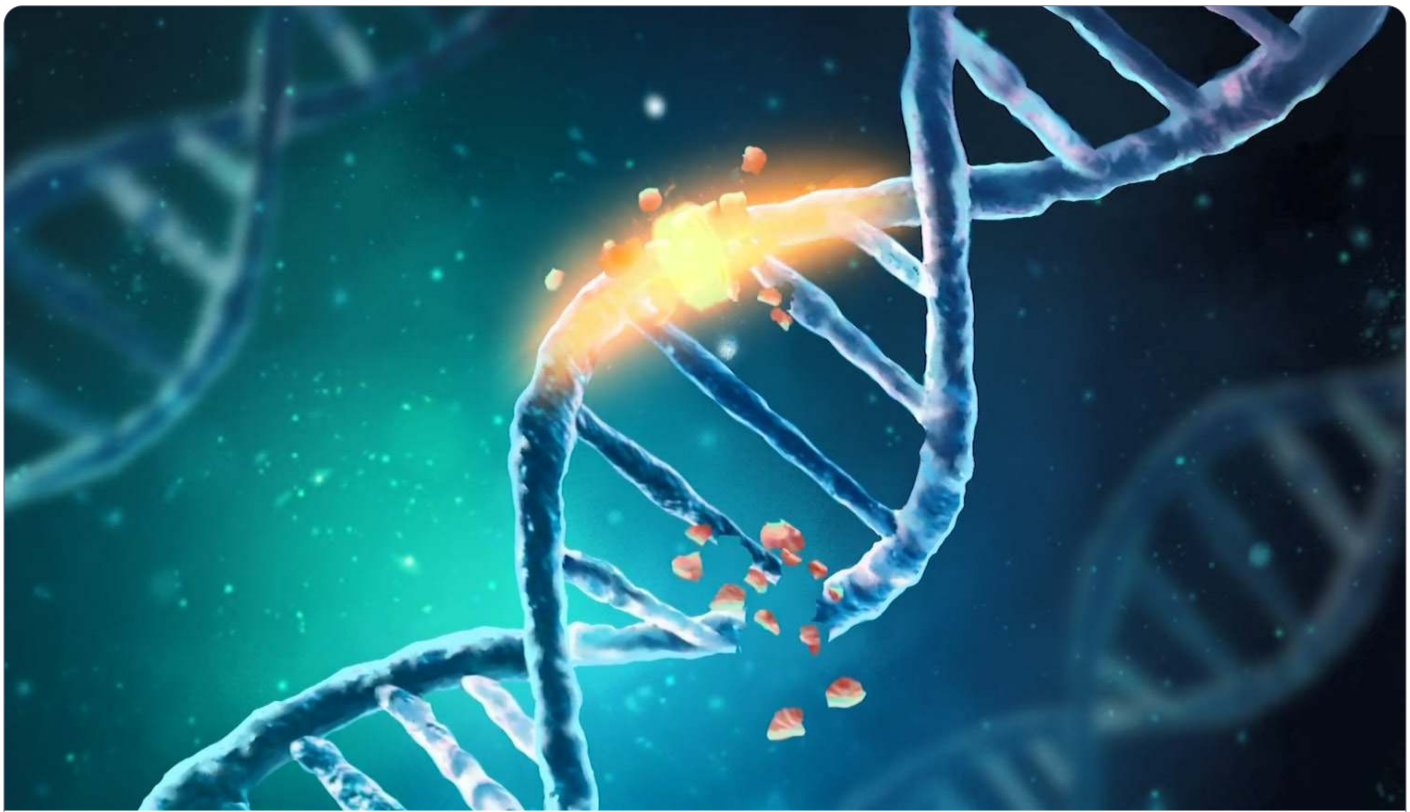

Figure 74: DNA damage leading to mutations

[195]Smith, A. L. M., Whitehall, J. C. & Greaves, L. C. Mitochondrial DNA mutations in ageing and cancer. Molecular Oncology 16, 3276–3294 (2022). https://doi.org/10.1002/1878-0261.13291

Post-mitotic cells—such as neurons, cardiomyocytes, and certain muscle cells—are particularly vulnerable to mitochondrial damage. Because these cells do not divide, mutations accumulated over time, especially those in mitochondrial DNA (Fig. 74), remain within the cell for its entire lifespan. Post-mitotic cells are extremely metabolically active: neurons require substantial energy to transmit signals, and heart cells continually pump blood. Consequently, their mitochondria function at maximum capacity, producing large quantities of reactive oxygen species (ROS). These reactive oxygen species damage mitochondria, triggering a cycle of increased ROS production and further damage. Over time, this cumulative damage can initiate pathological processes such as neurodegenerative disorders, cardiovascular diseases, cancer, and even lead to death.

This mechanism might explain why cardiovascular diseases, heart attacks, strokes, and cancers are the leading causes of death globally. Furthermore, the toxic impact of nanoplastics — which has dramatically intensified over the past 10 to 20 years — likely explains why these diseases are occurring at younger ages and have reached pandemic proportions, claiming tens of millions of lives annually. Nanoplastics primarily disrupt mitochondrial function, promote oxidative stress, and induce mutations in mitochondrial and nuclear DNA.

Hormonal System Disruption Triggered by MNPs

Plastic manufacturing involves chemicals that interfere with endocrine system function and disrupt hormonal balance. These chemicals can mimic, block, or alter the action of natural hormones, potentially leading to various health issues.

Over 3,000 chemical substances used in packaging have been detected in the human body.[196] Approximately 100 of those chemicals are classified as of high concern for human health.

Bisphenol A

Bisphenol A (BPA, $C_{15}H_{16}O_{2}$) is a synthetic plasticizer that is widely used in polycarbonate plastics (such as bottles and containers), epoxy resins (used for coating canned foods), and medical devices.

When heated, BPA migrates into food and beverages.

[196] Geueke, B. et al. Evidence for widespread human exposure to food contact chemicals. J Expo Sci Environ Epidemiol 1–12 (2024). https://doi.org/10.1038/s41370-024-00718-2

"BPA is acting as a 'rogue' hormone to out-compete the natural hormone that is usually involved in this pathway," said Professor Ian Rae, an expert on environmental chemicals from the School of Chemistry at the University of Melbourne (Fig. 75).[197]

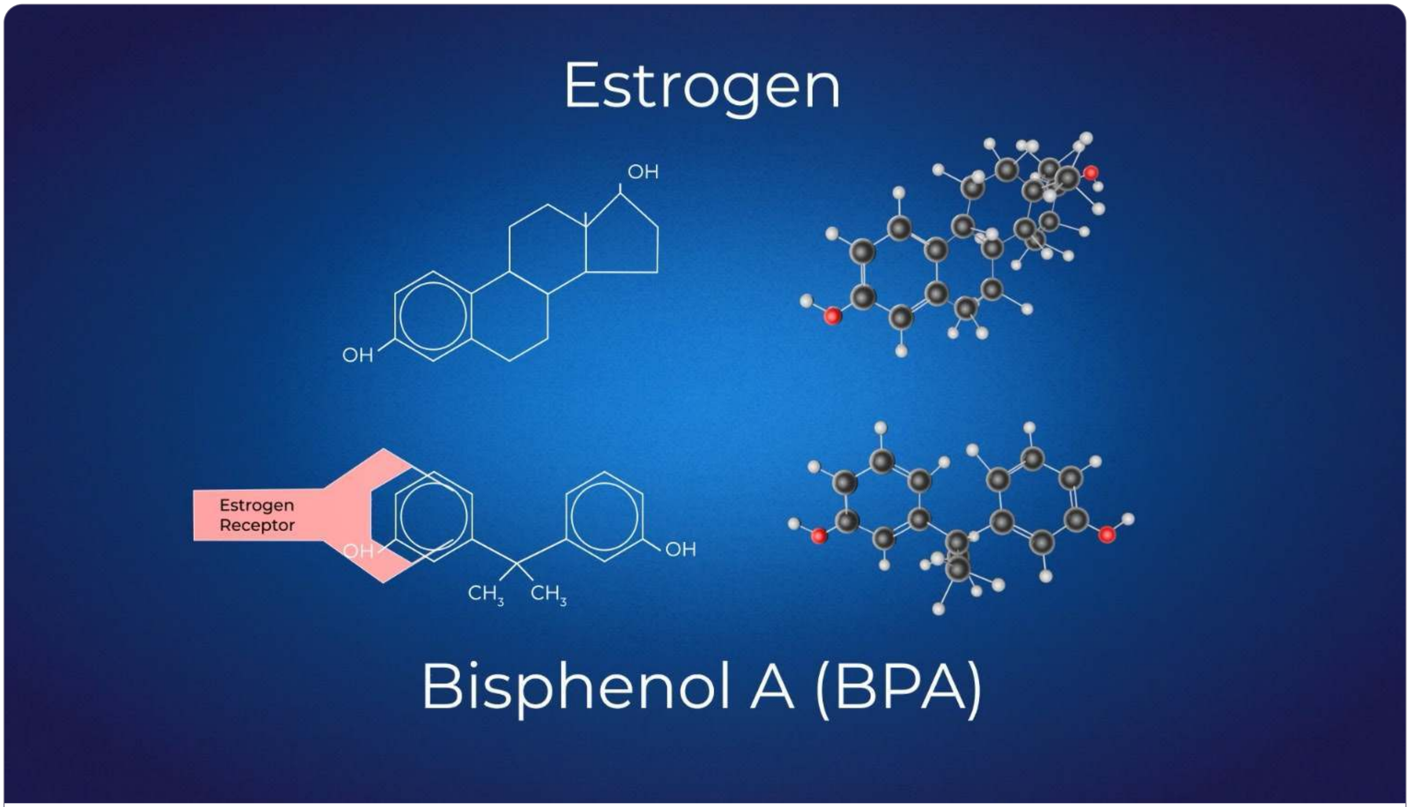

Figure 75: Bisphenol A (BPA, $C_{15}H_{16}O_2$) exerts endocrine-disrupting effects due to its structural similarity to the hormone estrogen

More than 8 million tons of bisphenol A are produced worldwide and approximately 100 tons are released into the atmosphere each year.[198]

Research shows that BPA and its substitute — bisphenol S (BPS) — disrupt the coordination of excitatory and inhibitory signals in the nervous system.[199] Both compounds induce similar pathological effects at high concentrations (Fig. 76). Experiments with brain cells have revealed that even small amounts of BPA or BPS, when exposed over a month, alter the chemical and electrical transmission of signals through the synapses.[200]

[197]New Atlas. Autism in boys linked to common plastic exposure in the womb. (2024) https://newatlas.com/health-wellbeing/prenatal-bisphenol-a-bpa-autism-boys (accessed 1 May 2025).
[198]Global Industry Analysts. Bisphenol A: Global strategic business report. Research and Markets. (2025) https://www.researchandmarkets.com/reports/1227819/bisphenol_a_global_strategic_business_report (accessed 1 May 2025)
[199]Schirmer, E., Schuster, S. & Machnik, P. Bisphenols exert detrimental effects on neuronal signaling in mature vertebrate brains. Commun Biol 4, 465 (2021). https://doi.org/10.1038/s42003-021-01966-w
[200]News-Medical. Plasticizers can impair important brain functions in humans. (2021) https://www.news-medical.net/news/20210412/Plasticizers-can-impair-important-brain-functions-in-humans.aspx (accessed 1 May 2025)

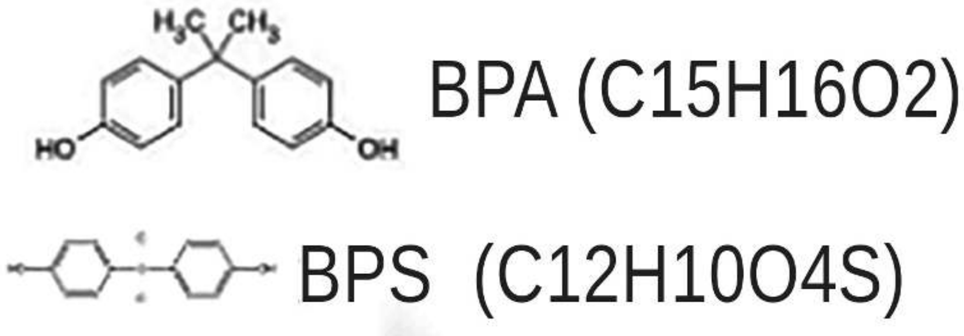

Figure 76: Molecular structures and chemical formulas of bisphenol A (BPA) and bisphenol S (BPS).

In 2023, a study found a larger amount of bisphenol A (BPA) and phthalates in children with attention deficit hyperactivity disorder (ADHD) compared to children without this condition.[201]

Researchers from the Florey Institute of Neuroscience and Mental Health in Melbourne found that boys were 6 times more likely to have a verified autism diagnosis by age 11 years than those whose mothers had lower levels of BPA during pregnancy.[202]

> *"BPA can disrupt hormone controlled male fetal brain development in several ways, including silencing a key enzyme, aromatase, that controls neurohormones and is especially important in fetal male brain development,"* said Professor Ponsonby.
>
> ***"This appears to be part of the autism puzzle."***[197]

The suppression of the enzyme aromatase may explain the gender disparity in autism diagnoses: 4 to 5 boys for every one girl.[203] While autism is less common in girls, they tend to experience more severe forms of the condition.[204]

Bisphenol A (BPA) also contributes to the development of type 2 diabetes by causing hyperglycemia and insulin resistance.[205] Global mortality from diabetes continues to rise steadily (Fig. 77).

[201] EarthDay.org. Babies vs. Plastics Report. (2023) https://www.earthday.org/babies-vs-plastics-what-every-parent-should-know (accessed 1 May 2025).
[202] Symeonides, C., Vacy, K., Thomson, S. et al. Male autism spectrum disorder is linked to brain aromatase disruption by prenatal BPA in multimodal investigations and 10HDA ameliorates the related mouse phenotype. Nat Commun 15, 6367 (2024). https://doi.org/10.1038/s41467-024-48897-8
[203] Zeidan, J. et al. Global prevalence of autism: A systematic review update. Autism Research 15, 778–790 (2022). https://doi.org/10.1002/aur.2696
[204] Frazier, T. W., Georgiades, S., Bishop, S. L. & Hardan, A. Y. Behavioral and Cognitive Characteristics of Females and Males With Autism in the Simons Simplex Collection. Journal of the American Academy of Child & Adolescent Psychiatry 53, 329-340.e3 (2014). https://doi.org/10.1016/j.jaac.2013.12.004
[205] Sun, Q. et al. Association of Urinary Concentrations of Bisphenol A and Phthalate Metabolites with Risk of Type 2 Diabetes: A Prospective Investigation in the Nurses' Health Study (NHS) and NHSII Cohorts. Environ Health Perspect 122, 616–623 (2014). https://doi.org/10.1289/ehp.1307201

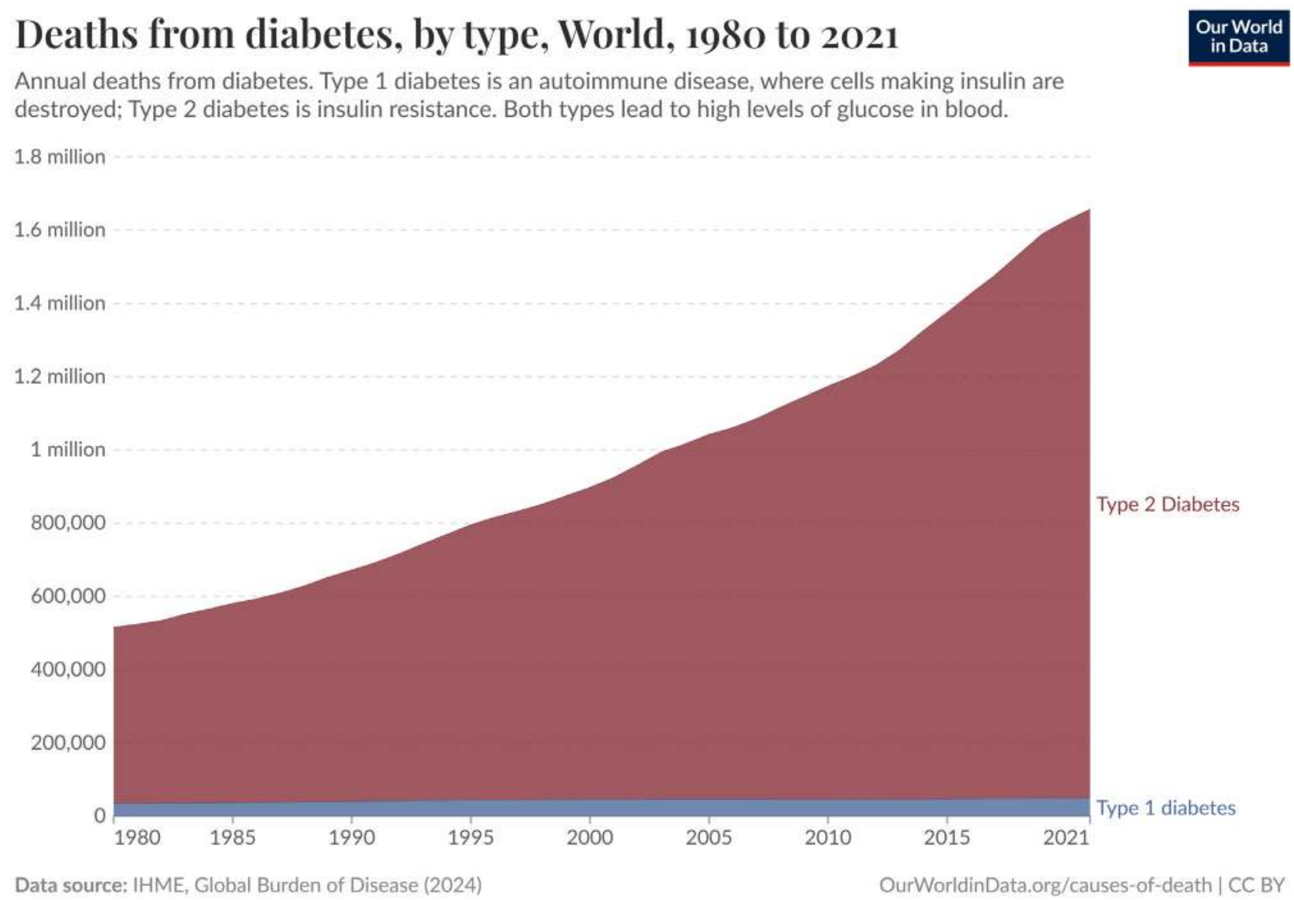

Figure 77: Deaths from diabetes, by type, World, 1980 to 2021
Source: https://ourworldindata.org/grapher/deaths-from-diabetes-by-type.

Phthalates

Phthalates are a group of chemical compounds primarily used as plasticizers, which are substances that make plastics, such as polyvinyl chloride (PVC), more flexible, softer, and more durable.

Phthalates are widely used in industry and everyday life, but their ability to interfere with the endocrine system raises concerns.[206] Molecular formula (Fig. 78).

Phthalates are not hormones, but they can suppress the action of androgens (such as testosterone), which is particularly critical for male development. Their exposure is associated with reduced sperm motility and abnormalities in the development of reproductive organs (such as cryptorchidism in newborns). Higher concentrations of phthalates have been found in men diagnosed with infertility.

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[206]Arrigo, F., Impellitteri, F., Piccione, G. & Faggio, C. Phthalates and their effects on human health: Focus on erythrocytes and the reproductive system. Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology 270, 109645 (2023). https://doi.org/10.1016/j.cbpc.2023.109645

Figure 78: Chemical Structure Depiction National Center for Biotechnology Information. Bisphenol A, 2D Structure. Source: PubChem. https://pubchem.ncbi.nlm.nih.gov/compound/1017#section=2D-Structure (accessed 1 May 2025).

Phthalates are not hormones themselves, but they can suppress the action of androgens (such as testosterone), which is especially critical for male development. Exposure to phthalates has been linked to reduced sperm motility and abnormalities in the development of reproductive organs (e.g., cryptorchidism in newborns). Higher concentrations of phthalates have been found in men diagnosed with infertility.

In women, phthalates can disrupt the menstrual cycle and increase the risk of miscarriages and preterm births. Fetal exposure to phthalates during pregnancy may lead to delayed brain development, lower IQ, and behavioral problems in the offspring.[207]

Scientists have demonstrated a causal link between environmental phthalates (toxic chemicals found in everyday consumer products) and the increased growth of uterine fibroids, the most common tumors in women.[208]

Exposure to phthalates found in plastics increases the risk of childhood cancers by 20%, with a threefold rise in cases of malignant bone tumors and a twofold increase in the incidence of lymphoma and leukemia.[209]

A study involving over 5,000 American mothers found that phthalates are associated with the risk of delivering low-birth-weight babies and preterm infants.[210]

[207]Welch, B. M. et al. Associations Between Prenatal Urinary Biomarkers of Phthalate Exposure and Preterm Birth: A Pooled Study of 16 US Cohorts. JAMA Pediatrics 176, 895–905 (2022). https://doi.org/10.1001/jamapediatrics.2022.2252
[208]Iizuka, T. et al. Mono-(2-ethyl-5-hydroxyhexyl) phthalate promotes uterine leiomyoma cell survival through tryptophan-kynurenine-AHR pathway activation. Proceedings of the National Academy of Sciences 119, e2208886119 (2022). https://doi.org/10.1073/pnas.2208886119
[209]Ahern, T. P. et al. Medication–Associated Phthalate Exposure and Childhood Cancer Incidence. JNCI: Journal of the National Cancer Institute 114, 885–894 (2022). https://doi.org/10.1093/jnci/djac045
[210]Trasande, L. et al. Prenatal phthalate exposure and adverse birth outcomes in the USA: a prospective analysis of births and estimates of attributable burden and costs. The Lancet Planetary Health 8, e74–e85 (2024). https://doi.org/10.1016/S2542-5196(23)00270-X

The authors note that these factors moderately increase the likelihood of infant mortality and may also impact children's academic performance, as well as raise the risk of heart disease, diabetes, and mental disorders, such as autism and ADHD[211] in children.

Chemical additives in plastics contribute to the development of obesity.[212] According to data from the World Health Organization (WHO), from 1990 to 2020, the global obesity rate among adults more than doubled, while among adolescents, it increased fourfold.[213] Obesity trends among adults and youth in the United States (Fig. 79-80)

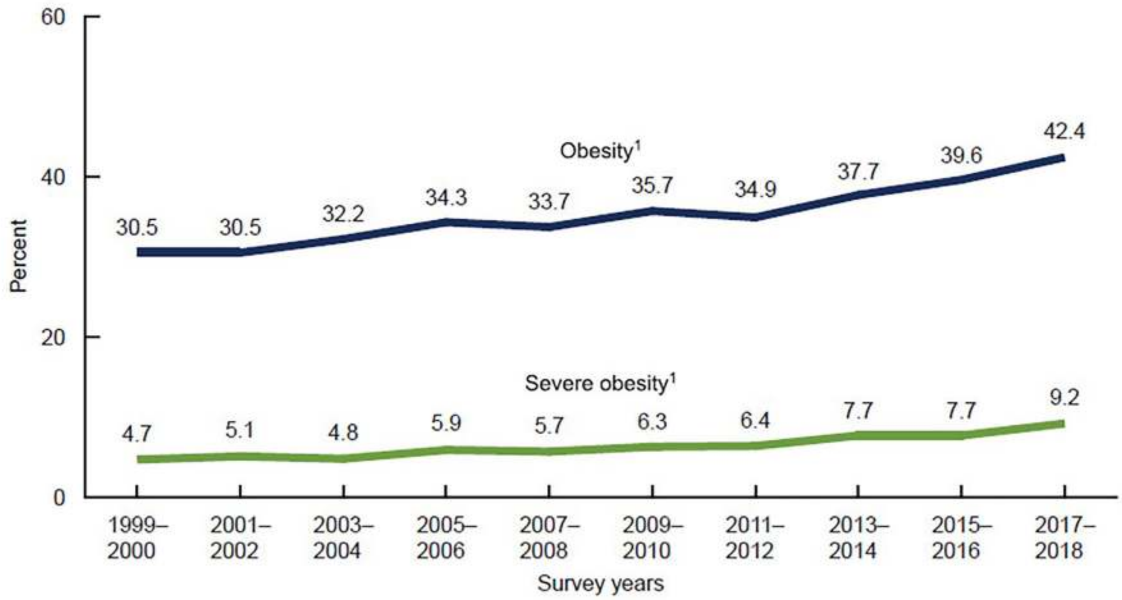

Figure 79: Trends in age-adjusted obesity and severe obesity prevalence among adults ages 20 and over: United States, 1999–2000 through 2017–2018
Source: National Institute of Diabetes and Digestive and Kidney Diseases. Overweight & obesity statistics. NIDDK. (2021) https://www.niddk.nih.gov/health-information/health-statistics/overweight-obesity (accessed 1 May 2025).

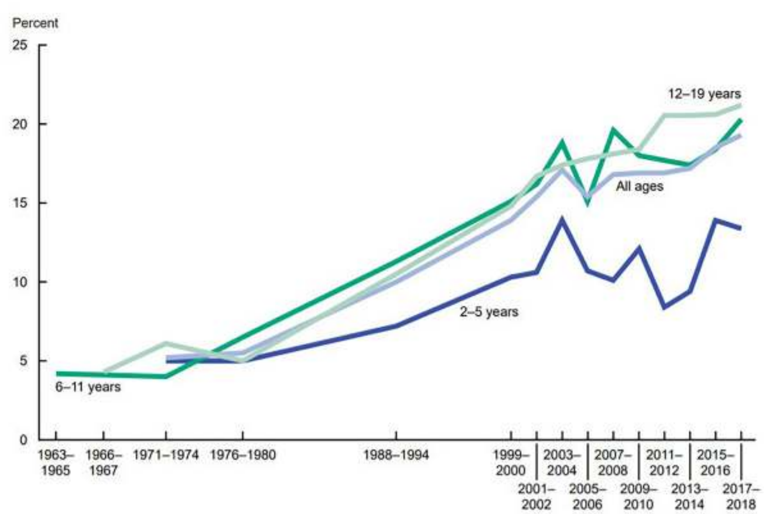

Figure 80: Trends in obesity among children and adolescents ages 2–19 years, by age: United States, 1963–1965 through 2017–2018

Source: National Institute of Diabetes and Digestive and Kidney Diseases. Overweight & obesity statistics. NIDDK. (2021) https://www.niddk.nih.gov/health-information/health-statistics/overweight-obesity (accessed 1 May 2025).

[211]Baker, B. H. et al. Ultra-processed and fast food consumption, exposure to phthalates during pregnancy, and socioeconomic disparities in phthalate exposures. Environment International 183, 108427 (2024). https://doi.org/10.1016/j.envint.2024.108427

[212]Völker, J., Ashcroft, F., Vedøy, Å., Zimmermann, L. & Wagner, M. Adipogenic Activity of Chemicals Used in Plastic Consumer Products. Environ. Sci. Technol. 56, 2487–2496 (2022). https://doi.org/10.1021/acs.est.1c06316

[213]World Health Organization. Obesity and overweight. WHO Fact Sheets. (2025) https://www.who.int/news-room/fact-sheets/detail/obesity-and-overweight (accessed 10 May 2025).

Electrostatic Charge of Nanoplastics as a Key Driver of Their High Toxicity for the Human Body

The human body continuously generates bioelectric energy. All physiological processes, from heart activity and sensory perception to higher cognitive functions, are driven by chemical reactions initiated by the movement of electrical charges. Intracellular and extracellular fluids, which contain proteins, are primarily composed of water with electropolar properties. Consequently, electrostatic interactions, including hydrogen bonds, ionic bonds, and hydrophobic packing, play a crucial role in the formation of protein structures necessary for their function and, as a result, for the maintenance of the organism's vitality.[214]

Bioelectricity directly influences cell function through the interaction of ion channels and membrane potentials. Each cell maintains a difference in electrical potential between its internal and external environments — known as the resting membrane potential — achieved through the difference in ion concentration inside and outside the cell (Fig. 81). The main types of ion channels present in the human body include sodium, potassium, calcium, and chloride channels. These channels, along with the membrane potential, facilitate key functions of various cell types (Figs. 82–83).

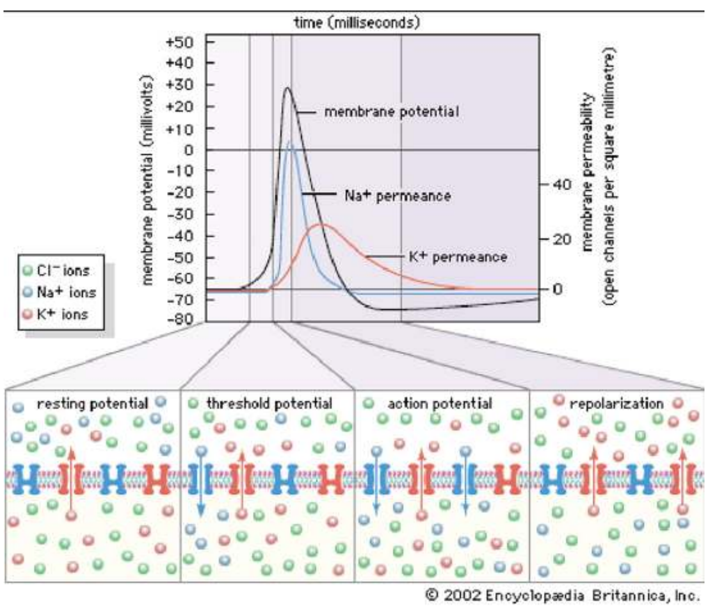

Figure 81: Ion permeability and the action potential. Changes in ion permeance underlying the action potential. Electrical potential is graded at left in millivolts, ion permeance at right in open channels per square millimetre. At the resting potential, the membrane potential is close to E_K, the equilibrium potential of K^+. When sodium channels open, the membrane depolarizes. When depolarization reaches the threshold potential, it triggers an action potential. Generation of the action potential brings the membrane potential close to E_{Na}, the equilibrium potential of Na^+. When sodium channels close (lowering Na^+ permeance) and potassium channels open (raising K^+ permeance), the membrane repolarizes.

Source: Encyclopædia Britannica. Neuron. Britannica. (2025). https://www.britannica.com/science/neuron (accessed May 1, 2025).

[214]Azim Premji University. The Biology of Electricity: How electricity is critical to the functioning of the human body. (2022) https://azimpremjiuniversity.edu.in/news/2022/the-biology-of-electricity (accessed 1 May 2025).

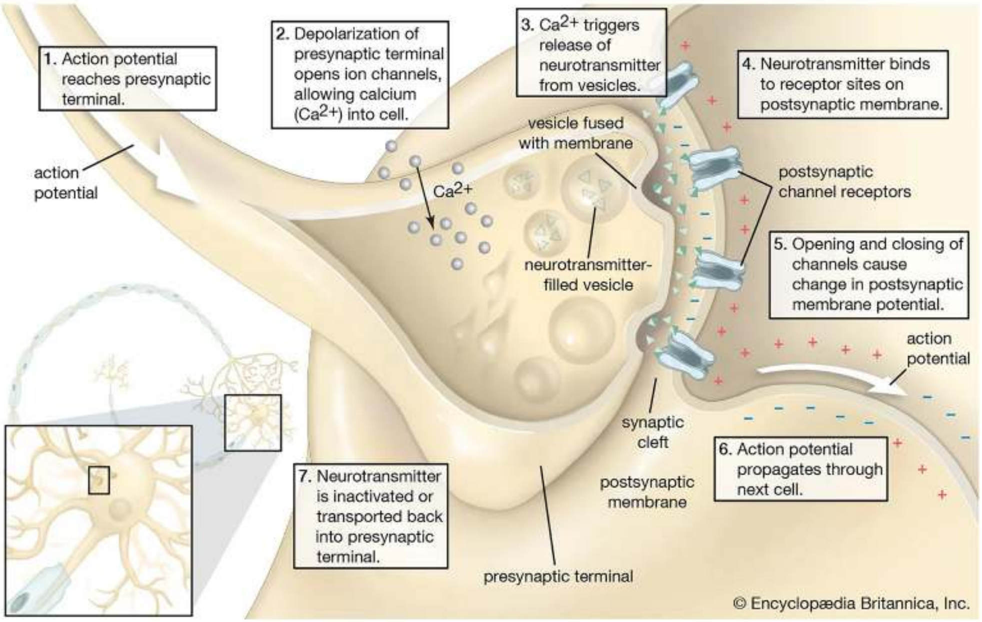

Figure 82: Synapse: Chemical transmission of a nerve impulse at the synapse
The arrival of the nerve impulse at the presynaptic terminal stimulates the release of neurotransmitters into the synaptic gap. The binding of neurotransmitters to receptors on the postsynaptic membrane stimulates the regeneration of the action potential in the postsynaptic neuron.
Source: Encyclopædia Britannica. Neuron. Britannica. (2025).
https://www.britannica.com/science/neuron (accessed 1 May 2025).

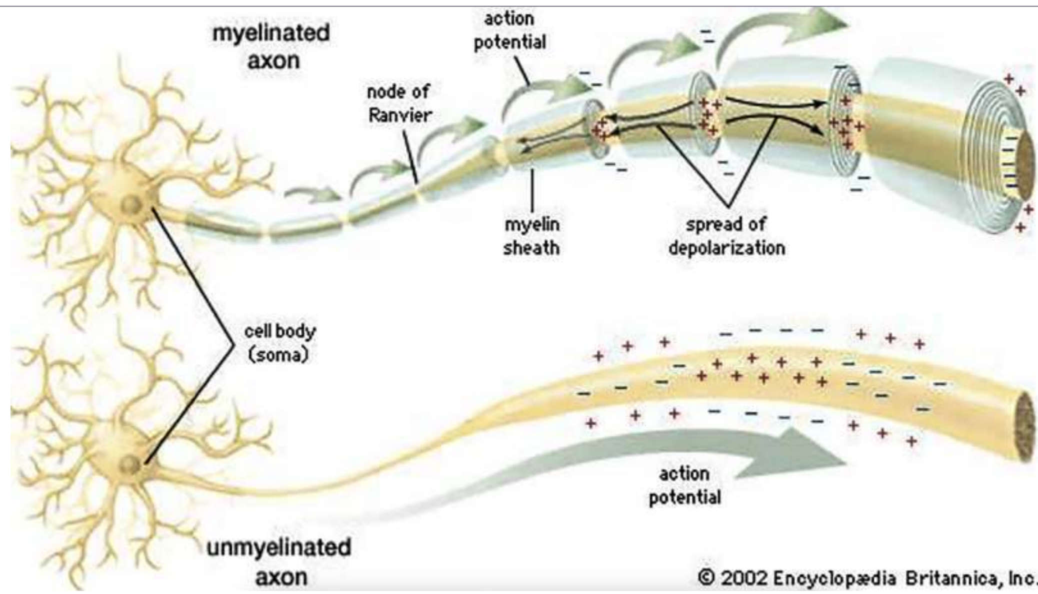

Figure 83: Neuron: Conduction of an action potential
In a myelinated axon, the myelin sheath prevents the local current (small black arrows) from flowing across the membrane. This forces the current to travel down the nerve fibre to the unmyelinated nodes of Ranvier, which have a high concentration of ion channels. Upon stimulation, these ion channels propagate the action potential (large green arrows) to the next node. Thus, the action potential jumps along the fibre as it is regenerated at each node, a process called saltatory conduction. In an unmyelinated axon, the action potential is propagated along the entire membrane, fading as it diffuses back through the membrane to the original depolarized region.
Source: Encyclopædia Britannica. Neuron. Britannica. (2025).
https://www.britannica.com/science/neuron (accessed 1 May 2025).

Bioelectricity generated within the human body—such as during muscle contractions or nerve signal transmission—is entirely natural and harmless, as it is a fundamental part of physiological processes. However, when micro- and nanoplastics enter the body, they carry with them an electrostatic charge that they can retain for extended periods. It is this charge that poses a potential health risk by interfering with vital biological functions.

Nanoplastics are plastic particles smaller than 1 micrometer. Due to their unique structure, they can accumulate electrostatic charges, making them a growing concern for scientists. When micro- or nanoplastic particles become electrified through the **triboelectric effect** (as a result of contact and friction with other surfaces), they acquire either a positive or negative charge. This charge significantly influences how these particles behave in both the human body and the environment.

The unique structure of nanoplastic particles allows them to adsorb pollutants, ions, and organic molecules, which enhances their role as carriers of toxins in ecosystems.[215, 216]

The chemical composition of nanoplastics plays a key role in determining their electrostatic properties: polymers such as polystyrene (PS), polyethylene (PE), or polypropylene (PP) often contain functional groups — carboxyl (-COOH), sulfate ($-SO_3H$), or amino ($-NH_2$) — that can become ionized depending on environmental conditions. For example, a study published in the journal Langmuir showed that polystyrene nanoparticles with carboxyl groups (PS-COOH) have a negative zeta potential, whereas those with amino groups ($PS-NH_2$) have a positive one — confirming the influence of functional groups on nanoplastic charge.[217]

The process of charge accumulation is not limited to chemical properties alone. During manufacturing or mechanical processes, such as friction, nanoplastics can become charged through contact electrification. A study conducted on plastic containers revealed that polystyrene is capable of accumulating a charge of up to –10 kV, which can be retained for an extended period and attracts oppositely charged particles such as dust or bacterial spores.[218] Moreover, variations in polymer structure — for example, the presence of polar groups — allow nanoplastics to exhibit either positive or negative charge depending on the pH of the environment. In acidic environments, amino groups may give particles a positive charge, while in alkaline conditions, carboxyl groups dominate and impart a negative charge — findings that have been confirmed in studies involving Arabidopsis thaliana plants.[219]

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[215] Rai, P. K., Sonne, C., Brown, R. J. C., Younis, S. A. & Kim, K.-H. Adsorption of environmental contaminants on micro- and nano-scale plastic polymers and the influence of weathering processes on their adsorptive attributes. Journal of Hazardous Materials 427, 127903 (2022). https://doi.org/10.1016/j.jhazmat.2021.127903

[216] Zhang, W. et al. The mechanism for adsorption of Cr(VI) ions by PE microplastics in ternary system of natural water environment. Environmental Pollution 257, 113440 (2020). https://doi.org/10.1016/j.envpol.2019.113440

[217] Perini, D. A. et al. Surface-Functionalized Polystyrene Nanoparticles Alter the Transmembrane Potential via Ion-Selective Pores Maintaining Global Bilayer Integrity. Langmuir 38, 14837–14849 (2022). https://doi.org/10.1021/acs.langmuir.2c02487

[218] Baribo, L. E., Avens, J. S. & O'Neill, R. D. Effect of Electrostatic Charge on the Contamination of Plastic Food Containers by Airborne Bacterial Spores. Applied Microbiology 14, 905–913 (1966). https://doi.org/10.1128/am.14.6.905-913.1966

[219] Sun, XD., Yuan, XZ., Jia, Y. et al. Differentially charged nanoplastics demonstrate distinct accumulation in Arabidopsis thaliana. Nat. Nanotechnol. 15, 755–760 (2020). https://doi.org/10.1038/s41565-020-0707-4

Thus, understanding the structure of nanoplastics and their electrostatic characteristics not only reveals their physical nature, but also lays the foundation for analyzing how these particles can affect ecosystems and living organisms. These topics will be explored further in the context of their pathogenic mechanisms.

