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Review Article

Cellular and Systemic Impacts of Microplastics and Nanoplastics

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Abstract

Plastics are synthetic polymers that have become an essential part of everyday life due to their low cost, durability, and flexibility. However, plastics in the environment break down into microplastics (MPs, <5 mm) and nanoplastics (NPs, <0.1 µm), and are potential threats to ecosystems and general health. Micro- and nanoplastics (MNPs) are ubiquitous in air, water, and soil and can be ingested through consumption or inhaled through respiration. Once inside, MNPs can then enter cells via various pathways, such as endocytosis and diffusion. The interactions of MNPs with the cells depend on their size, shape, and surface properties. MNPs can cause oxidative stress, inflammation, organelle damage, membrane disruption, and cell death. Studies indicate that MNP exposure can cause reproductive toxicity, metabolic dysfunction, cognitive decline, and increased risk of cancer and chronic diseases. Harmful plastic additives such as phthalates, BPA, and PBDEs, and adsorbed pollutants, such as heavy metals and PAHs, further amplify the toxic effects. The synergistic impact of MNPs with these substances aggravates cellular damage. Given the global rise in plastic production and persistence of MNPs in the environment, urgent action is needed to protect ecology and human health. This paper advocates stricter regulations on plastic waste management, health-focused research, the development of bioremediation technologies, and the broader adoption of sustainable waste management practices. Understanding the pathways, toxicity, and long-term impacts of MNPs is necessary for developing effective public health policies and reducing future risks.

Keywords: Microplastics, nanoplastics, cellular and systemic effects, environmental pollution

Introduction

Plastic polymers are made of repeating chemical units. Most plastics are manufactured using fossil fuels, such as petroleum and natural gas, through the polymerization process. Plastics are lightweight, long-lasting, and can be molded into different shapes. Such characteristics have made them suitable for widespread use in packaging, clothing, electronics, medical devices, and construction materials. While plastics have many uses, they do not biodegrade, leading to long-term pollution problems, particularly when they are degraded into smaller fragments such as MPs and NPs (Wright et al., 2013; Song et al., 2017; Da Costa, 2018; Gigault et al., 2018). These particles, collectively referred to as MNPs, are now widespread in the environment (Lima et al., 2015; Zhao et al., 2014; Anderson et al., 2016; Browne et al., 2011). Studies indicate that MNPs have deleterious effects on ecosystems and human health.

Since 1950, global plastic production has increased by an average of 8.4% each year (Geyer et al., 2017), with a brief slowdown to 2.2% during the first year of the COVID-19 pandemic. Production soon surpassed pre-pandemic levels, driven by increased demand for sterile single-use packaging (OECD, 2022; PlasticsEurope, 2022; Houssini et al., 2025; Peng et al., 2021).

By August 2021, the pandemic had generated an estimated 8.4 ± 1.4 million tons of plastic waste worldwide, with about 25.9 ± 3.8 thousand tons entering the ocean. In the River Thames, microplastic levels during late-2020 lockdowns were 77% higher than usual, with 82% of particles identified as fibers likely originating from masks and other PPE (Peng et al., 2021; Devereux et al., 2023).

Over time, sunlight (UV rays) and environmental friction break down plastics into MNPs. Because these particles are extremely small and cannot be filtered out of drinking water or removed from food sources, they pose a persistent threat to the ecosystems and human health.

MNPs are widespread in the environment and have been detected in human organs, tissues, and even cells (Yee et al., 2021). Studies indicate that MNPs can enter the body through the skin, lungs, or digestive tract. Healthy skin blocks most particles, but damaged skin lets smaller ones in. Inhaled MNPs from pollution, tires, or textiles can damage lung cells, cause inflammation, and lead to fibrosis, with smaller particles causing greater risks. Consumed MNPs from food or drinks can pass the gut barrier, build up in organs, disturb gut bacteria, and cause oxidative stress. They may also cross the brain and placenta barriers, impact the kidneys, ovaries, and immune cells, and raise the risk of chronic diseases (Grote et al., 2023).

This paper explores the interactions of MNPs with human cells and their impact on human health. Understanding the extent of MNP contamination and its toxicity mechanisms is vital for evaluating the risks associated with chronic exposure and directing future research, public health policies, and pollution control strategies.

Uptake and Interaction of MNPs with the Cell Membrane

MNPs can be brought into a cell via different mechanisms, such as phagocytosis (in which the cell engulfs large particles, pinocytosis (the cell uptakes extracellular fluids by forming vesicles), clathrin-mediated endocytosis (integrating into a cell by forming vesicles from the cell membrane), and caveolae-mediated endocytosis (utilizing the caveolae to transport substances) (Yee et al., 2021).

The interactions of MNPs with cells depend on the size, shape, and surface characteristics of the particles. In marine crustaceans (such as *Paracyclopina nana*), smaller particles (<0.5 µm) were found to be more bioavailable than the larger ones (>6 µm) (Jeong et al., 2015), prompting stronger biological responses. Conversely, in zebrafish (*Danio rerio*), larger particles were found to cause more oxidative stress and affect metabolism (Lu et al., 2016).

MPs can enter cells through diffusion, facilitated diffusion, endocytosis, or breakdown of phospholipid molecules in the cell membrane (Liu et al., 2021; Monnery et al., 2017). MPs attached to the cell membrane stretch and weaken the membrane and disrupt normal cell functions (Fleury and Baulin, 2021). MPs also trigger cell apoptosis (cell death) and oxidative damage through excessive reactive oxygen species (ROS) production. This degrades the phospholipid of the cell membrane, a process known as lipid peroxidation (Jia et al., 2023; Kadac-Czapska et al., 2024).

MPs also reduce lysosomal function, alter cellular pH, and disrupt the cell recycling (autophagy) process (Deng et al., 2022; Kadac-Czapska et al., 2024). Lysosomal damage can damage other cellular organelles. For example, some mussel species (*Mytilus galloprovincialis* and *M. edulis*) exposed to MPs showed swollen lysosomes, mitochondrial damage, and increased cell death (Avio et al., 2015; Canesi et al., 2016; Wang et al., 2013).

Inflammatory Responses at the Cellular and Tissue Levels

Disruption of Cellular Signaling Pathways (Figure 1)

MNPs may interrupt the functions of various cell signaling pathways, such as the Nrf2, PI3K/Akt, MAPK, JNK, p53, p38, ERK1/2, and TGF-β pathways (Das, 2023). Such dysregulations of signaling pathways could be due to inflammation caused by enhanced production of some pro-inflammatory cytokines, such as TNF-α, IL-1β, and IL-6 (Mattioda et al., 2023; Wu et al., 2023). Chronic inflammation can speed up the cell aging process (Goa et al., 2022) and further disrupt these pathways (Li et al., 2023).

