Environmental Science & Technology

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Viewpoint

Time: A Key Driver of Uncertainty When Assessing the Risk of Environmental Plastics to Human Health

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Cite This: *Environ. Sci. Technol.* 2021, 55, 12766–12769

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KEYWORDS: *plastic pollution, time, microplastic, nanoplastic, risk assessment*

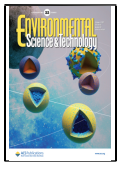
Time flies over us, but leaves its shadow behind

(Nathaniel Hawthorne, 1860).

The "shadow" of plastic pollution looms large over environmental and human health research, but *time* is an overlooked variable as we attempt to understand, assess and mitigate the adverse impacts of synthetic polymer ubiquity. Plastic debris has infiltrated the environment to a level where we find it in air, water, soil, and food; yet, we still have only a rudimentary understanding of how environmental plastics affect human health. Here, we argue that *time* is the principal but currently underappreciated determinant that is impeding a reliable assessment of human health risks posed by environmental plastics. *Time* changes plastics, impacting both their physicochemical properties and their role as environmental toxicants, thereby creating a barrier to performing reliable risk assessment (Figure 1). However, the importance of *time* has yet to be realized and its impact integrated into the life-cycle and risk assessments of present-day plastic polymers.

A newly produced consumer product made from conventional plastic will have well-defined characteristics, including a known monomeric and polymeric composition, a known size, geometry and porosity, a known internal chemistry of additives (e.g., phthalate-based plasticizers), and a known external surface chemistry of characteristic coatings (e.g., antimicrobials, flame retardants, etc.).[1] *Time* spent in the environment changes all of this. The size of the plastic will change from macroplastic (>5 mm diameter) to microplastic (>1 μm to <5 mm) to nanoplastic (<1 μm), but our knowledge on the corresponding rate of change remains limited. Macroscopic meshworks of polymerized monomers break apart and become fragmented,[10] releasing

Received: April 20, 2021
Published: September 14, 2021



https://doi.org/10.1021/acs.est.1c02580
Environ. Sci. Technol. 2021, 55, 12766–12769

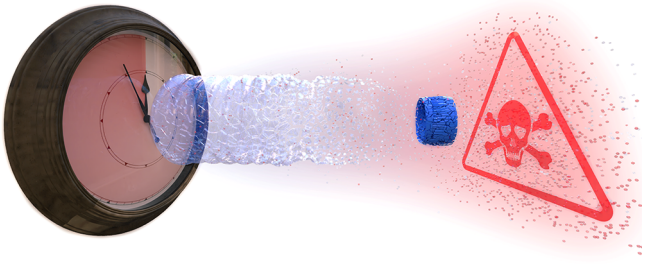


Figure 1. Properties of synthetic mass-produced polymers of daily use are changing as a function of *time* spent in the environment: well-defined macropolymers considered safe upon production, over time are being transformed into a plurality of microplastics and nanoplastics, which are ill-defined as to their shape, size, transport, persistence, behavior, chemical composition, chemical and biological sorbates, as well as the type and magnitude of corresponding risks they pose.

internal additives while becoming ground into small pieces of unpredictable number, size and shape by mechanical stress from human use, from macrobiotic and microbial assault, and from environmental stress caused by soil, sediment, wind, surf, and wave action. Plastic monomers, plasticizers, and uncharacterized degradation products are further released, while fragments scavenge pollutants, nutrients and microbes from the environment and accumulate them on their surfaces. With increasing environmental residence *time*, environmental chemicals accumulate on the polymeric surfaces and all components are subject to further significant and mostly unpredictable changes. The end result is a shuttling and unloading of plastics-associated chemical and biological agents into new and unexpected locations and hosts,[2] including[9] a broad spectrum of biota and human populations worldwide. By changing the nature of plastic debris over *time*, this fosters an increasing uncertainty of latent hazards, exposure doses, and associated risks of the ecological and human exposures incurred.

As the previously well-defined plastic chemistry becomes ill-defined and more complex, this allows for new risks to arise, including:

(i) chemical risks from poorly defined, complex mixtures of polar and hydrophobic adsorbing environmental pollutants;
(ii) biological risks from the colonization of polymeric surfaces with microbial biofilms and biogenic compounds; and
(iii) physical risks from the geometry and surface characteristics of weathered and fragmented plastic polymers that may range from perfectly smooth spheres to spikes with sharp abrasive edges and needle-like tips that may mimic the appearance of asbestos and the corresponding, potentially devastating health risks posed.