Thanks to their high dielectric permittivity (the ability to retain an electric charge), nanoplastics, once inside the body, continue to accumulate harmful charges that under normal conditions would be neutralized or dissipated through the body's natural conductive systems. This disrupts the body's self-regulation processes, creating risks for cellular structures due to prolonged exposure to abnormal electrostatic energy.

To grasp the scale of the threat posed by nanoplastics entering the body, we can turn once again to the body's bioelectrical systems — complex mechanisms where electrical impulses serve as the language of intercellular communication.

Every movement and thought is made possible by invisible signals delivering commands to cells. Neurons exchange information via electrical impulses, muscles contract in response to these signals, and the brain processes information through a combination of bioelectrical and chemical interactions. Even breathing, reflexes, vision, and hearing depend on tiny electrical discharges that regulate the function of organs.

These invisible currents, refined over millions of years of evolution, translate bioelectrical impulses into the language of life. But their harmony is disrupted by foreign elements: microscopic particles of nanoplastics.

Once inside the body, nanoplastics can adsorb ions and create zones of abnormal electrical conductivity, disrupting the natural ionic balance and the processes of local charge neutralization regulated by intercellular fluids. Ion adsorption on the surface of nanoplastics leads to the accumulation of electrostatic charge on these particles. This phenomenon can trigger oxidative stress through the generation of reactive oxygen species (ROS) and interfere with electrochemical communication between cells, impairing their function.

This is confirmed by research[220] showing that 100 nm polystyrene particles, even in the presence of sodium ions (Na^+), remained stable and adsorbed onto bacterial surfaces despite their negative charge. For example, experiments with Staphylococcus aureus and Klebsiella pneumoniae demonstrated that nanoplastics significantly alter the zeta potential of cells, making their surfaces more negatively charged and thereby disrupting the natural electrostatic balance.

[220] Zając, M. et al. Exposure to polystyrene nanoparticles leads to changes in the zeta potential of bacterial cells. Sci Rep 13, 9552 (2023). https://doi.org/10.1038/s41598-023-36603-5

Charged nanoplastic particles can affect the electric fields surrounding cells, distorting signal transmission. This is similar to interference in radio communication: instead of clear commands, there's chaotic noise that disrupts how cells exchange information. While direct effects on nerve cells were not studied and conclusions about human impact remain preliminary and require further investigation, the observed changes in bacterial surface charge suggest that nanoplastic can modify the electrochemical properties of cell membranes. For instance, at concentrations above 64 micrograms per milliliter, polystyrene particles cause significant shifts in zeta potential, which could potentially impair the function of ion channels or receptors critical for intercellular communication.

The ability of nanoparticles to "stick" to surfaces, as shown in atomic force microscopy images in the aforementioned study (Fig. 84), poses a risk of long-term exposure. Once embedded in tissues, the particles can form persistent electrostatic anomalies that sodium and potassium ions cannot fully neutralize, especially if nanoplastic penetrates inside cells, bypassing the protective mechanisms of intercellular fluid.

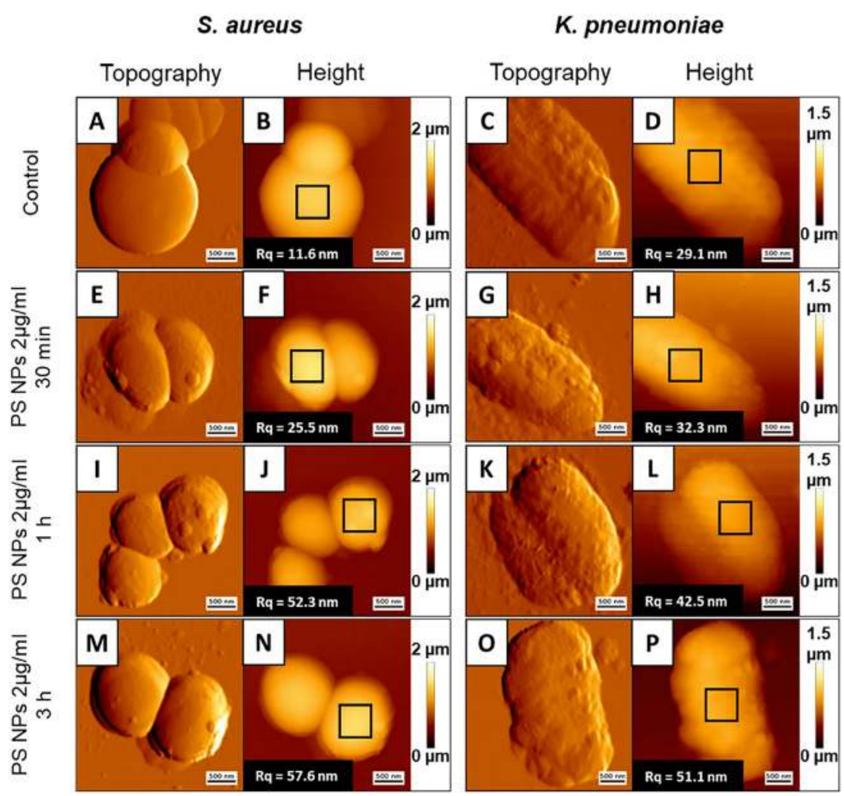

Figure 84: Surface topography (A, C, E, G, I, K, M, O) and height images (B, D, F, H, J, L, N, P) of S. aureus ATCC 6538 and K. pneumoniae ATCC 4352 strains exposed to 100 nm polystyrene nanoparticles at a concentration of 2 μg/mL for 0.5 h (E–H), 1 h (I–L), and 3 h (M–P), compared to the untreated control (A–D). Scale bar = 500 nm. The panels indicate areas (black squares) from which the root mean square (RMS) surface roughness was calculated. The roughness values (Rq) reflect the RMS deviation of surface height profiles over the measurement length.

Source: Zając, M. et al. Exposure to polystyrene nanoparticles leads to changes in the zeta potential of bacterial cells. Scientific Reports, 13, 9552 (2023). https://doi.org/10.1038/s41598-023-36603-5

The danger of the pathogenic charge accumulated on nanoplastics also lies in its ability to create electrical interference around immune cells. This is confirmed by a study[221] showing that positively charged nanoplastics (PS-NH_2) significantly reduce the viability of immune cells and the stability of lysosomal membranes compared to negatively charged ones (PS-COOH), highlighting the critical role of surface charge in their interactions with cells.

Electrostatically charged micro- and nanoplastic (MNP) particles demonstrate an increased ability to adsorb onto cell membranes, tissues, and other biological surfaces—literally sticking to them. This adhesion raises the risk of both mechanical and chemical damage to cells, disrupting their structure and function.

Such charges may also facilitate the penetration of MNP particles through complex biological barriers like the blood–brain barrier or the blood–placenta barrier. As a result, toxins may reach the brain or developing fetus, increasing the risks of neurotoxic effects and fetal development disorders.

The electrostatic influence of nanoplastics may interfere with the structure and function of proteins, ion channels, and cell receptors, which in turn disrupts cell signaling, triggers oxidative stress, and weakens immune defense. These disruptions can initiate a cascade of pathological processes, including chronic inflammation, neurodegenerative disorders, malignant tumor formation, and systemic dysfunction, significantly raising the risk of severe diseases.

Thus, the accumulation of electrostatic charge on nanoplastics is not merely a physical phenomenon — it is a mechanism that amplifies the danger of micro- and nanoplastics (MNPs). This is especially critical given the fact that electrostatic charge can persist on MNPs for extended periods, and that these particles are extremely resistant to elimination from the human body.

Studying this phenomenon is now of utmost importance, as it leads to a deeper understanding of how pathogenic electrical charges accumulated on nanoplastics could evolve into a macroscopic threat to the survival of the human species itself.

Until recently, it was believed that the foundation of cellular energy—proton transport—was governed purely by chemistry: protons were thought to "hop" from one water molecule to another. However, a new study published in Proceedings of the *National Academy of Sciences* radically changes this view. It turns out that proton transport in living organisms depends not only on chemical properties, but also on quantum factors—specifically, the spin of electrons and the chirality of biological molecules (Fig. 85).

[221]Murano, C., Bergami, E., Liberatori, G., Palumbo, A. & Corsi, I. Interplay Between Nanoplastics and the Immune System of the Mediterranean Sea Urchin Paracentrotus lividus. Front. Mar. Sci. 8, 647394 (2021). https://doi.org/10.3389/fmars.2021.647394

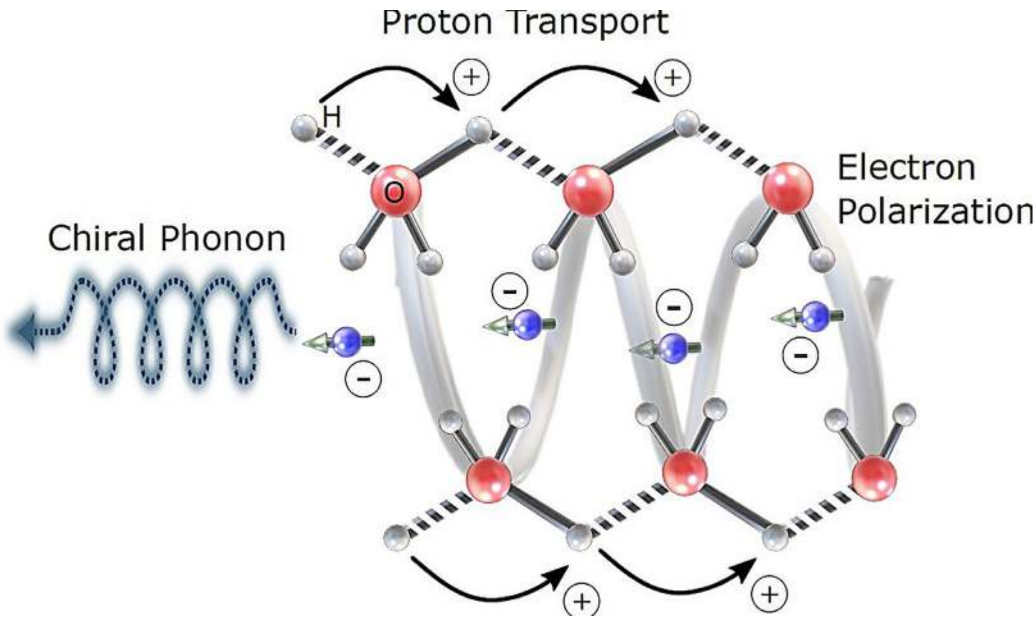

Figure 85: A schematic toy model. The proton transport is accompanied by electron polarization in chiral media. Due to the CISS effect this electric polarization is producing spin polarization. Preserving angular momentum generates chiral phonons that enhance proton transfer.
Source: Goren, N. et al. Coupling between electrons' spin and proton transfer in chiral biological crystals. PNAS 122, e2500584122 (2025). https://doi.org/10.1073/pnas.2500584122

A study conducted by Israeli scientists at the Hebrew University revealed that in proteins such as lysozyme, proton transfer significantly accelerates when electrons with the "right" spin are introduced — and slows down when the spin is opposite. This is due to the fact that protons and electrons in living systems operate as a coordinated quantum mechanism. Even minimal changes in their spin orientation can influence fundamental biological processes — energy production, metabolism, and intracellular regulation.

> As noted by the study's lead researcher, Naama Goren, *"Our findings show that the way protons move in biological systems isn't just about chemistry—it's also about quantum physics."* This suggests that even the slightest disruptions in electric charge or magnetic orientation can affect cellular metabolism, energy production, and overall health.[222]

[222]Phys.org. Quantum effects in proteins: How tiny particles coordinate energy transfer inside cells. (2025) https://phys.org/news/2025-05-quantum-effects-proteins-tiny-particles.html (accessed 10 May 2025).

Systemic Effects of MNPs on Human Organs and Functional Systems

Once micro- and nanoplastics (MNPs) enter the human body, they circulate through the bloodstream, reaching all organs and tissues (Fig. 86). Plastic particles have been detected in human blood, heart and bone tissue, brain, placenta, lungs, liver, and other organs.[223]

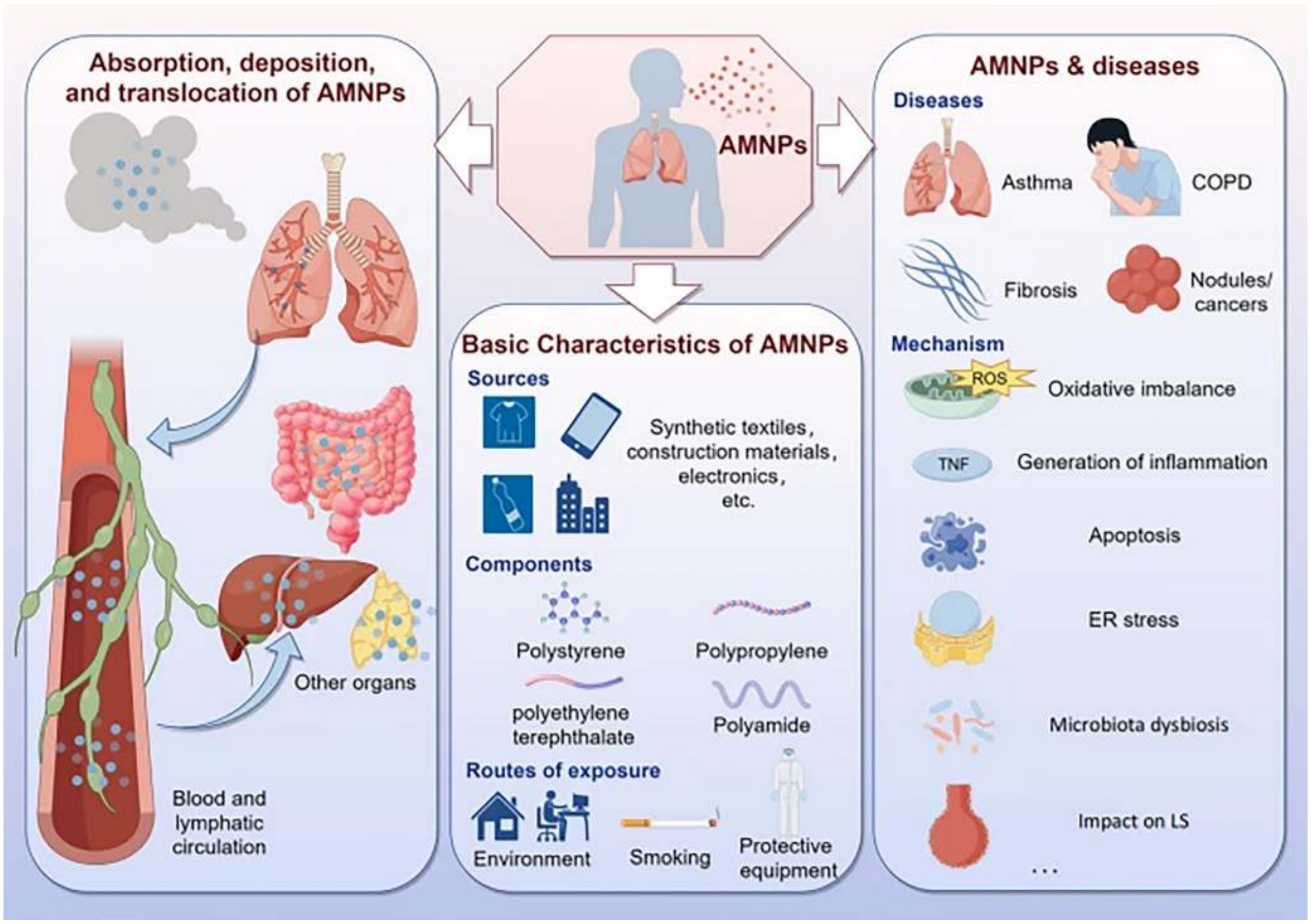

Figure 86: Inhalation of MNPs and their toxic effects on the human body

Source: Gou, Z., Wu, H., Li, S., Liu, Z. & Zhang, Y. Airborne micro- and nanoplastics: emerging causes of respiratory diseases. Particle and Fibre Toxicology 21, 50 (2024). https://doi.org/10.1186/s12989-024-00613-6

[223] Khan, A. & Jia, Z. Recent insights into uptake, toxicity, and molecular targets of microplastics and nanoplastics relevant to human health impacts. iScience 26, 106061 (2023). https://doi.org/10.1016/j.isci.2023.106061

Respiratory System Damage From Inhaled MNPs

One of the primary routes for MNPs to enter the human body is through inhalation. Research conducted by Chinese scientists[224] revealed that during two hours of active time spent outdoors, adults inhale approximately 106,000 microplastic particles, while children inhale about 73,700.

Due to their thermodynamic properties, particles smaller than 0.1 micrometers can effectively deposit throughout the respiratory tract, from the upper airways to the alveoli.[225]

The lungs have a vast alveolar surface area (approximately 150 m^2) and a thin tissue barrier (less than 1 micrometer), enabling nanoplastics to easily enter the bloodstream (Fig. 87).

Microplastics were detected in 13 out of 20 human lung tissue samples.[226]

According to the study involving 22 patients with respiratory diseases, microplastics were found in all sputum samples,[228] ranging from 18.75 to 91.75 particles per 10 ml.[229] A connection between allergic rhinitis and microplastics has also been established.[230]

MNPs are closely linked to the onset and progression of various respiratory conditions, including asthma, pulmonary fibrosis, chronic obstructive pulmonary disease (COPD), and tumors.[229] Research revealed that 97% of malignant lung specimens contained microplastic fibers.[231]

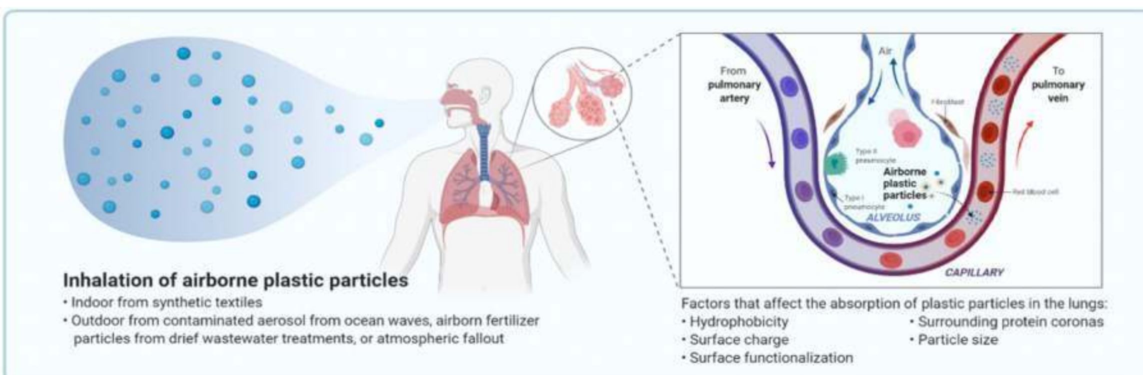

Figure 87: Inhalation pathway of plastic particles entering the human body.[227]

[224]Peking University College of Environmental Science and Engineering. Prof. Yi Huang's team made new progress in atmospheric microplastic distribution and its human health risk. CESE. (2022) https://cese.pku.edu.cn/kycg/156506.htm (accessed 1 May 2025).
[225]Gou, Z., Wu, H., Li, S., Liu, Z. & Zhang, Y. Airborne micro- and nanoplastics: emerging causes of respiratory diseases. Particle and Fibre Toxicology 21, 50 (2024). https://doi.org/10.1186/s12989-024-00613-6
[226]Amato-Lourenço, L. F. et al. Presence of airborne microplastics in human lung tissue. Journal of Hazardous Materials 416, 126124 (2021). https://doi.org/10.1016/j.jhazmat.2021.126124
[227]Yee, M. S.-L. et al. Impact of Microplastics and Nanoplastics on Human Health. Nanomaterials 11, 496 (2021). https://doi.org/10.3390/nano11020496
[228]Huang, S. et al. Detection and Analysis of Microplastics in Human Sputum. Environ. Sci. Technol. 56, 2476–2486 (2022). https://doi.org/10.1021/acs.est.1c03859
[229]Huang, X., Saha, S. C., Saha, G., Francis, I. & Luo, Z. Transport and deposition of microplastics and nanoplastics in the human respiratory tract. Environmental Advances 16, 100525 (2024). https://doi.org/10.1016/j.envadv.2024.100525
[230]Tuna, A., Taş, B.M., Başaran Kankılıç, G. et al. Detection of microplastics in patients with allergic rhinitis. Eur Arch Otorhinolaryngol 280, 5363–5367 (2023). https://doi.org/10.1007/s00405-023-08105-7
[231]Dris, R. et al. A first overview of textile fibers, including microplastics, in indoor and outdoor environments. Environmental Pollution 221, 453–458 (2017). https://doi.org/10.1016/j.envpol.2016.12.013

Possible mechanisms include oxidative stress, inflammation, and disruption of the lung microbiome. Micro- and nanoplastics (MNPs) can trigger pulmonary inflammation.[232]

According to a World Health Organization (WHO) report, lower respiratory tract infections remain the deadliest infectious disease globally, ranking as the fifth leading cause of death worldwide. Additionally, deaths from tracheal, bronchial, and lung cancers have risen, now ranking as the sixth leading cause of mortality.[233]

Neurotoxic Effects of MNPs: Damage to the Central and Peripheral Nervous Systems

Research confirms that neurological disorders are the leading cause of physical and cognitive disability worldwide, currently affecting approximately 3.4 billion people. The absolute number of patients has significantly increased over the past 30 years.[234] Moreover, the burden of chronic neurodegenerative diseases is expected to at least double over the next two decades.

According to WHO data, one in eight people worldwide suffers from a mental health disorder.[235]

The prevalence of bipolar disorder among adolescents and young adults globally has risen from 79.21 per 100,000 people in 1990 to 84.97 per 100,000 in 2019.[236] Over the past three decades, incidence rates have increased for both men and women (Fig. 88).

Recent studies indicate a rise in mental health disorders among children and adolescents. According to the 2022 National Healthcare Quality and Disparities Report, from 2016 to 2019, the rates of emergency department (ED) visits with a principal diagnosis related to mental health only increased for ages 0-17 years, from 784.1 to 869.3 per 100,000 population. Additionally, from 2008 to 2020, the rates of death from suicide among people age 12 and over increased 16% overall, from 14.0 to 16.3 per 100,000 population.[237]

A report from the health insurance company Blue Cross Blue Shield reveals that diagnoses of clinical depression, also known as major depression, have risen by 33% since 2013. "Some of the literature is already starting to predict that by 2030, depression will be the number-one cause for loss of longevity or life. The report notes that women and men with depression may on average lose up to 9.6 years of healthy life.[238]

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[232]Bengalli, R. et al. Characterization of microparticles derived from waste plastics and their bio-interaction with human lung A549 cells. Journal of Applied Toxicology 42, 2030–2044 (2022). https://doi.org/10.1002/jat.4372

[233]World Health Organization. The top 10 causes of death. WHO Fact Sheets. (2024) https://www.who.int/news-room/fact-sheets/detail/the-top-10-causes-of-death (accessed 1 May 2025).

[234]World Health Organization. Over 1 in 3 people affected by neurological conditions, the leading cause of illness and disability worldwide. (2024) https://www.who.int/news/item/14-03-2024-over-1-in-3-people-affected-by-neurological-conditions--the-leading-cause-of-illness-and-disability-worldwide (accessed 1 May 2025).

[235]World Health Organization. Mental disorders. WHO Fact Sheets. (2022) https://www.who.int/news-room/fact-sheets/detail/mental-disorders (accessed 1 May 2025).

[236]Zhong, Y. et al. Global, regional and national burdens of bipolar disorders in adolescents and young adults: a trend analysis from 1990 to 2019. Gen Psych 37, e101255 (2024). https://doi.org/10.1136/gpsych-2023-101255

[237]U.S. Department Of Health And Human Services. 2022 National Healthcare Quality and Disparities Report. Rockville, MD: Agency for Healthcare Research and Quality. (2022) https://www.ncbi.nlm.nih.gov/books/NBK587174 (accessed 1 May 2025).

[238]Blue Cross Blue Shield. Major depression: The impact on overall health. Report. (2018) https://www.bcbs.com/news-and-insights/report/major-depression-the-impact-on-overall-health (accessed 1 May 2025).

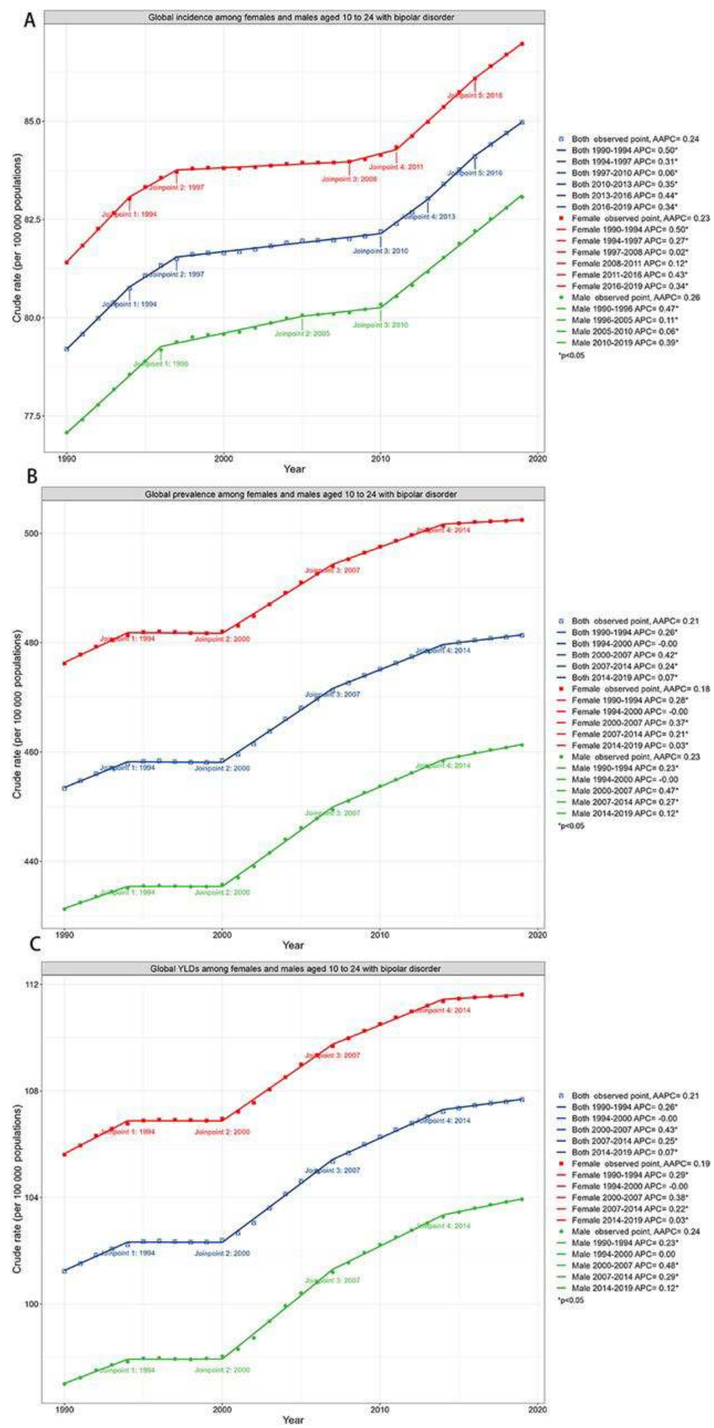

Figure 88: Joinpoint regression analysis of global bipolar disorder incidence, prevalence and years lived with disability (YLDs) of all, female and male adolescents and young adults ages 10–24 from 1990 to 2019. *p<0.05; AAPC, average annual percentage change; APC, annual percentage change; YLDs, years lived with disability.

Source: Zhong, Y. et al. Global, regional and national burdens of bipolar disorders in adolescents and young adults: a trend analysis from 1990 to 2019. Gen Psych 37, e101255 (2024). https://doi.org/10.1136/gpsych-2023-101255

Over the past few decades, diagnoses of attention-deficit/hyperactivity disorder (ADHD) have steadily increased. National surveys in the United States show a rise in prevalence from 6.1% to 10.2% over the 20-year period from 1997 to 2016 (Fig. 89).[239]

A 2023 review covering 31 countries found declining literacy and numeracy skills (Fig. 90).[240]

[239] Xu, G., Strathearn, L., Liu, B., Yang, B. & Bao, W. Twenty-Year Trends in Diagnosed Attention-Deficit/Hyperactivity Disorder Among US Children and Adolescents, 1997-2016. JAMA Network Open 1, e181471 (2018). https://doi.org/10.1001/jamanetworkopen.2018.1471

[240] Organisation for Economic Co-operation and Development. Do adults have the skills they need to thrive in a changing world? OECD Publications. (2024) https://www.oecd.org/en/publications/do-adults-have-the-skills-they-need-to-thrive-in-a-changing-world_b263dc5d-en.html (accessed 1 May 2025).

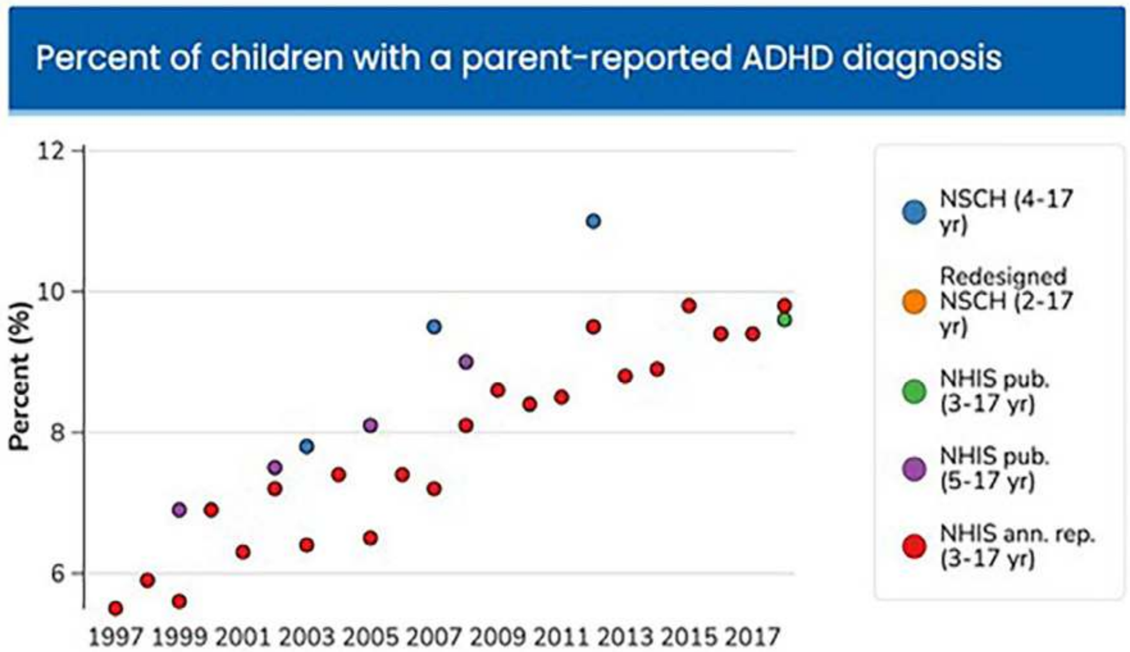

Figure 89: Graph of ADHD prevalence trends from 1997 to 2016. Xu, G., Strathearn, L., Liu, B., Yang, B. & Bao, W. Twenty-Year Trends in Diagnosed Attention-Deficit/Hyperactivity Disorder Among US Children and Adolescents, 1997-2016.
Source: JAMA Network Open 1, e181471 (2018). https://doi.org/10.1001/jamanetworkopen.2018.1471

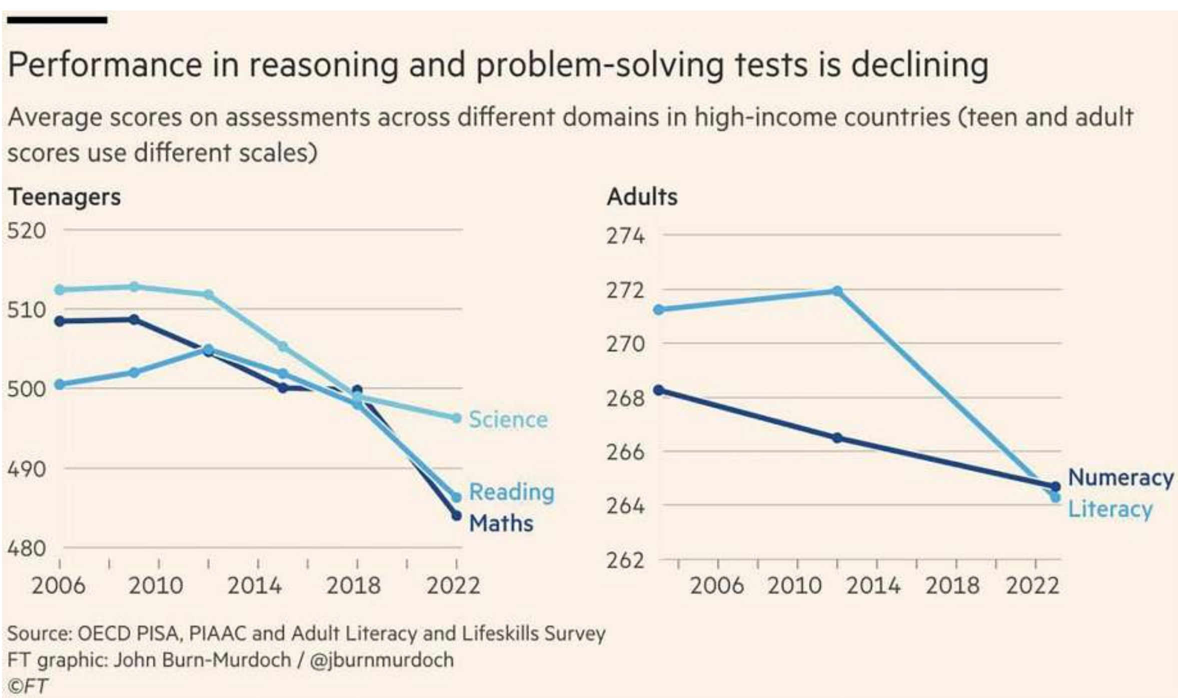

Figure 90: Performance on logic and problem-solving tests declines.
Source: OECD PISA, PIAAC and Adult Literacy and Lifeskills Survey
FT graphic: John-Murdoch / @jburnmurdoch

Trends in the rise of neurodegenerative and neuropsychiatric disorders clearly correlate with the increasing presence of plastics in the environment (Fig. 96-97).

The highest concentrations of nanoplastics were found in human brain tissue — 7 to 30 times higher than in the liver or kidneys. Brain tissue samples from individuals diagnosed with dementia showed even greater MNP presence — up to 10 times higher — compared to brain tissue from individuals without dementia (Fig. 91).[241] The predominant particles in the brain were tiny polyethylene fragments or flakes, one of the most commonly used plastics in packaging.

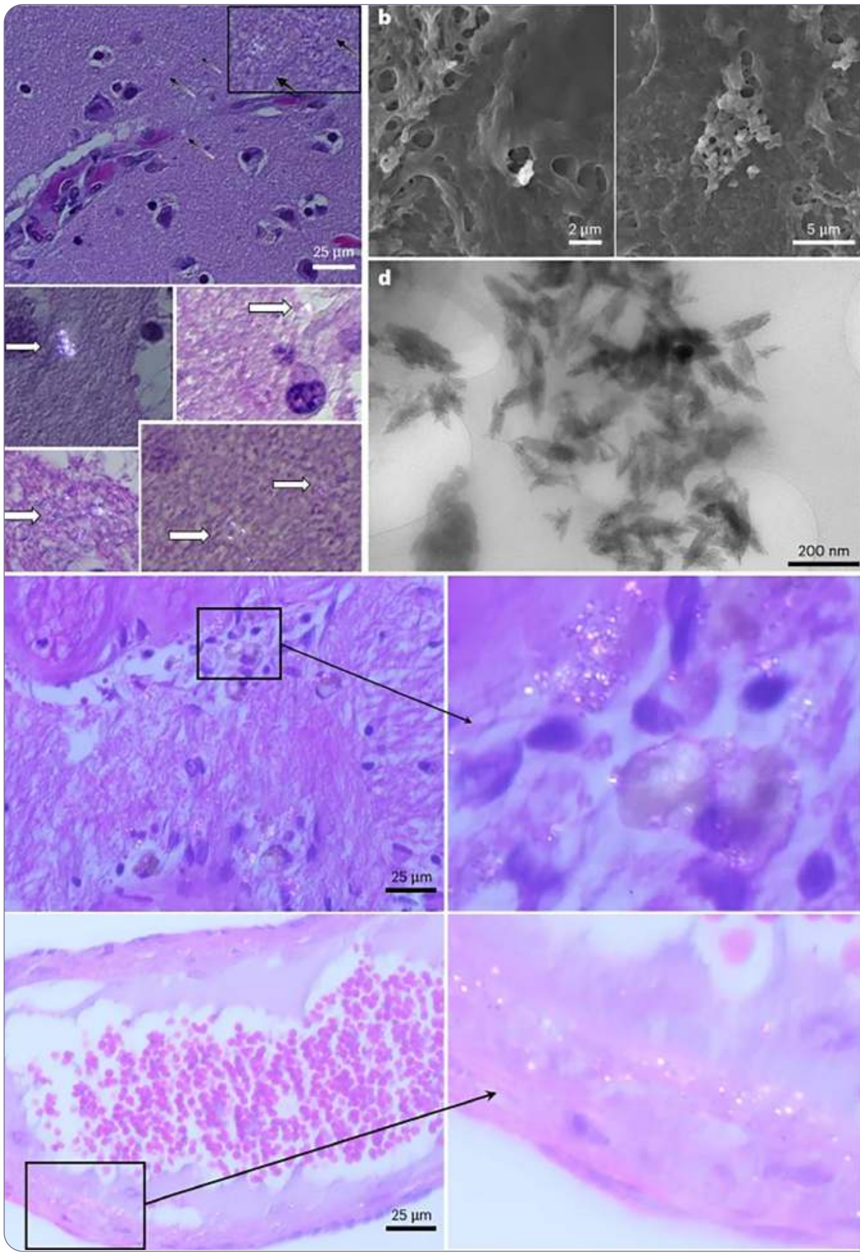

Figure 91: a,b, Polarization wave microscopy (a, black arrows indicate refractory inclusions; inset is a digital magnification for clarity) and SEM (b, visual fields are 15.4 and 20.1 µm wide) were used to scan sections of brain from decedent human samples. c, Large (>1 µm) inclusions were not observed; additional polarization wave examples are highlighted (white arrows highlight submicron refractory inclusions). Resolution limitations of these technologies drove the use of TEM to examine the extracts from the pellets used for Py-GC/MS. d, Example TEM images resolved innumerable shard- or flake-like solid particulates following dispersion, with dimensions largely <200 nm in length and <40 nm in width. e,f, Polarization wave microscopy reveals substantially more refractile inclusions in dementia cases, especially in regions with associated immune cell accumulation (e) and along the vascular walls (f). All images were collected on a small subset of participants (n = 10 for normal brains; n = 3 for dementia cases) to provide visual evidence to support analytical chemistry.
Source: Nihart, A.J., Garcia, M.A., El Hayek, E. et al. Bioaccumulation of microplastics in decedent human brains. Nat Med 31, 1114–1119 (2025). https://doi.org/10.1038/s41591-024-03453-1

[241]Nihart, A.J., Garcia, M.A., El Hayek, E. et al. Bioaccumulation of microplastics in decedent human brains. Nat Med 31, 1114–1119 (2025). https://doi.org/10.1038/s41591-024-03453-1

New data confirm that from 2016 to 2024, over eight years, the amount of plastic in the human brain has increased by 50%.[241]

> *"The concentrations we saw in the brain tissue of normal individuals, who had an average age of around 45 or 50 years old, were 4,800 micrograms per gram. (...) That's the equivalent of an entire standard plastic spoon. That would mean that our brains today are 99.5% brain and the rest is plastic."* said co-lead study author Matthew Campen from the University of New Mexico.[242]

Given the rising levels of plastic particles in the atmosphere, water, and food, it is certain that the amount of nanoplastics in our bodies will continue to grow. If this trend persists, the plastic content in the brain could increase by another 50% within the next four years.