Studies link MNP exposure to autoimmune disorders. In experimental rheumatoid arthritis (RA) models, polystyrene MPs aggravated inflammation of the synovial membrane (Chang and Tang, 2023). Studies also indicate that Nps may push macrophages toward a pro-inflammatory M1 state, a pathway linked to RA and systemic lupus erythematosus (SLE) (Jiang et al., 2024). Clinically, the American Medical Association warns that early-life exposure to microplastics may disrupt immune development and increase susceptibility to immune-mediated disorders (AMA, 2024).

MNPs have also been found to affect reproductive health in females. Exposure to MNPs activates the NLRP3/caspase-1 pathways, leading to the release of interleukin-18 and chronic inflammation (Kadac-Czapska et al., 2024). In males, MNPs can reduce sperm quality by affecting the NRF2-HO-1-NFKB pathway (Wei et al., 2022). Studies with mice indicate that MNPs trigger the autophagy pathway (PINK1/Parkin) in spermatocytes (Liu et al., 2022). In fish, MNPs significantly impact hormone production and cytochrome P450 pathways in the testis (Wang et al., 2019).

In lung cells, polystyrene microplastics were found to stress the endoplasmic reticulum, leading to cell death (Jeon et al., 2023). In endothelial cells, MNPs suppress the vascular endothelial growth factor (VEGF) signaling process, which suppresses cell growth (Lee et al., 2023). In cardiomyocytes, MNPs may damage mitochondria. This triggers the cGAS-STING pathway, promoting increased cell inflammation and aging (Wang et al., 2024).

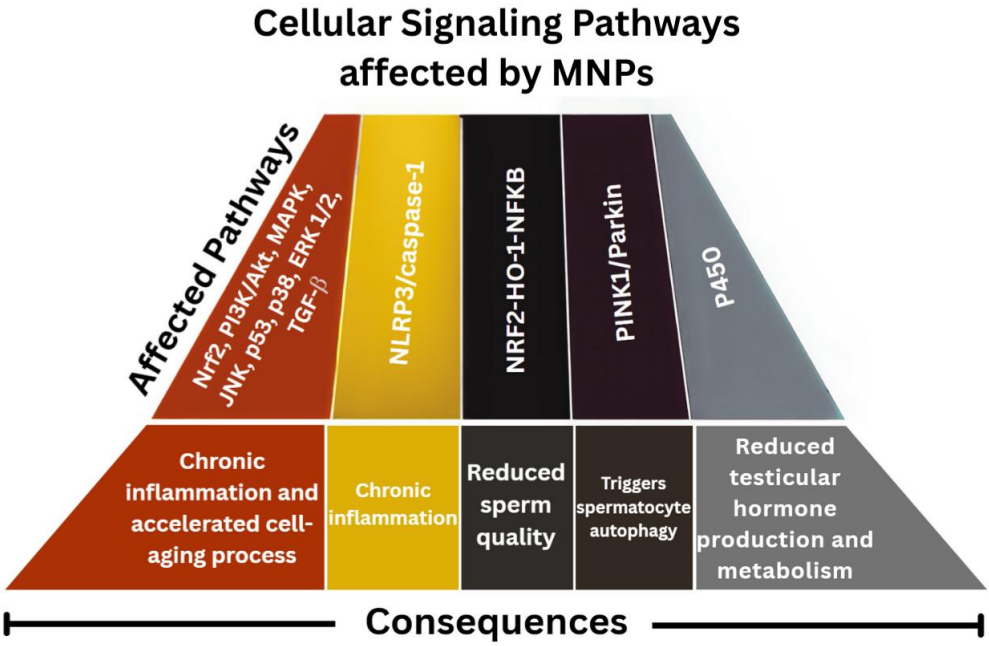

Figure 1: The figure shows the disruption of various biological pathways and their health consequences.

Inflammatory and Immune Response to MPs and NPs.

MNPs are xenobiotic materials. Studies indicate that they can interact with and activate immune cells. Besides triggering excessive production of pro-inflammatory cytokines (Dong et al., 2020; Prietl et al., 2014; Weber et al., 2021), lysosomal damage, membrane destabilization, and oxidative stress can also occur in cells (Dong et al., 2020; Chen et al., 2021). Studies with animals show that rats had inflammatory responses in their

intestinal tissue (Wang et al., 2023), and fish experienced inflammation in their liver and intestines (Buwono et al., 2022).

Studies suggest a possible link between MPs and various diseases. For example, when lipids are damaged by excessive ROS production, they produce reactive aldehydes that can bind to proteins and DNA, upsetting their functions (Gentile et al., 2017). This can cause serious disease conditions, such as atherosclerosis, neuronal damage (Lawrence and Zoncu, 2019), cancer (Nam, 2011; Murata, 2012), lung disease (Boukhenouna et al., 2018; Dong et al., 2020), immune damage (Kadac-Czapska et al., 2024), and cognitive deterioration (Holtzman, 2019; Musi et al., 2018; Zhang et al., 2019). Furthermore, MNPs can increase inflammatory markers in cells (Hu, 2020; Pulvirenti et al., 2022), blocking the cell cycle and enhancing the cellular aging process (Mahmud et al., 2024). These potential risks to human cells highlight the necessity for continued research and address the problems associated with MNPs exposure.

Toxic Effects of Plastic Additives and Absorbed Pollutants

Plastic Additives and Their Cellular Effects (Figure 2)

Additives, such as DEHP (diethylhexyl phthalate) and DINP (diisononyl phthalate), are often included with plastics to improve their properties and performance (Marturano et al., 2017). Some additives are EDCs (endocrine-disrupting compounds), which can cause serious reproductive and developmental issues. In men, EDC exposure has been linked to decreased fertility and increased risk of prostate and testicular cancers (Lahimer et al., 2023). In females, it may increase the risk of early menopause, irregular menstrual cycles, reduced egg quality, and disrupted ovarian function (Laws et al., 2021).

Phthalates

Phthalates are a group of chemicals predominantly used to enhance the flexibility and durability of plastics. DEHP and DINP are commonly used plasticizers in cosmetics, medical devices, and household products (Marturano et al., 2017). These chemicals do not tightly adhere to the plastic polymers and can easily leach into the environment (Liu et al., 2024). Studies have shown that DEHP can cause neurotoxicity, immunotoxicity, metabolic disruption, and endocrine damage in dolphins and Chinese hamsters (Chang et al., 2017; Radke et al., 2020; Weaver et al., 2020).

