Evaluating scenarios toward zero plastic pollution


Plastic pollution is a pervasive and growing problem. To estimate the effectiveness of interventions to reduce plastic pollution, we modeled stocks and flows of municipal solid waste and four sources of microplastics through the global plastic system for five scenarios between 2016 and 2040. Implementing all feasible interventions reduced plastic pollution by 40% from 2016 rates and 78% relative to 2010 levels by 2025 (24, 25). The European Union recently adopted a directive on single-use plastics (26), and the Basel Convention was amended to regulate the international trade of plastic waste (27). The scientific community and non-governmental organizations are also working to identify solutions (21, 28). Despite these efforts, a global evidence-based strategy that includes practical and measurable interventions aimed at reducing plastic pollution does not yet exist.

Modeling approach

Designing an effective global strategy requires an understanding of the mitigation potential of different solutions and the magnitude of global effort needed to appreciably reduce plastic pollution. To estimate mitigation potential under different intervention scenarios, we developed the Plastics-to-Ocean (P2O) model. P2O is a data-driven coupled ordinary differential equation (ODE) model that calculates the flow of plastics through representative systems. We used the model to characterize key stocks and flows for land-based sources of plastic pollution across the entire value chain for municipal solid waste (MSW) macroplastics (figs. S1 and S2) and four sources of primary microplastics (those entering the environment as microplastics) [supplementary materials (SM) section 15 and figs. S3 to S6]. Crucially, it provides estimates of plastic waste input into the environment. Costs are calculated as a function of modeled plastic flows, and changes in costs due to production scale and technological advancement are accounted for through learning curves and returns to scale (SM section 16.1).

We calculated projected growth in demand for plastic using country-level population size (29), per capita macroplastic MSW (30, 31), and microplastic-generating product use and loss rates. Per capita waste generation and waste management processes (such as collection costs, collection and processing rates, and recycling recovery value) and rates of primary microplastic generation vary by geography and plastic.

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Table 1. Summary statistics and comparison of end-of-life fates for MSW plastic under BAU and SCS. Shown from left to right are plastic mass, percent of total plastic demand under different end-of-life fates for year 2016 and for year 2040 under the Business as Usual (BAU) and System Change scenarios (SCS), and percent change in plastic mass, under different end-of-life fates for SCS in 2040 relative to 2016 and BAU in 2040. Values in square brackets represent the lower and upper bounds of the 95% CI for the values above them. Dashes indicate undefined values whose calculation involves division by zero.

<table>
<thead>
<tr>
<th>End-of-life fate</th>
<th>Plastic mass (Mt/year)</th>
<th>Fate as % plastic demand</th>
<th>SCS 2040 % change</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2016 BAU 2040</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2016 BAU 2040</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reduction</td>
<td>0 [0, 0]</td>
<td>0 [0, 0]</td>
<td>0 [0, 0]</td>
</tr>
<tr>
<td>Substitution</td>
<td>0 [0, 0]</td>
<td>0 [0, 0]</td>
<td>0 [0, 0]</td>
</tr>
<tr>
<td>Disposal</td>
<td>97 [83, 97]</td>
<td>44 [39, 45]</td>
<td>24 [22, 26]</td>
</tr>
<tr>
<td>Mismanned</td>
<td>91 [84, 100]</td>
<td>42 [39, 45]</td>
<td>10 [-51, 54]</td>
</tr>
<tr>
<td>Open burning*</td>
<td>49 [40, 60]</td>
<td>54 [41, 47]</td>
<td>53 [48, 54]</td>
</tr>
<tr>
<td>Dumpsite*</td>
<td>12 [7.4, 21]</td>
<td>13 [8, 22]</td>
<td>7.3 [-49, -99]</td>
</tr>
</tbody>
</table>

*Components of the mismanaged end-of-life fate. These categories sum to the total for mismanaged waste.
category or source (6, 32–34). To account for these differences, the global population was split across eight geographic archetypes according to World Bank income categories (low income, lower- and upper-middle income, and high income) and United Nations urban-rural classifications (29). Populations were further differentiated by their distance to water (<1 km or >1 km) to estimate their relative flows of plastic pollution into terrestrial versus aquatic (lakes, rivers, and marine environments) systems. To account for different waste management pathways (35) and movement rates of waste in the environment (35), MSW plastics were differentiated into three material categories: rigid monomaterial, flexible monomaterial, and multilayer. Four microplastic sources were modeled: synthetic textiles, tires, plastic pellets, and personal care products.

Five scenarios were developed to estimate reductions in plastic pollution over the period 2016 to 2040. Scenarios were defined by four high-level classes of interventions (reduce, substitute, recycle, and dispose) and eight system interventions: (i) reducing plastic quantity in the system, (ii) substituting plastics with alternative materials and delivery systems, (iii) implementing design for recycling, (iv) increasing collection capacity, (v) scaling up sorting and mechanical recycling capacity, (vi) scaling up chemical conversion capacity, (vii) reducing postcollection environmental leakage, and (viii) reducing trade in plastic waste (table S7).