Micro- and nanoplastics (MNPs) enter the brain through the bloodstream, crossing the blood-brain barrier (BBB), and via inhalation through the olfactory nerves (Fig. 92).

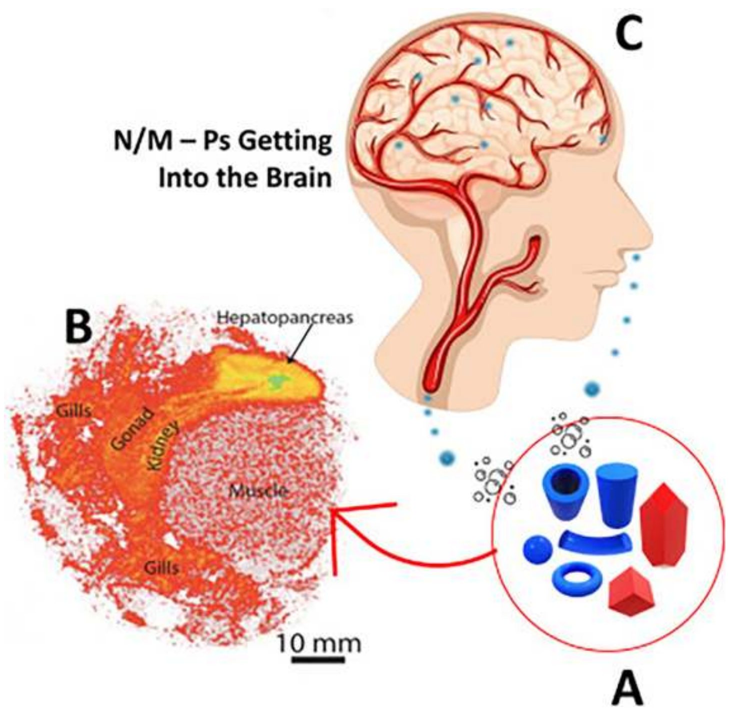

Figure 92: N/M-P getting into the organs: N/M – P (A) on being part of the human cycle taken up by the human body and further by the organs. Over time, N/M-Ps are distributed in various body organs (B, Copyright Permission form ACS, 2014) and are getting into the brain via BBB and nasal route, integrating with CNS systems including neurons. Some parts of this figure are adopted from open sources like Freepik and Pixaby.

Source: Kaushik, A., Singh, A., Kumar Gupta, V. & Mishra, Y. K. Nano/ micro-plastic, an invisible threat getting into the brain. Chemosphere 361, 142380 (2024). https://doi.org/10.1016/j.chemosphere.2024.142380

[241]Nihart, A.J., Garcia, M.A., El Hayek, E. et al. Bioaccumulation of microplastics in decedent human brains. Nat Med 31, 1114–1119 (2025). https://doi.org/10.1038/s41591-024-03453-1
[242]VRT NWS. Brain contains "full plastic spoonful" of microplastics. (2025) https://www.vrt.be/vrtnws/nl/2025/02/04/microplastics-in-de-hersenen (accessed 1 May 2025).

The blood-brain barrier is a specialized physiological system that regulates the transfer of substances from the bloodstream to the central nervous system (Fig. 93). It selectively allows nutrients and oxygen to pass while blocking toxins and pathogens (Fig. 94). This mechanism provides critical protection for the brain, maintaining the homeostasis of the neuronal environment.

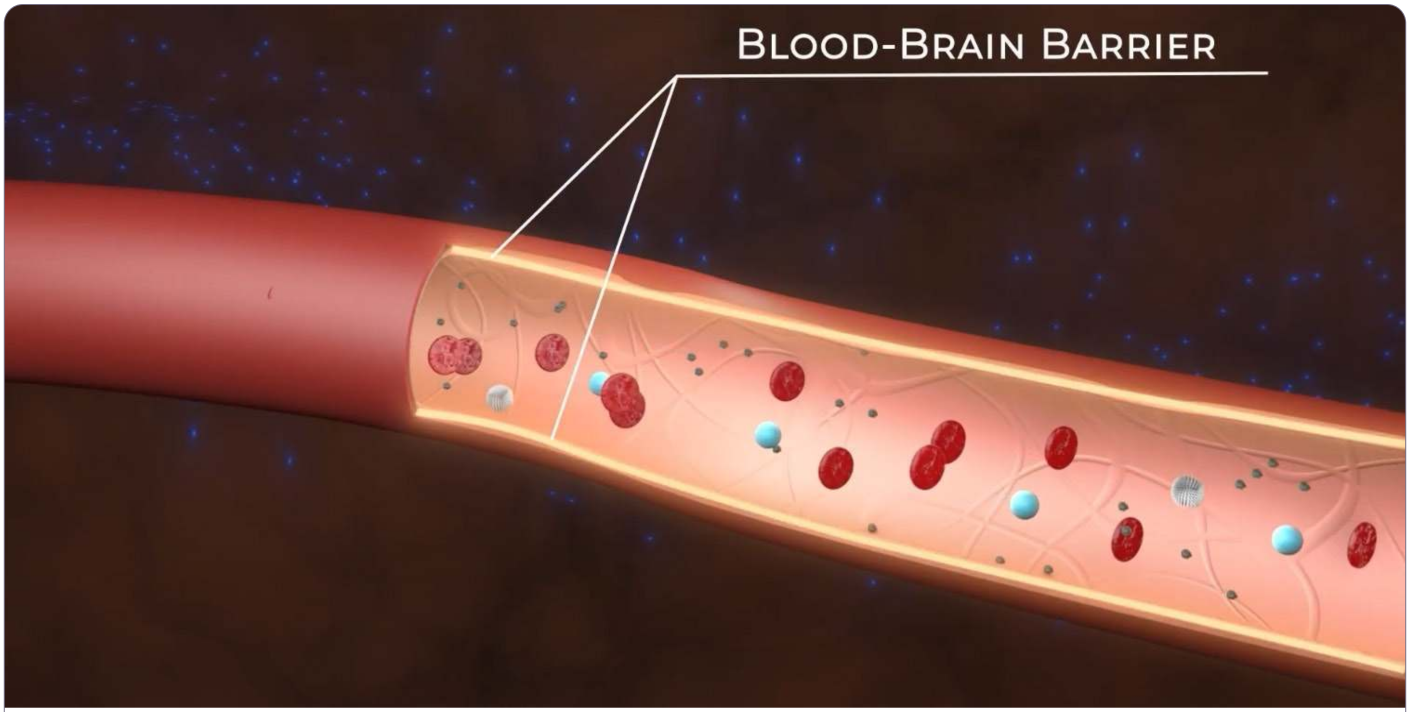

Figure 93: Schematic illustration of a brain blood vessel

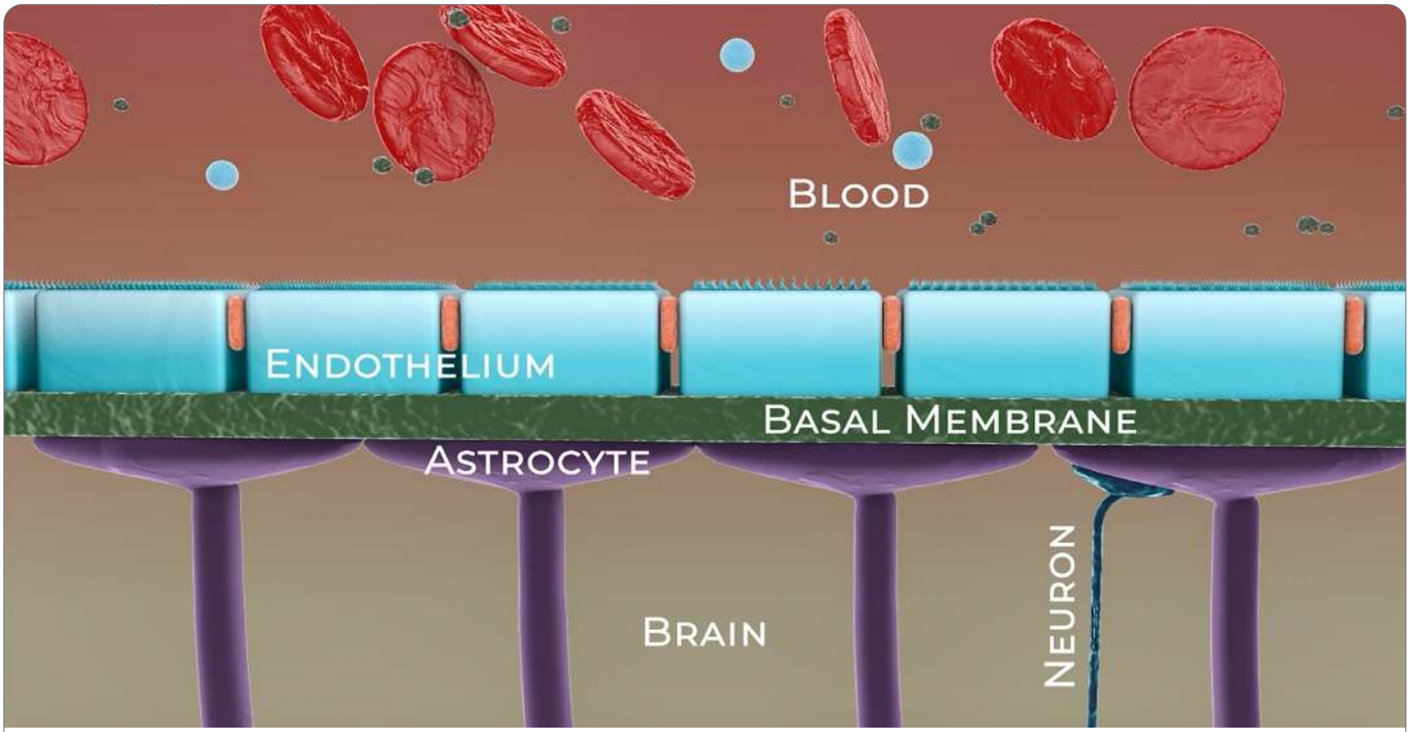

Figure 94: Schematic illustration of the blood-brain barrier

Due to their submicron size and physicochemical properties, plastic nanoparticles can penetrate the brain within just two hours of entering the body.[243]

When inhaled, plastic nanoparticles travel through the olfactory nerves directly to the brain region responsible for processing odors (Fig. 95).[244] As a result, they take a shorter and more direct route to the brain than to other organs.

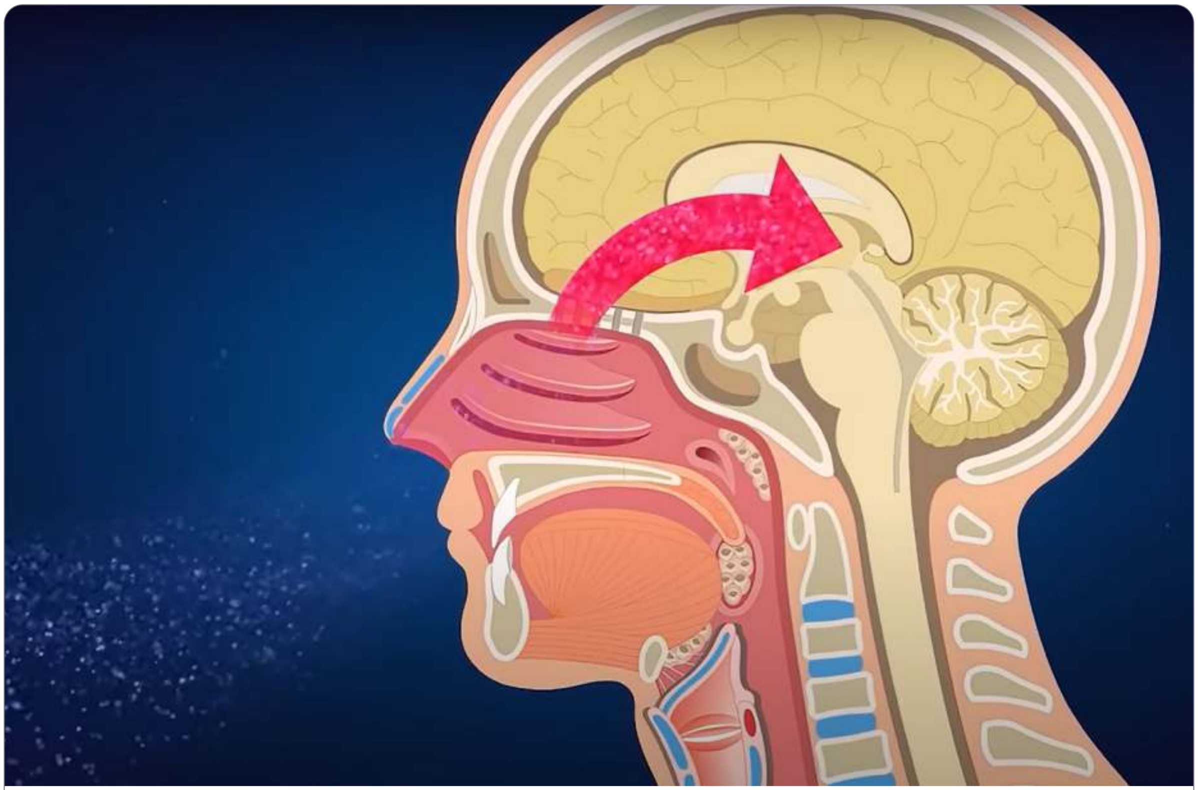

Figure 95: Penetration of nanoplastics (NPs) through olfactory nerves into the brain

Once nanoplastics penetrate the brain, they disrupt the function of brain cells — neurons. Research has shown that the surface properties and electric charge of nanoparticles significantly affect their interaction with neurons and the transmission of nerve impulses.

The electrostatic charge of nanoplastics allows them to freely interfere with the function of every cell in the human body, penetrating cells, causing oxidative stress and chronic inflammation, impairing mitochondrial function, and potentially leading to mitochondrial destruction and cell death.

The study[245] has demonstrated that negatively charged nanoparticles can induce depolarization of neuronal membranes, altering their electrical activity.

[243]Kopatz, V. et al. Micro- and Nanoplastics Breach the Blood–Brain Barrier (BBB): Biomolecular Corona's Role Revealed. Nanomaterials 13, 1404 (2023). https://doi.org/10.3390/nano13081404
[244]Amato-Lourenço, L. F. et al. Microplastics in the Olfactory Bulb of the Human Brain. JAMA Netw Open 7, e2440018 (2024). https://doi.org/10.1001/jamanetworkopen.2024.40018
[245]Dante, S. et al. Selective Targeting of Neurons with Inorganic Nanoparticles: Revealing the Crucial Role of Nanoparticle Surface Charge. ACS Nano 11, 6630–6640 (2017). https://doi.org/10.1021/acsnano.7b00397

Experiments revealed that negatively charged nanoplastic particles selectively bind to neurons actively involved in nerve impulse transmission. These particles adhere to neuronal cell bodies, dendrites, and synaptic clefts, while glial cells, which lack electrical activity, do not interact with them.

Thus, the electrical activity of neurons serves as the primary trigger for the binding of negatively charged nanoplastics to cell membranes.

Research indicates that micro- and nanoplastics tend to accumulate in the lipid-rich myelin sheath of the brain, which surrounds neurons and facilitates nerve signal conduction.[246] Nanoplastics trigger the degradation of the myelin sheath around axons, [247, 248] disrupting the transmission of nerve impulses between neurons.

Impact of Nanoplastics on Neurons

The effects of nanoplastics on neurons can occur through the following mechanisms:

1. Influence on Neuronal Membrane Potential

Neurons function due to a membrane potential difference (approximately -70 mV at rest), maintained by ion gradients (Na^+, K^+, Cl^-, etc.) and the activity of ion channels. When a charged nanoplastic particle is near a neuronal membrane, it can alter the electric field and destabilize the membrane potential. This may lead to depolarization or hyperpolarization, and in severe cases, spontaneous neuronal activation or signal blockage.

2. Electrostatic Interaction with Ion Channels

Ion channels in neuronal membranes contain charged amino acids, particularly in the channel's "gate" regions. A nanoplastic particle with a strong negative or positive charge can electrostatically interact with these sites, altering the channel's configuration. This may cause channel blockage or improper activation, disrupting normal neuronal function.

3. Disruption of Synaptic Function

Synapses rely on the precise activity of Ca^{2+}, Na^+ ions, and neurotransmitters.[249] Electrostatically charged nanoplastic particles can interfere with neurotransmitter release or generate false signals, potentially disrupting the transmission of nerve impulses.

[246] Peking University College of Environmental Science and Engineering. Prof. Yi Huang's team made new progress in atmospheric microplastic distribution and its human health risk. CESE. (2022) https://cese.pku.edu.cn/kycg/156506.htm (accessed 1 May 2025).
[247] Kim, D. Y. et al. Effects of Microplastic Accumulation on Neuronal Death After Global Cerebral Ischemia. Cells 14, 241 (2025). https://doi.org/10.3390/cells14040241
[248] Zhang, Y. et al. Selective bioaccumulation of polystyrene nanoplastics in fetal rat brain and damage to myelin development. Ecotoxicology and Environmental Safety 278, 116393 (2024). https://doi.org/10.1016/j.ecoenv.2024.116393
[249] Moiniafshari, K. et al. A perspective on the potential impact of microplastics and nanoplastics on the human central nervous system. Environmental Science: Nano 12, 1809–1820 (2025). https://doi.org/10.1039/D4EN01017E

4. Oxidative Stress and Inflammation

Charged nanoplastics can increase levels of reactive oxygen species, resulting in oxidative stress. Oxidative stress in neurons occurs when reactive oxygen species exceed the cell's ability to neutralize them. This damages DNA, cellular structures such as membranes, proteins, and mitochondria, impairing normal neuronal function. As a result, the cell loses its ability to effectively transmit nerve impulses, leading to degradation and, ultimately, cell death. Since neurons have limited regenerative capacity, damage caused by oxidative stress is often irreversible and can contribute to progressive declines in memory, attention, and other cognitive functions.

5. Impact on Mitochondrial Function

Nanoplastics with a positive electrostatic charge can penetrate cells and accumulate in mitochondria, disrupting their membrane potential. This impairs the respiratory chain, causing electron leaks that react with oxygen to form reactive oxygen species, particularly superoxide anions. Their excessive accumulation amplifies oxidative stress and may damage cellular structures.

6. Mitochondrial Mutations

Nanoplastic particles can damage mitochondrial DNA, disrupting normal mitochondrial function. This affects critical cellular processes, including energy production, oxidative stress regulation, programmed cell death, and metabolism. Disruptions in these systems can create conditions that promote the development of diseases.

7. Reactive Properties of Nanoplastic Surfaces

The high specific surface area of nanoplastics is a key factor driving their elevated chemical reactivity and ability to generate reactive oxygen species. Compared to microplastics, nanoparticles have a surface area per unit mass that is tens or even hundreds of times larger, significantly enhancing their interactions with biomolecules and the surrounding environment.

The electrostatic charge on plastic particles can disrupt neuronal function by blocking or distorting the transmission of nerve impulses. This leads to malfunctions in the nervous system and can trigger a wide range of pathological conditions in the body. These effects manifest as various neurological, autonomic, cognitive, and psychiatric disorders (Table 2).

Category	Manifestation	Cause / Mechanism
Motor Disorders	Paralysis	Disruption in the transmission of motor impulses from the central nervous system to the muscles
	Seizures	Imbalance between excitatory and inhibitory neural signals
	Loss of sensation	Malfunction in sensory neural pathways transmitting information from receptors to the brain
	Impaired coordination	Damage to the cerebellar or spinal conduction pathways
Sensory Impairments	Speech, vision, and hearing disorders	Damage to neural pathways connected to sensory and motor centers in the brain
Autonomic Dysfunctions	Breathing, heart rate, and digestive issues	Disruption of the autonomic nervous system
	Impaired thermoregulation and organ dysfunction	Dysfunction in autonomic regulatory centers
Cognitive Impairments	Memory and attention deficits	Structural or functional changes in the cerebral cortex
	Altered consciousness, coma	Damage to the brain's reticular formation, which plays a key role in regulating wakefulness and consciousness
Psychological and Emotional Disorders	Anxiety, depression, mood disturbances	Neurotransmitter imbalances; damage to emotional centers in the brain

Table 2. Spectrum of Pathological Conditions Caused by the Impact of Nanoplastics on Neurons

The effects of nanoplastic exposure on nerve cells are linked to a wide range of disorders, including multiple sclerosis, amyotrophic lateral sclerosis, Alzheimer's disease, Parkinson's disease, autoimmune disorders, epilepsy, ischemic and hemorrhagic stroke, depression, anxiety and cognitive disorders, schizophrenia, bipolar disorder, autism, and more.

Micro- and Nanoplastics as a Risk Factor for Autism Spectrum Disorders

Alongside the rise in environmental plastic pollution, there has been an increase in the prevalence of autism spectrum disorders (ASD) (Fig. 96–97).

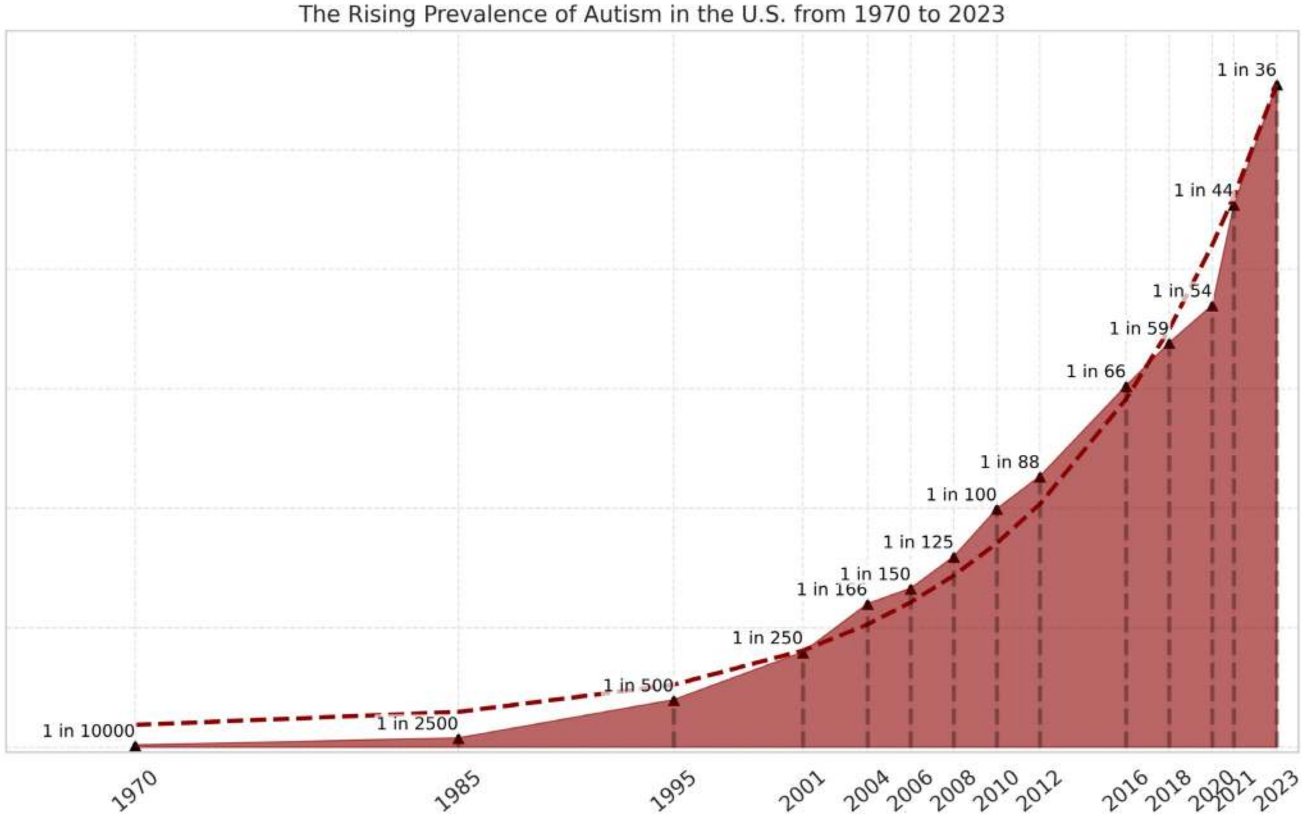

Figure 96: Increase in autism prevalence in the United States from 1970 to 2023.
Source: Rogers, T. The political economy of autism. Substack.
https://tobyrogers.substack.com/p/the-political-economy-of-autism (accessed May 1, 2025).

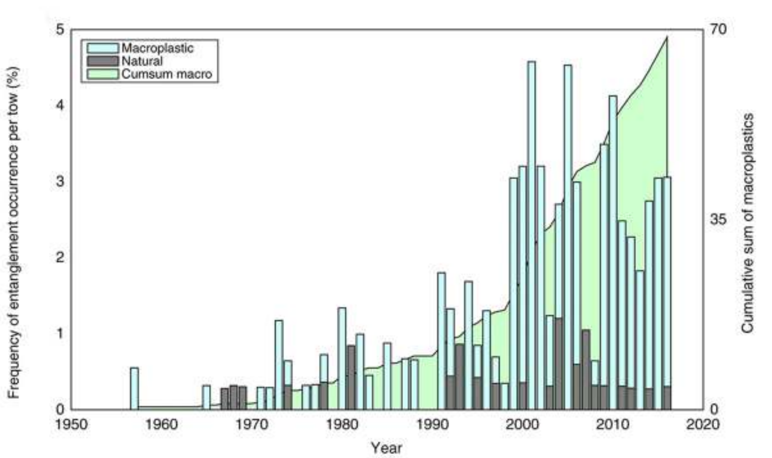

Figure 97: Increase in ocean plastics from 1957 to 2020.

Source: Ostle, C. et al. The rise in ocean plastics evidenced from a 60-year time series. Nat Commun 10, 1622 (2019). https://doi.org/10.1038/s41467-019-09506-1

According to the CDC's Autism and Developmental Disabilities Monitoring (ADDM) Network, 1 in 36 children in the United States was diagnosed with ASD in 2020, reflecting a 317 % increase in cases since 2000.[250, 251]

The human nervous system develops from the embryonic stage and through early childhood. Studies suggest a potential link between exposure to micro- and nanoplastics (MNPs) and the development of ASD. Experimental data from Korean researchers demonstrate that prenatal and postnatal exposure to MNPs may contribute to neurodevelopmental disorders.[252]

A study on the molecular effects of polystyrene nanoplastics on human neural stem cells showed that nanoplastic exposure can lead to tissue damage and neurodevelopmental diseases.[253]

Research on rodents[254] revealed that maternal exposure to micro- and nanoplastics during pregnancy and lactation can impair hippocampal neurogenesis in offspring and reduce the volume of brain structures, including the motor cortex, hippocampus, hypothalamus, medulla oblongata, and olfactory bulb.

It is well established that alterations in the structure and function of neural tissue proteins play a critical role in the development of numerous disorders, including autism.[255]

Recent studies indicate that nanoplastics interact with proteins primarily via weak interactions, such as hydrophobic interactions, hydrogen bonds, Van der Waals attraction forces, and electrostatic forces.[256] These interactions cause structural deformations in protein molecules, disrupting their functionality. Given the role of proteins in forming neural networks and synaptic transmission, such changes may contribute to the development of ASD.

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[250] Autism Parenting Magazine. Autism Statistics You Need To Know in 2024. (2025) https://www.autismparentingmagazine.com/autism-statistics (accessed 1 May 2025).

[251] Centers for Disease Control and Prevention. Autism Prevalence Higher, According to Data from 11 ADDM Communities. https://www.cdc.gov/media/releases/2023/p0323-autism.html (accessed 1 May 2025).

[252] Zaheer, J. et al. Pre/post-natal exposure to microplastic as a potential risk factor for autism spectrum disorder. Environment International 161, 107121 (2022). https://doi.org/10.1016/j.envint.2022.107121

[253] Martin-Folgar, R. et al. Molecular effects of polystyrene nanoplastics on human neural stem cells. PLOS ONE 19, e0295816 (2024). https://doi.org/10.1371/journal.pone.0295816

[254] Kim, N.-H., Choo, H.-I. & Lee, Y.-A. Effect of nanoplastic intake on the dopamine system during the development of male mice. Neuroscience 555, 11–22 (2024). https://doi.org/10.1016/j.neuroscience.2024.07.018

[255] Panisi, C. & Marini, M. Dynamic and Systemic Perspective in Autism Spectrum Disorders: A Change of Gaze in Research Opens to A New Landscape of Needs and Solutions. Brain Sciences 12, 250 (2022). https://doi.org/10.3390/brainsci12020250

[256] Windheim, J. et al. Micro- and Nanoplastics' Effects on Protein Folding and Amyloidosis. International Journal of Molecular Sciences 23, 10329 (2022). https://doi.org/10.3390/ijms231810329

Role of MNPs in the Pathogenesis of Cardiovascular Diseases

Plastic particles not only circulate in the bloodstream but can also settle on vascular walls, triggering a cascade of pathological changes. Particularly concerning is the detection of microplastics in atherosclerotic plaques.[257] A recent study found that patients with microplastics in their carotid arteries had a 4.5 times higher risk of heart attack, stroke, and death. This indicates that plastic fragments actively contribute to the formation and destabilization of atherosclerotic plaques, promoting their rupture and thrombus formation.[258] MNPs also impair the integrity of the endothelium, the critical layer of cells lining the inner surface of blood vessels, which regulates vascular tone, prevents thrombus formation, and mitigates inflammatory responses.

Endothelial damage caused by plastic particles leads to chronic inflammation and an increased risk of thrombosis, which is especially dangerous in arteries supplying the heart and brain.[259] Microplastics interact with blood components, such as platelets and red blood cells, promoting platelet aggregation and initiating clot formation. Additionally, the surface of microplastics can cause mechanical damage to cells and activate blood clotting cascades, potentially leading to chronic hypercoagulation and microvascular disorders over time.

Immune cells can engulf microplastic particles but lack the mechanisms to fully break them down, resulting in cell deformation and increased size. The accumulation of these altered cells in the small vessels of the brain contributes to microthrombus formation, impairing cerebral blood flow and elevating the risk of stroke, including in younger individuals.[260]

Chronic reduction in oxygen supply to the brain (hypoxia) leads to neuronal death and the development of neurodegenerative changes, including brain tissue atrophy.[261] Prolonged exposure to these processes may reduce the volume of specific brain structures.

Due to their electrostatic charge, MNPs actively interact with cellular membranes, disrupting their electrical potential. This, in turn, affects vascular contractility, signal transmission in myocytes, and heart rhythm.

Mortality from cardiovascular diseases continues to rise steadily worldwide (Fig. 98). Particular attention should be given to sudden cardiac death syndrome among young adults aged 25–44[262] (Fig. 99), which is recognized as a leading cause of death in the United States. Over the past two decades, the number of cases has surged dramatically. Given the widespread presence of MNPs, their potential role in these tragic events cannot be ruled out.

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[257] Liu, S. et al. Microplastics in three types of human arteries detected by pyrolysis-gas chromatography/mass spectrometry (Py-GC/MS). Journal of Hazardous Materials 469, 133855 (2024). https://doi.org/10.1016/j.jhazmat.2024.133855

[258] Marfella, R. et al. Microplastics and Nanoplastics in Atheromas and Cardiovascular Events. N Engl J Med 390, 900–910 (2024). https://doi.org/10.1056/NEJMoa2309822

[259] Rajendran, D. & Chandrasekaran, N. Journey of micronanoplastics with blood components. RSC Adv. 13, 31435–31459 (2023). https://doi.org/10.1039/D3RA05620A

[260] Huang, H. et al. Microplastics in the bloodstream can induce cerebral thrombosis by causing cell obstruction and lead to neurobehavioral abnormalities. Sci. Adv. 11, eadr8243 (2025). https://doi.org/10.1126/sciadv.adr8243

[261] Kaushik, A., Singh, A., Kumar Gupta, V. & Mishra, Y. K. Nano/micro-plastic, an invisible threat getting into the brain. Chemosphere 361, 142380 (2024). https://doi.org/10.1016/j.chemosphere.2024.142380

[262] Zuin, M. et al. Trends in Sudden Cardiac Death Among Adults Aged 25 to 44 Years in the United States: An Analysis of 2 Large US Databases. JAHA 14, e035722 (2025). https://doi.org/10.1161/JAHA.124.035722

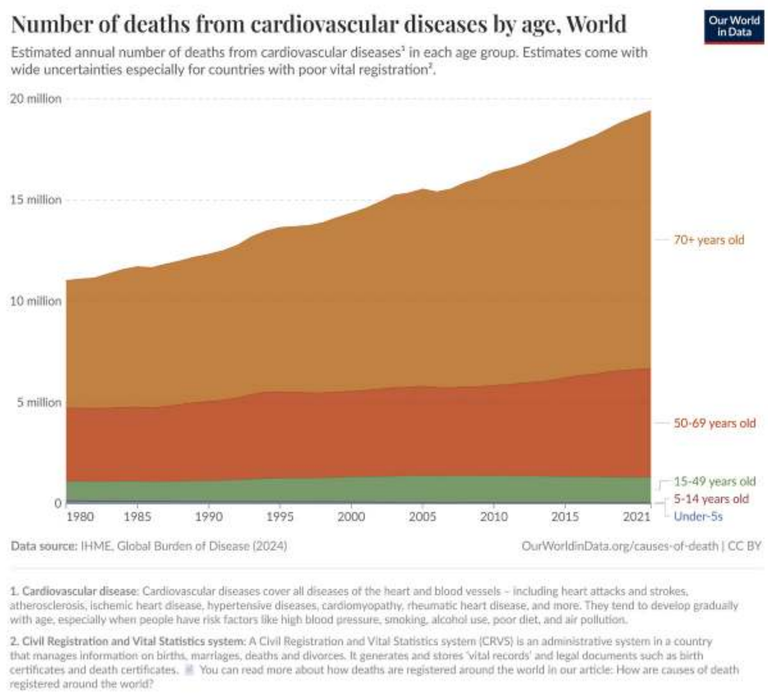

Figure 98: Number of deaths from cardiovascular diseases by age, worldwide

Source: Our World in Data. https://ourworldindata.org/grapher/cardiovascular-disease-deaths-by-age

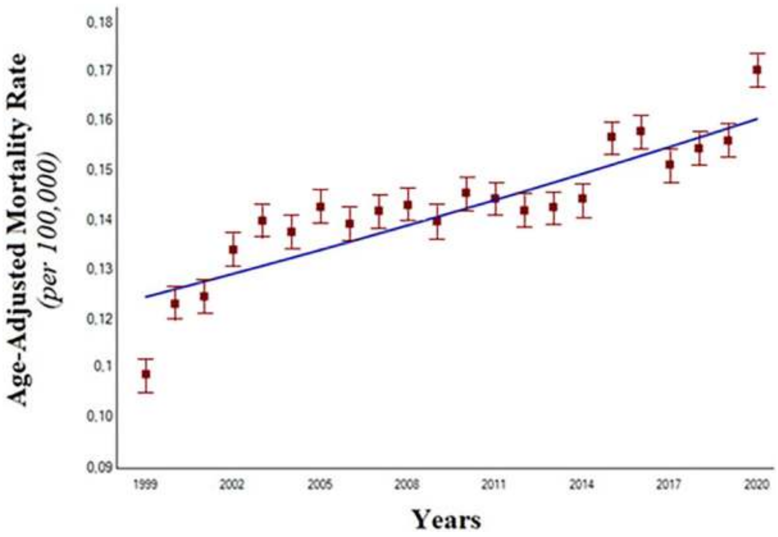

Figure 99: Trends in age-adjusted mortality rates due to sudden cardiac death, with associated 95% confidence intervals, in United States early adults, aged 25 to 44 years, 1999 to 2020.

Source: Zuin, M. et al. Trends in Sudden Cardiac Death Among Adults Aged 25 to 44 Years in the United States: An Analysis of 2 Large US Databases. JAHA 14, e035722 (2025). https://doi.org/10.1161/JAHA.124.035722

Another critical issue is the rise in sudden infant death syndrome (SIDS). In the United States alone, the rate of SIDS increased by 15% from 2019 to 2020, moving from the fourth to the third leading cause of infant mortality.[263] While the exact causes of SIDS remain unclear, many scientists suggest that factors disrupting the regulation of heart rhythm and vascular tone in infants may play a key role. Nanoplastics, capable of crossing the placenta and accumulating in the tissues of a developing fetus, are considered a likely risk factor. Increasingly, researchers are converging on the view that nanoplastics may be a key candidate for the role of an "invisible killer."

[263]Shapiro-Mendoza, C. K. et al. Sudden Unexpected Infant Deaths: 2015–2020. Pediatrics 151, e2022058820 (2023). https://doi.org/10.1542/peds.2022-058820

The heart, one of the body's most energy-demanding organs, critically depends on the efficient functioning of mitochondria to supply its energy needs. Exposure to microplastic particles disrupts mitochondrial processes, potentially leading to energy deficits in the myocardium and, consequently, impaired cardiac function.