Phthalates are harmful to the respiratory system, contributing to allergies, rhinitis, asthma, and lung toxicity (Zou et al., 2020; Yu and Wang, 2024). Children exposed to DEHP-contaminated HVAC filter dust exhibited asthma symptoms (Bi et al., 2018). Infants exposed to DEHP through PVC respiratory tubing were found to produce respiratory distress syndrome (Roth et al., 1988).

BPA (Bisphenol A)

Bisphenol A (BPA) is mostly used in food packaging, polycarbonate plastics, and dental objects. BPA can disrupt the male reproductive system and metabolic processes (Cimmino et al., 2022). Studies link BPA to miscarriages (Lathi et al., 2014), fetal chromosomal abnormalities (Yamada et al., 2002; Allard and Colaiacovo, 2010), and reduced FSH (follicle-stimulating hormone) production (Lahimer et al., 2023). Studies also indicate that BPA can cross the blood–brain barrier, leading to neurodegenerative and neuro-developmental disorders (Wang et al., 2019). They have also been implicated in epigenetic changes, impacting gene expression and long-standing health (Lombó et al., 2015; Junge et al., 2018).

PBDEs (Polybrominated Diphenyl Ethers)

PBDEs are flame-retardant compounds used in electronics, textiles, and foam products. Studies have shown that PBDEs can damage thyroid function (Renzelli et al., 2023). Higher levels of PBDE in plasma were found to be linked with decreased TSH (thyroid-stimulating hormone) production in men (Hagmar et al., 2001). Studies also linked PBDEs with low birth weight, birth length, and head circumference in newborns (Chen et al., 2015).

Toxicity of Contaminants Associated with MNPs (Figure 2)

MPs accumulate toxic metals from the environment (Weis and Alava, 2023). Studies tested the binding affinity of different types of MPs, such as PVC, nylon, polystyrene, low-density polyethylene, high-density polyethylene, polycarbonate, polyester, and polyurethane, with heavy metals including cadmium, copper, lead, and zinc (Munier and Bendell, 2018; Kazmiruk et al., 2024). Among these, low-density polyethylene showed the strongest bonding affinity to heavy metals.

MPs may contain harmful chemical substances, such as DDT (dichlorodiphenyl-trichloroethane), and PAHs (polycyclic aromatic hydrocarbons), which have been shown to cause several health problems, such as cancer, congenital abnormalities, and genetic mutations (Jiang et al., 2014). PAHs can also suppress the immune system and damage the nervous system (Yu et al., 2022). Previous studies have indicated that MPs and environmental toxins together can be more harmful than each present alone (Sun et al., 2021). For example, marine mussels (*Mytilus* spp.) exposed to both MPs and the PAH caused more tissue damage and increased oxidative stress than those exposed to either pollutant alone (Paul-Pont et al., 2016). Similarly, NPs combined with phenanthrene caused more toxicity to crustaceans, such as *Daphnia magna*, than either substance by itself (Ma et al., 2016). In another study, clams (*Scrobicularia plana*) exposed to MPs alone showed little to no harm but showed substantial tissue damage when benzo[a]pyrene (BaP), a cancer-causing PAH, was attached to MPs (O'Donovan et al., 2018).

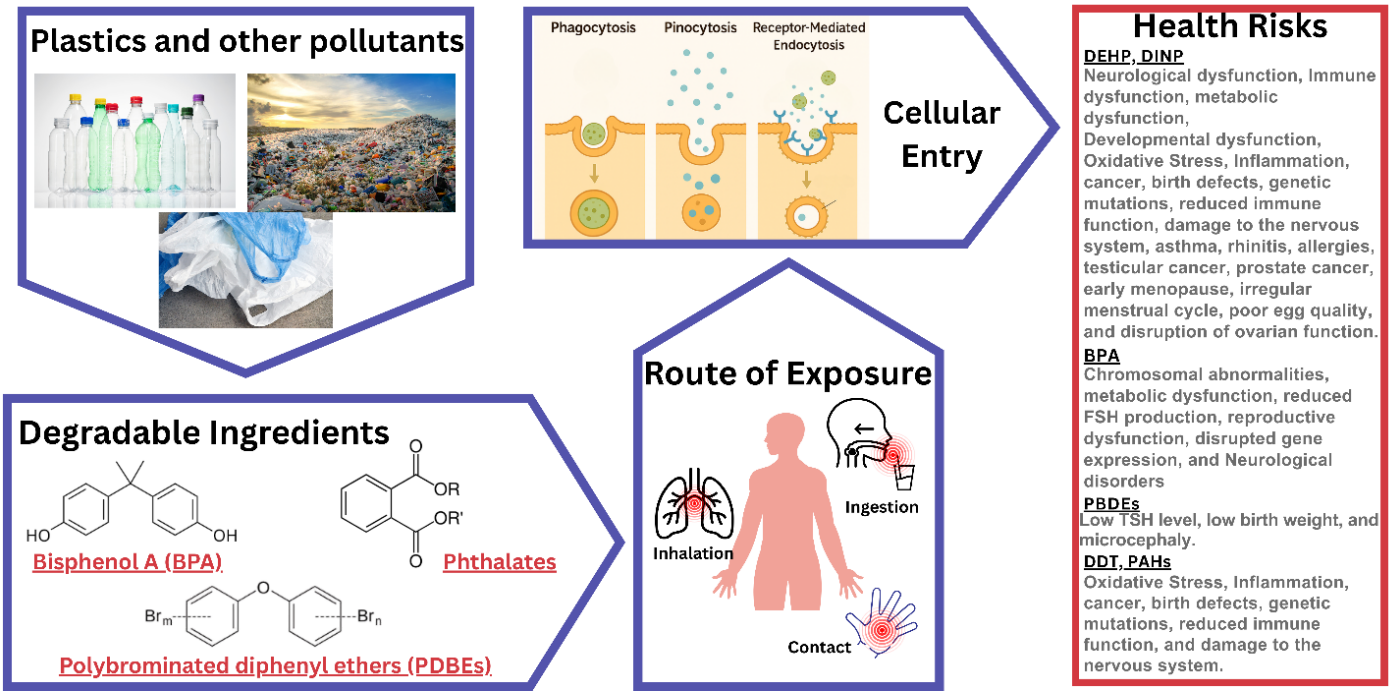

Figure 2: The figure illustrates the toxic effects of various plastic additives and absorbed pollutants on human health.

