

## The Global Plastic Toxicity Debt

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Plastics are solids with an interior and a surface. Fragmentation of plastics in the environment, coupled with the release of chemical additives from these plastics, lead to a potential future peak release of toxic compounds (including chemical additives and nanoplastics).

Humanity has produced a staggering volume and diversity of plastic materials. A significant proportion of this is accumulating as waste in a range of environmental compartments. The behavior and fate of plastics in the environment is a complex issue, strongly influenced by the unique properties of a given type of plastic, including shape and size, polymer type, the additives and impurities present in the plastic and the extent of prior environmental decay. The parameter space is so large that we may never know how all plastic types interact chemically and physically in every environmental situation or impact each unique ecosystem. Nevertheless, research in this area continues to make rapid and impressive progress, shedding light on many of these factors using short-term experiments.

One key aspect of plastic pollution has been mostly overlooked, relating to longer-term consequences of plastic degradation and pollution release, and we call this the “toxicity debt” (Figure 1). In conservation biology, the number of species that are doomed to extinction because of habitat loss and fragmentation, but that have not yet gone extinct because

of time lags to reach equilibrium conditions, are called extinction debt.<sup>1</sup> In analogy to this, we propose that there is a toxicity debt that we incur by having large amounts of plastic currently in the environment, exposed to degradation, but that has many more years of decay and release of toxic compounds to follow. This does not refer, therefore, to future pollution with plastic but to the current state of plastic pollution already present in the environment; but effects are of course compounded with any future pollution.

What are the underlying causes of this toxicity debt? This debt arises from a combination of three factors. First, plastics are fundamentally solids, with a surface area and polymeric molecular structure. Second, all plastics contain additional chemicals (additives), the purpose of which is to give certain properties to plastics during their useful life; plastics may also contain additional unintentional chemicals (impurities), such as catalyst residues, unreacted monomers or breakdown products.<sup>2</sup> Selected additives and impurities possess toxic properties, with implications for ecosystem and human health. Third, over time under environmental conditions, plastics fragment into smaller pieces, increasing the surface area of the solid plastic, further releasing trapped additives and impurities.

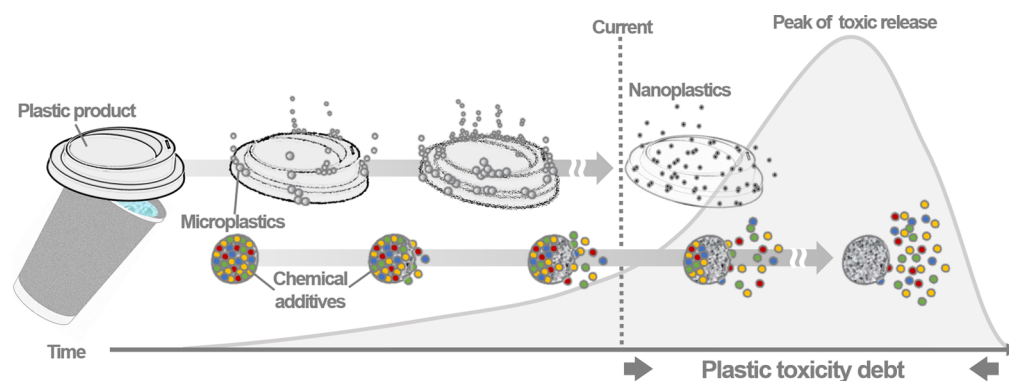
The first two points, that plastics are solid bodies with additives and impurities “stored” within the structural volume of the plastic is a key property of this contaminant suite. These compounds are not immediately released into the environment, because this process is limited by slow rates of diffusion of the additive or impurity to the surface of the plastic item. Time scales over which additives and impurities are released from a plastic item vary extremely widely, from an estimated billions of years for brominated flame retardants to years for certain plasticizers, such as phthalates, adipates, and trimellitates.

The third key point is that plastic items tend to fragment in the environment. Termed microplastics when fragments are below 5 mm in size, such fragments can degrade further to reach nanoparticle size.<sup>3</sup> Several crucial properties change along this pathway to smaller particle sizes: the interior volume becomes smaller, the surface area of the plastic fragment

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**Figure 1.** Development of an environmental plastic toxicity debt.

increases, with the increasing release of additives and impurities as the diffusion pathway to reach the fragment surface shortens. This means that we must expect larger amounts of potentially toxic compound cocktails to be released into the environment that exponentially increase with increasing time of environmental exposure of plastics. This time-delayed release of plastic additives and impurities forms a late pulse of potentially toxic compounds that contributes to the toxicity debt.

In addition, multiple smaller nanoplastic fragments are created, which can themselves give rise to toxic effects. The toxicity of nanoplastic fragments in the environment is an area of active research, with detrimental impacts including oxidative stress, downregulated gene expression, and behavioral disorders in aquatic organisms.<sup>4</sup> This is a serious issue, since there are likely to be several orders of magnitude more nanoplastic particles in the environment than microplastic particles. This time-delayed appearance of nanoplastics and their toxic effects may be much more severe than effects related to the current levels of toxic chemicals released from micro- and nanoplastics. We, therefore, explicitly include this increased production of nanoplastics in the environment in our concept of toxicity debt.

Plastics have been produced at an industrial scale since the 1950s. Given the production patterns, which have been steeply increasing, and the time scales of degradation with estimated half-lives ranging from less than a year to several thousand years depending on the plastic and its chemistry,<sup>5</sup> we very likely have not reached the peak of toxic release from the sum total of all environmentally available plastic on Earth. This is a sobering thought.

There are some immediate research needs that arise from recognition of this impending plastic toxicity debt, as well as important consequences for policy. First, we need to understand how different plastics fragment in the environment and the time scales of fragmentation. This calls for innovative approaches that go beyond short-term laboratory incubations and involve longer-term approaches. Second, we need to study the release of additives, impurities, and other compounds from different plastic chemistries and piece sizes under environmentally relevant conditions, including in water, soil, or when ingested by organisms. We know comparatively little about the migration behavior of the various types of additives out of plastic pieces in the environment. This is because studies on migration behavior have typically addressed plastic materials during their useful life, for example when packing material is in contact with food.<sup>6</sup>

On the policy side, this realization of a toxicity debt should become an additional, central argument in the discussion to curb single-used plastic use and to encourage the development of more intelligent polymers, designed for performance during their entire life cycle, including after end of life. Additionally, we need to include additives in policy considerations: behavior of additives should not only be appraised during the useful life of plastic but also in terms of their future release to the environment.

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### Notes

The authors declare no competing financial interest.

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