Gastrointestinal Dysfunction Due to MNP Exposure

The gut is the body's largest immune organ, housing approximately 70% of all immune cells, around 500 million neurons, and over 100 trillion microorganisms.[264] The gut microbiota plays a vital role in maintaining immune health, and its imbalance can weaken immunity and contribute to various diseases. Often referred to as the "second brain" due to its dense neural network and ability to communicate with the central nervous system,[265] the gut engages in complex biochemical signaling with the brain through the "gut–brain axis," which significantly influences both physical and psycho-emotional health (Fig. 100).

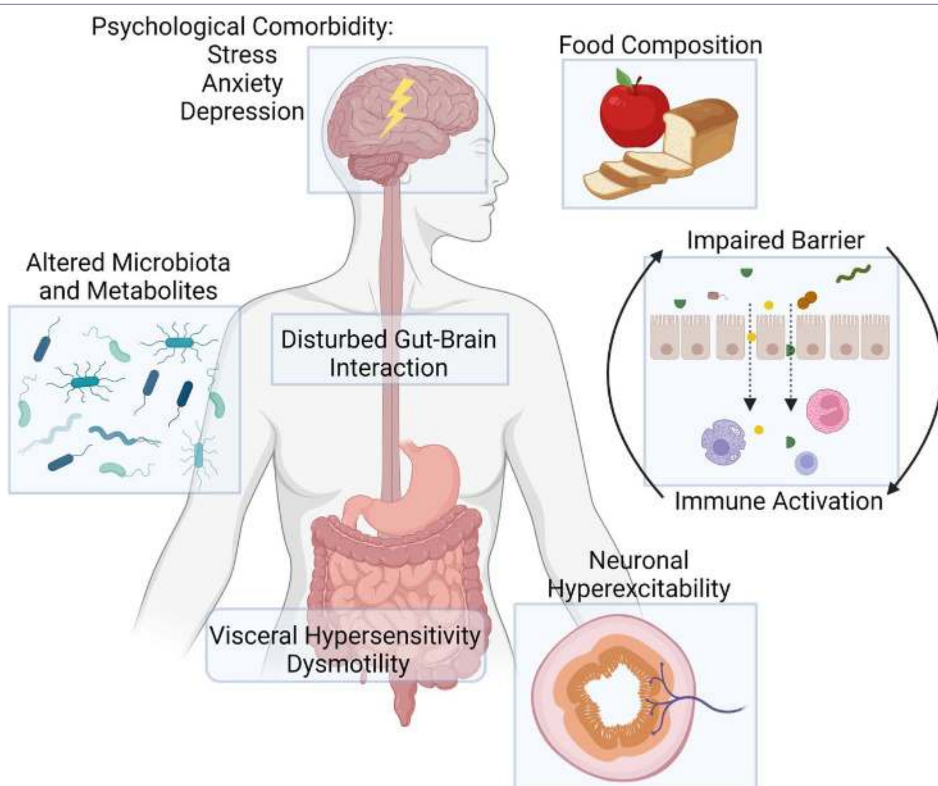

Figure 100: Pathophysiological mechanisms in disorders of gut–brain interaction.
Source: Vanuytsel, T., Bercik, P. & Boeckxstaens, G. Understanding neuroimmune interactions in disorders of gut–brain interaction: from functional to immune-mediated disorders. Gut 72, 787–798 (2023). https://doi.org/10.1136/gutjnl-2020-320633

264 Yu, C. D., Xu, Q. J. & Chang, R. B. Vagal sensory neurons and gut-brain signaling. Current Opinion in Neurobiology 62, 133–140 (2020). https://doi.org/10.1016/j.conb.2020.03.006

265 Sofield, C. E., Anderton, R. S. & Gorecki, A. M. Mind over Microplastics: Exploring Microplastic-Induced Gut Disruption and Gut-Brain-Axis Consequences. Current Issues in Molecular Biology 46, 4186–4202 (2024). https://doi.org/10.3390/cimb46050256

A healthy gut barrier prevents microbes and foreign particles from passing from the gut lumen into the bloodstream.[265] Micro- and nanoplastics compromise this barrier, increasing intestinal wall permeability. This leads to inflammation in the gut and other organs, weakening immunity. Simultaneously, MNPs alter the composition of the gut microbiota, causing an imbalance between beneficial and pathogenic microorganisms.[266] This disrupts digestion, reduces the body's ability to break down food allergens, and heightens the risk of food allergies.[267]

This creates a vicious cycle: plastic disrupts the gut microbiota, increases inflammation, and compromises the integrity of the intestinal wall. As a result, toxins, bacteria, and plastic particles begin to enter the bloodstream. Their presence in the blood triggers an immune response that leads to chronic inflammation throughout the body. From the bloodstream, these toxins, bacteria, and nanoplastics can cross the blood-brain barrier and reach the brain, where they provoke inflammatory reactions. In turn, these processes further impair immune response, heighten the body's stress response, and may negatively affect the gut microbiota through neuroendocrine mechanisms—thus closing the vicious cycle along the "gut–brain" axis. Disruption of the interaction between the gut microbiome and the central nervous system is directly linked to neurological disorders. For instance, children with autism spectrum disorders exhibit significant microbiota imbalances, confirmed by microbiological analysis and assessments of digestive system function.[268]

Studies of patients with inflammatory bowel disease show a positive correlation between disease severity and microplastic concentration in feces. Patients with inflammatory bowel diseases have higher microplastic levels (41.8 particles/g) compared to healthy individuals (28.0 particles/g). Additionally, significant microplastic accumulation was observed in ulcerative lesions of the rectal mucosa in these patients.[269] Furthermore, microplastics remaining in the gut continue to exert harmful effects long after their initial entry into the body.

Impacts of MNPs on the Immune System

MNPs disrupt the immune response in the body, creating conditions conducive to the proliferation of pathogens. Charged MNPs attract other molecules more easily—such as toxins, heavy metal salts, bacteria, and viruses (see Fig. 101). This makes them a kind of "transport platform" for toxic compounds, amplifying the biological activity and toxicity of these substances. The electrostatic charge on nanoplastics also acts like an energy source or "battery," helping viruses and bacteria stay viable for longer periods.

In addition, charged micro- and nanoplastic particles can remain suspended in water and air for extended periods. They rise more easily into aerosols and enter the respiratory system, increasing the likelihood of their absorption into the human body.

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[265] Sofield, C. E., Anderton, R. S. & Gorecki, A. M. Mind over Microplastics: Exploring Microplastic-Induced Gut Disruption and Gut-Brain-Axis Consequences. Current Issues in Molecular Biology 46, 4186–4202 (2024). https://doi.org/10.3390/cimb46050256

[266] Winiarska, E., Jutel, M. & Zemelka-Wiacek, M. The potential impact of nano- and microplastics on human health: Understanding human health risks. Environmental Research 251, 118535 (2024). https://doi.org/10.1016/j.envres.2024.118535

[267] Bora, S. S. et al. Microplastics and human health: unveiling the gut microbiome disruption and chronic disease risks. Front. Cell. Infect. Microbiol. 14, 1492759 (2024). https://doi.org/10.3389/fcimb.2024.1492759

[268] Su, Q., Wong, O.W.H., Lu, W. et al. Multikingdom and functional gut microbiota markers for autism spectrum disorder. Nat Microbiol 9, 2344–2355 (2024). https://doi.org/10.1038/s41564-024-01739-1

[269] Yan, Z. et al. Analysis of Microplastics in Human Feces Reveals a Correlation between Fecal Microplastics and Inflammatory Bowel Disease Status. Environ. Sci. Technol. 56, 414–421 (2022). https://doi.org/10.1021/acs.est.1c03924

The cumulative effects of MNP on the microbiome, pathogens, and the immune system pose complex health risks. Immune cells that come into contact with microplastics die approximately three times faster than those that do not encounter them.[270]

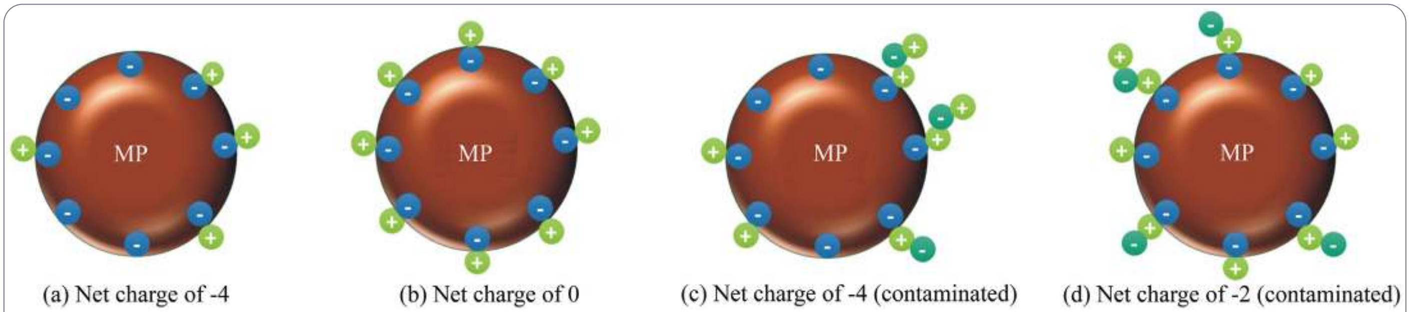

Figure 101: Illustration of the effect of microplastic surface charges caused by water contaminants.
Source: Rahman, A. M. N. A. A. et al. A review of microplastic surface interactions in water and potential capturing methods. Water Science and Engineering 17, 361–370 (2024).
https://doi.org/10.1016/j.wse.2023.11.008

Microplastic particles are capable of adsorbing viruses onto their surfaces due to electrostatic and hydrophobic interactions, thereby extending their viability.[271] Viruses on the surface of microplastics can remain active for up to three days — sufficient time to travel from wastewater treatment facilities to beaches, for example.[272] Microplastics facilitate the spread of pathogens and may contribute to their genetic recombination. Research has shown that plastic particles not only impair the effectiveness of medications but can also induce the development of antibiotic-resistant bacterial strains.[273] Charged particles of micro- and nanoplastics serve as platforms for the colonization of microorganisms.[274] Bacteria and fungi, utilizing the electrostatic fields of nanoplastics, exhibit accelerated growth. Research on daphnia has shown that exposure to nanoplastics induces oxidative stress and increases the incidence of fungal infections by a factor of 11 (specifically the species Metschnikowia).[275] This aligns with the global expansion of the range and resistance of fungal diseases, which the WHO has identified as an increasing threat to public health.

> ***"Emerging from the shadows of the bacterial antimicrobial resistance pandemic, fungal infections are growing, and are ever more resistant to treatments, becoming a public health concern worldwide"*** said Dr Hanan Balkhy, WHO Assistant Director-General, Antimicrobial Resistance.[276]

[270]Plastics News. Study highlights health hazards of microplastics. (2019) https://www.plasticsnews.com/news/study-highlights-health-hazards-microplastics (accessed 1 May 2025).
[271]Moresco, V. et al. Binding, recovery, and infectiousness of enveloped and non-enveloped viruses associated with plastic pollution in surface water. Environmental Pollution 308, 119594 (2022). https://doi.org/10.1016/j.envpol.2022.119594
[272]University of Stirling. Hitch-hiking viruses can survive on microplastics in freshwater, new study finds. (2022) https://www.stir.ac.uk/news/2022/june-2022-news/hitch-hiking-viruses-can-survive-on-microplastics-in-freshwater-new-study-finds (accessed 1 May 2025).
[273]Dick, L. et al. The adsorption of drugs on nanoplastics has severe biological impact. Sci Rep 14, 25853 (2024). https://doi.org/10.1038/s41598-024-75785-4
[274]Rahman, A. M. N. A. A. et al. A review of microplastic surface interactions in water and potential capturing methods. Water Science and Engineering 17, 361–370 (2024). https://doi.org/10.1016/j.wse.2023.11.008
[275]Manzi, F., Schlösser, P., Owczarz, A. & Wolinska, J. Polystyrene nanoplastics differentially influence the outcome of infection by two microparasites of the host Daphnia magna. Phil. Trans. R. Soc. B 378, 20220013 (2023). https://doi.org/10.1098/rstb.2022.0013
[276]World Health Organization. WHO releases first-ever list of health-threatening fungi. (2022) https://www.who.int/news/item/25-10-2022-who-releases-first-ever-list-of-health-threatening-fungi (accessed 1 May 2025).

Fungal metabolites released in the presence of micro- and nanoplastics are associated with tumor growth [277] and chronic inflammation. Fungal DNA has been detected in specific types of cancer, indicating a potential role for micro- and nanoplastics in carcinogenesis.[278]

Carcinogenic Properties of MNPs: Mutation Pathways and Metastatic Progression

As mentioned in previous sections of this report, micro- and nanoplastics are significant factors in the development of malignant tumors, given their negative impact at both the cellular and systemic levels.

Research indicates that microplastics and nanoplastics may act as hidden catalysts for tumor progression, particularly through enhancing cell migration and fueling metastasis.[279] It has also been found that MNP particles can persist within cells for extended periods and be passed on to daughter cells during division.

Currently, the mortality rate from oncological diseases continues to rise globally (Fig. 102).

It is projected that by 2050, the number of new cancer cases will increase by 77%.[280]

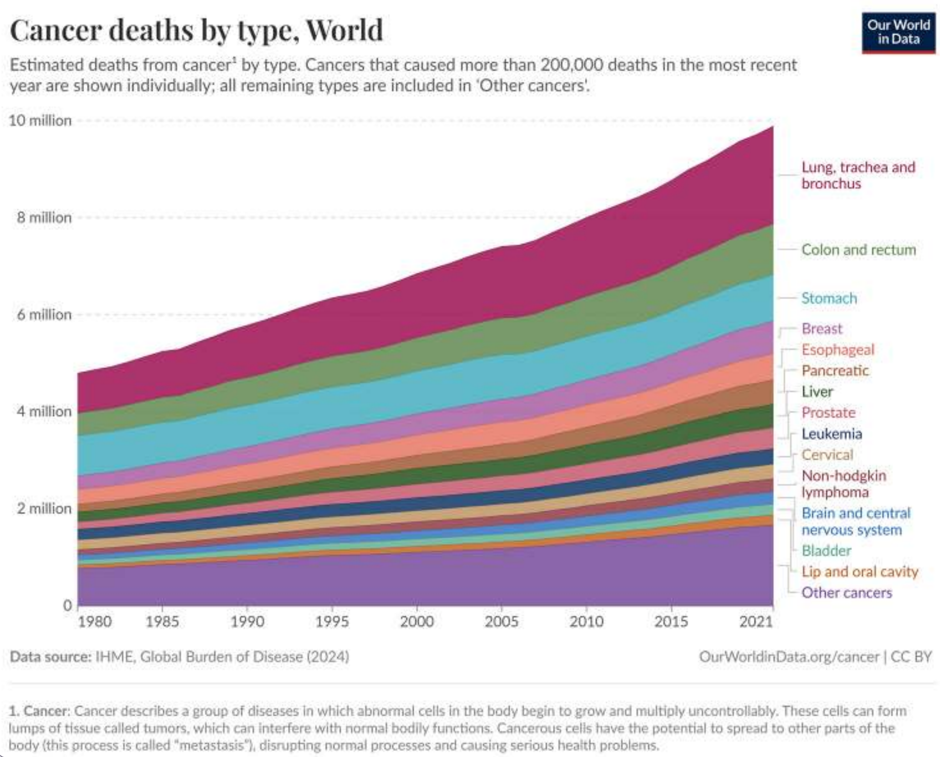

Figure 102: Cancer deaths by type, World

Source: Our World in Data https://ourworldindata.org/grapher/cancer-deaths-by-type-grouped

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[277] Aykut, B., Pushalkar, S., Chen, R. et al. The fungal mycobiome promotes pancreatic oncogenesis via activation of MBL. Nature 574, 264–267 (2019). https://doi.org/10.1038/s41586-019-1608-2

[278] Dohlman, A. B. et al. A pan-cancer mycobiome analysis reveals fungal involvement in gastrointestinal and lung tumors. Cell 185, 3807-3822.e12 (2022). https://doi.org/10.1016/j.cell.2022.09.015

[279] Brynzak-Schreiber, E. et al. Microplastics role in cell migration and distribution during cancer cell division. Chemosphere 353, 141463 (2024). https://doi.org/10.1016/j.chemosphere.2024.141463

[280] World Health Organization. Global cancer burden growing, amidst mounting need for services. (2024) https://www.who.int/news/item/01-02-2024-global-cancer-burden-growing--amidst-mounting-need-for-services (accessed 1 May 2025).

Effects of MNPs on Calcium Metabolism and Bone Structure

Plastic particles can infiltrate even the musculoskeletal system — the foundation of human physical function (Fig. 103). In a realm where a precise balance exists between destruction and construction, where bones are renewed daily, joints mitigate friction, and muscles support movement and warmth, microplastics — partly due to their electrostatic charge — can substitute for building molecules and initiate slow, destructive processes.

Research shows that microplastics can penetrate bone tissue, where their molecular structure allows them to mimic calcium and other minerals essential for bone metabolism. As a result, plastic may be mistakenly perceived by the body as a building material for bones. The body literally begins to "build" bones from plastic.

This disruption in molecular recognition is associated with a range of negative consequences: microplastics can impair the functions of osteoblasts and osteoclasts, disrupt calcium and phosphorus metabolism, thereby contributing to the development of osteoporosis. Inflammatory cascades are triggered, gene expression is altered, and bone tissue loses density and strength. Additionally, the presence of nanoplastics may cause chronic inflammation, damaging joint cartilage and bone tissue, which is linked to an increased risk of osteoarthritis, pain syndromes, and stiffness in movement.[281, 282]

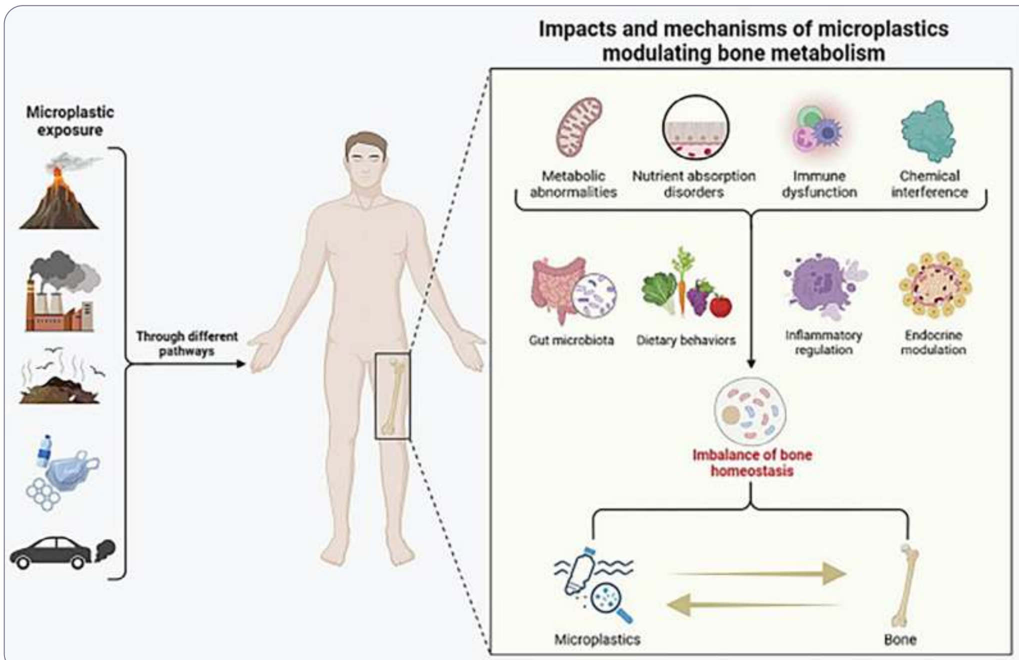

Figure 103: Impacts and mechanisms of microplastics modulating the bone metabolism. Source: Zhang, Y.-W. et al. Bridging relevance between microplastics, human health and bone metabolism: Emerging threats and research directions. Environmental Chemistry and Ecotoxicology 6, 422–435 (2024). https://doi.org/10.1016/j.enceco.2024.08.006

[281]Zhang, Y.-W. et al. Bridging relevance between microplastics, human health and bone metabolism: Emerging threats and research directions. Environmental Chemistry and Ecotoxicology 6, 422–435 (2024). https://doi.org/10.1016/j.enceco.2024.08.006
[282]China Environment News. Microplastics "secretly attack" the human body, how much damage can they cause? (2025) https://cenews.com.cn/news.html?aid=1205048 (accessed 1 May 2025).

Research on rodents has demonstrated that the number of osteoblasts significantly decreased in mice exposed to polystyrene microplastics.[280]

Plastic poses a considerable threat to skeletal muscle as well. Studies show that nanoplastics can infiltrate muscle cells, disrupting mitochondrial function. This leads to an energy deficit, activates aggressive forms of reactive oxygen species, accelerates cellular aging, impairs muscle recovery after exertion, and contributes to muscle atrophy. Older adults and patients with chronic illnesses are particularly vulnerable.

Micro- and nanoplastics accumulate in bone marrow,[283] disrupting the formation of stem cells (both hematopoietic and mesenchymal),[284] from which red blood cells, white blood cells, platelets, osteocytes, chondrocytes, and adipocytes are derived. Their dysfunction results in systemic damage to the body.

Reproductive Disorders Associated With MNP Exposure: Infertility and Erectile Dysfunction

Declining Fertility

Predictions indicate that by 2045, the world may become completely infertile.[285]

As early as 2018, a group of leading physicians and scientists at the **XIII International Symposium on Spermatology** in Stockholm urged governments to recognize the decline in male fertility as a serious public health issue and to acknowledge the importance of male reproductive health for the survival of the human species.[286]

Contrary to popular belief, reproductive health is not solely determined by hormonal balance, genetics, and lifestyle. An increasing number of scientific studies point to the critical role of mitochondria in the processes of conception and embryo development. These tiny organelles, responsible for producing the energy necessary for all life processes, play a crucial role in fertility for both men and women, and their significance for human reproductive function is proving to be much deeper than previously understood.

Dysfunctions in mitochondrial activity can be a cause of infertility in both women and men. In men, mitochondria located in the tail of sperm are responsible for the motility necessary for fertilization. Malfunctions in their operation reduce sperm motility and can lead to abnormalities.

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[280] World Health Organization. Global cancer burden growing, amidst mounting need for services. (2024) https://www.who.int/news/item/01-02-2024-global-cancer-burden-growing--amidst-mounting-need-for-services (accessed 1 May 2025).
[283] Guo, X. et al. Discovery and analysis of microplastics in human bone marrow. Journal of Hazardous Materials 477, 135266 (2024). https://doi.org/10.1016/j.jhazmat.2024.135266
[284] Sun, R. et al. Preliminary study on impacts of polystyrene microplastics on the hematological system and gene expression in bone marrow cells of mice. Ecotoxicology and Environmental Safety 218, 112296 (2021). https://doi.org/10.1016/j.ecoenv.2021.112296
[285] The Guardian. Shanna Swan: 'Most couples may have to use assisted reproduction by 2045'. (2021) https://www.theguardian.com/society/2021/mar/28/shanna-swan-fertility-reproduction-count-down (accessed 1 May 2025).
[286] Levine, H. et al. Male reproductive health statement (XIIIth international symposium on Spermatology, may 9th–12th 2018, Stockholm, Sweden. Basic Clin. Androl. 28, 13 (2018). https://doi.org/10.1186/s12610-018-0077-z

Studies conducted by Chinese scientists have found microplastics in all sperm samples, averaging two particles measuring up to 7 micrometers, most commonly polystyrene.[287] The presence of microplastics is associated with morphological abnormalities in sperm and shortened telomeres. Due to their microscopic size and charge, nanoplastics can cross the blood-testis barrier and infiltrate the reproductive organs, disrupting their functions. Particular concern is raised by the observed trend of a 62.3% decline in the overall sperm count in men from 1973 to 2018[288] (Fig. 104).

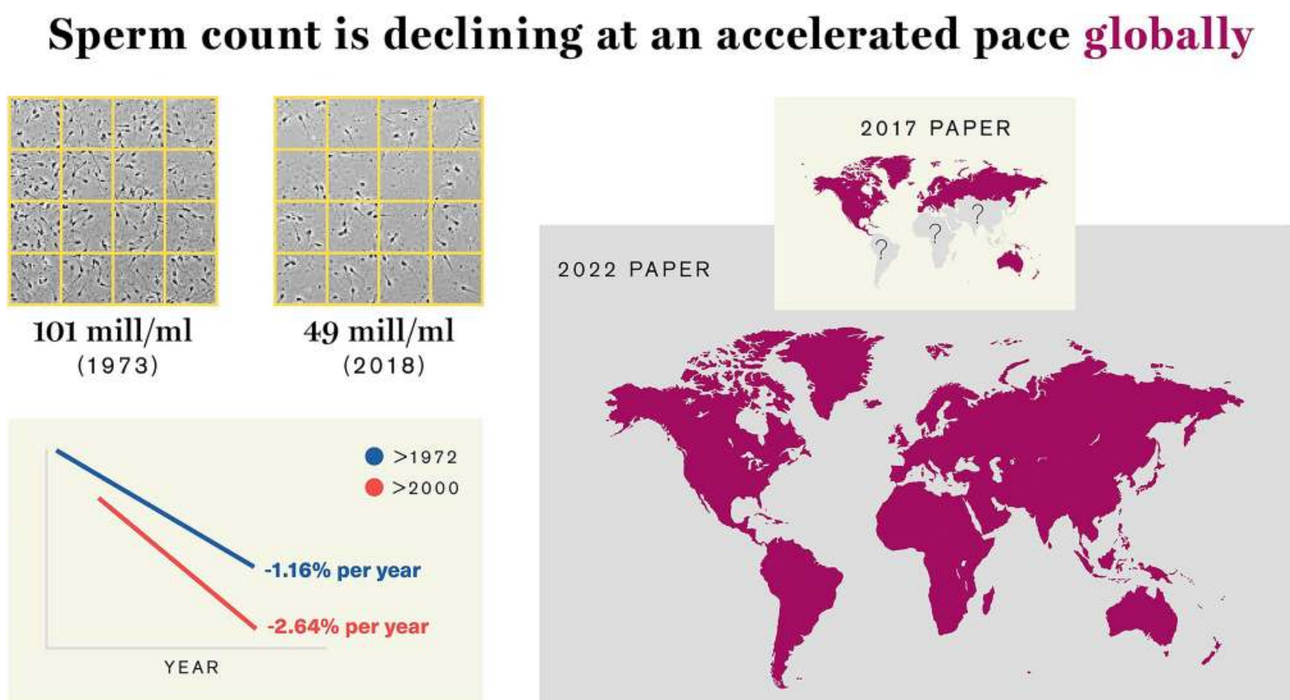

Figure 104: Graphical abstract: Sperm counts are declining at an accelerating rate worldwide
Source: Levine, H. et al. Temporal trends in sperm count: a systematic review and meta-regression analysis of samples collected globally in the 20th and 21st centuries. Human Reproduction Update 29, 157–176 (2023). https://doi.org/10.1093/humupd/dmac035

While many factors influence fertility, an increasing number of scientists are leaning toward the view that chemical compounds found in plastics play a key role in this process. Phthalates, used to make plastics flexible, disrupt hormonal balance, reduce libido, and may contribute to premature sexual maturation and testicular dysfunction.

The situation regarding female fertility is equally concerning. A 2025 study found microplastic particles in the follicular fluid of the ovaries in 14 out of 18 women, averaging over 2,000 particles per milliliter, most of which were less than 5 micrometers in diameter[289] (Fig. 105).

[287]Li, N. et al. Prevalence and implications of microplastic contaminants in general human seminal fluid: A Raman spectroscopic study. Science of The Total Environment 937, 173522 (2024). https://doi.org/10.1016/j.scitotenv.2024.173522
[288]Levine, H. et al. Temporal trends in sperm count: a systematic review and meta-regression analysis of samples collected globally in the 20th and 21st centuries. Human Reproduction Update 29, 157–176 (2023). https://doi.org/10.1093/humupd/dmac035
[289]Montano, L. et al. First evidence of microplastics in human ovarian follicular fluid: An emerging threat to female fertility. Ecotoxicology and Environmental Safety 291, 117868 (2025). https://doi.org/10.1016/j.ecoenv.2025.117868

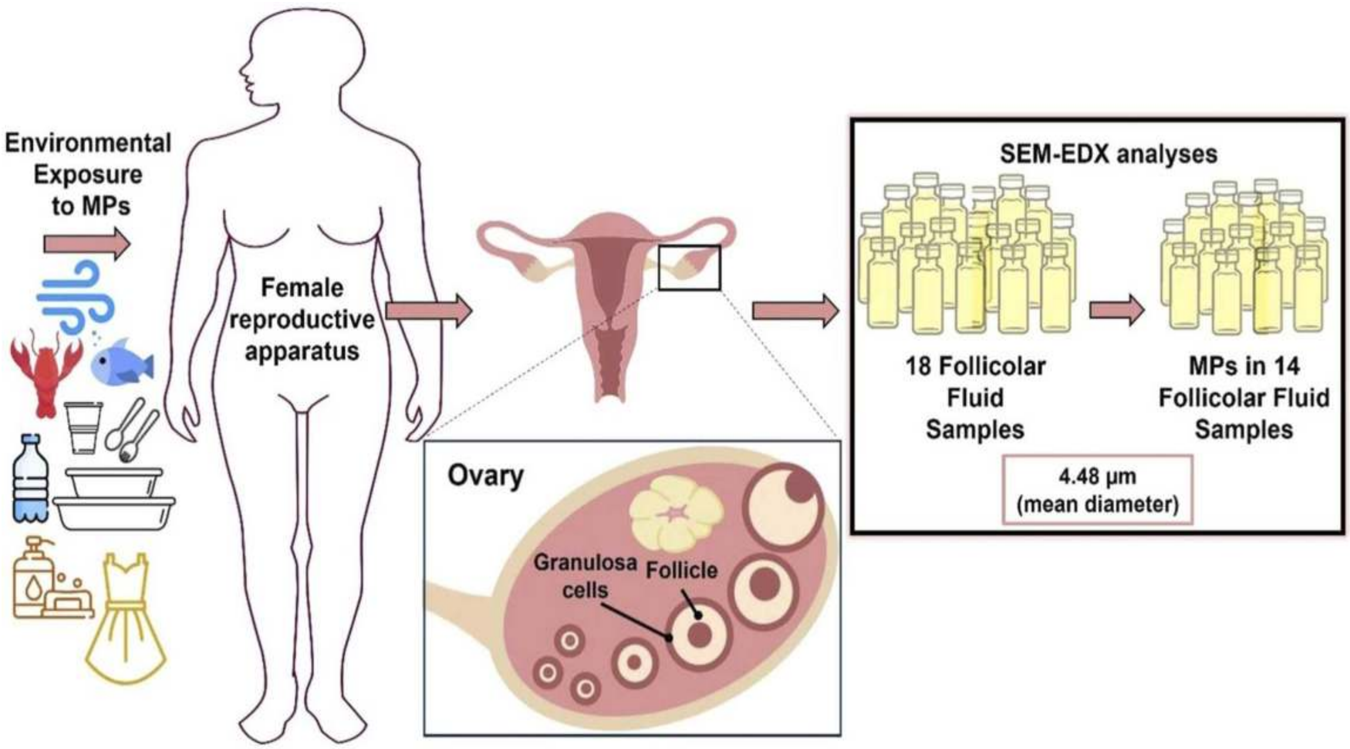

Figure 105: Schematization of the mechanism by which MPs pass into the ovarian follicular fluid: through environmental exposure (inhalation, ingestion and dermal contact) they enter the human body, reaching the female reproductive apparatus, particularly crossing the blood-follicle barrier.
Source: Montano, L. et al. First evidence of microplastics in human ovarian follicular fluid: An emerging threat to female fertility. Ecotoxicology and Environmental Safety 291, 117868 (2025).
https://doi.org/10.1016/j.ecoenv.2025.117868

These data indicate the ability of plastic particles to cross the hematofollicular barrier in the ovaries. At the cellular level, micro- and nanoplastics can damage DNA, disrupt cell division, and induce inflammation. Their interference with hormonal regulation, impairment of placental functions, influence on angiogenesis, and association with the development of uterine fibroids have been demonstrated.

Erectile Dysfunction

Results from a national study in Japan revealed a decline in erectile function and sexual activity among younger generations.[290] Assessment based on the Erection Hardness Score (EHS) identified a 30.9% prevalence of erectile dysfunction (ED), affecting approximately 14 million men. Sexual desire, erection rigidity, orgasms, and satisfaction were lower than expected among young Japanese men, particularly those aged 20–24, though these factors tended to worsen with age. Notably, the prevalence rate in the 20–24 age group was 26.6%, nearly equivalent to that of the 50–54 age group (27.8%) (Fig. 106, 107).

[290] Tsujimura, A. et al. Erectile Function and Sexual Activity Are Declining in the Younger Generation: Results from a National Survey in Japan. The World Journal of Men's Health 43, 239–248 (2025). https://doi.org/10.5534/wjmh.240137

Additionally, a separate global study reported that three out of four men experience symptoms of ED, indicating that the condition is not rare and may affect men of any age.

Japan's first official national survey on sexual function, conducted in 1998, estimated approximately 11.3 million men with moderate to complete ED. Additionally, national surveys on male infertility in Japan, conducted in 1996 and 2015, revealed striking data. In the 2015 study, 13.5% of men faced male infertility due to ED as the primary cause, nearly four times higher than in 1996.

The collective body of current scientific evidence suggests that micro- and nanoplastics in the body are a hidden but significant cause of declining reproductive health. These particles infiltrate reproductive organs, impair mitochondrial function, cause inflammation, disrupt hormonal balance, and damage DNA, reducing sperm motility and morphological quality. Their presence in semen and follicular fluid indicates their ability to cross biological barriers and exert profound systemic effects. This poses a threat not only to individual health but also to the future reproductive capacity of humanity as a whole.

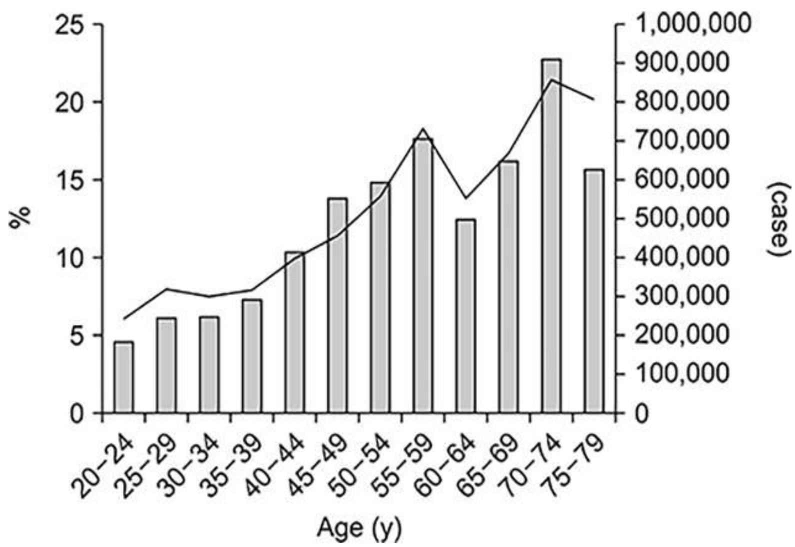

Figure 106: Prevalence and number of patients with erectile dysfunction as evaluated by the prevalence of erectile dysfunction (ED) estimated from the question "Do you feel troubled by ED?".

Source: Tsujimura, A. et al. Erectile Function and Sexual Activity Are Declining in the Younger Generation: Results from a National Survey in Japan. The World Journal of Men's Health 43, 239–248 (2025). https://doi.org/10.5534/wjmh.240137

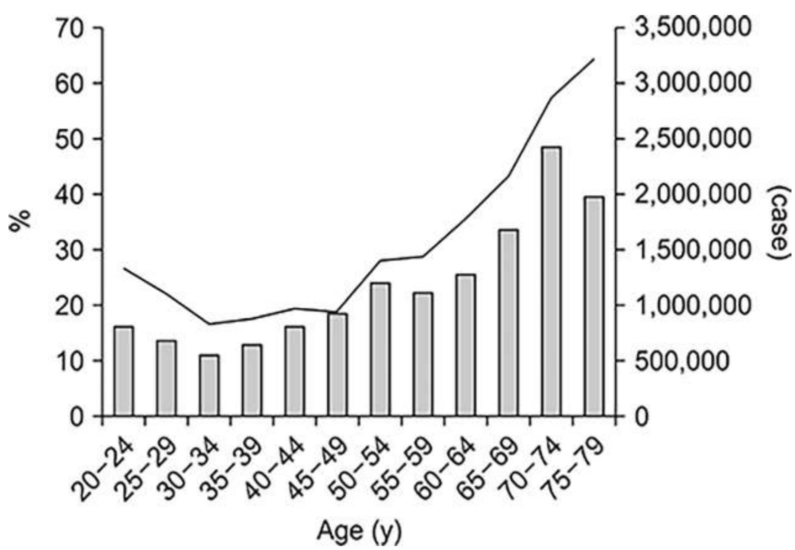

Figure 107: Graph showing the prevalence and number of patients with erectile dysfunction as evaluated by the Erection Hardness Score

Source: Tsujimura, A. et al. Erectile Function and Sexual Activity Are Declining in the Younger Generation: Results from a National Survey in Japan. The World Journal of Men's Health 43, 239–248 (2025). https://doi.org/10.5534/wjmh.240137

MNP Penetration Through the Placental Barrier and Its Effects on the Developing Body

Prenatal Exposure to Micro- and Nanoplastics on the Fetus

Pregnant women are particularly vulnerable to the effects of microplastics.[291] Plastic particles that enter the mother's body can cross the placenta, interfering with the secretion of hormones that regulate pregnancy and increasing the risk of preterm birth, miscarriage, and fetal developmental disorders (Fig. 108). In 2020, an estimated 13.4 million children (1 in 10) were born preterm (<37 weeks), making it a leading cause of infant mortality. Surviving preterm infants face a higher risk of serious illnesses and chronic conditions.[292]

The developing endocrine system of children is highly sensitive to chemicals in plastics, which can mimic or block hormones[293] (Fig. 109). Exposure to infants can even occur through breast milk. Additionally, nanoplastics may have delayed effects, disrupting the formation of reproductive cells during childhood and adolescence, potentially reducing fertility in adulthood.