Strategies for Exposure Prevention

Recent studies have focused on the harmful impacts of MNPs on both the environment and living organisms. To reduce this damage, coordinated actions from governments, NGOs, and individuals are crucial to contain plastic pollution and mitigate the damaging effects of MNPs. Key strategies for mitigation may include:

- Developing or supporting laws that reduce plastic waste production.
- Developing public health-focused research methods.
- Promoting bioremediation techniques that boost the plastic-degrading activity of soil microbes
- Following the "Reduce, Reuse, Recycle" principle and ensuring proper waste disposal

- Using advanced plastic breakdown methods, such as photocatalysis and electro-Fenton reactions (an advanced oxidation process used to degrade organic pollutants) instead of landfilling. This will help limit microplastic formation.

Discussion

The abundance of evidence linking MNPs to significant health risks is concerning. MNPs can penetrate cells via multiple pathways. Since 2022, biomonitoring studies have detected microplastics in human whole blood (~80% of donors), deep lung tissue, cardiovascular tissues, and even the olfactory bulb, supporting the possibility of systemic effects of MNP particles (Leslie et al., 2022; Jenner et al., 2022; Amato-Lourenço et al., 2024).

Upon entering the cells, MNPs cause damage through oxidative stress, inflammation, lysosomal dysfunction, and interference with signaling pathways. These effects may lead to organ-specific pathologies and systemic disorders, including reproductive toxicity, endocrine disruption, neurodegeneration, immune dysfunction, and even cancer (Yang et al., 2023; Jahedi et al., 2025). However, there are limitations to our current understanding of MNP toxicity. Much of the available data comes from animal studies or lab experiments, which may not fully represent how MNPs affect the human body. This makes it difficult to directly apply the findings to real-world health risks.

Another challenge is the wide variation in MNP size, shape, surface properties, and how they interact with biological systems and the environment. These differences make it difficult to compare results across studies. While smaller particles often cause stronger biological effects, some studies demonstrate that larger particles can also cause significant damage, such as oxidative stress (Jahedi et al., 2025).

The occurrence of chemical additives, such as phthalates, BPA, and PBDEs, and the ability of MNPs to absorb environmental pollutants, adds more complexity. The combined toxic effects of MNPs, the chemical additives, and the environmental pollutants are still not well understood and need more research. Additionally, there is a lack of long-term epidemiological data to assess the chronic effects of MNP exposure in humans. As global plastic production gradually increases and is expected to continue in the coming decades (Houssini et al., 2025), coordinated and aggressive research using standardized methodologies may be required to assess real-world exposure and associated risks.

Regardless of how plastics are currently manufactured, they take anywhere from 100 to 1000 years to decompose. Thus, the potential use of plastics that break down quickly and do not generate MNPs would be of enormous advantage. Recently, a group developed an algae-based polymer that appears to be completely biodegradable without producing microplastics (Allemann et al., 2024; Sexton, 2025). Hopefully, this and other plant-based polymers may replace those currently polluting our environment.

Conclusions

MNPs are widespread environmental pollutants that have deleterious effects at both cellular and molecular levels. These particles can enter the cells, disrupt cell function, and contribute to various organ and system dysfunctions. Additionally, various plastic additives and the pollutants carried by MNPs cause various cellular toxicities. Therefore, MNPs are of growing public health concern. To address this issue, a broad and coordinated effort is needed. This includes more human-based research, better testing methods, tighter controls on harmful plastic chemicals, and stronger waste management systems. Public health policies should also focus on protecting vulnerable groups like children and pregnant women, who may be more sensitive to MNP exposure.

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References

Allard P, Colaiácovo M.P. (2010). Bisphenol A impairs the double-strand break repair machinery in the germline and causes chromosome abnormalities. Proc Natl Acad Sci U S A., 107 (47), 20405-10. https://doi.org/10.1073/pnas.1010386107.

Allemann, M.N., Tessman, M., Reindel, J. *et al.* Rapid biodegradation of microplastics generated from bio-based thermoplastic polyurethane. *Sci Rep* 14, 6036 (2024). https://doi.org/10.1038/s41598-024-56492-6

AMA. (2024). What doctors wish patients knew about microplastics. *American Medical Association* https://www.ama-assn.org/delivering-care/prevention-wellness/what-doctors-wish-patients-knew-about-microplastics

Amato-Lourenço, L. F., Dantas, K. C., Ribeiro, G., Paes, V. R., Ando, R. A., Freitas, R. D., & (2024). Microplastics in the olfactory bulb of the human brain. *JAMA Network Open, 7(9)*, e2440018. https://doi.org/10.1001/jamanetworkopen.2024.40018

Anderson, J. C., Park, B. J., & Palace, V. P. (2016). Microplastics in aquatic environments: Implications for Canadian ecosystems. *Environmental Pollution, 218*, 269–280. https://doi.org/10.1016/j.envpol.2016.06.074

Avio, C. G., Gorbi, S., Milan, M., Benedetti, M., Fattorini, D., D'Errico, G., Pauletto, M., Bargelloni, L., Regoli, F. (2015). Pollutants bioavailability and toxicological risk from microplastics to marine mussels. *Environmental Pollution, 198*, 211–222.

Bi, C., Maestre, J. P., Li, H., Zhang, G., Givehchi, R., Mahdavi, A., Kinney, K. A., Siegel, J., Horner, S. D., & Xu, Y. (2018). Phthalates and organophosphates in settled dust and HVAC filter dust of U.S. low-income homes: Association with season, building characteristics, and childhood asthma. *Environment international, 121(Pt 1)*, 916–930. https://doi.org/10.1016/j.envint.2018.09.013

Boukhenouna, S., Wilson, M. A., Bahmed, K., Kosmider, B. (2018). Reactive oxygen species in chronic obstructive pulmonary disease. *Oxidative Medicine and Cellular Longevity*, 5730395. https://doi.org/10.1155/2018/5730395

Browne, M. A., Crump, P., Niven, S. J., Teuten, E., Tonkin, A., Galloway, T., & Thompson, R. (2011). Accumulation of microplastic on shorelines worldwide: Sources and sinks. *Environmental Science & Technology, 45 (21)*, 9175–9179. https://doi.org/10.1021/es201811s

Buwono, N. R., Risjani, Y., Soegianto, A. (2022). Oxidative stress responses of microplastic-contaminated Gambusia affinis obtained from the Brantas River in East Java, Indonesia. *Chemosphere*, *293*, 133543.

