The Single-Use Plastics System

The factors which have prompted the ubiquitous use of plastic – its low cost, robust mechanical properties, resistance to degradation, and light weight – are the very factors which have led to its extensive environmental contamination. Single-use plastics make up 40-50% of the 400 million tons of plastic produced annually, and they overwhelmingly end up in landfills or discarded into terrestrial or aquatic ecosystems[1]. If not responsibly disposed of, plastics can cause an array of environmental problems. Plastic in landfills or the environment can take tens to thousands of years to degrade, at enormous economic costs from lost capital, dissuaded consumer activity, and interference with industrial activities, among others.[2-4] Environmental advocates have drawn attention to the disconnect between the fact that single-use plastics are used only once, yet persist in the environment for such a long time. Governments have begun to enact regulations to curb their use.

System Components

Following the human-technical-environmental systems framework[5], human, technical, environmental, institutional, and knowledge components are identified by italics. A full table of system components is shown in Appendix A.

Single-use plastic products are plastic goods designed for disposal after one use; examples include many different kinds of plastic bags, packaging material, cutlery, straws, containers, and bottles. *Fossil fuel reservoirs* including coal, natural gas, and oil deposits provide the small molecules called *monomers* that are the source for almost all plastics (380 million metric tons in 2015) and energy for plastics processing.[1] "Polymers" are a class of materials defined by the chemical linkage of these monomers. Plastics are a type of synthetic polymer; there are also natural polymers, including proteins and cellulose.

Monomer producers extract the raw materials from fossil fuel reservoirs for plastics production. *Plastics processors* convert monomers into polymer pellets and mold polymers into specific shapes for their intended use. Primarily, these producers are large multinational petrochemical companies, including ExxonMobil, Shell, and Dow. *Renewable monomer sources* are organic reservoirs of plastic monomers (e.g. corn, potato starch, and agriculture waste) that provide a small but increasing portion of the building blocks for plastic production (approximately 2 million metric tons in 2019).[6] *Goods producers* create products which are packaged in or utilize as part of their function single-use plastics (e.g. food or household products). *End-use consumers* in household and occupational settings use and dispose of single-use plastics.

Manufacturing technology used in the plastic production process involves reactors and catalysts (chemical compounds) to convert monomers into polymers and extruders (machinery) to melt and shape plastics into their desired end shape. *Incinerators* are used to burn and recover energy from plastics at their end of life. *Recycling plants* separate, melt, and pelletize plastics for re-use. *Composting facilities* process compostable materials, including biodegradable plastics, in a nutrient- and oxygen-rich environment to enable their digestion or breakdown by microbes. *Landfills* collect plastic waste deposited in solid waste streams.

Waterways and the *atmosphere* transport microplastics, the breakdown product of single-use plastics, across the globe in approximately equivalent amounts.[7] *Ecosystems* in all parts of the world contain plastics, where micro- and macroorganisms (defined as too small or able to be seen by the naked eye, respectively) can ingest littered or leaked single-use plastics and microplastics.

Markets provide the economic impetus for plastics production and consumption. *National plastic laws* may regulate the types and volumes of single-use plastics produced, circumstances under which single-use plastics can be used, and the allowable end-of-life pathways for single-use plastic disposal. *Sub-national and local plastic laws* provide the same types of regulation as national plastic laws on smaller geographic scales. *Corporate partnerships* join businesses involved in plastic consumption in knowledge and capital sharing towards reducing the environmental impact of single-use plastics.

Methods of plastics production and processing draw upon knowledge about how to extract monomers from fossil fuels and renewable organic reservoirs, methods to synthesize polymers from monomers, and processes to mold plastics into their engineered shape. Knowledge about the extent of greenhouse gas discharges (CO_2-equivalent) into the environment during the production, processing, and disposal of single-use plastics is compiled in *emissions inventories*. The evolving understanding of *health dangers of microplastics* is built on studies of how microplastics affect animal and human health.