The blood–placenta barrier (BPB) plays a critical role in regulating the exchange of substances between mother and fetus, protecting the fetus from harmful agents. However, studies show that micro- and nanoplastics can penetrate BPB. In 2020, a study led by Antonio Ragusa using Raman microspectroscopy (a method that analyzes light scattering to determine the chemical composition of materials) detected microplastics in the placentas of four out of six women with normal pregnancies. The samples contained 12 particles ranging 5–10 μm, including polypropylene and pigments used in cosmetics, paints, adhesives, and hygiene products.[294]

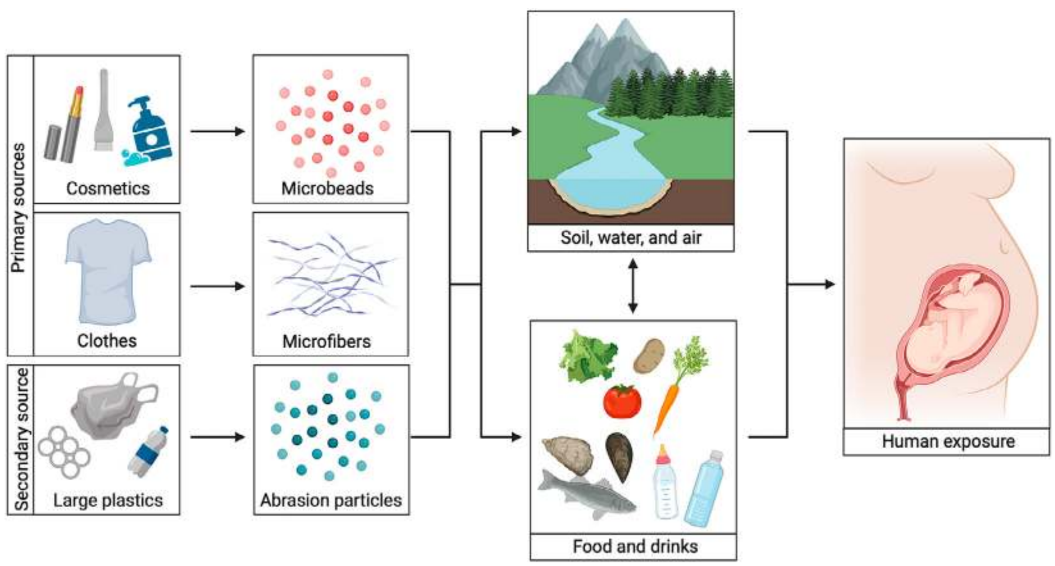

Figure 108: Maternal exposure to microplastics
Source: Hofstede, L. T., Vasse, G. F. & Melgert, B. N. Microplastics: A threat for developing and repairing organs? Cambridge Prisms: Plastics 1, e19 (2023). https://doi.org/10.1017/plc.2023.19

[291] Dugershaw-Kurzer, B. et al. Nanoparticles Dysregulate the Human Placental Secretome with Consequences on Angiogenesis and Vascularization. Advanced Science 11, 2401060 (2024). https://doi.org/10.1002/advs.202401060
[292] World Health Organization. 1 in 10 babies worldwide are born early, with major impacts on health and survival. (2023) https://www.who.int/news/item/06-10-2023-1-in-10-babies-worldwide-are-born-early--with-major-impacts-on-health-and-survival (accessed 1 May 2025).
[293] Sharma, R. K. et al. Impact of Microplastics on Pregnancy and Fetal Development: A Systematic Review. Cureus 16, e60712 (2024). https://doi.org/10.7759/cureus.60712
[294] Ragusa, A. et al. Plasticenta: First evidence of microplastics in human placenta. Environment International 146, 106274 (2021). https://doi.org/10.1016/j.envint.2020.106274

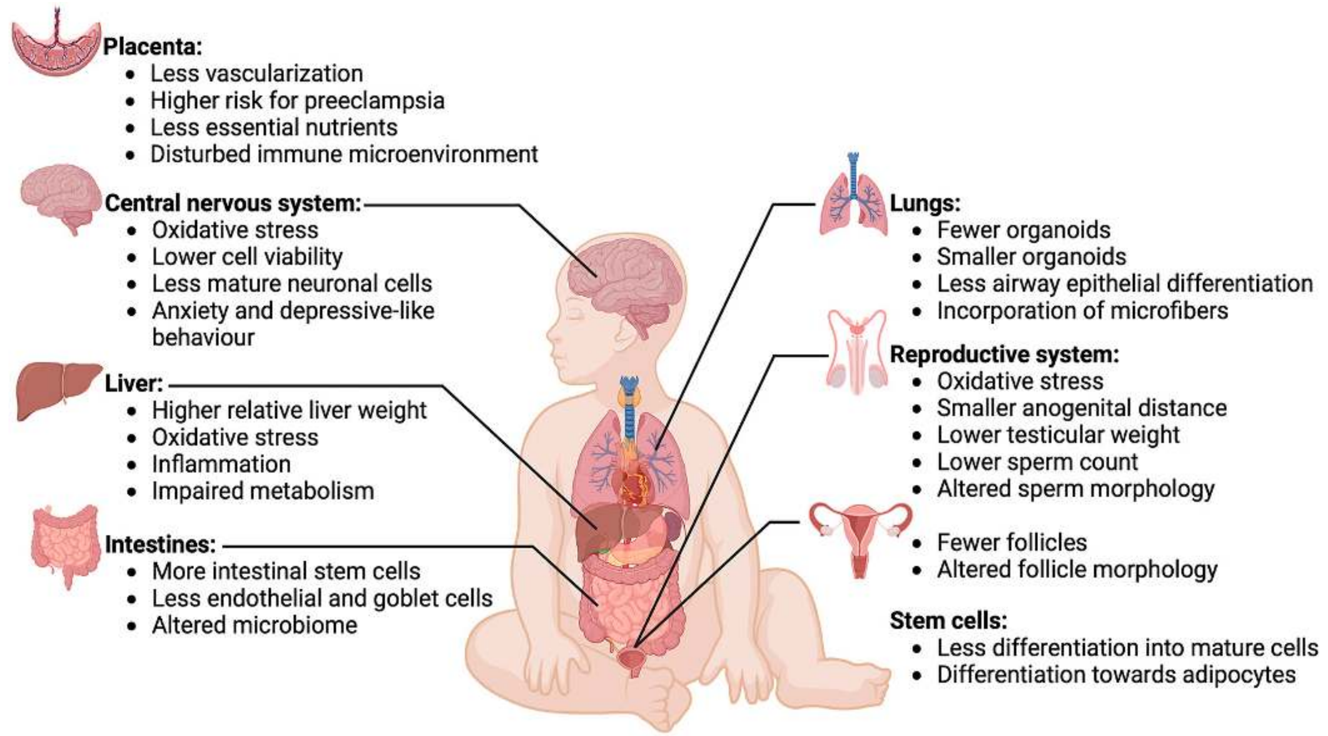

Figure 109: Effects of microplastics on various organs and tissues of a developing fetus
Source: Hofstede, L. T., Vasse, G. F. & Melgert, B. N. Microplastics: A threat for developing and repairing organs? Cambridge Prisms: Plastics 1, e19 (2023). https://doi.org/10.1017/plc.2023.19

A study conducted by the University of New Mexico found that the concentration of micro- and nanoplastics in the placentas of preterm infants is higher than in those of full-term infants. Analysis of 158 placentas using mass spectrometry revealed that women who gave birth prematurely had greater accumulation of plastic particles.[295]

> *“Nanoparticles apparently have an indirect effect on the child in the womb by inhibiting the formation of blood vessels via messenger substances,”* said biologist Tina Bürki.[296]

Nanometer-sized polystyrene particles can cause brain developmental disorders, especially cognitive deficits.[297] According to research, exposure to microplastics during pregnancy and the first few months of life may result in permanent alterations to the reproductive axis and central nervous system in the offspring of different species.[298]

[295]Jochum, M. et al. Elevated Micro- and Nanoplastics Detected in Preterm Human Placentae. Preprint (2025). https://doi.org/10.21203/rs.3.rs-5903715/v1
[296]Federal Office of Public Health. Impact of pollution on embryonic development - Nanoparticles: Risk for babies in the womb. FOPH. (2024) https://www.bit.admin.ch/en/nsb?id=101285 (accessed 1 May 2025).
[297]Jeong, B. et al. Maternal exposure to polystyrene nanoplastics causes brain abnormalities in progeny. Journal of Hazardous Materials 426, 127815 (2022). https://doi.org/10.1016/j.jhazmat.2021.127815
[298]Sharma, R. K. et al. Impact of Microplastics on Pregnancy and Fetal Development: A Systematic Review. Cureus 16, e60712 (2024). https://doi.org/10.7759/cureus.60712

Postnatal Exposure to Micro- and Nanoplastics in Infants

Newborns face continuous exposure to micro- and nanoplastics (MNPs) from the environment. A 2020 study[299] found that infants can ingest up to 4.5 million plastic particles per day solely from feeding with polypropylene bottles, which constitute the majority of baby bottles used worldwide.

Infants may also ingest microplastics through breast milk. In 2022, an analysis of breast milk from 34 healthy women detected microplastics in 76% of the samples[300](Fig. 110). MNPs can have delayed effects, disrupting the development of reproductive cells during childhood and adolescence, which can reduce fertility in adulthood.Additional data show that MNP levels in infant feces are 14 times higher than in adults.[301]

Nanoplastics and associated chemicals disrupt the molecular structure and functionality of breast milk. These compounds can alter proteins in human breast milk and infant formulas, potentially leading to developmental issues later in life.[302, 303]

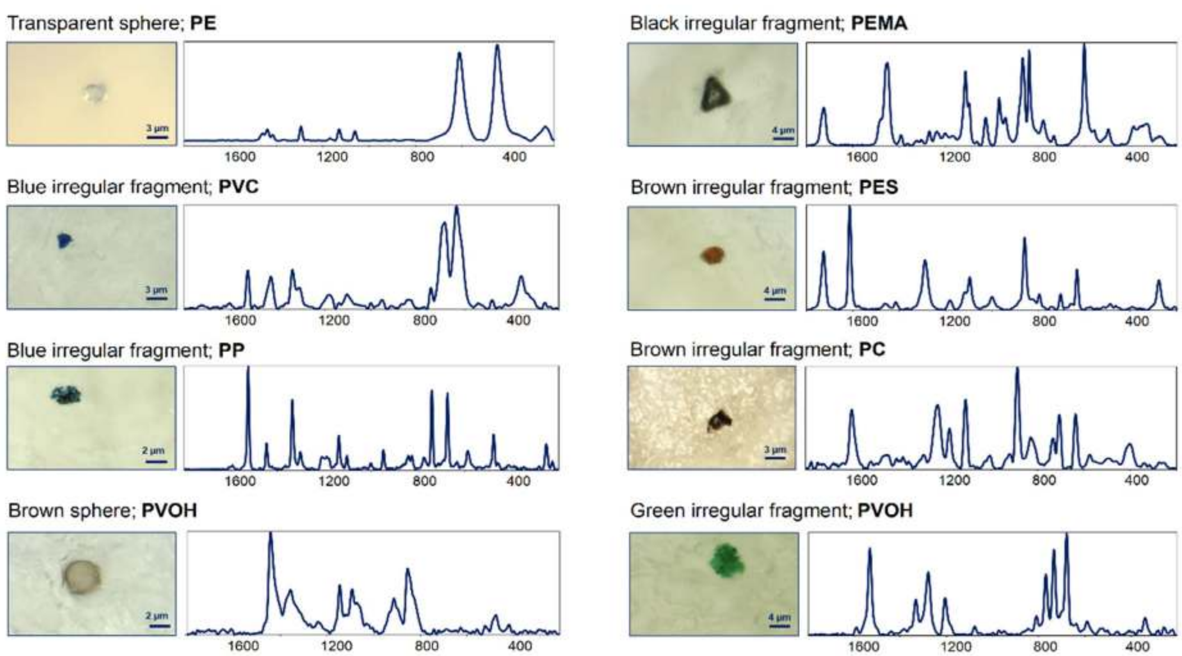

Figure 110: Microphotographs and Raman spectra (wavenumbers, cm−1) of some selected MPs found in the analysed breastmilk samples. PE: polyethylene; PVC: polyvinyl chloride; PP: polypropylene; PVOH: polyvinyl alcohol; PEVA: poly(ethylene-co-vinyl acetate); PEMA: poly(ethyl methacrylate); PES: polyester, and PC: polycarbonate. Source: Ragusa, A. et al. Raman Microspectroscopy Detection and Characterisation of Microplastics in Human Breastmilk. Polymers 14, 2700 (2022). https://doi.org/10.3390/polym14132700

[299]Li, D., Shi, Y., Yang, L. et al. Microplastic release from the degradation of polypropylene feeding bottles during infant formula preparation. Nat Food 1, 746–754 (2020). https://doi.org/10.1038/s43016-020-00171-y

[300]Ragusa, A. et al. Raman Microspectroscopy Detection and Characterisation of Microplastics in Human Breastmilk. Polymers 14, 2700 (2022). https://doi.org/10.3390/polym14132700

[301]Zhang, J., Wang, L., Trasande, L. & Kannan, K. Occurrence of Polyethylene Terephthalate and Polycarbonate Microplastics in Infant and Adult Feces. Environ. Sci. Technol. Lett. 8, 989–994 (2021). https://doi.org/10.1021/acs.estlett.1c00559

[302]Yadav, A., Vuković, L. & Narayan, M. An Atomic and Molecular Insight into How PFOA Reduces α-Helicity, Compromises Substrate Binding, and Creates Binding Pockets in a Model Globular Protein. J. Am. Chem. Soc. 146, 12766–12777 (2024). https://doi.org/10.1021/jacs.4c02934

[303]Karim, A. et al. Interfacial Interactions between Nanoplastics and Biological Systems: toward an Atomic and Molecular Understanding of Plastics-Driven Biological Dyshomeostasis. ACS Appl. Mater. Interfaces 16, 25740–25756 (2024). https://doi.org/10.1021/acsami.4c03008

High concentrations of MNPs exert a cumulative toxic effect on the developing body. Nanoplastics, by penetrating cells, can cause structural DNA damage and disrupt metabolic processes. These effects increase the risk of genetic mutations and long-term pathologies, posing a threat to the health of future generations.

Effects of MNP Exposure and Its Link to Congenital Abnormalities

Beyond its ability to infiltrate tissues and cells, micro- and nanoplastics (MNPs) possess another dangerous characteristic: they can be "inherited" by future generations. During cell division, fragments of MNPs are transferred from one cell to another. Due to their minuscule size and electrostatic charge, these particles can easily cross the blood–placenta barrier and enter fetal tissues and cells, exerting harmful effects on the developing organism. As emphasized throughout this report, one of the primary consequences of micro- and nanoplastic exposure is mitochondrial dysfunction.

A recent Mendelian randomized study has provided compelling evidence of a causal link between the expression of mitochondrial proteins and the risk of congenital anomalies. The study used genetic variants as instrumental variables to reduce the biases typically associated with observational data. Among 66 mitochondrial protein traits examined, significant associations were found with developmental defects of the heart, ear, nervous system, genitourinary system, and limbs. These findings support the hypothesis that mitochondrial activity plays a critical role in embryonic morphogenesis.[304]

Mutations in mitochondrial DNA (mtDNA), whether inherited or occurring de novo, are responsible for a wide range of clinical syndromes including MELAS, MERRF, NARP, Leigh Syndrome, and others. These mutations primarily affect organs with high energy demands—such as the heart, brain, muscles, and eyes. Transmission occurs exclusively through the maternal line due to the mitochondrial origin of the oocyte (Fig. 111). These disorders often manifest early in life and are characterized by severe neurological and metabolic impairments.

Children with mitochondrial disorders often face developmental delays, muscle weakness, cognitive impairments, and coordination issues. Conditions such as Kearns-Sayre syndrome, Barth syndrome, Alpers' disease, and others can lead to severe outcomes, including disability or even death.

Over the past two decades, physicians have reported a concerning rise in congenital birth defects among newborns. In China alone, the incidence nearly tripled—from 99.15 per 10,000 births in 2005 to 290.27 per 10,000 in 2022 (Fig. 112).[305] Similar trends have been observed in other countries as well. While this surge is driven by multiple factors, a growing body of scientific evidence points to a new and rapidly escalating threat: microplastics, and especially nanoplastics, which are capable of penetrating embryonic tissues and interfering with the formation of organs and biological systems.

[304]Li, X. et al. Mitochondrial proteins and congenital birth defect risk: a mendelian randomization study. BMC Pregnancy Childbirth 25, 444 (2025). https://doi.org/10.1186/s12884-025-07562-8

[305]Wei, W. et al. Analyzing the Trends and Causes of Birth Defects — Jinan City, Shandong Province, China, 2005–2022. CCDCW 5, 978–983 (2023). https://doi.org/10.46234/ccdcw2023.184

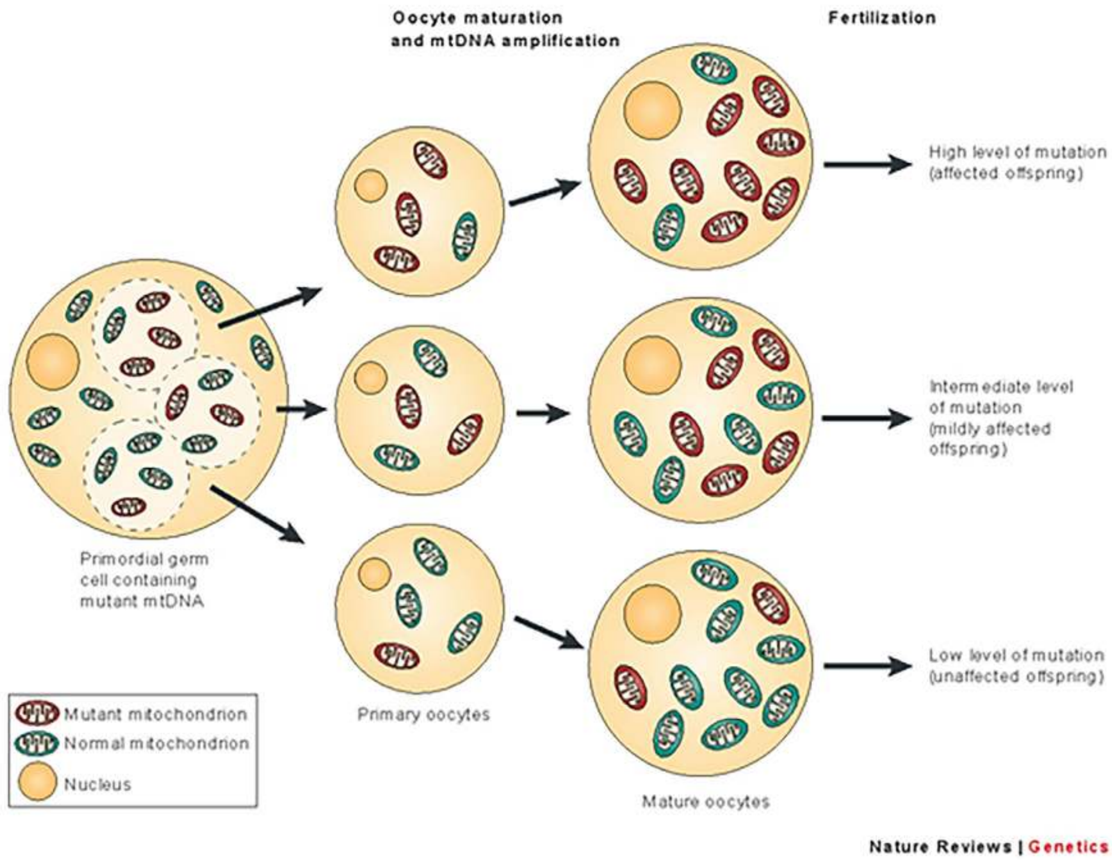

Figure 111: The mitochondrial genetic bottleneck.

During the production of primary oocytes, a selected number of mitochondrial DNA (mtDNA) molecules are transferred into each oocyte. Oocyte maturation is associated with the rapid replication of this mtDNA population. This restriction-amplification event can lead to a random shift of mtDNA mutational load between generations and is responsible for the variable levels of mutated mtDNA observed in affected offspring from mothers with pathogenic mtDNA mutations. Mitochondria that contain mutated mtDNA are shown in red, those with normal mtDNA are shown in green.

Source: Taylor, R., Turnbull, D. Mitochondrial DNA mutations in human disease. Nat Rev Genet 6, 389–402 (2005). https://doi.org/10.1038/nrg1606

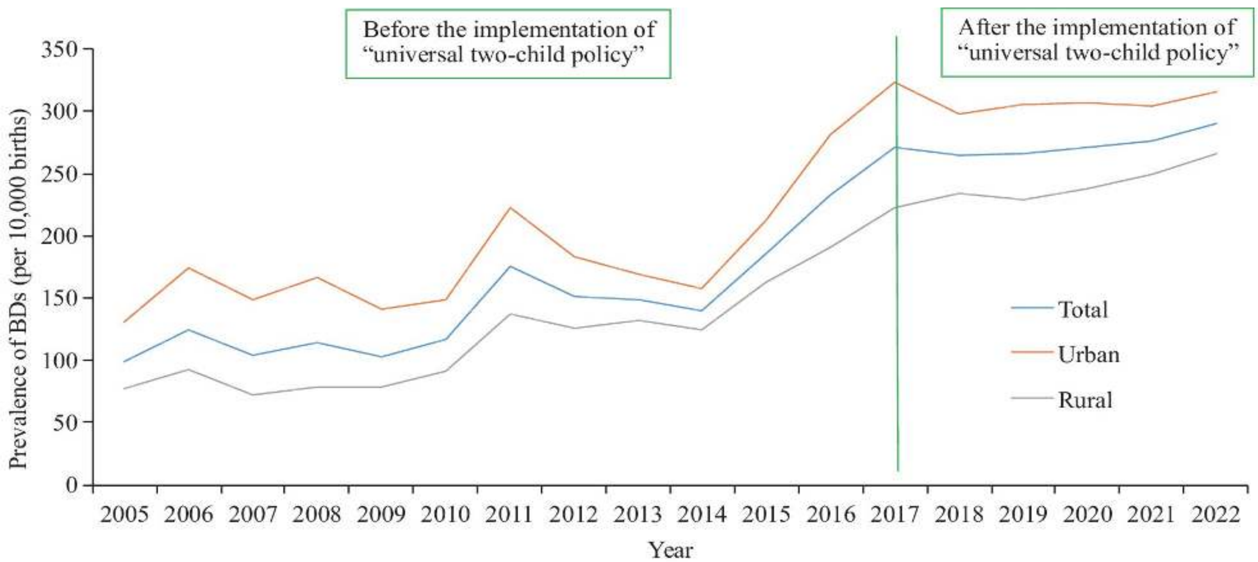

Figure 112: The prevalence of birth defects between urban areas and rural areas from 2005 to 2020. Source: Wei, W. et al. Analyzing the Trends and Causes of Birth Defects — Jinan City, Shandong Province, China, 2005–2022. CCDCW 5, 978–983 (2023). https://doi.org/10.46234/ccdcw2023.184

The electrostatic charge carried by nanoplastics poses a particular threat to embryonic tissues, where even a single error can result in a developmental abnormality. These particles exhibit increased adhesion to cell surfaces, including neural crest cells — key players in the formation of the heart, blood vessels, and craniofacial structures. In experimental studies on chicken embryos, nanoplastics induced severe defects, including malformations of the heart and major vessels. One of the most rapidly increasing abnormalities is gastroschisis — a developmental defect of the anterior abdominal wall in which fetal organs protrude outside the body through an opening in the skin and muscle (Figs. 113, 114, 115). According to international data, the prevalence of this condition has risen by 161% over the past three decades, with rates among mothers under the age of 20 increased severalfold.[306] It is hypothesized that nanoplastics interfere with abdominal wall development during early pregnancy (weeks 4–8), triggering inflammation and disrupting the closure of the ventral body wall.

Figure 113-115: Gastroschisis

[306] Feldkamp, M. L. et al. Gastroschisis prevalence patterns in 27 surveillance programs from 24 countries, International Clearinghouse for Birth Defects Surveillance and Research, 1980–2017. Birth Defects Research 116, e2306 (2024). https://doi.org/10.1002/bdr2.2306

Another condition—hypospadias, a congenital defect in which the urethra in boys opens in an abnormal location[307]—has also shown a steady increase (Fig. 116, 117, 118). For example, in the United States, from 1997 to 2018, the incidence of hypospadias increased by approximately 1.06 cases per 1,000 live male births (from 6.1 to 7.16 per 1,000), representing a roughly 17% rise.[308] Studies using animal models have shown that exposure to phthalates—chemicals commonly found in microplastics—disrupts testosterone synthesis in male fetuses.

Figure 116-118: Hypospadias

These substances, anchored to the charged surface of nanoplastics, are easily transported into the bloodstream and placenta, amplifying hormonal disruptions during critical periods of sexual differentiation. Against this backdrop, there has been an increase in the incidence of Down syndrome, trisomy, atrioventricular heart defects, and other serious conditions, rising from 12.78 per 10,000 live births in 1999–2001 to 15.55 per 10,000 in 2016–2020.[309]

Concurrently, there is a rise in neuropsychiatric issues among children, including anxiety disorders and cognitive deficits. While a direct causal link with microplastics is still under investigation, known mechanisms — such as inflammation, epigenetic modulation, and mitochondrial dysfunction — provide grounds to suspect microplastics as a contributing factor.[307, 310]

[307]Chen, M. J., Karaviti, L. P., Roth, D. R. & Schlomer, B. J. Birth prevalence of hypospadias and hypospadias risk factors in newborn males in the United States from 1997 to 2012. Journal of Pediatric Urology 14, 425.e1-425.e7 (2018). https://doi.org/10.1016/j.jpurol.2018.08.024
[308]Lavoie, C. et al. Comparing the incidence of hypospadias across the United States: A contemporary analysis. Journal of Pediatric Urology 21, 627–632 (2025). https://doi.org/10.1016/j.jpurol.2025.01.002
[309]Stallings, E. B. et al. National population-based estimates for major birth defects, 2016–2020. Birth Defects Research 116, e2301 (2024). https://doi.org/10.1002/bdr2.2301
[310]Zhang, Y., Wang, J., Yang, H. & Guan, Y. The potential mechanisms underlying phthalate-induced hypospadias: a systematic review of rodent model studies. Front. Endocrinol. 15, (2024). https://doi.org/10.3389/fendo.2024.1490011
[311]Chen, M. J., Karaviti, L. P., Roth, D. R. & Schlomer, B. J. Birth prevalence of hypospadias and hypospadias risk factors in newborn males in the United States from 1997 to 2012. Journal of Pediatric Urology 14, 425.e1-425.e7 (2018). https://doi.org/10.1016/j.jpurol.2018.08.024

Conclusions and Prospects.
Is It Possible to Reduce the Impact of MNPs on Human Health?

The analysis of aggregated data demonstrates that micro- and nanoplastics represent a significant and underestimated risk factor for human health. Current scientific evidence strongly indicates that MNPs are an integral part of the global toxic burden on the human body. Due to their ability to cross biological barriers and accumulate in various tissues — including the brain, heart, lungs, and placenta — MNPs exert toxic effects at molecular, cellular, and systemic levels. In combination with chemical additives and environmental pollutants adsorbed onto their surfaces, plastic particles act as triggers for chronic inflammation, oxidative stress, mitochondrial dysfunction, and DNA mutations — processes underlying a wide range of diseases, including neurodegenerative, oncological, cardiovascular, endocrine, and autoimmune disorders. Particularly alarming is the fact that MNP particles are virtually non-excretable, accumulating in the body with age and intensifying their cumulative impact.

Current evidence confirms that avoiding exposure to MNPs is virtually impossible: they are present in the air we breathe, the water we drink, the food we eat, and even within the cells of animals and plants we consume. As a result, human exposure to plastic particles is both ubiquitous and continuous, from prenatal development through the final stages of life. Inhalation is particularly concerning, as nanoparticles can bypass the blood–brain barrier and accumulate directly in brain tissue, making the central nervous system one of the most vulnerable targets.

An additional biological risk stems from the electrostatic activity of MNPs, which enhances their interaction with biological structures and disrupts cellular homeostasis. Moreover, MNPs may act as carriers for pathogens and antibiotic-resistant microorganisms, giving plastic pollution a distinctly interdisciplinary dimension — one that intersects ecology, toxicology, immunology, neurology, and reproductive medicine.

In this regard, one of the strategic directions proposed by ALLATRA as part of a broader effort to counter the threat of MNPs is the development of methods to neutralize or shield the electrostatic charge of nanoplastics. Reducing the electrostatic activity of such particles could significantly lower their harmful effects and slow their accumulation in the body. According to the authors of this report, charge shielding or neutralization methods may reduce the potential risks associated with MNPs by at least 50 %. This could provide crucial time to develop more comprehensive strategies for diagnosing, preventing, and removing MNPs from the body. In this context, further research in the fields of biophysics, nanotechnology, and molecular toxicology becomes especially important.

Despite the growing number of scientific publications on this topic, the impact of MNPs on human health remains poorly understood and insufficiently considered in the development of public health and environmental protection strategies. Given the scale of plastic pollution, the biological activity of these particles, and the potentially irreversible consequences of their effects, this area demands urgent attention from the scientific community and health authorities. It also calls for the systematization of existing data, the development of standardized risk assessment frameworks, and the expansion of intergovernmental and international scientific collaboration.

ANALYSIS OF MODERN STRATEGIES FOR REDUCING PLASTIC POLLUTION

Technologies for Removing Large Plastic Debris From Aquatic Ecosystems

Mitigation efforts aimed to address ocean pollution have primarily focused on removing visible, large debris from the water's surface. One of the most ambitious projects to date is *The Ocean Cleanup* initiative, which targets the collection of plastics and other types of floating waste. Its floating systems capture surface-level debris (Fig. 119), which is then sorted and prepared for recycling or disposal.

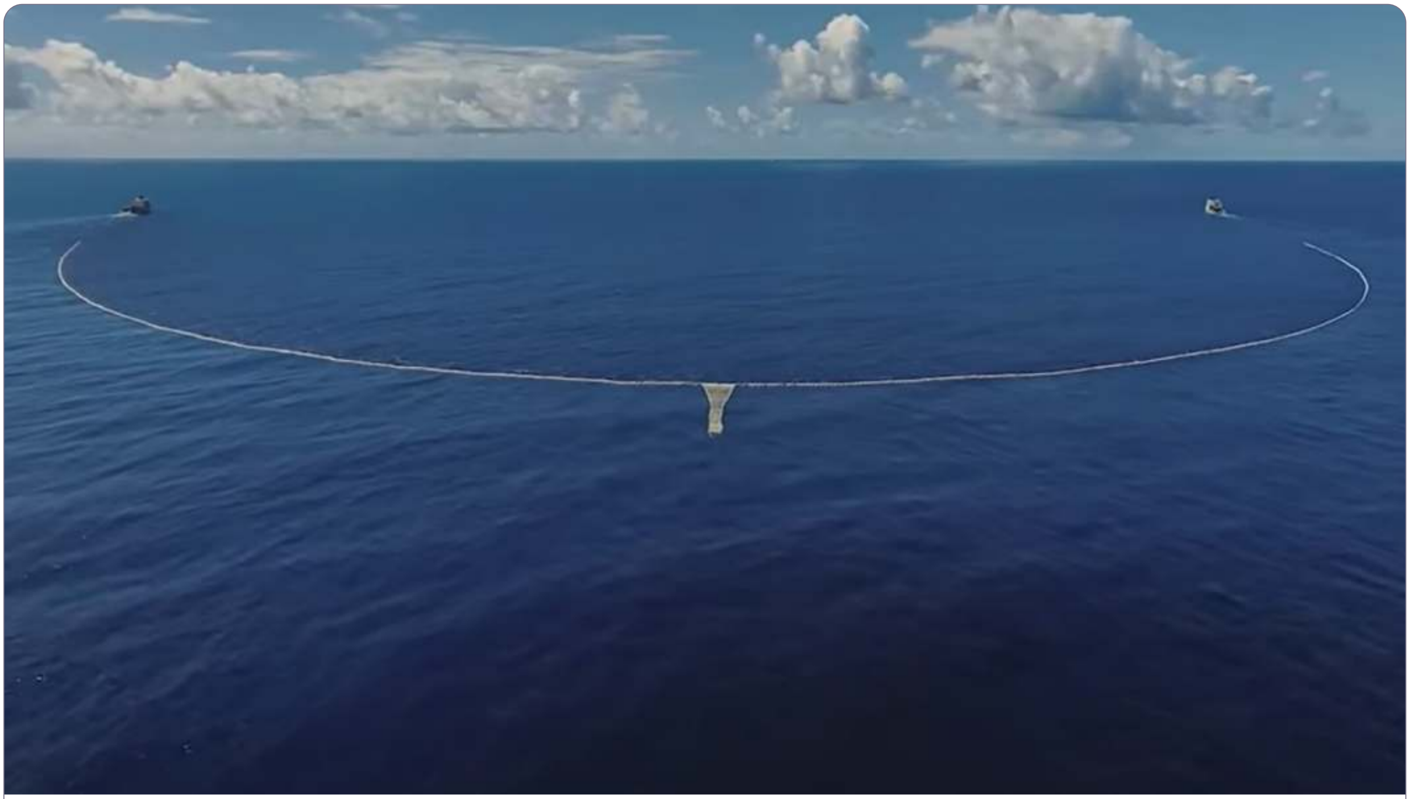

Figure 119: The image shows the Ocean Cleanup technology in action. A long, U-shaped floating barrier made of durable material collects plastic debris from the ocean surface.
Source: The Ocean Cleanup. Cleaning up plastic pollution from the oceans.
https://theoceancleanup.com (accessed 1 May 2025).

While this method shows promise, several critical issues must be considered:

1. The debris collection process is not selective, meaning that along with plastic waste, living organisms — such as microscopic algae, fish larvae, and jellyfish — may also be captured. Currently, there are no quantitative assessments of the volume of bycatch, but the potential large-scale removal of these organisms could have harmful consequences for marine ecosystems by disrupting natural food chains. Despite measures aimed at protecting marine life, the issue remains unresolved.

2. Activists are genuinely committed to cleaning the ocean, yet **the current efforts remain insufficient to yield meaningful results.**

As of November 2024, *The Ocean Cleanup* initiative has removed approximately 20,000 tons of plastic waste from the world's oceans. This is undoubtedly a noteworthy achievement. However, against a backdrop of the global crisis, it accounts for only 0.01% of the estimated 200 million tons of plastic currently polluting the ocean. Furthermore, it is important to factor in the ongoing influx of new waste, which amounts to approximately 11 million tons annually (Fig. 120). These figures underscore the vast disproportion between cleanup efforts and the scale of the problem.

3. **The key issue remains the fate of the collected plastic.** Current global recycling rates for plastic waste do not exceed 9 % (Fig. 121). As a result, there is a strong likelihood that a significant portion of the recovered plastic will end up in landfills, which fails to address pollution over the long term.

Figure 120: The chart compares three key metrics related to plastic pollution in the oceans: the estimated mass of floating plastic debris, the annual input of plastic into the ocean, and the quantity collected by *The Ocean Cleanup*. Data source: The Ocean Cleanup. https://theoceancleanup.com (accessed 1 May 2025).

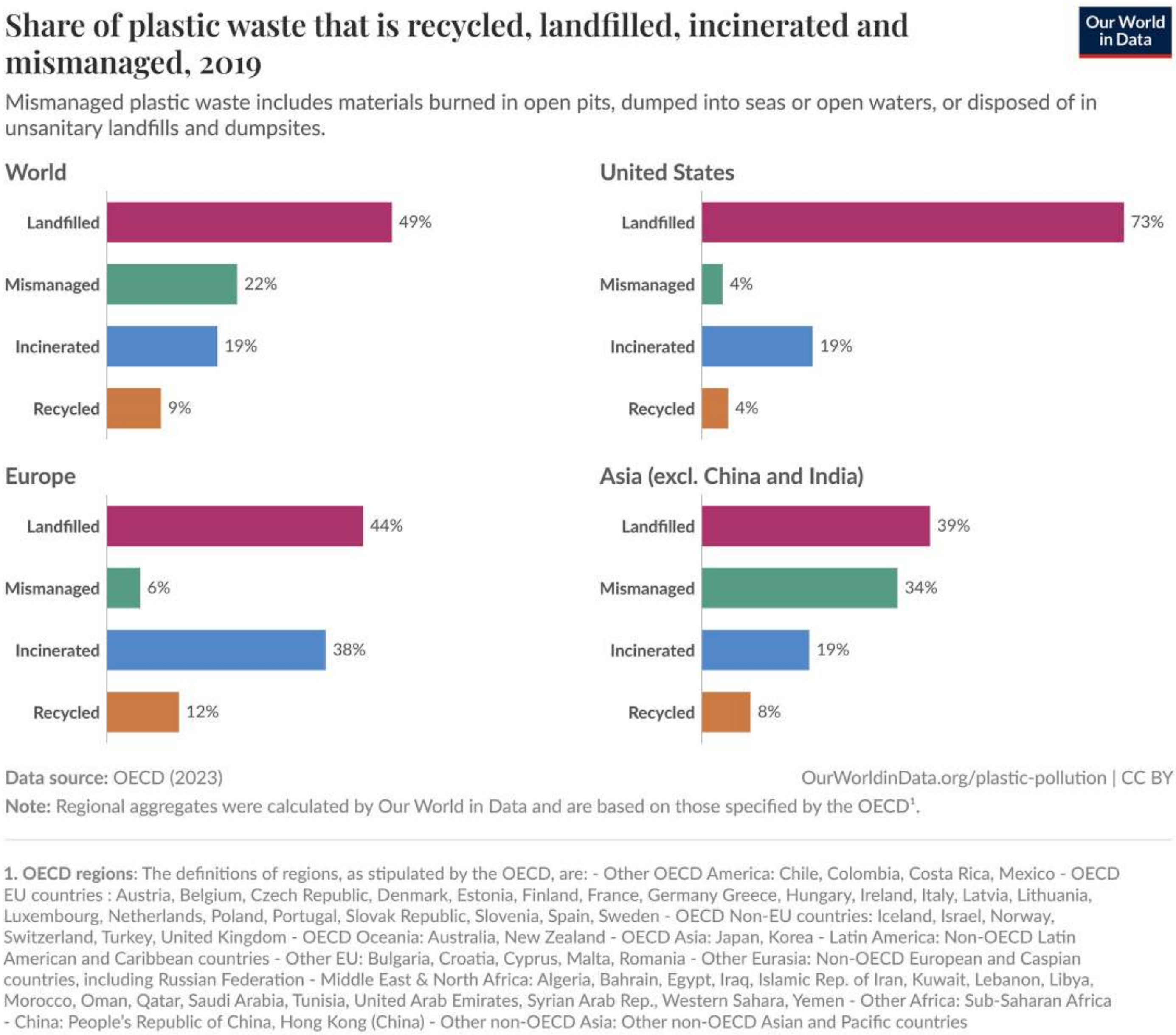

Figure 121: Share of plastic waste that is recycled, landfilled, incinerated and mismanaged, 2019. Mismanaged plastic waste includes materials burned in open pits, dumped into seas or open waters, or disposed of in unsanitary landfills and dumpsites.