Canesi, L., Ciacci, C., Fabbri, R., Balbi, T., Salis, A., Damonte, G., Cortese, K., Caratto, V., Monopoli, M. P., Dawson, K., et al. (2016). Interactions of cationic polystyrene nanoparticles with marine bivalve hemocytes in a physiological environment: Role of soluble hemolymph proteins. *Environmental Research, 150*, 73–81.

Chang, L., & Tang, Z. (2023). Microplastics aggravate rheumatoid arthritis by affecting the proliferation, migration, and inflammation of fibroblast-like synovial cells by regulating mitochondrial homeostasis. *International Immunopharmacology, 120*, 110268. https://doi.org/10.1016/j.intimp.2023.110268

Chang, Y. J., Tseng, C. Y., Lin, P. Y., Chuang, Y. C., Chao, M. W. (2017). Acute exposure to DEHP metabolite, MEHP cause genotoxicity, mutagenesis and carcinogenicity in mammalian Chinese hamster ovary cells. *Carcinogenesis, 38 (3)*, 336–345. https://doi.org/10.1093/carcin/bgx009

Chao, H. R., Wang, S. L., Lee, W. J., Wang, Y. F., Papke, O. (2007). Levels of polybrominated diphenyl ethers (PBDEs) in breast milk from central Taiwan and their relation to infant birth outcome and maternal menstruation effects. *Environment International, 33*, 239–245. https://doi.org/10.1016/j.envint.2006.09.013

Chen, H. L., Gibbins, C. N., Selvam, S. B., Ting, K. N. (2021). Spatio-temporal variation of microplastic along a rural to urban transition in a tropical river. *Environmental Pollution, 289*, 117895. https://doi.org/10.1016/j.envpol.2021.117895

Chen, L., Wang, C., Cui, C., Ding, G., Zhou, Y., Jin, J, et al. (2015). Prenatal exposure to polybrominated diphenyl ethers and birth outcomes, *Environmental Pollution, 206*, 32-37. https://doi.org/10.1016/j.envpol.2015.06.019.

Cimmino, I., Fiory, F., Perruolo, G., Miele, C., Beguinot, F., Formisano, P., & Oriente, F. (2020). Potential Mechanisms of Bisphenol A (BPA) Contributing to Human Disease. *International journal of molecular sciences, 21(16)*, 5761. https://doi.org/10.3390/ijms21165761

Da Costa, Joao. (2018). Micro- and nanoplastics in the environment: Research and policymaking. Current *Opinion in Environmental Science & Health. 1*, 12-16. https://doi.org/10.1016/j.coesh.2017.11.002.

Das, A. (2023). The emerging role of microplastics in systemic toxicity: Involvement of reactive oxygen species (ROS). *Science of the Total Environment, 895*, 165076. https://doi.org/10.1016/j.scitotenv.2023.165076

Deng, J., Ibrahim, M. S., Tan, L. Y., Yeo, X. Y., Lee, Y. A., Park, S. J., et al. (2022). Microplastics released from food containers can suppress lysosomal activity in mouse macrophages. *J. Hazardous Materials, 435*, 128980.

Devereux, R., Ayati, B., Westhead, E. K., Jayaratne, R., & Newport, D. (2023). Impact of the COVID-19 pandemic on microplastic abundance along the River Thames. *Marine Pollution Bulletin, 190*, 114784. https://doi.org/10.1016/j.marpolbul.2023.114784

Dong, C. D., Chen, C. W., Chen, Y. C., Chen, H. H., Lee, J. S., Lin, C. H. (2020). Polystyrene microplastic particles: In vitro pulmonary toxicity assessment. *J. Hazardous Materials, 385*, 121575. https://doi.org/10.1016/j.jhazmat.2019.121575

Fleury, J.-B., Baulin, V. A. (2021). Microplastics destabilize lipid membranes by mechanical stretching. *Proc. National Academy of Sciences, 118 (30)*, e2104610118. https://doi.org/10.1073/pnas.2104610118

Gentile F, Arcaro A, Pizzimenti S, Daga M, Cetrangolo GP, Dianzani C, et al. (2017) DNA damage by lipid peroxidation products: implications in cancer, inflammation and autoimmunity. *AIMS Genet, 4 (2)*,103-137. https://doi.org/10.3934/genet.2017.2.103.

Geyer, R., Jambeck, J. R., & Law, K. L. (2017). Production, use, and fate of all plastics ever made. *Science Advances, 3(7)*, e1700782. http://doi.org/10.1126/sciadv.170078

Gigault, J., Halle, A., Baudrimont, M., Pascal, P.-Y., Gauffre, F., Phi, T.-L., El Hadri, H., Grassl, B., & Reynaud, S. (2018). Current opinion: What is nanoplastic? *Environmental Pollution, 235*, 1030–1034. https://doi.org/10.1016/j.envpol.2018.01.024

Grote, K., Brüstle, F., Vlacil, A.-K. (2023). Cellular and systemic effects of micro- and nanoplastics in mammals - What we know so far. *Materials, 16 (8)*, 3123. https://doi.org/10.3390/ma16083123

Grote, K., Brüstle, F., & Vlacil, A.-K. (2023). Cellular and Systemic Effects of Micro- and Nanoplastics in Mammals - What We Know So Far. *Materials*, *16*(8), 3123. https://doi.org/10.3390/ma16083123

Guo, J., Huang, X., Dou, L., Yan, M., Shen, T., Tang, W., & Li, J. (2022). Aging and aging-related diseases: from molecular mechanisms to interventions and treatments. *Signal transduction and targeted therapy, 7(1)*, 391. https://doi.org/10.1038/s41392-022-01251-0

Hagmar, L., Björk, J., Sjödin, A., Bergman, Å., Erfurth, E. M. (2001). Plasma levels of persistent organohalogens and hormone levels in adult male humans. *Archives of Environ. Health, 56 (2)*, 138–143. https://doi.org/10.1080/00039890109604061

Holtzman, D., Ulrich, J. (2019). Senescent glia spell trouble in Alzheimer's disease. *Nature Neuroscience, 22*, 683–684. https://doi.org/10.1038/s41593-019-0395-2

Hu, M., Palić, D. (2020). Micro- and nano-plastics activation of oxidative and inflammatory adverse outcome pathways. Redox Biology, 37, 101620. https://doi.org/10.1016/j.redox.2020.101620

Houssini, K., Li, J. & Tan, Q. Complexities of the global plastics supply chain revealed in a trade-linked material flow analysis. *Commun Earth Environ* 6, 257 (2025). https://doi.org/10.1038/s43247-025-02169-5

Jahedi F, Jaafarzadeh Haghighi Fard N. Micro- and nanoplastic toxicity in humans: Exposure pathways, cellular effects, and mitigation strategies. Toxicol Rep. 2025 May 10;14:102043. https://doi.org/10.1016/j.toxrep.2025.102043.