Interactions

Interactions between the three sets of material components (human, technical, and environmental components) in the context of the non-material components (institutions and knowledge) are organized here into pathways focused on key interactions. See Figure 2 for a full interaction matrix. Figure 3 illustrates the pathway of interactions for each subsection.

a) Plastics Production

Plastics are ubiquitous in the modern economy, and the plastics economy is affected by supply and demand. Monomer producers, plastics producers, goods producers, and end-use consumers interact in markets (Figure 2, box 1-1). Production of plastics is growing globally at a compound annual growth rate of 8.4%.[8] In 2013, the plastics industry produced 78 million metric tons of single-use plastic packaging for consumer goods, worth an estimated $260 billion.[9] Plastics consumption is linked to consumer economies which promote the convenience of single-use products, where economic growth is connected to consumer spending.

Monomer producers extract raw materials from fossil fuel sources as well as renewable sources (Figure 2, box 1-3). Fossil fuel reservoirs provide the building blocks for most plastic materials from oil, natural gas, and coal extraction (Figure 2, box 3-2).[1] This means that the present-day plastics economy is fundamentally linked to the use and extraction of fossil fuels. Monomers are converted to single-use plastics (Figure 2, box 2-2) and sales of plastic products in turn provide revenue to goods producers (Figure 2, box 2-1).

Manufacturing technology releases GHGs during plastics production and processing (Figure 2, box 2-3). Total GHG emissions from plastics manufacturing and disposal globally is larger than that of the fourth largest country emitter.[8] Accounting for the full life cycle of plastics, 1.7 billion metric tons of CO_2-equivalent were released from the plastics industry in 2015. If the current growth rate of plastics consumption continues, emissions will grow to 6.5 billion metric tons by 2050, accounting for 15% of the global carbon budget.[8]

In the past decade, some monomer producers have devoted increasing effort to extracting or producing chemically identical building blocks from renewable resources (Figure 2, Box 1-3), and developing new methods to do so. Recent developments in polymer science has enabled the extraction of monomers from corn, sugar beet, vegetable oils, wheat, and other plant wastes, among many other sources (Figure 2, box 3-2).[10] Plastics made from organic sources are often called “bio-based plastics”; it is important to note that bio-based and biodegradable (discussed further below) refer to different characteristics.

b) Plastics Pollution

Plastics in the environment harm ecosystems (Figure 2, box 3-3). Historically, the majority of plastics (79%) have been released by end-use consumers into the environment (Figure 2, box 1-3) or landfilled.[1] Landfills leak plastic waste into the environment (Figure 2, box 2-3). Animals ingest plastics when they mistake them for food. Floating plastic waste can transport invasive species that disrupt fragile ecosystems. Plastic waste can clog sewers and create breeding grounds for malaria-spreading mosquitoes, while releasing toxic gases. Plastics in the bottom of landfills leach chemicals that spread into groundwater reservoirs.

Environmental processes break down single-use plastics and create microparticulate plastic pieces (“microplastics”), which are smaller than 5 mm (Figure 2, box 3-3). This degradation can result from physical, chemical, and biological factors, such as from ultraviolet degradation from sunlight.[11] The atmosphere and waterways then transport microplastics regionally and globally (Figure 2, box 3-3). Micro-, aquatic, and terrestrial organisms ingest microplastics, where they can have a host of toxicological effects and enter complex food chains.[12] In turn, humans may accumulate microplastics by ingestion of these organisms. Microplastics in the air and waterways may also harm human health (Figure 2, box 3-1), though knowledge of potential health effects remains uncertain.[13]

b) Plastics End-of-Life

End-use consumers dispose of single-use plastics, which go to landfills, incinerators, recycling plants, or composting facilities (Figure 2, box 1-2). Consumers can choose one of several disposal options, depending on the nature of the plastic material. Recycling plants capture plastics and process them into pellets for reuse (Figure 2, box 2-2); 9% of historical plastics have been recycled.[1] The remaining 12% have been incinerated[1]; incinerators burn plastics to capture stored energy (Figure 2, box 2-2). Both recycling plants and incinerators release GHGs during plastic disposal (Figure 2, box 2-3).