Data source: OECD (2023) – Learn more about this data
Note: Regional aggregates were calculated by Our World in Data and are based on those specified by the OECD.
OurWorldinData.org/plastic-pollution | CC BY
https://ourworldindata.org/grapher/share-plastic-fate?time=2019..latest

Moreover, ocean cleanup operations involve significant financial costs. For example, the remoteness of the Great Pacific Garbage Patch is located far from the territorial waters of any country, creating a situation where no single nation is clearly responsible for funding or carrying out cleanup efforts. According to Charles Moore — an oceanographer and researcher who first discovered the Great Pacific Garbage Patch — a full-scale cleanup of the patch would "bankrupt any country" that attempts such an effort. It is also important to note that five similar garbage patches have been identified across the world's oceans (Fig. 122), further exacerbating the problem.

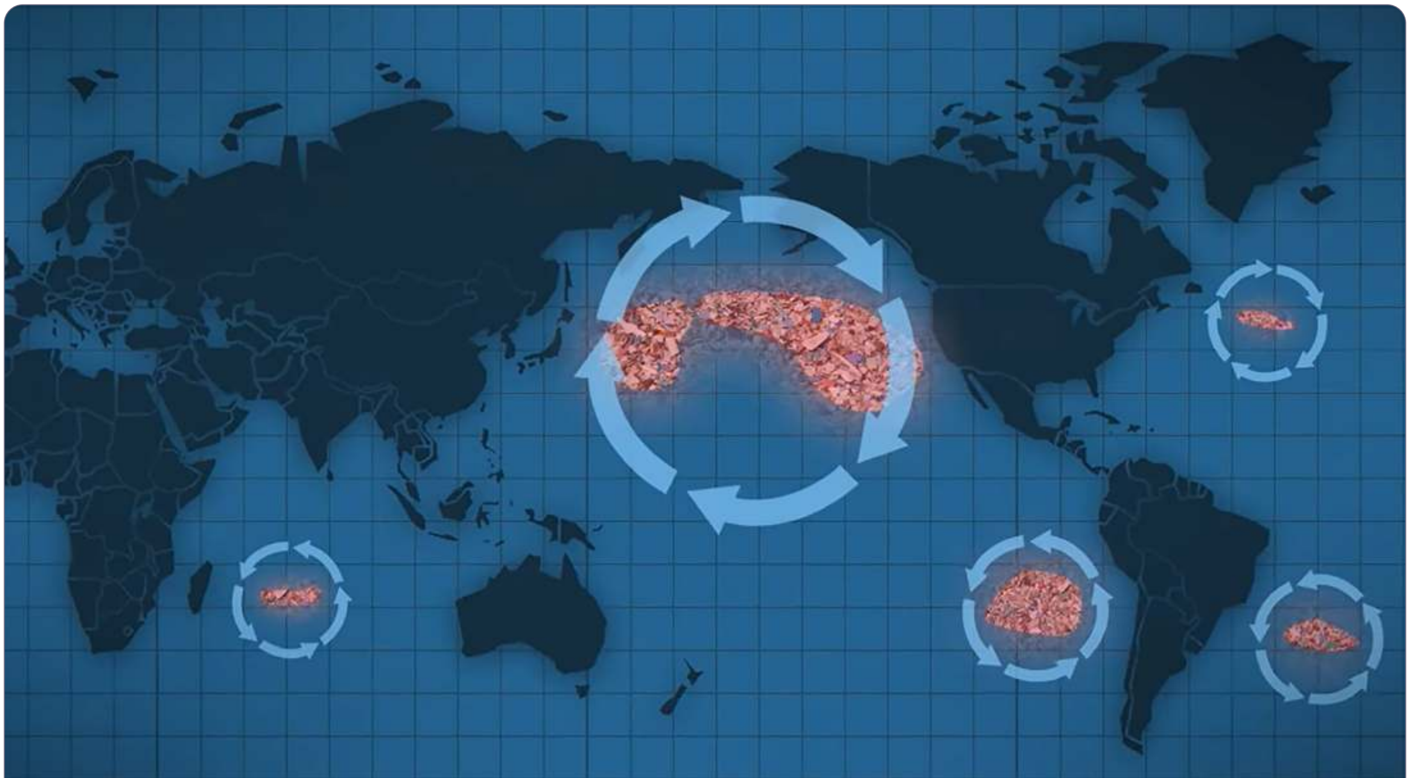

Figure 122: Schematic illustration showing the locations of the five major garbage patches in the world's oceans

It is important to note that large visible debris is only a part of the broader issue of plastic pollution in the ocean. According to marine biologist Melanie Bergmann of the Alfred Wegener Institute, "This only refers to the plastic on the ocean's surface, which represents just a small portion — less than 1 % of what is actually in the ocean."

As plastic breaks down into micro- and nanoplastics, the task of cleaning the ocean of this type of pollution becomes significantly more challenging. Some experimental technologies for removing microplastics from the water already exist. For example, researchers at Sichuan University have created a tiny robo-fish (Fig. 123) capable of swimming in aquatic environments and adsorbing nearby free-floating bits of microplastics.[311] This 13 millimeters long bionic robot effectively collects microplastics thanks to strong chemical bonds and electrostatic interactions between the materials of its body and the microplastic components, such as organic dyes, antibiotics, and heavy metals.

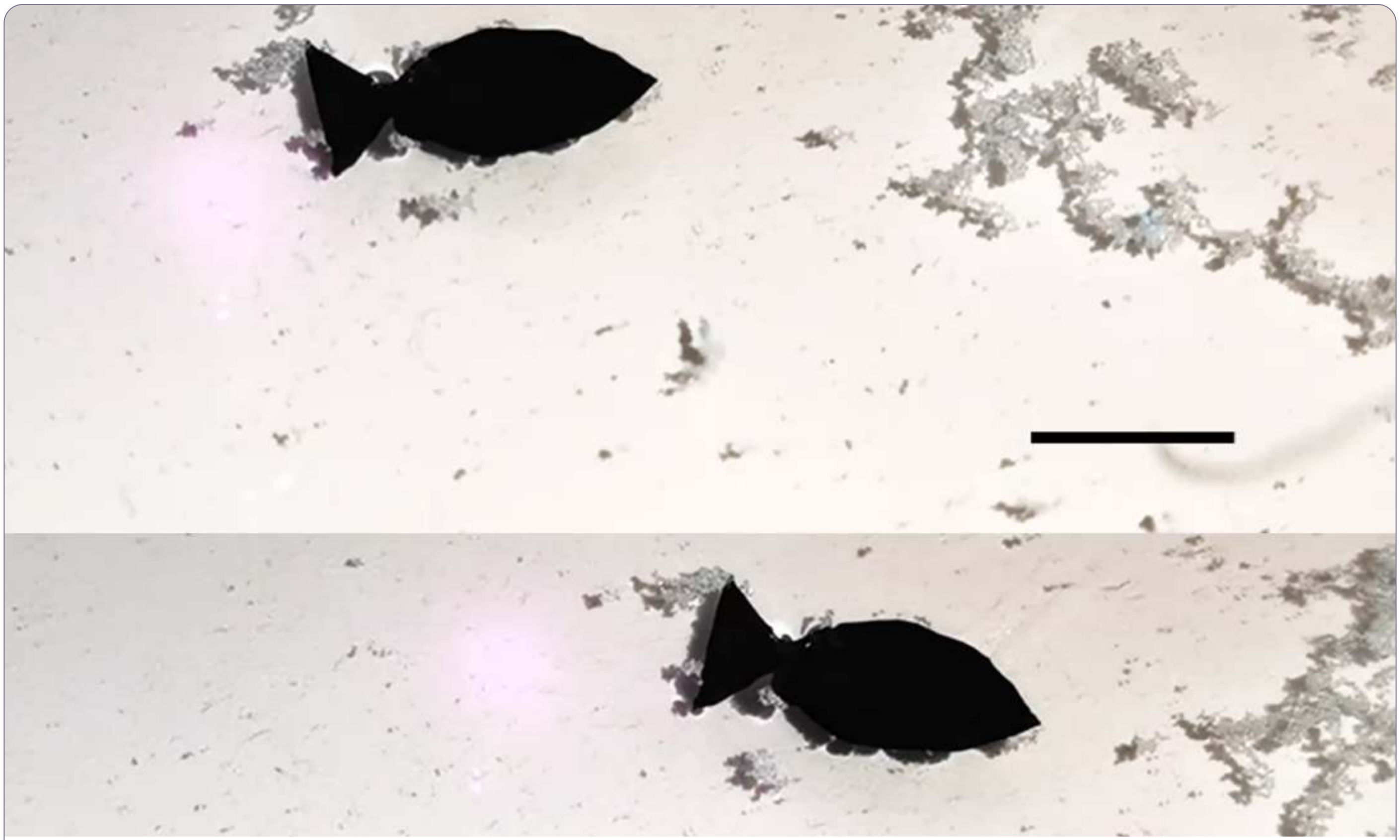

Figure 123: The image shows a tiny robotic fish created by researchers at Sichuan University. This compact device, resembling a real fish, can swim around, actively adsorbing free-floating microplastics.
Source: https://www.theguardian.com/environment/2022/jun/22/scientists-unveil-bionic-robo-fish-to-remove-microplastics-from-seas

However, despite these innovations, the practical application of such technologies on a global scale is currently limited. The tiny robots adsorb microplastics only in their immediate vicinity, making the process localized. Even in large numbers, they are unable to cover the vast scale of the ocean. Moreover, they could become part of the food chain. There are also uncertainties regarding the robots' ability to function in the harsh ocean conditions, such as currents, pressure, and salinity. Therefore, existing solutions are not yet effective enough and face serious challenges in scaling up.

[311]Wang, Y. et al. Robust, Healable, Self-Locomotive Integrated Robots Enabled by Noncovalent Assembled Gradient Nanostructure. Nano Lett. 22, 5409–5419 (2022). https://doi.org/10.1021/acs.nanolett.2c01375

Current Methods for Removing Micro- and Nanoplastics

There is growing interest in the potential use of microorganisms, particularly bacteria, for the enzymatic breakdown of synthetic polymers, especially polyethylene terephthalate (PET). This technology is often presented as an environmentally friendly alternative to traditional plastic waste disposal methods, such as incineration. However, the empirical data accumulated so far casts doubt on its effectiveness, safety, and scalability for industrial use.

In 2016, a team of Japanese scientists led by Shosuke Oda discovered the bacterium called *Ideonella sakaiensis*, capable of breaking down PET through the production of two enzymes — PETase and MHETase. This breakthrough was a significant event in microbiology.[312] However, laboratory studies showed that the degradation process is exceedingly slow: it took the bacteria about seven weeks to break down a 20-gram plastic film under optimal conditions. Clearly, this rate of degradation cannot be considered satisfactory for addressing the scale of plastic pollution. On a global scale, where millions of tons of plastic enter the environment every year, such a slow pace is akin to trying to empty the ocean with a teaspoon.

Scientific efforts have focused on modifying the PETase enzyme that bacteria use to break down plastic. However, researchers admit that the enzyme from *Ideonella sakaiensis* is still in the early stages of its evolution. Its efficiency is low, its stability is limited, and accelerating the reaction requires temperatures not found in natural environments. Even genetic engineering can't yet predict which mutations will actually lead to improvement. As Elizabeth Bell from the U.S. National Renewable Energy Laboratory put it, progress is more like "two steps forward, one step back."

Moreover, enzymatic breakdown is far from universal. Only certain plastics, such as PET, can theoretically degrade this way. Common plastics like polyethylene and polypropylene remain virtually impervious to microbial breakdown. Scientists at *Nature* have asserted: most plastics are too energy-dense to be effectively broken down by biochemical means.

Even if a highly efficient microbe could be developed, a far more troubling question arises: could it ever be safely released into the environment? **Any genetically modified bacterium poses a potential risk of causing an environmental catastrophe. Currently, nearly all countries strictly regulate or completely ban releasing such organisms into the wild.**

The reasons are clear: there's no telling how these bacteria might behave after "completing their mission." Could they start breaking down other vital organic compounds? Might they outcompete essential microbes? Could they trigger mutations with even more unpredictable consequences?

In this way, one environmental crisis could easily be replaced by another — one that is far more unpredictable and destructive.

While fundamental research into bacterial plastic degradation holds undeniable value, at this stage the technology cannot be considered an effective, scalable, or safe solution to the problem of plastic pollution.

[312]Yoshida, S. et al. A bacterium that degrades and assimilates poly(ethylene terephthalate). Science 351, 1196–1199 (2016). https://doi.org/10.1126/science.aad6359

Study on the Effect of Boiling Water on Microplastic Removal: Efficiency and Risks

Biomedical engineering and microplastic researchers from Guangzhou Medical University and Jinan University (China) conducted a study[313] investigating the impact of boiling water with elevated calcium salt content (i.e., hard water) on microplastic removal.

The researchers collected tap water samples of varying hardness levels from the city of Guangzhou. Three types of plastic particles—polystyrene, polyethylene, and polypropylene — ranging in size from 0.1 to 150 micrometers were added to the samples. The water was boiled for five minutes, then cooled, and the residual microplastic concentration was measured.

During the boiling process, calcium-rich hard water formed insoluble calcium carbonate ($CaCO_3$), commonly known as limescale. The researchers hypothesized that microplastic particles could bind to calcium carbonate crystals and precipitate, which could explain the observed reduction in microplastic concentrations after boiling.

The highest purification efficiency was observed in samples with high water hardness (300 mg $CaCO_3$ per liter), where boiling removed up to 90% of microplastics. In contrast, in samples with soft water (less than 60 mg $CaCO_3$ per liter), the effect was significantly weaker, with only about 25% of plastic particles being removed.

However, despite some positive effects of boiling hard water, an important concern arises: the potential release of micro- and nanoplastic particles into the air. As water boils, steam is produced, and along with it, microplastic particles can be aerosolized. Inhalation of these particles poses a far more serious health risk than ingestion through food or water.

Studies show that upon inhalation, nanoplastics can reach the brain within two hours. In contrast, when microplastics enter the digestive system, a portion of them is excreted. The accumulation of plastic particles in the brain is associated with long-term risks, as their removal from brain tissues is virtually impossible.

Thus, while boiling may reduce microplastic content in drinking water, it potentially increases the risk of airborne contamination, posing a greater threat to human health. This underscores the urgent need for safer and more effective methods of water purification.

[313]BYu, Z., Wang, J.-J., Liu, L.-Y., Li, Z. & Zeng, E. Y. Drinking Boiled Tap Water Reduces Human Intake of Nanoplastics and Microplastics. Environ. Sci. Technol. Lett. 11, 273–279 (2024). https://doi.org/10.1021/acs.estlett.4c00081

Pyrolysis as a Method for Plastic Processing: Efficiency and Risks

Pyrolysis is one of the technologies for plastic waste processing, based on the thermal decomposition of plastic materials at high temperatures in an environment with limited oxygen availability. The process is typically conducted at temperatures ranging from 300 to 800 °C and results in the production of gaseous and liquid hydrocarbon compounds, along with a solid carbon residue.

At elevated temperatures, the polymer chains of plastic materials break down to form a mixture of hydrocarbons that can be used as fuel. However, this method — along with conventional plastic incineration — carries significant environmental risks due to the release of nanoplastics.

Under the influence of high temperatures, plastic decomposes into ultra-fine particles, including nanoplastics (particles smaller than 100 nanometers). These particles are so small that modern filtration systems are incapable of capturing them completely, allowing their release into the atmosphere.

Plastic combustion is also accompanied by the emission of dioxins and furans—highly toxic compounds known to have carcinogenic effects.[314]

Thus, the use of pyrolysis and plastic incineration for fuel production entails considerable risk of airborne emissions, posing a threat not only to the environment but also to human health. This method of plastic disposal cannot be considered a safe or sustainable solution to the environmental pollution crisis. The true cost of such fuel is the threat it poses to human life and well-being.

[314] Baca, D. et al. Dioxins and plastic waste: A scientometric analysis and systematic literature review of the detection methods. Environmental Advances 13, 100439 (2023). https://doi.org/10.1016/j.envadv.2023.10043910.1126/science.aad6359

ALLATRA SCIENTIFIC COMMUNITY'S APPROACH TO COMBATING THE MICRO- AND NANOPLASTIC EPIDEMIC

Atmospheric Water Generator (AWG) Technologies for the Ocean Cleanup from MNPs

Restoring ecological balance calls for the widespread adoption of innovative technologies such as atmospheric water generators (AWGs). Today, these systems are available in a wide range — from household to industrial models. AWGs are capable of producing drinking water from air, effectively removing contaminants including microplastics (Fig.124). The water can also be mineralized to enhance taste and provide additional health benefits.

These generators operate by condensing moisture naturally present in the air.

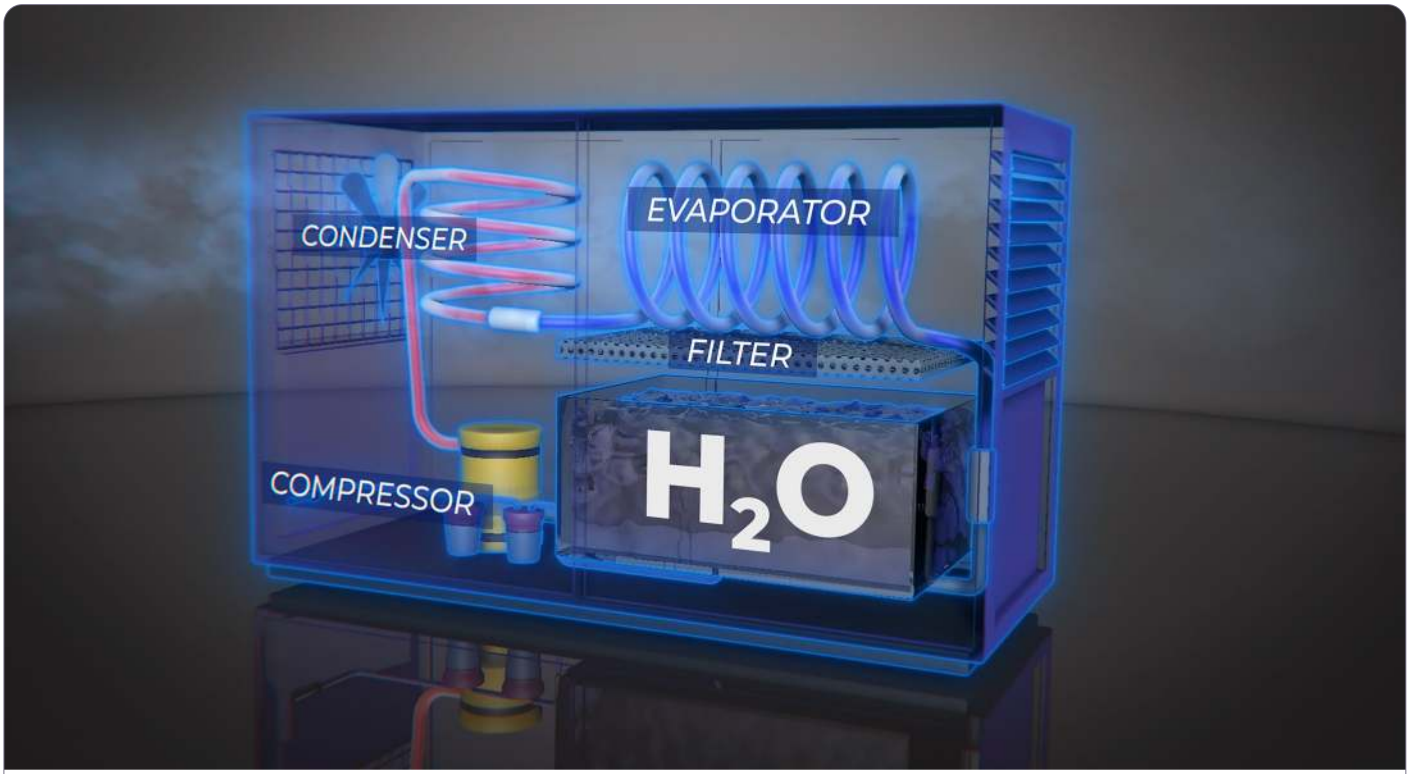

Figure 124: The image shows a schematic illustration of an atmospheric water generator, with its components and operating principle

AWGs function based on two core technologies:

1. Condensation-based technology. This method pulls ambient air into the unit and exposes it to a chilled surface or cooling coil, causing water vapor to condense into liquid form. The process is similar to how condensation forms on a cold object taken out of a freezer. Condensation-based AWGs perform best in warm and humid environments.

2. Adsorption-based technology. This method uses moisture-absorbing materials, such as silica gel, zeolites, or metal-organic frameworks, to capture humidity from the air. The absorbed water is then released when the material is heated.

Today, such systems are being used locally to supply drinking water, including in areas affected by climate-related disasters.

The large-scale deployment of AWGs to meet the needs of both industry and the public could significantly reduce ocean pollution within a few years. At present, household water sources, including water used for cooking, often come from reservoirs that contain high concentrations of micro- and nanoplastics. This contaminated water contributes to the accumulation of plastic in the human body. Shifting to air-derived water, rather than relying on polluted sources, could substantially improve the quality of drinking water.

Restoration of Ecosystems Using Natural Filtration and Atmospheric Water Generators

Effectively removing microplastics from used water requires the use of advanced technologies, including modern filtration and assimilation systems. In addition, wastewater treatment facilities should be retrofitted to ensure that treated water is not discharged into bodies of water, but instead directed into soil — where natural microorganisms are capable of breaking down plastic.[315]

These microorganisms are fundamentally different from genetically modified or artificially engineered strains developed in laboratories. Their presence in ecosystems is natural, and they do not display the characteristics of invasive species in these environments.

[315] Park, S. Y. & Kim, C. G. Biodegradation of micro-polyethylene particles by bacterial colonization of a mixed microbial consortium isolated from a landfill site. Chemosphere 222, 527–533 (2019). https://doi.org/10.1016/j.chemosphere.2019.01.159

Research[316] shows that certain soil-dwelling microbes native to natural environments[317] demonstrate significant effectiveness in degrading polymers[318] such as polyethylene[319] and polyethylene terephthalate (PET).[320] For example, the highest rate of fungal degradation — an average mass reduction of polyethylene by 36.4 ± 5.53% over 16 weeks — was observed in the Aspergillus oryzae A5, 1 strain.

The ability of microbes to biodegrade polymers lies in their production of enzymes that enable them to break down the complex molecular structures of plastics.[317]

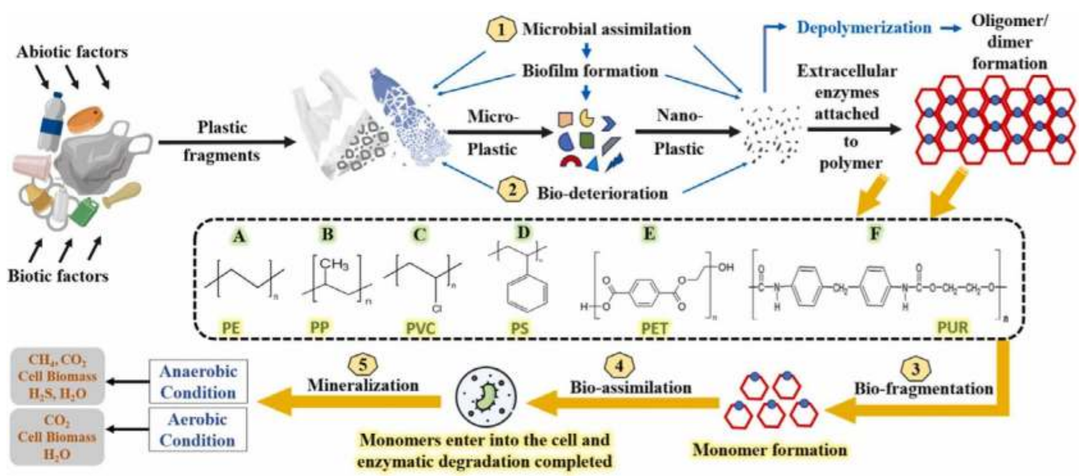

Figure 125: Micro- and nano- plastic degradation by bacterial enzymes
sciencedirect.com/science/article/pii/S2950194624000396

Source: Mandal, M., Roy, A., Popek, R. & Sarkar, A. Micro- and nano- plastic degradation by bacterial enzymes: A solution to 'White Pollution'. The Microbe 3, 100072 (2024). https://doi.org/10.1016/j.microb.2024.100072

These findings, confirmed through experimental observations, highlight the potential of natural microbial communities to reduce environmental contamination from micro- and nanoplastics.

"Among the several remediation techniques available to date, microbial remediation showed better promise to degrade or sustainably remove MNPs from the environment." according to a review study by Indian researchers.[318]

Thus, transitioning to air-derived water technologies will significantly improve the quality of consumed water. Combined with microbial remediation techniques, this approach could substantially reduce micro- and nanoplastic pollution in the environment.

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[316] Auta, H. S. et al. Enhanced microbial degradation of PET and PS microplastics under natural conditions in mangrove environment. Journal of Environmental Management 304, 114273 (2022). https://doi.org/10.1016/j.jenvman.2021.114273
[317] Mandal, M., Roy, A., Popek, R. & Sarkar, A. Micro- and nano- plastic degradation by bacterial enzymes: A solution to 'White Pollution'. The Microbe 3, 100072 (2024). https://doi.org/10.1016/j.microb.2024.100072
[318] Auta, H. S., Emenike, C. U., Jayanthi, B. & Fauziah, S. H. Growth kinetics and biodeterioration of polypropylene microplastics by Bacillus sp. and Rhodococcus sp. isolated from mangrove sediment. Marine Pollution Bulletin 127, 15–21 (2018). https://doi.org/10.1016/j.marpolbul.2017.11.036
[319] Muhonja, C. N., Makonde, H., Magoma, G. & Imbuga, M. Biodegradability of polyethylene by bacteria and fungi from Dandora dumpsite Nairobi-Kenya. PLOS ONE 13, e0198446 (2018). https://doi.org/10.1371/journal.pone.0198446
[320] Yoshida, S. et al. A bacterium that degrades and assimilates poly(ethylene terephthalate). Science 351, 1196–1199 (2016). https://doi.org/10.1126/science.aad6359

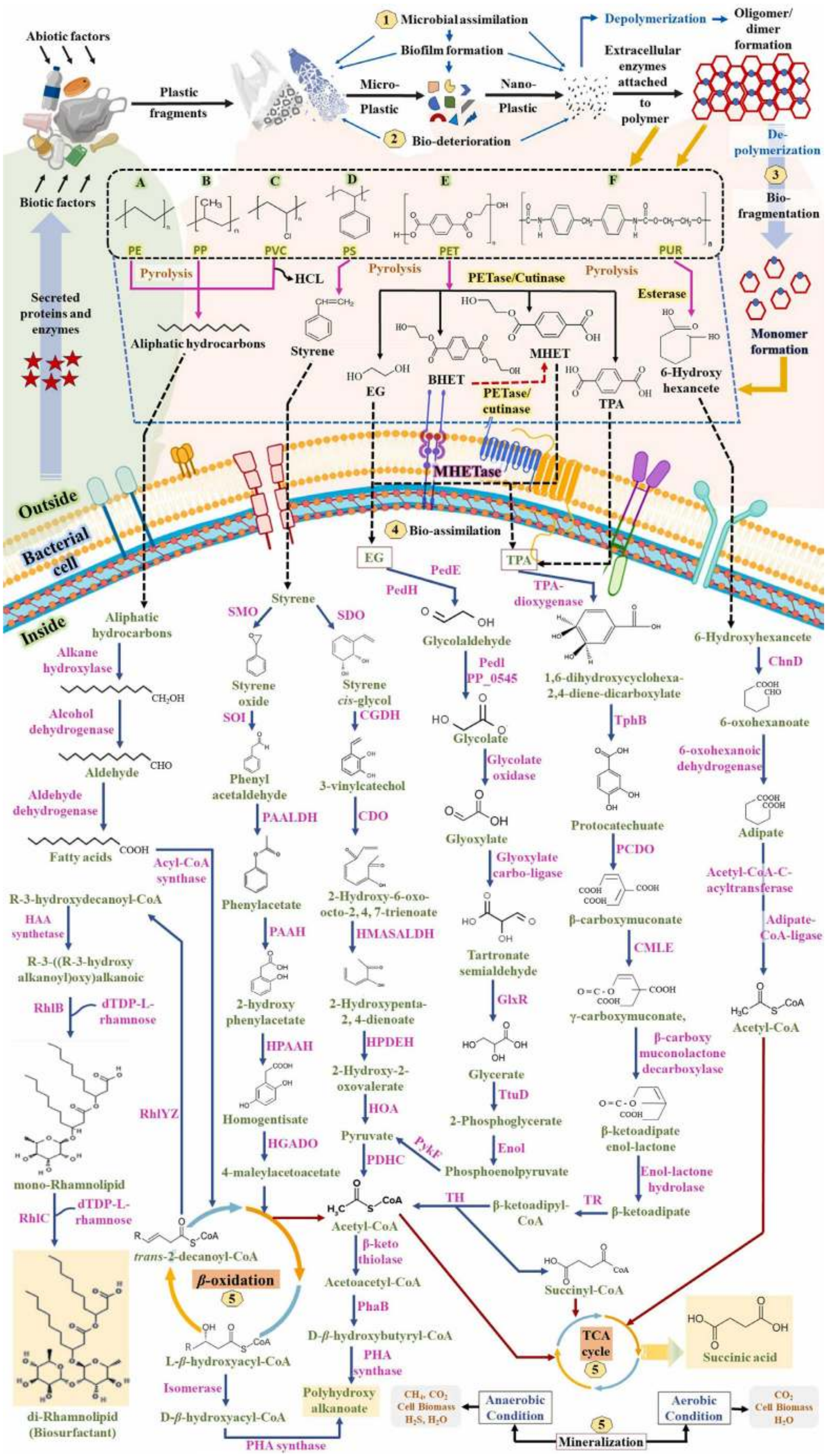

Figure 126: Wasted plastic is degraded into MNPs due to different abiotic and biotic factors

Source: Mandal, M., Roy, A., Popek, R. & Sarkar, A. Micro- and nano- plastic degradation by bacterial enzymes: A solution to 'White Pollution'. The Microbe 3, 100072 (2024). https://doi.org/10.1016/j.microb.2024.100072

In the upper layers of soil, just as in bodies of water, plastic concentrations will remain high for some time. However, as water penetrates deeper underground, a natural self-purification process occurs (Fig. 127). Soil-dwelling microorganisms help break down tiny nanoplastic particles.

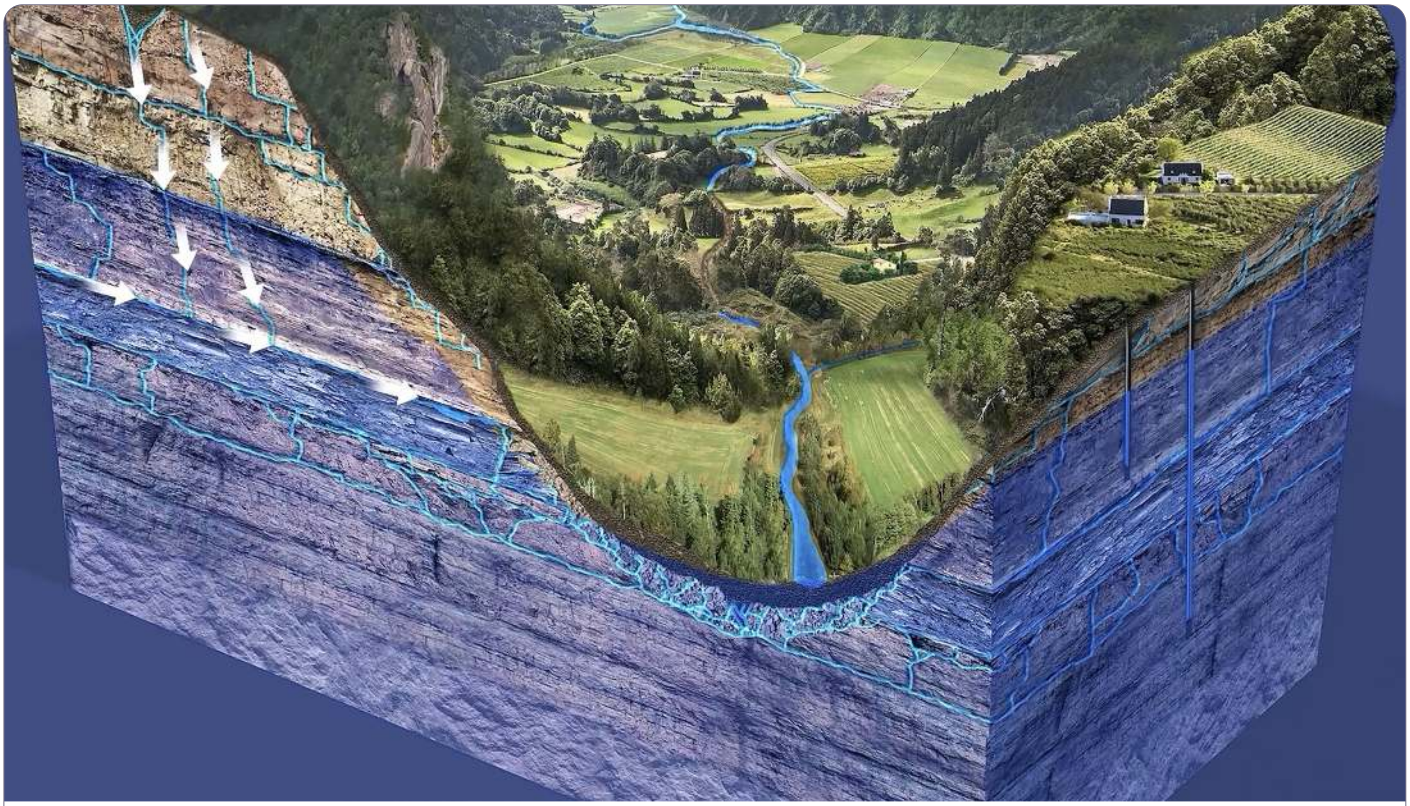

Figure 127: The image schematically illustrates the process of biological purification of wastewater discharged into the soil through geological layers. Arrows indicate the path of the wastewater as it passes through layers of soil and rock, where microorganisms and filtering materials remove contaminants. The soil layers are marked in different colors: brown for topsoil, gray for sand and gravel.

Increasing the volume of treated and filtered wastewater directed into the soil promotes the growth of microorganisms — bacteria, fungi, and archaea — that play a foundational role in building healthy soil, nutrient cycling, and overall ecosystem resilience. Over time, this purified water will percolate into deeper layers and eventually return to the oceans.

Installing atmospheric water generators in arid regions, along with the return of used water to the soil, presents a promising strategy for addressing the global water crisis and combating desertification. These efforts activate processes that support the restoration of vegetation and ecosystems.[321] The use of AWGs will also improve quality of life in local communities by helping to solve the issue of drinking water scarcity.

[321]Islam, W., Zeng, F., Alotaibi, M. O. & Khan, K. A. Unlocking the potential of soil microbes for sustainable desertification management. Earth-Science Reviews 252, 104738 (2024). https://doi.org/10.1016/j.earscirev.2024.104738

When combined with microbial remediation, the use of AWGs can be a major step toward sustainable water management and the recovery of degraded land.

A full transition to AWG technology would involve using atmospheric water for all human needs — domestic, industrial, and agricultural. Global-scale adoption of this approach would increase evaporation rates, resulting in ocean cooling and accelerated ocean cleansing. Additionally, by reducing excess atmospheric moisture, AWGs could lessen the intensity of extreme precipitation and wind events, potentially mitigating the destructive impact of natural disasters (see more in the film ***Water from Air: Humanity's Path to Survival*** for more).

Challenges and Risks Associated with the Use of Atmospheric Water Generators

However, there is a downside to the widespread deployment of AWGs. The core concern lies in the insufficient assessment of AWG's direct impact on human health. While the technology can indeed contribute to the purification of oceanic waters and improve thermal conductivity in the climate system, large-scale use of AWGs may also lead to a significant increase in atmospheric microplastic concentrations.

The operational mechanism of AWG involves the condensation of moisture from the atmosphere, which is then replenished through evaporation from ocean waters. Since these waters contain high concentrations of microplastics and nanoplastics, the vapor entering the atmosphere during this process may carry ultrafine plastic particles. As a result, in regions where AWG systems are deployed—including major metropolitan areas—the concentration of airborne nanoplastics people breathe may rise to levels currently observed in coastal zones. This presents a serious risk: increased atmospheric nanoplastic concentrations pose a threat to human health. Inhaled nanoplastics can accumulate in the human body, including in the brain.

And this is the critical point. It is essential to understand that the original idea of using AWGs as a tool to help purify ocean water was proposed by ALLATRA scientists over twenty years ago, at a time when atmospheric microplastic concentrations were still extremely low. Back then, the implementation of such technologies could have indeed delivered tangible environmental benefits without posing serious risks to human health.

However, the situation has changed drastically. Under current conditions, large-scale deployment of AWGs is more likely to increase airborne MNP concentrations. With current atmospheric MNP levels already high, introducing additional volumes through AWGs could prove fatal for human health.

Thus, a technology that was once seen as promising and innovative has now lost its relevance. As a global society, we missed a critically important window during which AWGs could have served as a viable solution. In the context of climate issues and environmental pollution, the factor of time plays a decisive role. What might have preserved the health of millions and truly contributed to cleaning the planet two decades ago now poses a potentially serious danger.

AWG is no longer a technology of the future—it is a reminder of a missed opportunity. In the current circumstances, the priority must shift to developing methods for removing MNPs from both the atmosphere and the human body. Above all, we need to buy ourselves time.

Innovative Scientific Approach to Reducing the Toxicity of Micro- and Nanoplastics

Given the presented data on the multi-level and cumulative impact of microplastics, and especially nanoplastics, on human health, it becomes evident that modern civilization is facing an ecological and biomedical challenge that transcends traditional notions of environmental pollution. This issue not only affects individual biospheres, but also the long-term sustainability of the Homo sapiens population.

To date, nearly all the plastic ever produced — over 9 billion tons — continues to accumulate in the environment, undergoing fragmentation into micro and nano-sized particles, which exhibit high chemical and biological activity. Micro- and nanoplastics have been found in soil, water, air, and across all major food categories, ranging from vegetables and fruits to meat, fish, honey, milk, and salt. This indicates the widespread infiltration of plastic particles into the food chain, significantly transforming the traditional understanding of “safe” or “healthy” food.

The route of particles penetration into the human body largely determines their biological behavior and distribution. While plastic entering through the digestive tract may be partially excreted, the inhalation route poses a significantly higher degree of risk. Inhaled nanoplastics settle in lung tissue, cross the blood-brain barrier, and may directly reach the brain, where they can accumulate over time. Natural detoxification mechanisms (such as the liver and kidneys) do not have effective means of recognizing and removing these particles.