Scenarios modeled include (i) “Business as Usual” (BAU), (ii) “Collect and Dispose,” (iii) “Recycling,” (iv) “Reduce and Substitute,” and (v) an integrated “System Change” scenario that implemented the entire suite of interventions (tables S8 and S57).

At all relevant geographical scales, waste production and handling data are notoriously difficult to obtain. Many model inputs have a high degree of uncertainty, which was propagated with Monte Carlo sampling. Data inputs and assigned uncertainties are described in SM section 5.6. In the absence of datasets with which to formally validate the model, we conducted sensitivity analyses to quantify the influence of individual model inputs and to identify key drivers of plastic pollution. Model outputs from the BAU scenario were also compared with results from other global studies (2, 5, 36).

**Business as usual**

The BAU scenario highlights the scale of the plastic pollution problem and provides a baseline from which to compare alternative intervention strategies (Fig. 1). At a global scale from 2016 to 2040, the annual rate of macro- and microplastic entering aquatic systems from land increased 2.6-fold (Fig. 1C and Table 1). Over the same period, the rate of plastic pollution retained in terrestrial systems increased 2.8-fold (Fig. 1D and Table 1).

When we modeled current commitments to reducing plastic pollution assuming full implementation (SM section 9.1), annual plastic pollution rates into aquatic and terrestrial environments decreased by only 6.6% [95% confidence interval (CI): 5.4, 7.9] and 7.7% [5.2, 10] by 2040, respectively (Fig. 1A) (37). This result confirms that current commitments coupled with appropriate policies can reduce plastic waste input into the environment but also shows that considerable additional effort will be needed to match the unprecedented scale of projected environmental plastic pollution.

Plastic pollution rates were found to be particularly sensitive to total plastic mass, collection rates, and the ratio of managed to mismanaged waste. For example, a 1-ton reduction in plastic MSW mass (through reduce and substitute interventions) decreased aquatic plastic pollution by an average of 0.088 tons in low- and middle-income archetypes and an average of 0.006 tons in high-income archetypes. Across all archetypes, an equivalent increase in the collection of plastic waste (through formal and informal sectors) resulted in an average 0.18-ton decrease in aquatic plastic pollution, whereas a similar decrease in postcollection mismanaged waste produced an average 0.10-ton decrease in aquatic plastic pollution.

**Scenarios to reduce plastic pollution**

The focus of plastic pollution reduction strategies can be broadly partitioned into upstream (preconsumption, such as reducing demand) and downstream (postconsumption, such as collection and recycling) measures. To parameterize the development of waste management and recycling solutions in the Collect and Dispose, Recycling, and System Change scenarios, we estimated maximum foreseen growth and implementation rates on the basis of historical trends and expert panel consensus assessment (SM section 1). Compared with BAU, the annual combined terrestrial and aquatic plastic pollution rates were reduced by 57% in...
The present value of cumulative, global waste management operations from 2016 to 2040 was approximated to assess the relative cost of each scenario (Fig. 3). Among scenarios, costs varied by less than 20% relative to BAU, were lowest under the System Change and Recycling scenarios, and were highest for the Collect and Dispose scenario. Costs under the System Change scenario were 18% [14, 23] lower than BAU, with increased waste management costs offset by costs savings from reduced plastic production and revenues from recyclable sales, which increased because of product redesign and improved economics of recycling (SM section 16.8). These costs represent only waste management costs, which are generally borne by taxpayers. Corporate engagement, through improved product design, alternative material development, and new business models will be necessary to achieve pollution levels observed in the System Change scenario. This engagement will likely require a substantial shift in private sector investment.

Our results underline the urgency with which extensive interventions are needed. Despite a considerable reduction in annual plastic production and an increase in the proportion of MSW that is effectively managed under the best-case System Change scenario, a substantial amount of plastic waste remained mismanaged (not collected and sorted, recycled, or safely disposed) between 2016 and 2040. When implementation of interventions begins in 2020, the cumulative mass of plastic pollution added between 2016 and 2040 amounts to 250 Mt [190, 310] in aquatic systems (Fig. 4A) and 460 Mt [300, 640] in terrestrial systems (Fig. 4B), which are approximately 1 and 2 times the total annual plastic production in 2016, respectively. If implementation of interventions is delayed

![Fig. 4. Cumulative mass of plastic MSW, 2016 to 2040.](image-url)
by only 5 years, an additional 300 Mt of mismanaged plastic waste is expected to accumulate in the environment.

Outlook by plastic category

The complex composition of multimaterial plastics limits the technical feasibility of sorting and reprocessing (39), decreasing the economic attractiveness of recycling. Accordingly, the annual production of these plastics decreased by 10 Mt [18, 20] from 2016 to 2040 under the System Change scenario, with a shift of similar magnitude to flexible monomaterial plastic production (20 Mt/year [19, 21]).