The range of uncertainties *time* introduces then impedes the process of risk assessment adopted by the United States and many other countries globally, that consists of (i) hazard identification, (ii) dose−response assessment, (iii) exposure assessment, and (iv) risk characterization. Over *time*, information fades from known to diffuse to unknown, presenting unique challenges in the context of toxicity assessment, exposure calculations and risk assessment. The *time* of macroplastic fragmentation and degradation is particularly critical, ultimately resulting in the formation of microplastics at first and then of nanoplastics, with the latter not being properly captured by current sampling and detection techniques,[3] yet having the highest propensity for uptake into the human body through the gut, the airways and the skin, and the subsequent distribution of these exposure agents by the circulatory system into human organs and tissues.[4]

How abundant are environmental nanoplastics and to what extent have they progressed their voyage into the human body? Although we do not yet know precisely, exposure is occurring from sources ranging from plastic-laden ambient air to drinking water to sea salt and seafood that all have been confirmed to show detectable microplastic contamination.[5,6] And studies of biomedical products (e.g., contact lenses, bite guards, artificial joints) have demonstrated that larger plastics can give rise to microplastics and nanoplastics, and that uptake and distribution within the human body of such materials is not only possible but known to occur.[7]

So how should we deal with *time*, the driver of uncertainty and, ultimately, a key determinant of the risk posed by environmental plastics? *Time* needs to enter into plastic design and life cycle considerations. With the annual plastic production volume now exceeding 368 million metric tons worldwide,[8] conventional single-use consumer plastics have not only outlasted their useful lifespan but they also have overstayed their initial, enthusiastic welcome on planet Earth.

As the principles of green chemistry are internalized as essential design criteria in modern high-volume manufacturing, nonrenewable energy (fossil fuel), carcinogenic monomers (vinyl chloride), and endocrine disrupting components and modifiers (such as bisphenol A and various alkyl phthalates) will have to be confined to the past at last. Successes in this area include the replacement of plastic microbeads with natural alternatives within personal care products[12] and the experimental use of biodegradable polymers in a variety of products, including biomedical applications.[13] Currently, these cases remain notable outliers. But it is *time* to find a more sustainable and safer alternative to present-day polymers, whose design criteria and composition—which were informed by yesterday's science—today are recognized as not being protective anymore of human health and ecosystem viability.[14] Moving forward, the polymeric material itself must have environmentally benign properties, such as those exhibited by biobased plastics or natural polymers (e.g., chitin or lignin), materials whose eventual fate, degradation and associated impacts upon the environment are deemed sufficiently understood and acceptable.[15] Use of nonfossil fuel-based polymers has potential but scalability remains a challenge. However, a transition to polymers of improved resource renewability, biodegradability, and recyclability is imperative.[16] Once accomplished, this long overdue shift finally will bring relief for human populations, aquatic life and the world's ecosystems that have been burdened with layers upon layers of first-generation, nonbiodegradable, nonrecyclable (i.e., only downcyclable) plastics.

However, when the *time* of safe, sustainable plastics finally arrives, the environmental pollution from existing plastics will continue to increase and reach peak concentrations further into the future as nanoplastics—a prognosis that previously has been reached when considering the inventory of environmental microplastics.[17] This regrettable future scenario stems from the fact that the disintegration of previously released macro- and microplastics will continue to produce nanoplastics for some *time*. An estimated 8 million metric tons of anthropogenic (macro-) plastics enters the oceans each year[18] to then become fragmented and converted into environmental nanoplastics[11] prior to their ultimate, much delayed complete destruction into

https://doi.org/10.1021/acs.est.1c02580
Environ. Sci. Technol. 2021, 55, 12766−12769

monomers and their elemental components upon mineralization. Much of this polymeric mass is deemed unrecoverable, constituting an inevitable precursor of the toxic, yet inevitable nanoplastics of the future.

Time thus is critical to consider, not only in the context of exposure and hazard, but also with respect to sources of plastics and their steadily increasing environmental inventories. Do we have a sufficient level of knowledge to (counter)act and take action now? When it comes to mass-produced, short-lived consumer products made from plastics, the answer is yes, it is *time* for a change. It is *time* to let go of first-generation polymers and to instead manufacture smart plastics that are benign by design,[14,19−21] synthetic polymers that are safe irrespective of *time*.

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Funding

This work was made possible in part by funding from the National Institutes of Health (U01DA053976), the National Science Foundation (2038087; 2028564; 2038372), the Kaplan Foundation (30009070), the Catena Foundation (00103668), and Plastic Oceans International.

Notes

The authors declare no competing financial interest.

Biography

Rolf Halden, PhD, PE, is a Professor at Arizona State University and Founding Director of the Biodesign Center for Environmental Health Engineering, the Human Health Observatory, the nonprofit OneWaterOneHealth, and the ASU startup company, AquaVitas LLC. Halden has authored over 250 research papers, patents, monographs, technical reports, book chapters, and the 2020 popular science book, *Environment*, published on the occasion of Earth Day 50. Halden is an expert in tracking harmful chemicals and infectious disease agents like SARS-CoV-2 by using wastewater treatment plants as chemical and biological observatories. His research team pioneered methods for detecting and quantifying threat agents in wastewater and sewage sludge and for estimating associated human exposures through the analysis of characteristic fecal and urinary human metabolites. Halden serves on the Expert Team of the U.S. American Chemical Society (ACS) and has been invited repeatedly to brief the Environmental Protection Agency, the Food and Drug Administration, the National Academies, the Centers for Disease Control and Prevention, and members of U.S. Congress on environmental health and sustainability challenges.

ACKNOWLEDGMENTS

We thank Dr. Chelsea Rochman (University of Toronto) for her critical reading of earlier drafts of this viewpoint.

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https://doi.org/10.1021/acs.est.1c02580
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