Jenner, L. C., Rotchell, J. M., Bennett, R. T., Cowen, M., Tentzeris, V., & Sadofsky, L. R. (2022). Detection of microplastics in human lung tissue using μFTIR spectroscopy. *Science of the Total Environment, 831*, 154907. https://doi.org/10.1016/j.scitotenv.2022.154907

Jeon, M. S., Kim, J. W., Han, Y. B., Jeong, M. H., Kim, H. R., Sik Kim, H., Park, Y. J., & Chung, K. H. (2023). Polystyrene microplastic particles induce autophagic cell death in BEAS-2B human bronchial epithelial cells. *Environmental toxicology*, *38*(2), 359–367. https://doi.org/10.1002/tox.23705

Jeong, C. B., Lee, M. C., Lee, K. W., Seo, J. S., Park, H. G., Rhee, J. S., & Lee, J. S. (2015). Identification and molecular characterization of dorsal and dorsal-like genes in the cyclopoid copepod Paracyclopina nana. *Marine genomics*, *24 Pt 3*, 319–327. https://doi.org/10.1016/j.margen.2015.08.002

Jia, R., Han, J., Liu, X., Li, K., Lai, W., Bian, L., Yan, J., Xi, Z. (2023). Exposure to polypropylene microplastics via oral ingestion induces colonic apoptosis and intestinal barrier damage through oxidative stress and inflammation in mice. *Toxics, 11 (2)*, 127. https://doi.org/10.3390/toxics11020127

Jiang, R. L., Xiao, B. C., Na, Y. U., Chen, L. Q. (2014). Research advances in the toxic effects of PAHs on aquatic animals. *Marine Fisheries*, *36*, 372–383.

Jiang, W., Liu, Y., Wu, Y., Zhang, L., Zhang, B., Zhou, S. (2024). Polystyrene nanoplastics of different particle sizes regulate the polarization of pro-inflammatory macrophages. *Frontiers in* Immunology, 15, 1349756. https://doi.org/10.3389/fimmu.2024.1349756

Junge, K. M., Leppert, B., Jahreis, S., Wissenbach, D. K., Feltens, R., Grützmann, K., et al. (2018). MEST mediates the impact of prenatal bisphenol A exposure on long-term body weight development. *Clinical Epigenetics, 10*, 58. https://doi.org/10.1186/s13148-018-0478-z

Kadac-Czapska, K., Ośko, J., Knez, E., & Grembecka, M. (2024). Microplastics and Oxidative Stress-Current Problems and Prospects. *Antioxidants (Basel, Switzerland), 13(5)*, 579. https://doi.org/10.3390/antiox13050579

Kazmiruk, T.N., Alava, J.J., Palsson, E., Bendell, L.I. (2024). Sorption of trace metals by macro- and microplastics within intertidal sediments: Insights from a long-term field study within Burrard Inlet, British Columbia, Canada, *Science of The Total Environment, Volume 951*, 175413. https://doi.org/10.1016/j.scitotenv.2024.175413.

Lahimer, M., Abou Diwan, M., Montjean, D., Cabry, R., Bach, V., Ajina, M., Ben Ali, H., Benkhalifa, M., & Khorsi-Cauet, H. (2023). Endocrine-disrupting chemicals and male fertility: from physiological to molecular effects. *Frontiers in public health, 11*, 1232646. https://doi.org/10.3389/fpubh.2023.1232646

Lathi, R. B., Liebert, C. A., Brookfield, K. F., Taylor, J. A., vom Saal, F. S., Fujimoto, V. Y., & Baker, V. L. (2014). Conjugated bisphenol A in maternal serum in relation to miscarriage risk. *Fertility and sterility, 102(1)*, 123–128. https://doi.org/10.1016/j.fertnstert.2014.03.024

Lawrence, R. E., Zoncu, R. (2019). The lysosome as a cellular center for signaling, metabolism, and quality control. *Nature Cell Biology, 21*, 133–142. https://doi.org/10.1038/s41556-018-0244-7

Laws, M. J., Neff, A. M., Brehm, E., Warner, G. R., & Flaws, J. A. (2021). Endocrine-disrupting chemicals and reproductive disorders in women, men, and animal models. *Advances in pharmacology, 92*, 151-190. https://doi.org/10.1016/bs.apha.2021.03.008

Leslie, H. A., van Velzen, M. J. M., Brandsma, S. H., Dick Vethaak, A., Garcia-Vallejo, J. J., & Lamoree, M. H. (2022). Discovery and quantification of plastic particle pollution in human blood. *Environment International, 163*, 107199. https://doi.org/10.1016/j.envint.2022.107199

Li, X., Li, C., Zhang, W., Wang, Y., Qian, P., & Huang, H. (2023). Inflammation and aging: signaling pathways and intervention therapies. *Signal transduction and targeted therapy, 8(1)*, 239. https://doi.org/10.1038/s41392-023-01502-8

Lima, André & Barletta, Mário & Costa, Monica. (2015). Seasonal distribution and interactions between plankton and microplastics in a tropical estuary. *Estuarine, Coastal and Shelf Science, 165*, 213-225. https://doi.org/10.1016/j.ecss.2015.05.018

Liu, L., Xu, K., Zhang, B., Ye, Y., Zhang, Q., Jiang, W. (2021). Cellular internalization and release of polystyrene microplastics and nanoplastics. *Science of the Total Environment, 779*, 146523. https://doi.org/10.1016/j.scitotenv.2021.146523

Liu, T., Hou, B., Wang, Z., & Yang, Y. (2022). Polystyrene microplastics induce mitochondrial damage in mouse GC-2 cells. *Ecotoxicology and environmental safety, 237*, 113520. https://doi.org/10.1016/j.ecoenv.2022.113520

Liu, Yuan & Wu, Nian-Nian & Xu, Ru & Li, Zhi-Hua & Xu, Xiang-Rong & Liu, Shan. (2024). Phthalates released from microplastics can't be ignored: Sources, fate, ecological risks, and human exposure risks. *TrAC Trends in Analytical Chemistry. 179*. 117870. https://doi.org/10.1016/j.trac.2024.117870.