Because of the relative ease of collection and sorting, recycling was dominated by rigid plastics in all archetypes and across all scenarios (Fig. 4C). Under the System Change scenario in 2040, rigid plastics represented 62% [58, 67] of the annual mass of recycling, with a sizeable component of flexible monomaterial plastic (33% [28, 37]) (Fig. 5A). In comparison, only 5.0% [4.2, 5.4] of recycled material was derived from multimaterial or multilayer waste plastic (Fig. 5A).

The diversity of polymer types, surface contamination, and low density of postconsumer flexible monomaterial limit their capacity for recycling, particularly in geographies where waste collection services are provided by the informal sector. At a global scale, the absolute and relative contribution of flexible monomaterial plastics to environmental pollution grew between 2016 and 2040, from 45% [35, 56] to 56% [40, 73] in aquatic environments and from 37% [18, 52] to 48% [22, 67] in terrestrial environments (Fig. 5, B and C). Accordingly, finding an economically viable solution to effectively manage flexible plastics will be essential for solving the plastic pollution problem.

Similarly, the proportion of total plastic pollution originating from microplastics in the System Change scenario grew from 11% [6.5, 18] to 23% [11, 42] in aquatic systems and from 16% [8.2, 27] to 31% [18, 51] in terrestrial systems over the modeled period (Fig. 5, B and C). Technologies to capture microplastics, which often rely on stormwater and wastewater management and treatment, are rarely economically feasible—even in wealthy regions—because of associated infrastructure costs. This technological challenge is particularly acute for tire particles, which contributed 93% [83, 96] of global microplastic pollution by mass in 2040.

Difficulties to overcome

Scaling collection to all households at a global level is a monumental task that would require connecting over a million additional households to MSW collection services per week from 2020 to 2040; the majority of these unconnected households are in middle-income countries. The effort to increase household waste collection will therefore require a key role for “waste pickers” [the informal collection and recycling sector (40)], who link the service chain (MSW collection) to the value chain (recycling) in low- and middle-income settings. Globally, this sector was responsible for 58% [55, 64] of postconsumer plastic waste collected for recycling in 2016. To incentivize the collection of low-value plastics (flexible monomaterial and multimaterial or multilayer plastic) by the informal sector, the profitability of recycling these materials would need to rise to create demand for their collection. Accordingly, investments in collection infrastructure must be coordinated with improved governance around collection, sorting, and safe management of generated waste (41).

Mismanaged plastic waste (in dumpsites, openly burned, or released into aquatic or terrestrial environments) is associated with a range of risks to human and ecological health (42). Substantial quantities of such waste are likely to continue to be emitted into the environment or openly burned through time. Under the System Change scenario, in addition to aquatic and terrestrial pollution, ~250 Mt [130, 380] of waste plastic would accumulate in open dumpsites from 2016 to 2040 and remain a potential source of environmental pollution (Fig. 4D). Many communities in emerging economies with inadequate waste management services and infrastructure burn waste residentially or in open dumpsites without emissions controls. Open burning transfers the pollution burden to air, water, and land through the generation of GHGs, particulate matter (including microplastic particles), and harmful chemicals such as dioxins and other persistent organic pollutants (43, 44). Despite its human health and environmental consequences, open burning was the single largest component of mismanaged plastic waste under all scenarios, with 1200 Mt [940, 1400] of plastic burned in the System Change scenario between 2016 and 2040 (Fig. 4D). It therefore remains a stubborn pollution and social injustice problem in need of an effective solution.

Although not strictly mismanaged, the net export of waste from high-income to upper- and lower-middle income countries grew from 2.7 Mt/year [2.4, 4.7] in 2016 to 3.8 Mt/year [0.7, 7.2] in 2040 under BAU. Although a comparatively small amount, these exports have the potential to increase the fraction of mismanaged plastic waste because receiving countries often have insufficient capacity to manage their own waste. Consequently, importing waste for recycling can have the unintended consequence of displacing these developing economies’ capacity to recycle their domestic waste (45).

Although efforts to measure the amount of plastic pollution entering rivers and oceans have increased in recent years (46–48), key data gaps remain. To better estimate the effects of consumer, corporate, and policy actions on solving the plastic pollution problem, additional empirical data are needed throughout the plastics system—particularly in developing economies. Moreover, a more complete accounting of the benefits, costs, and externalities of plastic use is needed to design policies that align social and financial incentives and minimize
Addressing the plastic pollution problem

Our analysis indicates that urgent and coordinated action combining pre- and postconsumption solutions could reverse the increasing trend of environmental plastic pollution. Although no silver bullet exists, even a 78% reduction from BAU pollution rates results in a massive accumulation of plastic waste in the environment. Moreover, even if this system change is achieved, plastic production and unsound waste management activities will continue to emit large quantities of GHGs. Further innovation in resource-efficient and low-emission business models, reuse and refurbil systems, sustainable substitute materials, waste management technologies, and effective government policies are needed. Such innovation could be financed by redirecting existing and future investments in virgin plastic infrastructure. Substantial commitments to improving the global plastic system are required from businesses, governments, and the international community to solve the ecological, social, and environmental problems of plastic pollution and achieve near-zero input of plastics into the environment.

REFERENCES AND NOTES