The highest concentration of microplastics is found near water bodies, coastal zones, and forest areas, especially in conditions of high humidity and temperature. In such landscapes, plastic lingers longer, participates in aerosol transport, induces oxidative stress in plants, and reduces the efficiency of photosynthetic processes. Coastal recreation, once considered a health-promoting activity, now carries an additional inhalation burden: according to estimates, the volume of inhaled plastic near open water bodies can be many times higher than the indicators of the urban environment.

Epidemiological studies show a consistent correlation between the levels of micro- and nanoplastic (MNP) pollution and the prevalence of chronic non-communicable diseases, including hypertension, diabetes, stroke, as well as depressive and cognitive disorders. Due to their ability to cross biological barriers and accumulate in various tissues, including the brain, heart, lungs, and placenta, MNPs exert toxic effects at the molecular, cellular, and organ levels. As plastics build up in the body, they produce immunosuppressive, inflammatory, and genotoxic effects. Despite progress in identifying these risks, effective mechanisms for neutralizing and removing MNPs from the human body have not yet been developed.

One of the most critical properties of nanoplastics with systemic biological implications is their ability to retain an electrostatic charge. Unlike inert particles, nanoplastics actively interact with cell surfaces, proteins, receptors, and even genetic material, forming stable molecular-level bonds. This property not only enhances the penetration of nanoplastics through biological barriers, including the blood-brain barrier, but also hinders their elimination, leading to prolonged retention in tissues, particularly in the brain. Electrostatic interactions trigger a cascade of cellular disruptions, including membrane depolarization, mitochondrial dysfunction, oxidative stress, and apoptosis, which significantly increases toxicity even at minimal concentrations of nanoplastic particles.

The authors of this report propose that the solution to neutralizing or shielding the electrostatic charge of micro- and nanoplastics could represent a fundamental breakthrough that could significantly reduce the biological activity of nanoplastics and slow the rate at which they accumulate in critical organs. According to the authors' estimates, electrostatic charge shielding or neutralization could reduce the potential danger of micro- and nanoplastics by at least 50%, making this research area critically important. This could provide the scientific community with the necessary window of time to develop more comprehensive approaches to diagnosing, detoxifying, and preventing the MNP-related effects. In this regard, research in biophysics, nanomaterials science, and molecular toxicology will be of paramount importance. Delays in addressing this issue could accelerate degradation processes.

Simultaneously with biomedical solutions, a scientifically backed strategy for the safe handling of plastic waste is urgently needed. The current waste disposal systems are unable to prevent further fragmentation of plastics and their entry into the biosphere. In the context of globalization, it is essential to develop an international technological platform for the creation, implementation, and scaling of safe plastic collection and recycling methods. Such measures can only be achieved through institutional support, cross-border regulations, and scientific diplomacy.

Raising awareness within the scientific community, healthcare professionals, and the general public has become particularly crucial. To date, most people are unaware of the full extent of the micro- and nanoplastics (MNPs) impact and continue to unknowingly contribute to their spread.

Thus, the issue of micro- and nanoplastics has ceased to be a potential threat and has transformed into a systemic risk factor. Now this area requires prioritized attention from the scientific community and healthcare authorities, data systematization, the development of risk assessment standards, and strengthening the intergovernmental and international cooperation. To develop effective solutions that safeguard biological security both in the short and long term, an interdisciplinary approach, institutional recognition, and international coordination of efforts are essential.

THE X FACTOR: ROLE OF MICRO- AND NANOPLASTICS IN THE DYNAMICS OF NATURAL DISASTERS

As noted in the chapter "*Impact of Micro- and Nanoplastics on the Climate,*" micro- and nanoplastic particles reduce the thermal conductivity of ocean water, leading to heat accumulation and, as a result, a critical rise in ocean temperatures. However, micro- and nanoplastics are not themselves a direct source of ocean warming.

Since the spring of 2023, and continuing for over a year, the average surface temperature of the World Ocean has been breaking historical records on a daily basis, marking an unprecedented event in the history of observations (Fig. 128). Scientists around the world are deeply concerned about this abnormal rise.

> Dr. Brian McNoldy, senior researcher at the Rosenstiel School of Marine and Atmospheric Science at the University of Miami, notes: ***"It's not just an entire year of record-breaking ocean temperatures, but it's the margin it's breaking them by — it's not even close to what the previous record was."***[322]

> Dr. Rob Larter, a British marine geophysicist, echoes these concerns: ***"It's quite scary, partly because I'm not hearing any scientists that have a convincing explanation of why it is we've got such a departure"…"But the impression at the moment is that things have gone further and faster than we expected."***[323]

Climate research data shows that current models predict a gradual increase in ocean surface temperatures, yet the observed rate of warming is significantly outpacing all projections. While scientists confirm anthropogenic climate change is a contributing factor, it alone cannot fully account for this unprecedented phenomenon.

[322]NBC News. '12 months of record ocean heat has scientists puzzled and concerned'. (2024) https://www.nbcnews.com/science/environment/oceans-record-hot-rcna143179 (accessed 10 May 2025).
[323]The New York Times. Scientists are freaking out about ocean temperatures. (2024) https://www.nytimes.com/2024/02/27/climate/scientists-are-freaking-out-about-ocean-temperatures.html (accessed 1 May 2025).

Professor John Abraham from the University of St. Thomas, a specialist in ocean temperature studies, has proposed the existence of previously unknown factors influencing long-term ocean surface temperature changes.[322] He emphasized these elements were not accounted for in existing climate models. The authors of this report hypothesize about a potential "X Factor" that may be driving additional warming in both oceanic and atmospheric systems.

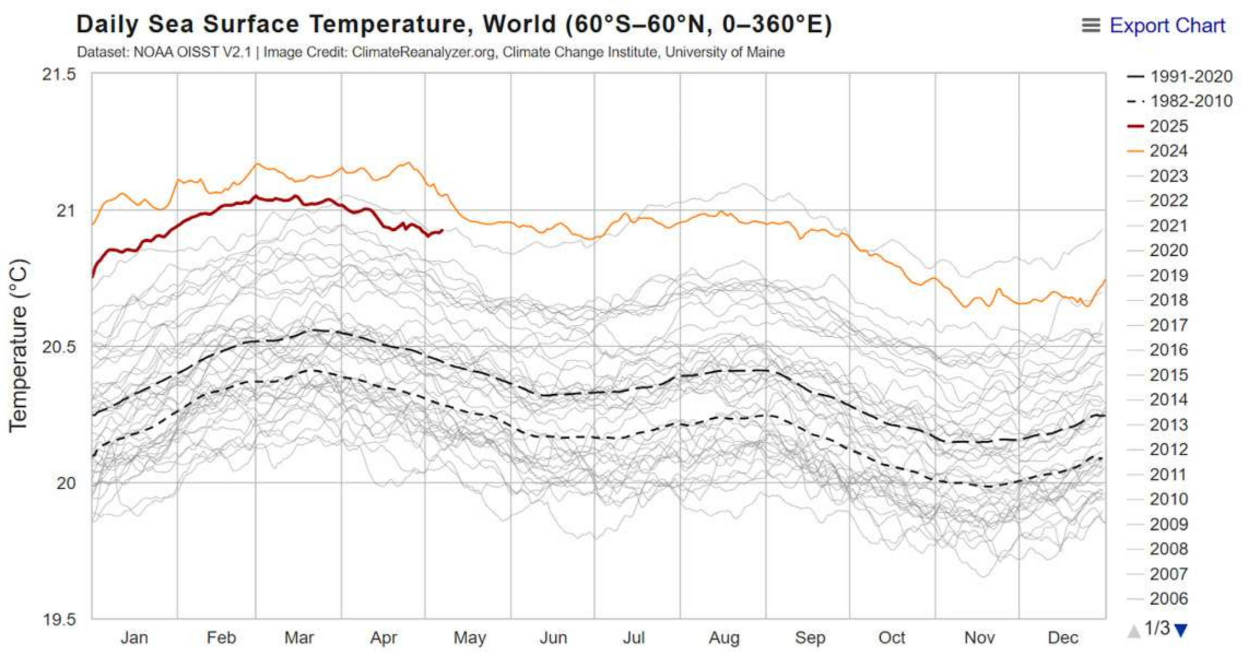

Figure 128: Average Daily Sea Surface Temperature , 1981–2025

Source: NOAA OISST V2.1 Dataset | Image source: ClimateReanalyzer.org, Climate Change Institute, University of Maine, Dataset: NOAA OISST."
https://climatereanalyzer.org/clim/sst_daily/?dm_id=world2

[322]NBC News. '12 months of record ocean heat has scientists puzzled and concerned'. (2024) https://www.nbcnews.com/science/environment/oceans-record-hot-rcna143179 (accessed 10 May 2025)

Could Micro- and Nanoplastics in the Ocean Be an Unidentified X Factor?

An analysis of the possibility that micro- and nanoplastics are the main driver behind current ocean warming reveals a critical contradiction. While nanoplastics do impair the ocean's ability to release heat, they do not generate thermal energy themselves—they merely hinder its escape.

Over the past 60 years, the deep ocean has been warming 15 times faster than it did over the previous 10,000 years,[324, 325] and this trend is accelerating every year. The rate of progression is becoming increasingly rapid. However, it requires an enormous amount of energy to raise the temperature at depths where sunlight no longer penetrates.[326, 327]

The large-scale influx of micro- and nanoplastics into the ocean began relatively recently—approximately 30 years ago. However, the accelerated warming of the ocean's deeper layers has been observed for over 60 years. This timeline reveals a key inconsistency: plastic pollution alone cannot account for the long-term, steadily increasing trend of deep ocean warming, which began well before these contaminants became widespread.

Solar radiation doesn't provide a sufficient explanation either. Sunlight penetrates the ocean only to a depth of about 200 meters. The water can be heated by the Sun to a maximum depth of about 700 meters as a result of mixing.[328] However, warming the much deeper layers —beyond the reach of sunlight—would require a vast and sustained energy source.

This suggests that the heat accumulating in the ocean must be coming from another source. Meanwhile, the presence of nanoplastics appears to trap this heat, preventing it from escaping into the atmosphere.

Since solar heating cannot explain the exponential rise in ocean temperatures, scientists have proposed that there may be additional, as yet unidentified, sources of heat operating in various regions of the ocean.

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[324]Rosenthal, Y. et al. Pacific Ocean Heat Content During the Past 10,000 Years. Science 342, 617–621 (2013). https://doi.org/10.1126/science.1240837
[325]Columbia Climate School. 'Is Global Heating Hiding Out in the Oceans?'. (2013) https://www.earth.columbia.edu/articles/view/3130 (accessed 10 May 2025).
[326]NOAA Ocean Service. 'How far does light travel in the ocean?'. (n.d.) https://oceanservice.noaa.gov/facts/light_travel.html (accessed 10 May 2025).
[327]NOAA Ocean Exploration. 'Marine Life'. (n.d.) https://oceanexplorer.noaa.gov/explainers/marine-life.html (accessed 10 May 2025).
[328]Climate.gov. 'The role of the ocean in tempering global warming'. (2014) https://www.climate.gov/news-features/blogs/enso/role-ocean-tempering-global-warming (accessed 10 May 2025).

Vertical Distribution of Temperature Anomalies

The analysis of global temperature fluctuations at various ocean depths, based on data from the Argo system over the past two decades, has revealed a series of anomalies that do not align with the conventional model of downward heat transfer from the surface to deeper ocean layers.[329, 330]

Statistically significant cases of temperature gradient inversion have been documented, in which warmer water masses are found beneath relatively cooler surface layers (Fig. 129). This type of temperature stratification is physically impossible under a strictly top-down heat transfer model, as thermal energy, according to the laws of physics, cannot pass through a colder intermediate layer from above.

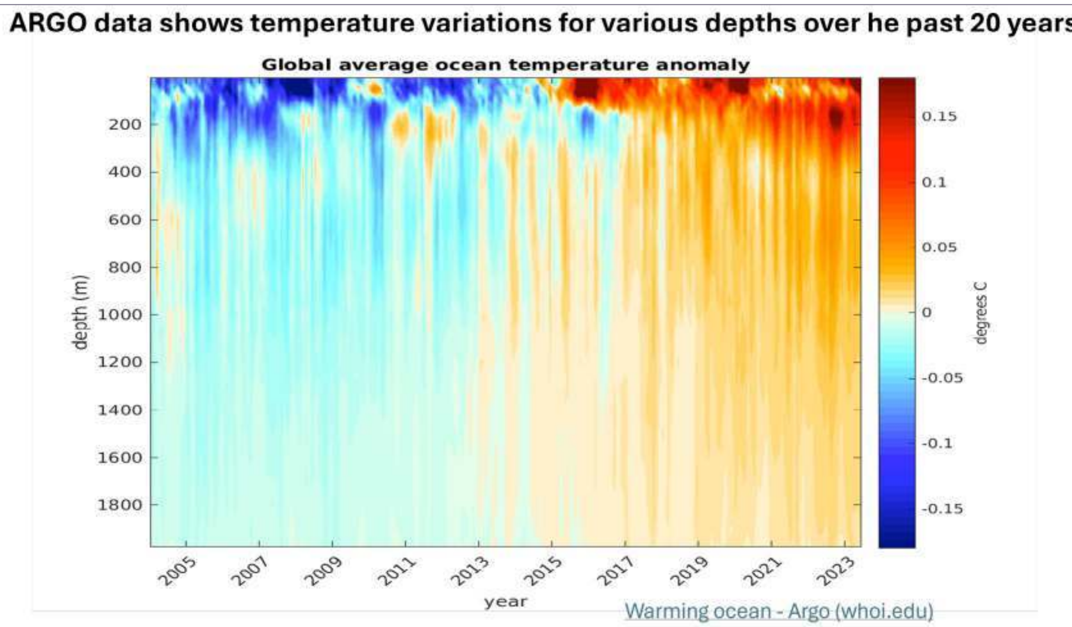

Figure 129: Global ocean temperature anomalies at depths of 0–6,250 feet (0–1,900 meters) since 2004
Source: Argo system – https://www2.whoi.edu/site/argo/impacts/warming-ocean/

Recent studies by scientists from the Ocean University of China[331] confirm the presence of thermal anomalies within ocean water columns that do not appear on the surface. The research has shown that one-third of marine heatwaves leave no trace on the ocean surface, while nearly half are only partially visible throughout their life cycle.

The annual number of these subsurface marine heatwaves has increased significantly over the past three decades due to ongoing ocean warming. The fact that a substantial portion of marine heatwaves is completely undetectable at the surface clearly indicates that they cannot be caused by atmospheric heat alone.

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[329] Johnson, Gregory C., et al. "Argo-Two Decades: Global Oceanography, Revolutionized." Annual Review of Marine Science, vol. 14, 2022, pp. 379–403. https://doi.org/10.1146/annurev-marine-022521-102008.

[330] Wong, Annie P. S., et al. "Argo Data 1999–2019: Two Million Temperature-Salinity Profiles and Subsurface Velocity Observations From a Global Array of Profiling Floats." Frontiers in Marine Science, vol. 7, 2020, article 700. https://doi.org/10.3389/fmars.2020.00700.

[331] Sun, D., Li, F., Jing, Z., Hu, S., & Zhang, B. (2023). Frequent marine heatwaves hidden below the surface of the global ocean. Nature Geoscience, 16(12), 1099–1104. https://doi.org/10.1038/s41561-023-01325-w

Study of Heat Sources at the Ocean Floor

Research and continuous monitoring of temperatures on the ocean floor remain extremely rare and limited to this day. For a long time, science has not prioritized tracking changes at such extreme depths. Modern monitoring systems, such as the ARGO buoy network, currently collect data from only about 0.03% of the ocean's surface area, with most buoys descending to just half the average ocean depth—falling short of reaching the seabed.[332]

To date, humanity has explored only about 3–3.5% of the ocean floor.[333] This is due to several significant challenges. First of all, the majority of the World Ocean lies at depths of 3,000 to 6,000 meters. The development of deep-sea vehicles capable of withstanding the immense pressure at depths of up to 6,000 meters requires substantial financial and technological resources.

Second, the expeditions themselves are extremely complex and expensive; throughout history, only eight specialized vehicles have ever been constructed for this purpose. For this reason, in some respects, we have studied outer space more thoroughly than the most remote regions of the World Ocean.

At the same time, it is becoming increasingly clear that geological processes on the ocean floor may play a significant role in climate change and in shaping the ocean's heat balance. The seafloor is home to millions of unique geological features — volcanoes, fault lines, and hydrothermal vents — that release tremendous amounts of energy. However, due to their inaccessibility and limited monitoring coverage, the full extent of their potential impact remains largely unknown to science.

Nevertheless, research on the ocean floor continues, and a number of studies have already pointed to localized heating of ocean water originating from the seafloor.

For example, **in two deep sections of the Argentine Basin**,[334] at depths greater than 4,500 meters, significant warming trends have been observed: 0.02 °C ± 0.01 °C per decade during the period from 2009 to 2019. That's a tremendous amount of energy required to heat such a vast volume of cold water on the ocean floor.

Right off the coast of West Antarctica, anomalous warming of the deep waters of the Weddell Sea[335] is taking place While the upper 700 meters of water show little to no warming, a consistent temperature increase is observed in deeper regions. On one side, the Weddell Sea is bordered by the West Antarctic Rift, and on the other by a submarine volcanic ridge with the South Sandwich Islands.

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[332] Argo Program. 'Mission'. (n.d.) https://argo.ucsd.edu/about/mission/ (accessed 10 May 2025).

[333] Bell, Katherine L. C., et al. "How Little We've Seen: A Visual Coverage Estimate of the Deep Seafloor." Science Advances, vol. 11, no. 19, 2025, eadp8602. https://doi.org/10.1126/sciadv.adp8602.

[334] Meinen, C. S., Perez, R. C., Dong, S., Piola, A. R. & Campos, E. Observed Ocean Bottom Temperature Variability at Four Sites in the Northwestern Argentine Basin: Evidence of Decadal Deep/Abyssal Warming Amidst Hourly to Interannual Variability During 2009–2019. Geophysical Research Letters 47, e2020GL089093 (2020). https://doi.org/10.1029/2020GL089093

[335] Strass, V. H., Rohardt, G., Kanzow, T., Hoppema, M. & Boebel, O. Multidecadal warming and density loss in the Deep Weddell Sea, Antarctica. Journal of Climate 33, 9863–9881 (2020). https://doi.org/10.1175/jcli-d-20-0271.1

The Role of Geothermal Heat Flux, Tectonic Activity, and Seafloor Volcanism

In the context of observed deep-water warming anomalies—where atmospheric influence is minimal—it seems logical to consider geothermal heat flow from Earth's interior as a potential source of additional heat. Traditionally, climate models treat geothermal heat flux from below as constant, at approximately 0.09 W/m² (or 90 mW/m²),[336] which is several orders of magnitude lower than solar radiation.[337, 338]

However, an increasing body of scientific evidence points to the significance of this underestimated source of heat. Large-scale geothermal studies have shown that the amount of heat flux emerging from the ocean floor depends on the age of the oceanic crust: it is highest in young seafloor spreading zones and lowest in older ocean basins (Fig. 130).[339]

These localized anomalies can influence the vertical temperature structure of the water, weaken the thermocline, and promote mixing of water masses, which in turn affects circulation, biological productivity, and even the stability of glaciers in polar regions.

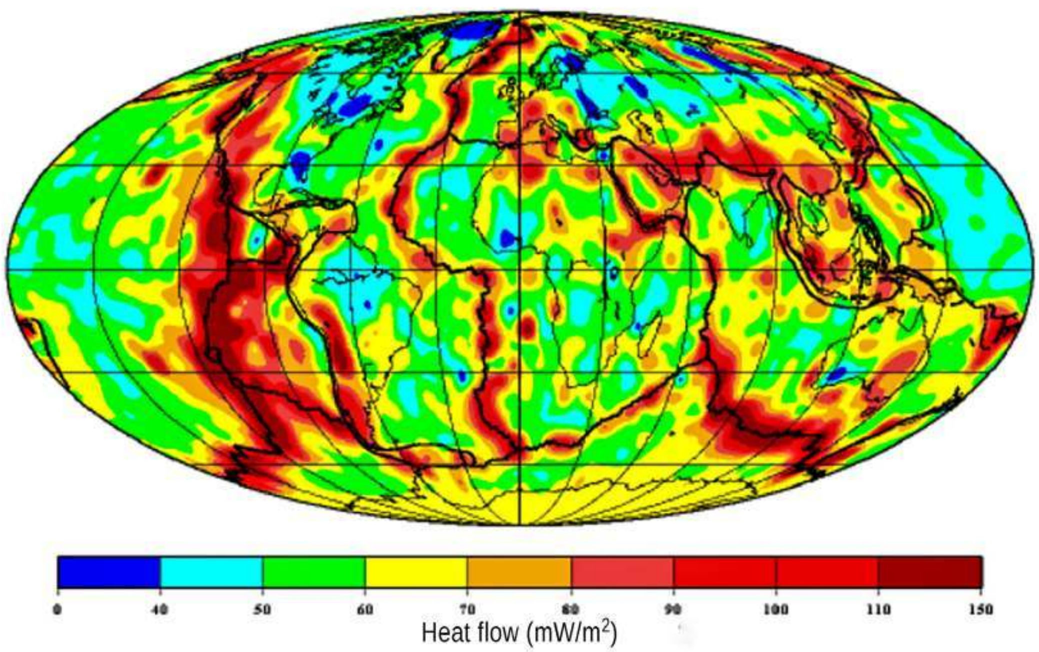

Figure 130: Global representation of heat flow based on observational data, supplemented with estimates derived from digital maps and empirical correlation with age.

Illustration adapted from: Vieira, F., & Hamza, V. M. Global heat flow: New estimates using digital maps and GIS techniques. International Journal of Terrestrial Heat Flow and Applied Geothermics. 1, 6–13 (2018).

[336] Pollack, H. N., Hurter, S. J. & Johnson, J. R. Heat flow from the Earth's interior: Analysis of the global data set. Rev. Geophys. 31, 267–280 (1993). https://doi.org/10.1029/93RG01249

[337] Kopp, G. & Lean, J. L. A New, Lower Value of Total Solar Irradiance: Evidence and Climate Significance. Geophysical Research Letters 38, L01706 (2011). https://doi.org/10.1029/2010GL045777

[338] World Energy Council. World Energy Resources: Solar 2013. (2013) https://www.worldenergy.org/publications (accessed 10 May 2025).

[339] Khutorskoy, M. D., & Polyak, B. G. (2014). Reflection of contrasting geodynamic settings in the thermal field. Georesources, (2), 24–43.

Geothermal Heat Flux — the quantity of thermal heat being released from Earth's interior through a unit area of the surface in a unit of time, measured in milliwatts per square meter (mW/m²).

While the average geothermal heat flux is about 40–60 mW/m² for continental areas and approximately 100 mW/m² for the ocean floor, certain regions exhibit values several times higher. The highest heat flux levels are recorded in tectonically and volcanically active zones—such as mid-ocean ridges and active rift zones—where the flux can exceed 200 to 1,000 mW/m².[340]

Exceptionally high heat flux is observed in hydrothermal vent fields—areas where hot fluids discharge directly onto the seafloor, with water temperatures reaching 350–400 °C. These systems create unique ecosystems and generate localized heat flow anomalies that significantly impact the thermal conditions of bottom waters.

The most thoroughly studied areas of elevated geothermal heat flux on the ocean floor are the mid-ocean ridges—zones where tectonic plates are spreading apart and new oceanic crust is actively forming. This global system of underwater ridges stretches for approximately 60,000 kilometers,[341] encircling the planet like the seams of a baseball. Mid-ocean ridges are characterized by a high concentration of hydrothermal vents, submarine volcanoes, and active fault lines that allow substantial amounts of heat energy from Earth's mantle to enter the ocean.[342]

In these regions, geothermal heat flux is 10 to 100 times higher than the average for the rest of the seafloor,[326] making mid-ocean ridges critical zones for heat exchange between Earth's interior and the World Ocean.

Professor Arthur Viterito of the University of Maryland has documented a rise in earthquake activity along mid-ocean ridges since 1995 (Fig. 131).[343] With a correlation coefficient of 0.7, this increase aligns with the global temperature rise, with temperature increases lagging approximately two years behind the uptick in seismic activity. This surge in seismicity is associated with the upward movement of magma, which creates new oceanic crust.

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[340] Polyak, B. G., & Khutorskoy, M. D. (2018). Heat flow from the Earth's interior as an indicator of deep-seated processes. Georesources, 20(4), Part 2, 366–376. https://doi.org/10.18599/grs.2018.4.366-376

[341] LaFemina, P. C. Plate Tectonics and Volcanism. in The Encyclopedia of Volcanoes (ed. Sigurdsson, H.) 65–92 (Academic Press, 2015). https://doi.org/10.1016/B978-0-12-385938-9.00003-1

[342] Baker, E. T. & German, C. R. On the Global Distribution of Hydrothermal Vent Fields. in Mid-Ocean Ridges: Hydrothermal Interactions Between the Lithosphere and Oceans (eds German, C. R., Lin, J. & Parson, L. M.) 245–266 (American Geophysical Union, 2004).

[343] Viterito, A. 1995: An Important Inflection Point in Recent Geophysical History. Int. J. Environ. Sci. Nat. Res. 29, 556271 (2022). https://doi.org/10.19080/IJESNR.2022.29.556271

Increase in the Number of Earthquakes on the Ocean Floor Along Mid-Ocean Ridges

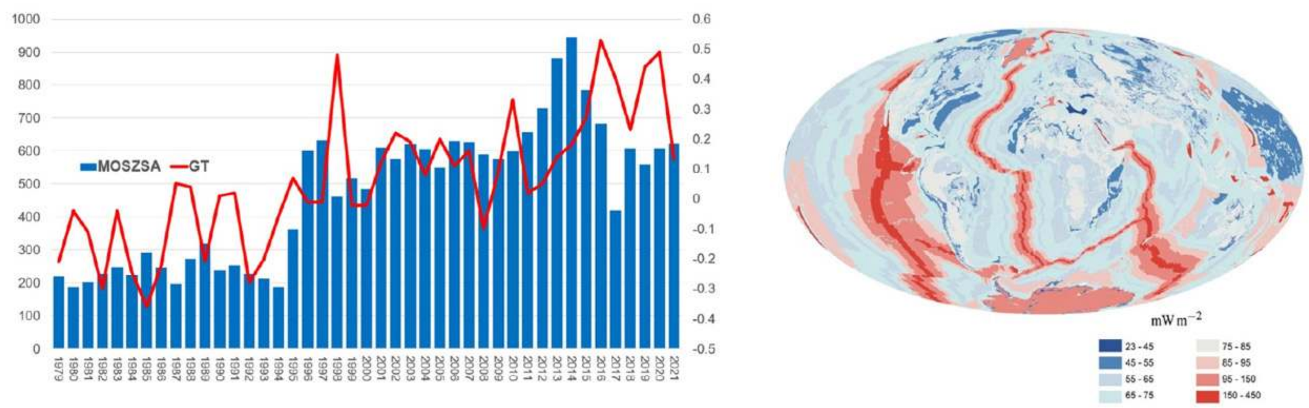

Figure 131: Concurrent increase in the number of ocean floor earthquakes (magnitude 4.0–6.0) and global atmospheric temperatures

Source: Viterito, A. (2022). "1995: An Important Inflection Point in Recent Geophysical History." International Journal of Environmental Sciences & Natural Resources, 29(5). https://doi.org/10.19080/ijesnr.2022.29.556271

Although there are no direct measurements of the volume of rising magma, the global seismic monitoring network allows scientists to estimate the scale of these processes indirectly by analyzing the number and intensity of seismic events, which have been increasing regardless of the amount of seismic data. According to Viterito's hypothesis, seismic and volcanic activity along the mid-ocean ridges leads to an increase in hydrothermal venting and ocean water heating, which in turn contributes to greenhouse gas emissions and atmospheric warming. In this way, Viterito demonstrates that oceans are warming not only from above, but also from below, as a result of geological processes.

Submarine volcanism may also play a major role in shaping the thermal regime of the ocean floor. Current data indicate that about 75% of all volcanic eruptions on Earth occur underwater.[344] It was previously believed that underwater eruptions occurred through the gentle outflow of lava, and that explosive eruptions were impossible due to the pressure of the water column. As a result, it was assumed that submarine volcanoes could not heat the water column, since the emerging lava would solidify almost immediately. However, recent research has changed our understanding of the eruption mechanisms of underwater volcanoes. Magma pressure ranges from 10,000 to 30,000 bar, while the pressure of the water column in the deepest parts of the ocean is only about 1,000 bar.When magma erupts,, it causes instantaneous boiling of water and the breakdown of H2O molecules, forming a gas-water cavity with pressures reaching hundreds or even thousands of bar.[345] This results in powerful explosive eruptions.

[344]Crisp, J. A. Rates of magma emplacement and volcanic output. J. Volc. Geotherm. Res. 20, 177–211 (1984). https://doi.org/10.1016/0377-0273(84)90039-8
[345]Lyons, J.J., Haney, M.M., Fee, D. et al. Infrasound from giant bubbles during explosive submarine eruptions. Nat. Geosci. 12, 952–958 (2019). https://doi.org/10.1038/s41561-019-0461-0

These eruptions are accompanied by the release of tephra and hydrotherms — giant jets of superheated water, with volumes that can reach the equivalent of 40 million Olympic-sized swimming pools. Such emissions can disrupt the ocean's thermal balance not only locally, but on a global scale.

Research conducted by the University of Leeds has revealed kilometer-scale fields of volcanic tephra on the Pacific Ocean floor,[346] providing strong evidence of powerful explosive submarine eruptions. A single eruption of this kind can release thermal energy on the order of 1 terawatt — twice the annual energy consumption of the United States.

> The contribution of explosive eruptions to ocean heating is further supported by Professor Bernd Zimanowski of Julius-Maximilians University in Bavaria, who explains:[347]
>
> *"With submarine lava eruptions, it takes a quite long time for the heat of the lava to be transferred to the water. In explosive eruptions, however, the magma is broken up into tiny particles. This may create heat pulses so strong that the thermal equilibrium currents in the oceans are disrupted locally or even globally."*[348]

Current estimates suggest that the number of hydrothermally active submarine formations ranges from 100,000 to as many as 10 million[349, 350]— an indication that the contribution of hydrothermal activity to the ocean's heat balance may be significantly underestimated. Explosive magma eruptions generate powerful thermal impulses capable of disrupting oceanic heat currents on a local scale. However, given the vast size of the ocean, even such intense underwater eruptions are not sufficient to heat it globally. Volcanoes are not uniformly distributed, their eruptions are episodic, and the total energy released is not enough to warm the entire ocean. Still, it may be sufficient to trigger localized heat waves in certain regions.

A specific example of such localized thermal anomalies is the phenomenon known as marine heatwaves — areas of ocean water that remain abnormally warm for extended periods. Another term for these events is blobs: massive patches of surface water with significantly elevated temperatures. Since 1995, the number of blobs has increased sharply,[351] and they are appearing more frequently in various parts of the world's oceans, including off the coasts of New Zealand, southwestern Africa, and the southern Indian Ocean.

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[346] Pegler, S.S., Ferguson, D.J. Rapid heat discharge during deep-sea eruptions generates megaplumes and disperses tephra. Nat Commun 12, 2292 (2021). https://doi.org/10.1038/s41467-021-22439-y

[347] Dürig, T., White, J.D.L., Murch, A.P. et al. Deep-sea eruptions boosted by induced fuel–coolant explosions. Nat. Geosci. 13, 498–503 (2020). https://doi.org/10.1038/s41561-020-0603-4

[348] University of Würzburg. How Volcanoes Explode in the Deep Sea. (2020) https://www.uni-wuerzburg.de/en/news-and-events/news/detail/news/how-volcanoes-explode-in-the-deep-sea (accessed 1 May 2025)

[349] Baker, E. T. et al. How many vent fields? New estimates of vent field populations on ocean ridges from precise mapping of hydrothermal discharge locations. Earth Planet. Sci. Lett. 449, 186–196 (2016). https://doi.org/10.1016/j.epsl.2016.05.031

[350] Science News Explores. Seafloor hosts surprising number of deep-sea vents. (2016) https://www.snexplores.org/article/seafloor-hosts-surprising-number-deep-sea-vents (accessed 10 May 2025).

[351] Laufkötter, C., Zscheischler, J. & Frölicher, T. L. High-impact marine heatwaves attributable to human-induced global warming. Science 369, 1621–1625 (2020). https://doi.org/10.1126/science.aba0690

One of the most well-known and extensive blobs formed in the Gulf of Alaska in 2013 and quickly spread across the Pacific Ocean. It covered an area of more than 4,000,000 square kilometers — larger than the entire country of India, and in some areas, sea surface temperatures exceeded the average by 5–6 degrees Celsius (Fig. 132). The blob drifted through the ocean from Alaska to Mexico over the course of three years, lasting until 2016. This phenomenon had a significant negative impact on the region's marine ecosystem and climate.

The most likely cause of the blob's formation was intense volcanic activity off the coast of Alaska and the presence of the Cobb magma plume,[352] which heated deep ocean waters that later rose to the surface in massive volumes.

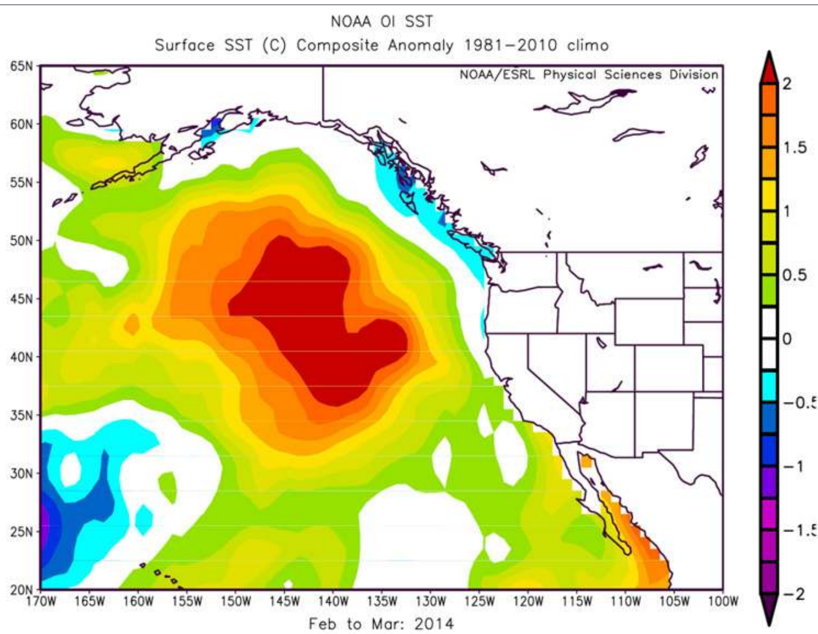


Figure 132: Map showing how the sea surface temperature (SST) anomaly migrated and spread along the U.S. West Coast by March 2015.

(Image courtesy of the NOAA/ESRL Physical Sciences Division, Boulder, Colorado)

In December 2019, a heat blob emerged in the southern Pacific Ocean, east of New Zealand, with temperatures on certain days reaching 6 °C above average. The blob covered an area of more than one million square kilometers—equivalent to 1.5 times the size of Texas or four times the size of New Zealand (Fig. 132). At the time, it was reported to be the largest heat blob in the world's oceans. Moreover, it was the second-largest such event ever recorded in this region.