Lombó, M., Fernández-Díez, C., González-Rojo, S., Navarro, C., Robles, V., Herráez, M. P. (2015). Transgenerational inheritance of heart disorders caused by paternal bisphenol A exposure. *Environmental Pollution, 206*, 667–678. https://doi.org/10.1016/j.envpol.2015.08.016

Lu, Y., Zhang, Y., Deng, Y., Jiang, W., Zhao, Y., Geng, J., et al. (2016). Uptake and accumulation of polystyrene microplastics in zebrafish (*Danio rerio*) and toxic effects in liver. *Environmental Science & Technology, 50 (7),* 4054–4060. https://doi.org/10.1021/acs.est.6b00183

Ma, Y., Huang, A., Cao, S., Sun, F., Wang, L., Guo, H., Ji, R. (2016). Effects of nanoplastics and microplastics on toxicity, bioaccumulation, and environmental fate of phenanthrene in fresh water. *Environmental Pollution, 219,* 166–173. https://doi.org/10.1016/j.envpol.2016.10.061

Magdouli, S., Daghrir, R., Brar, S. K., Drogui, P., Tyagi, R. D. (2013). Di(2-ethylhexyl) phthalate in the aquatic and terrestrial environment: A critical review. *J. Environmental Management, 127,* 36–49. https://doi.org/10.1016/j.jenvman.2013.04.013

Mahmud, F., Sarker, D. B., Jocelyn, J. A., & Sang, Q. A. (2024). Molecular and Cellular Effects of Microplastics and Nanoplastics: Focus on Inflammation and Senescence. *Cells, 13(21),* 1788. https://doi.org/10.3390/cells13211788

Marturano, V., Cerruti, P., Ambrogi, V. (2017). Polymer additives. *Physical Sciences Reviews, 2 (6),* 20160130. https://doi.org/10.1515/psr-2016-0130

Mattioda, V., Benedetti, V., Tessarolo, C., Oberto, F., Favole, A., Gallo, M., Martelli, W., Crescio, M. I., Berio, E., Masoero, L., Benedetto, A., Pezzolato, M., Bozzetta, E., Grattarola, C., Casalone, C., Corona, C., & Giorda, F. (2023). Pro-Inflammatory and Cytotoxic Effects of Polystyrene Microplastics on Human and Murine Intestinal Cell Lines. *Biomolecules, 13(1),* 140. https://doi.org/10.3390/biom13010140

Monnery, B. D., Wright, M., Cavill, R., Hoogenboom, R., Shaunak, S., Steinke, J. H. G., Thanou, M. (2017). Cytotoxicity of polycations: Relationship of molecular weight and the hydrolytic theory of the mechanism of toxicity. *International Journal of Pharmaceutics, 521 (1–2),* 249–258. https://doi.org/10.1016/j.ijpharm.2017.02.010

Munier, B., Bendell, L. (2018). Macro and micro plastics sorb and desorb metals and act as a point source of trace metals to coastal ecosystems. *PLoS ONE, 13 (2),* e0191759. https://doi.org/10.1371/journal.pone.0191759

Murata, M., Thanan, R., Ma, N., Kawanishi, S. (2012). Role of nitrative and oxidative DNA damage in inflammation-related carcinogenesis. *BioMed Research International,* 623019. https://doi.org/10.1155/2012/623019

Musi, N., Valentine, J. M., Sickora, K. R., Baeuerle, E., Thompson, C. S., Shen, Q., Orr, M. E. (2018). Tau protein aggregation is associated with cellular senescence in the brain. *Aging Cell, 17 (6),* e12840. https://doi.org/10.1111/acel.12840

Nam, T.-G. (2011). Lipid peroxidation and its toxicological implications. *Toxicological Research, 27 (1),* 1–6. https://doi.org/10.5487/TR.2011.27.1.001

O'Donovan, S., Mestre, N. C., Abel, S., Fonseca, T. G., Carteny, C. C., Cormier, B., Keiter, S. H., Bebianno, M. J. (2018). Ecotoxicological effects of chemical contaminants adsorbed to microplastics in the clam *Scrobicularia plana*. *Frontiers in Marine Science, 5,* 143. https://doi.org/10.3389/fmars.2018.00143

Paul-Pont, I., Lacroix, C., González Fernández, C., Hégaret, H., Lambert, C., Le Goïc, N., et al. (2016). Exposure of marine mussels *Mytilus* spp. to polystyrene microplastics: Toxicity and influence on fluoranthene bioaccumulation. *Environmental Pollution, 216,* 724–737. https://doi.org/10.1016/j.envpol.2016.06.039

Peng, Y., Wu, P., Schartup, A. T., & Zhang, Y. (2021). Plastic waste release caused by COVID-19 and its fate in the global ocean. *Proceedings of the National Academy of Sciences, 118*(47), e2111530118. https://doi.org/10.1073/pnas.2111530118

Prietl, B., Meindl, C., Roblegg, E., Pieber, T. R., Lanzer, G., Fröhlich, E. (2014). Nano-sized and micro-sized polystyrene particles affect phagocyte function. *Cell Biology and Toxicology, 30 (1)*, 1–16. https://doi.org/10.1007/s10565-013-9265-y

PlasticsEurope. (2022). *Plastics – the facts 2022*. https://plasticseurope.org/knowledge-hub/plastics-the-facts-2022/

Pulvirenti, E., Ferrante, M., Barbera, N., Favara, C., Aquilia, E., Palella, M., Cristaldi, A., Conti, G. O., Fiore, M. (2022). Effects of nano and microplastics on the inflammatory process: In vitro and in vivo studies systematic review. *Frontiers in Bioscience-Landmark, 27*, 287. https://doi.org/10.31083/j.fbl2710287

Radke, E. G., Braun, J. M., Nachman, R. M., Cooper, G. S. (2020). Phthalate exposure and neurodevelopment: A systematic review and meta-analysis of human epidemiological evidence. *Environment International, 137*, 105408. https://doi.org/10.1016/j.envint.2019.105408

Renzelli, V., Gallo, M., Morviducci, L., Marino, G., Ragni, A., Tuveri, E. et al. (2023). Polybrominated Diphenyl Ethers (PBDEs) and Human Health: Effects on Metabolism, Diabetes and Cancer. *Cancers, 15(17)*, 4237. https://doi.org/10.3390/cancers15174237

Roth, B., Herkenrath, P., Lehmann, H. J., Ohles, H. D., Homig, H. J., Benz-Bohm, G., et al. (1988). Di-(2-ethylhexyl)-phthalate as plasticizer in PVC respiratory tubing systems: Indications of hazardous effects on pulmonary function in mechanically ventilated, preterm infants. *European Journal of Pediatrics, 147 (1)*, 41–46. https://doi.org/10.1007/BF00442609

Sexton, C. (2024). Biodegradable breakthrough: Plastics that won't make us sick. *Earth.com*. https://www.earth.com/news/biodegradable-breakthrough-plastics-that-wont-make-us-sick/

Song, Y. K., Hong, S. H., Jang, M., Han, G. M., Jung, S. W., & Shim, W. J. (2017). Combined Effects of UV Exposure Duration and Mechanical Abrasion on Microplastic Fragmentation by Polymer Type. *Environmental science & technology, 51(8)*, 4368–4376. https://doi.org/10.1021/acs.est.6b06155

Sun, T., Zhan, J., Li, F., Ji, C., Wu, H. (2021). Evidence-based meta-analysis of the genotoxicity induced by microplastics in aquatic organisms at environmentally relevant concentrations. *Science of the Total Environment, 783*, 147076. https://doi.org/10.1016/j.scitotenv.2021.147076

Wang, F., Bexiga, M. G., Anguissola, S., Boya, P., Simpson, J. C., Salvati, A., Dawson, K. A. (2013). Time resolved study of cell death mechanisms induced by amine-modified polystyrene nanoparticles. *Nanoscale, 5 (22)*, 10868–10876. https://doi.org/10.1039/c3nr03869d

Wang, F., Zhang, Q., Cui, J., Bao, B., Deng, X., Liu, L., Guo, M. (2023). Polystyrene microplastics induce endoplasmic reticulum stress, apoptosis, and inflammation by disrupting the gut microbiota in carp intestines. *Environmental Pollution, 323*, 121233. https://doi.org/10.1016/j.envpol.2023.121233

Wang, H., Zhao, P., Huang, Q., Chi, Y., Dong, S., Fan, J. (2019). Bisphenol A induces neurodegeneration through disturbance of intracellular calcium homeostasis in human embryonic stem cell-derived cortical neurons. *Chemosphere, 229*, 618–630. https://doi.org/10.1016/j.chemosphere.2019.04.099

Wang, J., Li, Y., Lu, L., Zheng, M., Zhang, X., Tian, H., et al. (2019). Polystyrene microplastics cause tissue damage, sex-specific reproductive disruption, and transgenerational effects in marine medaka (*Oryzias melastigma*). *Environmental Pollution, 254*, 113024. https://doi.org/10.1016/j.envpol.2019.113024

Wang, K., Du, Y., Li, P., Guan, C., Zhou, M., Wu, L., et al. (2024). Nanoplastics cause heart aging/myocardial cell senescence through the Ca^{2+}/mtDNA/cGAS-STING signaling cascade. *Journal of Nanobiotechnology*, *22*, 96. https://doi.org/10.1186/s12951-024-02134-6

Weaver, J. A., Beverly, B. E., Keshava, N., Mudipalli, A., Arzuaga, X., Cai, C., et al. (2020). Hazards of diethyl phthalate (DEP) exposure: A systematic review of animal toxicology studies. *Environment International*, *145*, 105848. https://doi.org/10.1016/j.envint.2020.105848

Weber, A., Jeckel, N., Weil, C., Umbach, S., Brennholt, N., Reifferscheid, G., Wagner, M. (2021). Ingestion and toxicity of polystyrene microplastics in freshwater bivalves. Environmental Toxicology and *Chemistry*, *40 (8)*, 2247–2260. https://doi.org/10.1002/etc.5076

Wei, Zhaolan & Wang, Yunyi & Wang, Shuwei & Xie, Jing & Han, Qi & Chen, Mingqing. (2021). Comparing the effects of polystyrene microplastics exposure on reproduction and fertility in male and female mice. *Toxicology. 465*. 153059. https://doi.org/10.1016/j.tox.2021.153059.

Wright, S. L., Thompson, R. C., & Galloway, T. S. (2013). The physical impacts of microplastics on marine organisms: a review. *Environmental pollution*, *178*, 483–492. https://doi.org/10.1016/j.envpol.2013.02.031

Wu, D., Zhang, M., Bao, T. T., & Lan, H. (2023). Long-term exposure to polystyrene microplastics triggers premature testicular aging. *Particle and fibre toxicology*, *20*(1), 35. https://doi.org/10.1186/s12989-023-00546-6

Yang Z, DeLoid GM, Zarbl H, Baw J, Demokritou P. (2023). Micro- and nanoplastics (MNPs) and their potential toxicological outcomes: State of science, knowledge gaps and research needs. *NanoImpact.* https://doi.org/10.1016/j.impact.2023.100481.

Yee, M. S., Hii, L. W., Looi, C. K., Lim, W. M., Wong, S. F., Kok, Y. Y., et al. (2021). Impact of microplastics and nanoplastics on human health. *Nanomaterials, 11 (2)*, 496. https://doi.org/10.3390/nano11020496

Yu, Y. & Wang, J. (2024). Phthalate exposure and lung disease: the epidemiological evidence, plausible mechanism, and advocacy of interventions. *Reviews on Environmental Health*, *39*(1), 37-45. https://doi.org/10.1515/reveh-2022-0077

Yu, Y. Y., Jin, H., & Lu, Q. (2022). Effect of polycyclic aromatic hydrocarbons on immunity. *Journal of translational autoimmunity*, *5*, 100177. https://doi.org/10.1016/j.jtauto.2022.100177

Zhang, P., Kishimoto, Y., Grammatikakis, I., Gottimukkala, K., Cutler, R. G., Zhang, S., Abdelmohsen, K., Bohr, V. A., Misra Sen, J., Gorospe, M., & Mattson, M. P. (2019). Senolytic therapy alleviates Aβ-associated oligodendrocyte progenitor cell senescence and cognitive deficits in an Alzheimer's disease model. *Nature neuroscience*, *22(5)*, 719–728. https://doi.org/10.1038/s41593-019-0372-9

Zhao, S., Zhu, L., Wang, T., Li, D. (2014). Suspended microplastics in the surface water of the Yangtze Estuary System, China: First observations on occurrence and distribution. *Marine Pollution Bulletin*, *86*(1–2), 562–568. https://doi.org/10.1016/j.marpolbul.2014.06.032

Zou, Q.Y., Hong, S.L., Kang, H.Y., Ke, X., Wang, X., Li, J., Shen, Y. (2020). Effect of di-(2-ethylhexyl) phthalate (DEHP) on allergic rhinitis, *Scientific Reports*, *10*, 14625. https://doi.org/10.1038/s41598-020-71517-6