[352] Chadwick, J., Keller, R., Kamenov, G., Yogodzinski, G. & Lupton, J. The Cobb hot spot: HIMU-DMM mixing and melting controlled by a progressively thinning lithospheric lid. Geochem. Geophys. Geosyst. 15, 3107–3122 (2014). https://doi.org/10.1002/2014gc005334

James Renwick, a professor in the School of Geography, Environment and Earth Sciences at Victoria University of Wellington, noted,

"It's the biggest patch of above average warming on the planet right now. Normally the temperatures there are about 15°C, at the moment they are about 20°C."[353]

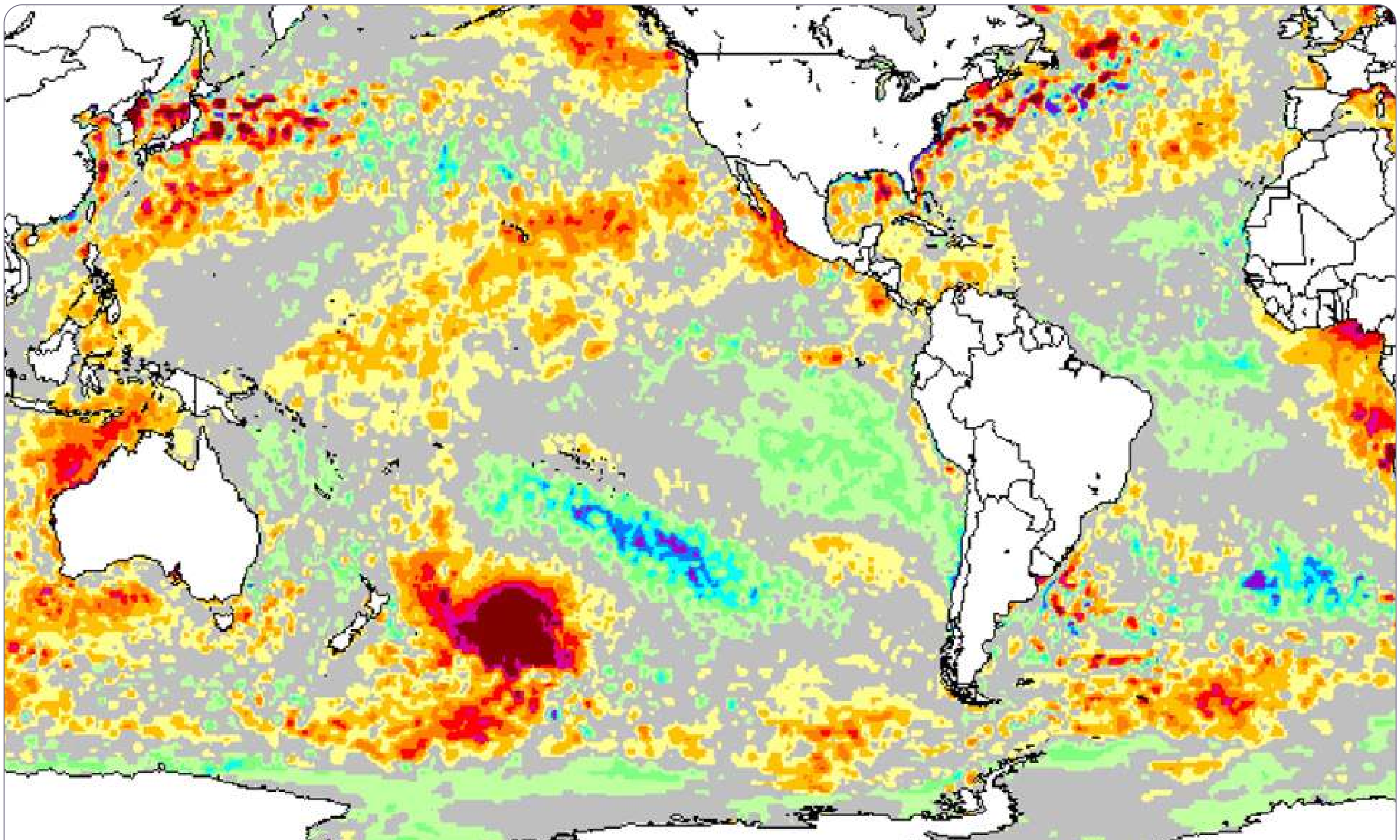


Figure 133: Sea surface temperature anomaly in the South Pacific Ocean on December 25, 2019

Source: The Guardian. Hot blob: vast patch of warm water off New Zealand coast puzzles scientists. (2019) https://www.theguardian.com/world/2019/dec/27/hot-blob-vast-and-unusual-patch-of-warm-water-off-new-zealand-coast-puzzles-scientists (accessed 11 May 2025)

The likely cause of this blob's formation was the activity of an ancient volcanic plateau located off the coast of New Zealand.[354]

[353]The Guardian. Hot blob: vast patch of warm water off New Zealand coast puzzles scientists. (2019) https://www.theguardian.com/world/2019/dec/27/hot-blob-vast-and-unusual-patch-of-warm-water-off-new-zealand-coast-puzzles-scientists (accessed 10 May 2025).
[354]Gase, A. et al. Subducting volcaniclastic-rich upper crust supplies fluids for shallow megathrust and slow slip. Sci. Adv. 9, eadh0150 (2023). https://doi.org/10.1126/sciadv.adh0150

Another notable example of how geothermal heat from magmatic processes contributes to ocean warming is the anomalous heating of Arctic seas along the Siberian coast. According to 2022 research, the Siberian Arctic is warming nearly four times faster than the global average — a rate significantly higher than previously accounted for in climate models, which came as a major surprise to scientists (Fig. 134).[355]

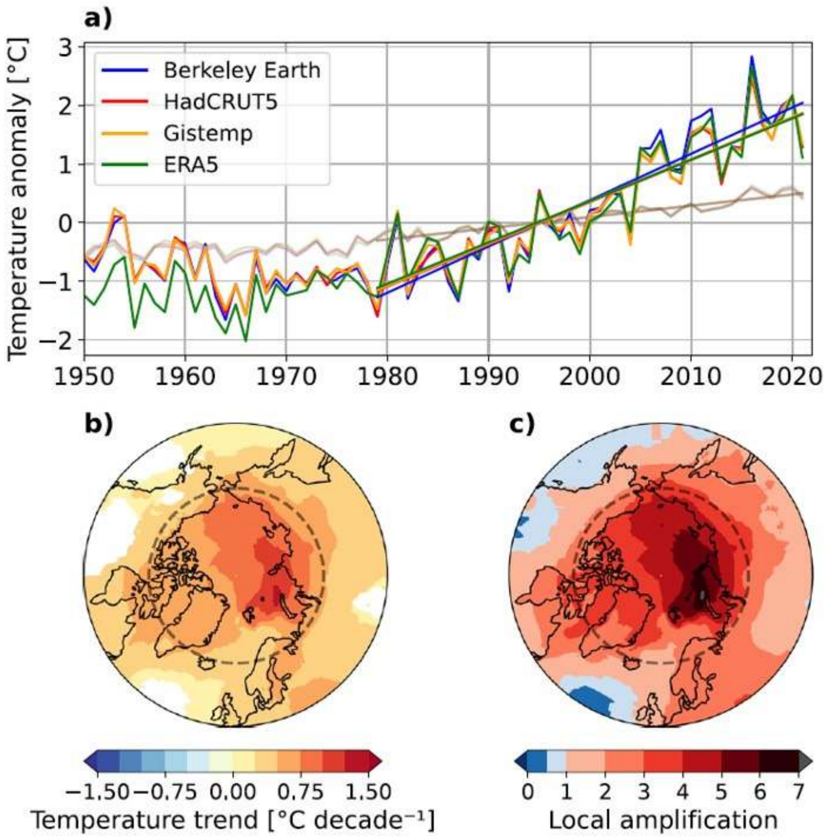


Figure 134: Annual mean temperature evolution in the Arctic
(a) Annual mean temperature anomalies in the Arctic (66.5°–90°N) (dark colours) and globally (light colours) during 1950–2021, derived from various observational datasets. Temperature anomalies have been calculated relative to the standard 30-year period of 1981–2010. The dashed line in (b) and (c) depicts the Arctic Circle (66.5°N latitude).

Source: Rantanen, M., Karpechko, A.Y., Lipponen, A. et al. The Arctic has warmed nearly four times faster than the globe since 1979. Commun Earth Environ 3, 168 (2022). https://doi.org/10.1038/s43247-022-00498-3

In this specific region of the world—near the Taymyr Peninsula—we are witnessing the activation of the Siberian magmatic plume, which is now rapidly rising in the same area where the Siberian Traps erupted 250 million years ago. Current evidence suggests that the plume head is actively eroding the East Siberian Craton, with magma spreading beneath its entire expanse (Fig. 135). Preliminary estimates suggest that the area of magma dispersal beneath Siberia may span 2,500 to 3,000 kilometers in diameter—an area comparable to the size of Australia.

[355] Rantanen, M., Karpechko, A.Y., Lipponen, A. et al. The Arctic has warmed nearly four times faster than the globe since 1979. Commun Earth Environ 3, 168 (2022). https://doi.org/10.1038/s43247-022-00498-3

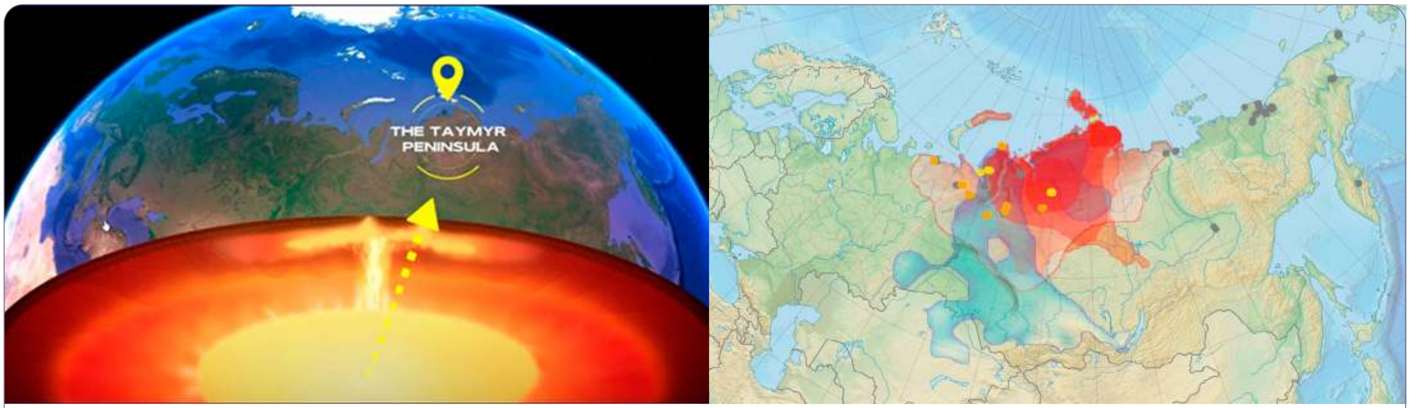


Figure 135: Localization of the plume's position based on results from various scientific studies

It is important to note that such intense warming of the Arctic seas is occurring specifically in the region in the vicinity of the Taymyr Peninsula. This anomaly, particularly in the oceanic zone of Siberia, can be explained by the thinner oceanic crust which conducts heat more efficiently, and the higher heat capacity of water compared to the atmosphere. Ocean water, therefore, intensively absorbs and retains heat from the ascending magma plume, even though the plume is rising beneath the continental crust at a relative distance from the coastline.

For a more detailed analysis of the Siberian magma plume, its impact on the climate system, associated risks, and potential solutions, refer to the report:

"ON THE THREAT OF A MAGMA PLUME ERUPTION IN SIBERIA AND STRATEGIES FOR ADDRESSING THE ISSUE"

The combined body of evidence strongly indicates that geological processes on the ocean floor are a significant factor in global warming. The rise in seismic and volcanic activity on the seafloor correlates with increasing global temperatures, suggesting a possible cause-and-effect relationship. Submarine eruptions—particularly those of an explosive nature—are capable of generating powerful thermal pulses that disrupt both local and even global heat balance. Hydrothermal systems and volcanic activity produce large-scale anomalies such as “blobs,” which have a marked impact on marine ecosystems and climate, while magmatic processes are responsible for abnormal warming of the Arctic seas.

Thus, the ocean is warming not only from the top, under the influence of the atmosphere, but also from below, due to dynamic processes in the Earth's interior. This requires a reevaluation of existing climate models and a deeper study of underwater geological activity as an important component of the overall heat balance of the planet.

However, there is one question that is of key importance: Why is there an increase in magmatic and tectonic activity on Earth at this time?

Brief Description of the Geodynamic Model of Climate Change on Earth in the Current Period

Over the past 30 years, Earth has experienced an unprecedented and synchronized escalation not only in climate change but also in anomalies across all layers of the planet and its geophysical parameters. These changes are increasing exponentially. A comprehensive analysis of scientific data indicates that the primary cause lies in astronomical cycles that recur every 12,000 years.

The hypothesis of cosmic influence is supported by similar changes that have been occurring simultaneously on other planets and moons in the Solar System. For example, wind speeds are increasing and hurricane zones are expanding on Uranus,[356] Jupiter,[357] and Venus.[358] Mars is experiencing polar ice cap melting,[359] while volcanic activity is increasing on both Venus[360] and Mars.[361] Additionally, seismic activity is intensifying[362] on Mars—a geologically "dead" planet—suggesting abnormal internal processes.

Critical shifts in Earth’s geosystem began to emerge around 1995, marked by significant geophysical anomalies such as a sharp acceleration in the planet’s rotation, a shift in Earth's axis, and the onset of rapid drift of the North Magnetic Pole (Fig. 136).

[356] de Pater, I. et al. Record-breaking storm activity on Uranus in 2014. Icarus 252, 121-128 (2015). https://doi.org/10.1016/j.icarus.2015.01.008

[357] Wong, M. H. et al. Evolution of the Horizontal Winds in Jupiter’s Great Red Spot From One Jovian Year of HST/WFC3 Maps. Geophysical Research Letters 48, e2021GL093982 (2021). https://doi.org/10.1029/2021GL093982

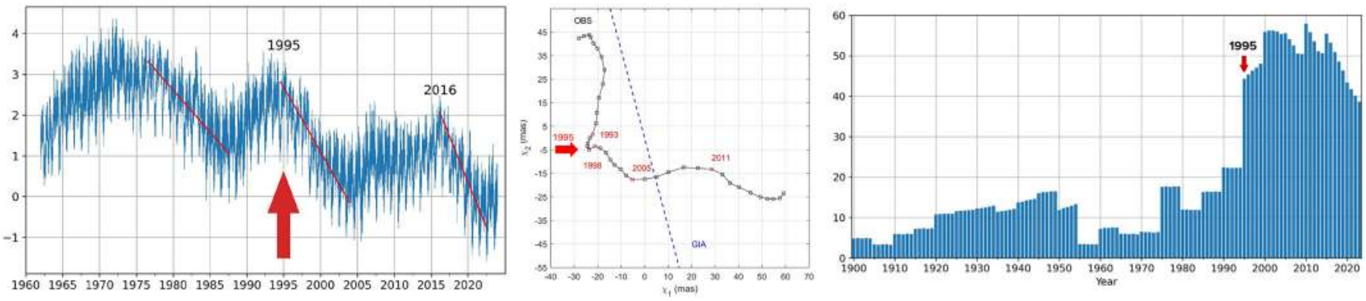
[358] Khatuntsev, I. V. et al. Cloud level winds from the Venus Express Monitoring Camera imaging. Icarus 226, 140–158 (2013). https://doi.org/10.1016/j.icarus.2013.05.018

[359] Sori, M. M. & Bramson, A. M. Water on Mars, With a Grain of Salt: Local Heat Anomalies Are Required for Basal Melting of Ice at the South Pole Today. Geophysical Research Letters 46, 1222–1231 (2019). https://doi.org/10.1029/2018GL080985

[360] Encrenaz, T. et al. HDO and SO2 thermal mapping on Venus - IV. Statistical analysis of the SO2 plumes. A&A 623, A70 (2019). https://doi.org/10.1051/0004-6361/201833511

[361] Broquet, A. & Andrews-Hanna, J. C. Geophysical evidence for an active mantle plume underneath Elysium Planitia on Mars. Nat Astron (2022). doi:10.1038/s41550-022-01836-3 https://doi.org/10.1038/s41550-022-01836-3

[362] Fernando, B. et al. A Tectonic Origin for the Largest Marsquake Observed by InSight. Geophysical Research Letters 50, e2023GL103619 (2023). https://doi.org/10.1029/2023GL103619



Sudden and abrupt acceleration in the rotation of the planet, as recorded by the Earth Orientation Center of the Paris Observatory

Data source: IERS Earth Orientation Center of the Paris Observatory. Length of Day – Earth orientation parameters. https://datacenter.iers.org/singlePlot.php?plotname=EOPC04_14_62-NOW_IAU1980-LOD&id=223

Abnormal shifts in earth's rotational axis: a sharp change in the direction of polar drift and a 17-fold increase in its speed.

Source: Deng, S., Liu, S., Mo, X., Jiang, L., & Bauer Gottwein, P. Polar Drift in the 1990s Explained by Terrestrial Water Storage Changes. Geophysical Research Letters, 48, e2020GL092114 (2021). https://doi.rg/10.1029/2020gl092114

Movement of the North Magnetic Pole: Previously shifting at a rate of 10 km per year, the North Magnetic Pole has suddenly accelerated to 55 km per year and changed its trajectory toward the Taimyr Peninsula in Siberia.

Data source: NOAA data on the position of the North Magnetic Pole https://www.ncei.noaa.gov/products/wandering-geomagnetic-poles

Figure 136: Changes in Earth's geophysical parameters in 1995

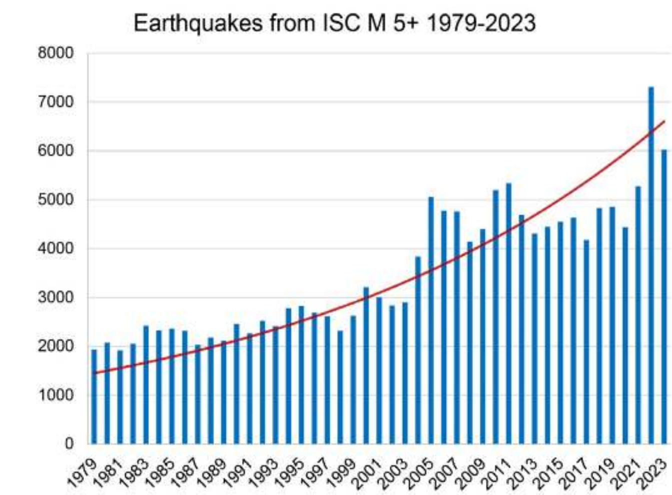
These anomalies indicate profound changes in the Earth's core, requiring quadrillions of times more energy than humanity has produced throughout the entire history of civilization. The cause is external cosmic influence affecting the Earth's core, as well as the cores of other planets in the Solar System. This external force amplifies mantle melting, causing it to rise closer to the surface. As a result, a chain reaction is triggered: volcanic and seismic activity intensifies, heating from the Earth's interior increases, and natural catastrophes grow in frequency worldwide.

Since 1995, there has been a noticeable increase in seismic activity, characterized by higher frequency, magnitude, and energy of earthquakes. This trend is visible both on land and in oceans, including regions where seismic activity was previously almost nonexistent. All of this points to the global scale of these changes. It is important to note that the rise in earthquakes with a magnitude of 5.0 or higher is not related to an increase in sensor networks or sensitivity, but genuinely reflects changes in Earth's geodynamics. According to data from the International Seismological Centre, the number of such earthquakes over the past 25 years has substantially increased and continues to rise (Fig. 137).

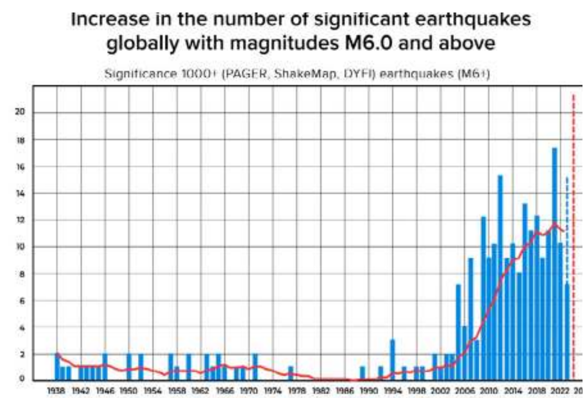
Furthermore, seismic activity is growing near volcanoes, including supervolcanoes such as Yellowstone in the USA, the Phlegraean Fields in Italy,[363] and Taupō in New Zealand[364]—as well as other volcanoes that erupted during previous 12,000-year cycles (Fig. 137).

[363]Fanpage.it. At Campi Flegrei 675 earthquakes in April 2023: it is the month with the most tremors in the last 20 years. (2023) https://www.fanpage.it/napoli/campi-flegrei-675-terremoti-aprile-2023 (accessed 1 May 2025).

[364]GeoNet. Strong M5.6 earthquake consistent with continued minor volcanic unrest at Taupō. Volcanic Alert Level remains at Level 1. (2022) https://www.geonet.org.nz/vabs/7tu66lDztDnIaYDG0LYSgl (accessed 1 May 2025).



Earthquakes of Magnitude 5.0 and Above According to the International Seismological Centre (ISC)



The number of significant earthquakes worldwide with a magnitude of 6.0 and higher. Earthquake selection was based on the significance criterion of 1,000+.
Data Source: U.S. Geological Survey (USGS)

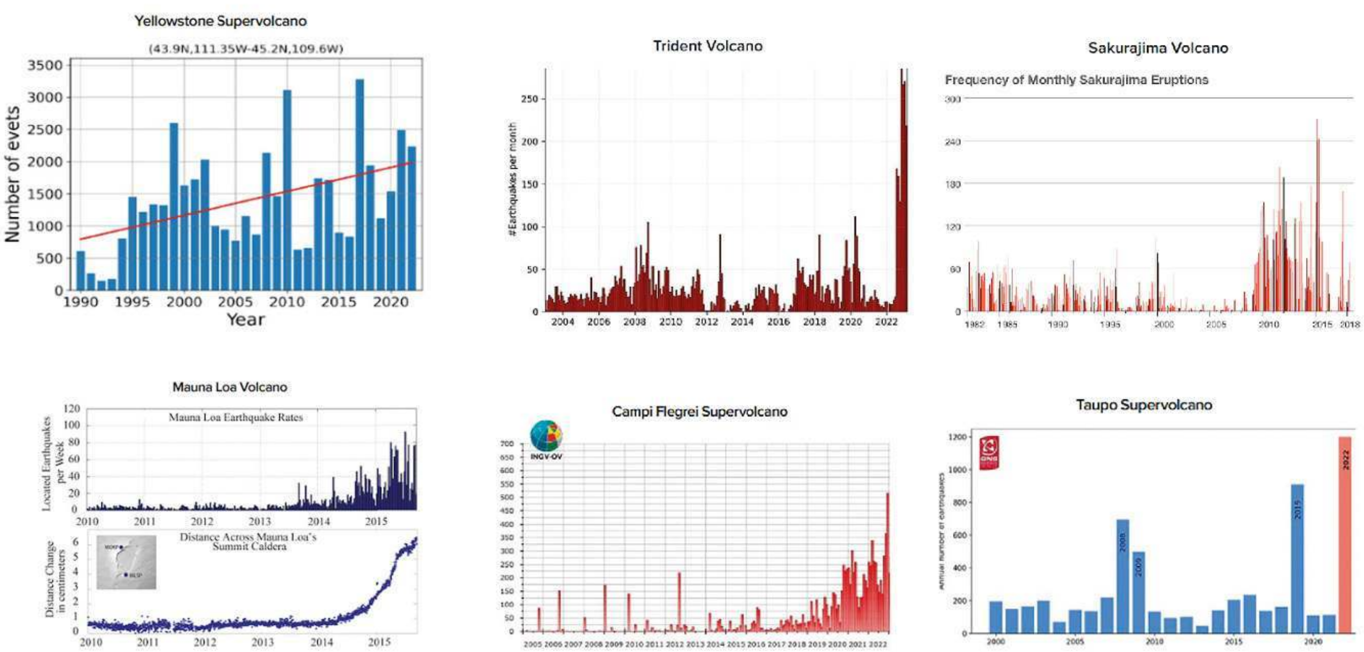


Figure 137: Increase in seismic activity worldwide as well as near volcanoes and supervolcanoes

An increasing number of days each year are marked by volcanic eruptions, with ejected lava often exhibiting anomalous properties such as overheating and a unique chemical composition characteristic of magma originating from the planet's deeper mantle layers.

A particularly concerning development is the growing frequency of deep-focus earthquakes, which occur at depths exceeding 300 kilometers—sometimes extending as deep as 750 kilometers beneath the Earth's surface. Unlike typical earthquakes that occur in the Earth's crust, these phenomena originate in the mantle, where the material is usually ductile, deforming like plastic rather than fracturing. This makes the nature of these earthquakes highly unusual.

Given that these deep-focus earthquakes occur under extreme pressure and temperature conditions, they are likely the result of powerful mantle explosions. Their energy is comparable to the simultaneous detonation of multiple nuclear bombs within Earth's mantle. Additionally, deep-focus earthquakes are often capable of triggering strong seismic events in the Earth's crust, amplifying their destructive impacts.

Since 1995, there has been a sharp increase in the number of such deep earthquakes (Fig. 138), coinciding with other geodynamic anomalies that began during the same period. The surge in the frequency of these intra-mantle explosions signals heightened energy activity within the Earth's interior and accelerated mantle melting, which could potentially lead to large-scale volcanic eruptions.

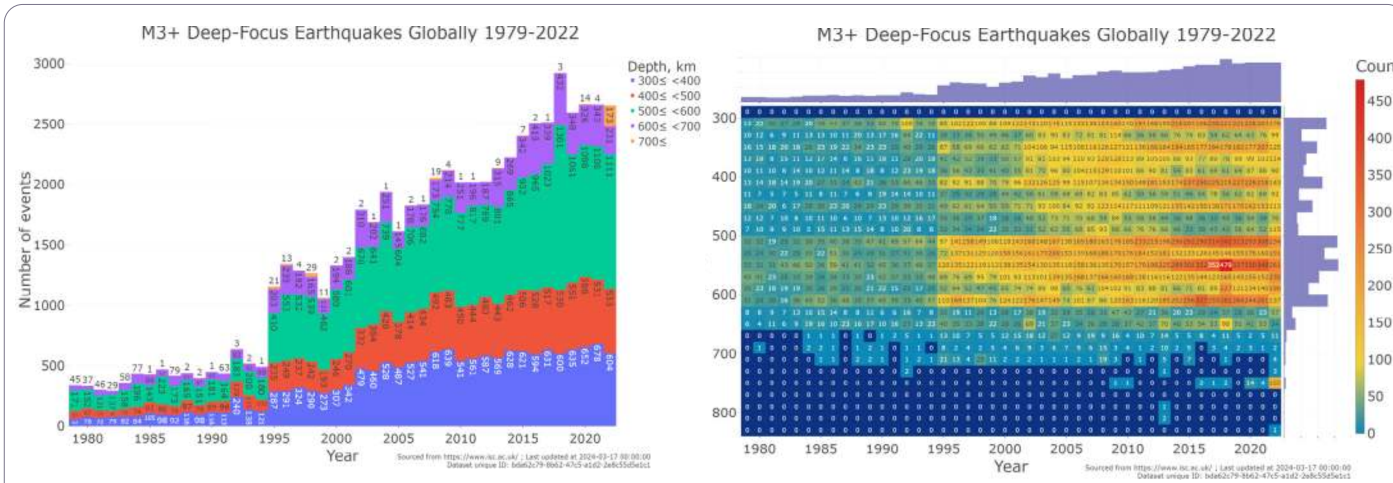


Figure 138: Increase in the number of deep-focus earthquakes at depths greater than 300 km
Data Source: International Seismological Centre (ISC) Database

Since 1995, under the influence of centrifugal forces, molten magma within Earth's mantle has begun rising more actively toward the surface, eroding and heating the lithosphere from within more intensely than usual. This upward movement of magma increases the geothermal heat flux from Earth's interior and activates magma plumes beneath the glaciers of West Antarctica, Central Greenland, and Siberia. As a result, glaciers and permafrost are melting from the bottom up at an accelerated pace.[365, 366, 367]

Thus, one of the key causes of ocean warming is rising magma, which particularly affects the oceanic crust—thinner and more vulnerable than continental crust—by heating it from below.

Historical records from geological strata and ice cores indicate that Earth has undergone similar catastrophic cycles approximately every 12,000 years. Moreover, every second cycle—roughly every 24,000 years—these planetary disasters have been even more intense (Fig. 139).

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[365]Rogozhina, I. et al. Melting at the base of the Greenland ice sheet explained by Iceland hotspot history. Nature Geosci 9, 366–369 (2016). https://doi.org/10.1038/ngeo2689

[366]Van Der Veen, C. J., Leftwich, T., Von Frese, R., Csatho, B. M. & Li, J. Subglacial topography and geothermal heat flux: Potential interactions with drainage of the Greenland ice sheet. Geophysical Research Letters 34, 2007GL030046 (2007). https://doi.org/10.1029/2007GL030046

[367]Dziadek, R., Ferraccioli, F. & Gohl, K. High geothermal heat flow beneath Thwaites Glacier in West Antarctica inferred from aeromagnetic data. Commun Earth Environ 2, 162 (2021). https://doi.org/10.1038/s43247-021-00242-3

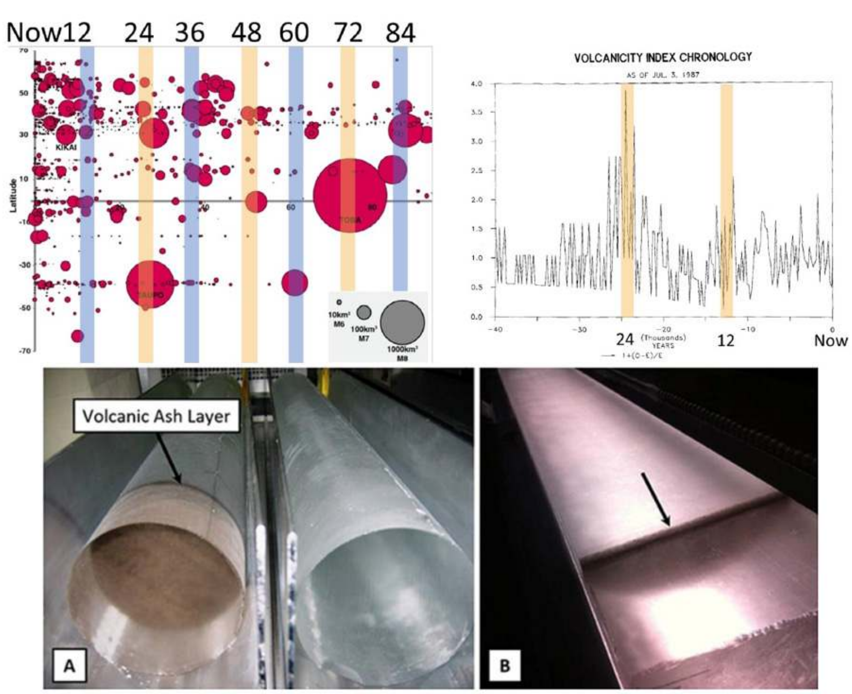


Figure 139: The graphs illustrate catastrophic volcanic activity every 12,000 years and even more intense events every 24,000 years

Sources:
Brown, S. K., Crosweller, H. S., Sparks, R. S. J., Cottrell, E., Deligne, N. I., Guerrero, N. O., Hobbs, L., Kiyosugi, K., Loughlin, S. C., Siebert, L., & Takarada, S. Characterisation of the Quaternary eruption record: analysis of the Large Magnitude Explosive Volcanic Eruptions (LaMEVE) database. Journal of Applied Volcanology, 3 (5) (2014). https://doi.org/10.1186/2191-5040-3-5
Bryson, R. A.. Late Quaternary Volcanic Modulation of Milankovitch Climate Forcing. Theoretical and Applied Climatology, 39, 115–125 (1989). https://doi.org/10.1007/bf00868307

Earth is currently entering one of these cycles. However, this time, due to anthropogenic pollution of the ocean with micro- and nanoplastics, the thermal imbalance within the mantle has intensified. This has led to an increase in the number of deep-focus earthquakes, the formation of new magma chambers, and a general destabilization of the planet. As a result, cataclysms are accelerating far more rapidly and severely than in previous cycles.

In fact, ocean pollution has become a primary reason why Earth may not withstand this cycle. It is important to understand that addressing ocean contamination by micro- and nanoplastics can slow the progression of these cataclysms—but it will not stop them.

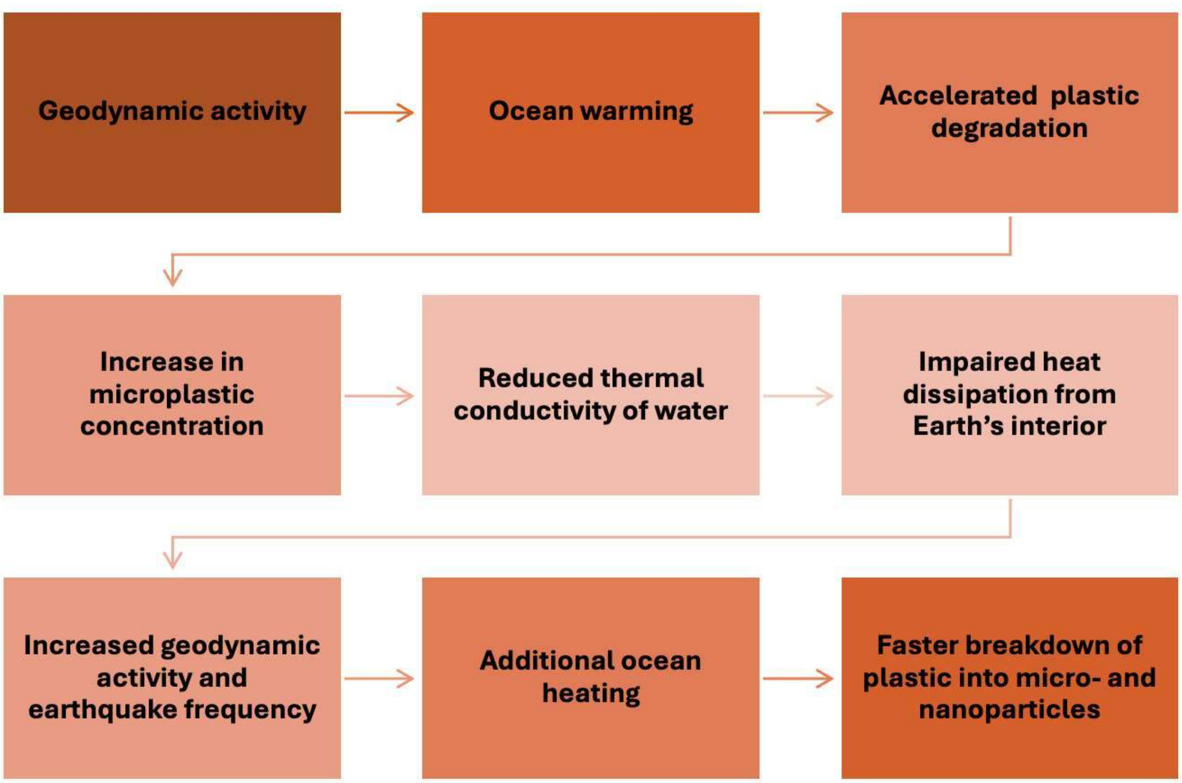
More detailed information about the current geodynamic activation of Earth's interior, the 12,000-year cycle of cataclysms, and possible solutions to this issue can be found in the report

“ON THE PROGRESSION OF CLIMATE CATACLYSMS ON EARTH AND THEIR CATASTROPHIC CONSEQUENCES.”

As shown by years of interdisciplinary research into geodynamic changes during the 12,000-year cycle, the primary cause of ocean heating is rising magma, which has a particularly strong impact on the oceanic crust due to its thinner and more vulnerable structure compared to the continental crust. Pollution of the World Ocean with plastic and the accumulation of micro- and nanoplastic particles has become a critical factor altering the thermophysical properties of the ocean. The presence of these synthetic particles in ocean water significantly reduces its ability to conduct heat, disrupting natural heat exchange processes between the deep ocean layers and the surface. Even more critically, it interferes with heat dissipation from the lithospheric plates. Under conditions of increased geodynamic activity during the 12,000-year cycle, this critical disruption of the ocean water's heat conductivity function not only intensifies the heating of the ocean and atmosphere, but also increases subsurface heating. As a result, mantle melting accelerates, further amplifying geodynamic activity.

This leads to the accumulation of excess energy in the Earth's interior, resulting in an increase in deep-focus earthquakes and the accelerated formation of new magma chambers. In turn, these processes further exacerbate planetary instability and accelerate ocean heating.

A dangerous feedback loop begins to form: geodynamic activity heats the ocean — the heat accelerates plastic degradation — rising concentrations of microplastics reduce the thermal conductivity of seawater — this disrupts heat dissipation from the Earth's interior — which further intensifies geodynamic activity and increases earthquake frequency — leading to even more ocean heating, which in turn speeds up the breakdown of plastic into micro- and nanoparticles.



This contributes to the rising frequency and intensity of extreme weather events and natural disasters—such as floods, hurricanes, and tropical cyclones—which are now occurring more intensely than ever before.

Thus, micro- and nanoplastic pollution of the ocean exerts not only a destructive effect on human health, ecosystems, the biosphere, and the climate system by intensifying ocean warming—it also acts as an amplifying factor in the already extreme catastrophes associated with the 24,000-year cycle that the Earth has now entered. This creates unprecedented risks not only for the survival of humanity but for the planet itself.

Addressing the global environmental, climatic, and geodynamic crisis requires international collaboration among scientists from multiple disciplines to urgently develop and implement comprehensive solutions. These must include ocean decontamination from micro- and nanoplastics, mitigation of their harmful effects on the human body, and fundamental responses to geodynamic threats.

Proposed solutions can be found in the relevant reports:

REPORT

“ON THE PROGRESSION OF CLIMATE CATACLYSMS ON EARTH AND THEIR CATASTROPHIC CONSEQUENCES.”

REPORT

“ON THE THREAT OF A MAGMA PLUME ERUPTION IN SIBERIA AND STRATEGIES FOR ADDRESSING THE ISSUE”

CONCLUSIONS: NANOPLASTICS ARE A CHALLENGE THAT MUSTN'T BE IGNORED

The problem of plastic pollution, particularly with micro- and nanoplastics (MNPs), has moved beyond the scope of localized environmental damage and has evolved into a complex global threat. Recent research confirms both the direct and indirect impact of MNPs on the climate system, ecosystem resilience, and human health. Microplastic particles are capable of penetrating living organisms, triggering inflammatory responses, disrupting hormonal balance, impairing immune and reproductive functions, and altering the physical and chemical properties of the environment, from ocean water to the atmosphere.

More than a decade ago, representatives of the ALLATRA international scientific community put forward the hypothesis that plastic pollution would exert an increasingly significant influence on climate anomalies and exacerbate public health challenges. Today, these hypotheses are being confirmed by independent studies conducted by leading scientific institutions. The rapid accumulation of data on the environmental and biological effects of MNPs is opening new avenues of analysis, including the transformation of climate patterns, changes in the hydrosphere, and the escalation of systemic risks to sustainable development.

Of particular concern is the discovery that even microscopic concentrations of nanoplastics can initiate cascading effects throughout the biosphere and climate system. Plastic is no longer just solid waste: it has become an active agent of transformation, impacting both the environment and the human body. Its consequences are already becoming apparent. The MNP crisis extends beyond ecology and medicine; it must also be understood in the context of national security, macroeconomics, and international relations.

As part of its strategy to counter this threat, the ALLATRA Movement has proposed two key directions, both with practical applications and predictive potential. The first involves the large-scale implementation of atmospheric water generation (AWG) technologies, which can simultaneously address freshwater scarcity and contribute to the removal of microplastic particles from the atmosphere and oceans. However, the deployment of AWG technologies must also take into account potential risks: specifically, the increased concentration of MNPs in the air and the resulting intensification of inhalation exposure in humans. This underscores the urgent need for the parallel development of highly effective filtration and protective systems.

The second strategic direction proposed by ALLATRA involves the development of methods to neutralize or shield the electrostatic charge of nanoplastics — one of the primary factors contributing to their toxicity. Charged nanoplastic particles actively interact with cell membranes, proteins, and genetic material, forming stable molecular bonds. These particles can penetrate biological barriers, including the blood-brain barrier, accumulating in tissues, and trigger a cascade of cellular disruptions — from oxidative stress to apoptosis. Reducing the electrostatic activity of micro- and nanoplastics could significantly decrease their harmful effects and slow their accumulation in the human body.

According to the authors of the report, shielding or neutralizing the electrostatic charge of MNPs can reduce their potential hazard by at least 50%, making this area of research critically important. Such measures would provide a necessary window of time to develop more comprehensive strategies for diagnosing, preventing, and removing MNPs from the human body, as well as for cleaning up the biosphere. In this context, research in the fields of biophysics, nanotechnology, and molecular toxicology becomes especially significant.

Thus, an effective response to the threat posed by MNPs requires not isolated measures, but a global and interdisciplinary approach. Coordinated efforts are needed across scientific research, technological innovation, regulatory frameworks, and international cooperation. Plastic pollution must not be viewed as a narrow environmental issue, but rather as a systemic challenge that affects public health, safety, resource security, and the resilience of social infrastructure.

What makes this report unique is its comprehensive, interdisciplinary approach, integrating data from physics, chemistry, biology, and medicine. This synthesis allows the issue of MNPs to be viewed as a civilizational challenge requiring solutions at multiple levels. The global community is only beginning to grasp the true scale of this threat. While no universal solution currently exists, it is the pursuit of such a solution and the advancement of scientific collaboration that may pave the way toward overcoming the crisis. The primary challenge is not the absence of a solution, but the ability to identify one before reaching a critical tipping point.

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Alqahtani, S., Alqahtani, S., Saquib, Q. & Mohiddin, F. Toxicological impact of microplastics and nanoplastics on humans: understanding the mechanistic aspect of the interaction. Front. Toxicol. 5, 1193386 (2023). https://doi.org/10.3389/ftox.2023.1193386

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