Compostable plastics are a new alternative to historically available disposal options. Most existing compostable single-use plastics are made of poly(lactic acid) ("PLA") or a PLA blend, which only meets composting certification requirements under industrial composting conditions (i.e. in elevated temperature and oxygen- and nutrient-rich environments).[14] Recent advancements in polymer science have produced plastics which break down under ambient composting conditions, such as poly(hydroxyalkanoates) ("PHAs"), but these materials have not yet found significant commercial presence.[15]

Bio-based plastics are sourced from renewable sources. Biodegradable plastics are able to be broken down by microbes on measurable time scales (typically one year for most certifications). Bio-based and biodegradable characteristics are exclusive properties. A bio-based plastic may be, but *is not necessarily*, biodegradable, and vice versa. For example, Coca-Cola's PlantBottle™ is made of poly(ethylene terephthalate) (PETE) with monomers sourced from renewable organic supplies. PETE, whether it comes from plants or fossil fuels, is not a biodegradable plastic.

Interventions

This section identifies ways in which different interveners can act to modify interactions in the system. Figure 4 provides a complete intervention matrix.

Potential interveners in the single-use plastics system include *national and local governments*, *international organizations*, *industry groups*, *environmental organizations*, *goods producers*, *plastic producers*, and *consumers*. This section summarizes three different types of potential interventions: voluntary actions and initiatives; government regulations including bans and taxes; and transitioning to a circular economy for plastics.

a) Voluntary actions and initiatives

Environmental organizations have engaged in multiple efforts to highlight the problem of plastic pollution and advocated for the implementation of measures to address it. One way in which this occurs is through awareness-raising campaigns that attempt to influence consumer purchasing (Figure 4, box 1-1), for example encouraging consumers to use less plastic. Major environmental organizations such as the Natural Resources Defense Council, the World Wildlife Fund, Recycle India, and UNESCO Bangkok have advocated for plastics awareness and actions, including by consumers.

In addition, environmental groups and international organizations have worked together with corporate partnerships in multi-stakeholder groups to implement plastics use and waste reduction strategies (Figure 4, box 2-20. For example, The Sustainable Packaging Coalition brings together major consumer brands (such as Coca-Cola, Target, and Procter & Gamble) with industry groups (such as the Flexible Packaging Association and the American Chemistry Council), government agencies (such as the City of Cambridge, CalRecycle, and the United States Environmental Protection Agency), and manufacturers to improve the sustainability of packaging across industries.

Initiatives by consumers to limit single-use plastic consumption (Figure 4, 1-1) often achieve more impactful (per person/good) actions in short periods of time and can be effective in pushing companies towards change, but usually only include a smaller, engaged portion of a constituency (e.g. encouraging communities to buy food from farmers markets to avoid plastic waste entirely).[16-17] Producer-led initiatives are often more impactful in creating industry-wide change, but often take the form of small, incremental steps that achieve goals over longer time periods (e.g. reducing the amount of plastic used to wrap a good by 5%).

b) Government regulations on single-use plastics

An increasing number of national and local governments are instituting bans or taxes on the use of single-use plastic (Figure 4, box 2-1). Interestingly, taxes tend to curb consumption more than bans under current circumstances, as putting the onus on consumers to bring their packaging (e.g. reusable bags) appears generally more effective than bans which tend to not encompass all possibilities and allow retailers to find workarounds.[18] More than 240 counties and cities in the US have enacted such laws.[19] Globally, at least 127 countries have some regulations on plastic bags.[20] In Kenya, manufacturing, importing, or selling a plastic bag is punishable by up to a $40,000 fine or four years in jail; using a banned bag offers up to a $500 fine or up to a year in jail.[21] Other efforts by national and local governments include the encouragement of composting and recycling, and associated infrastructure development (Figure 4, box 1-2).

Though these laws are broadly effective in reducing overall plastic use, they may lead to unintended consequences (e.g. consumers buying thicker bags as trash bags) and raise questions about equity.[18] Lobbying efforts supported by producer companies have resulted in the passage of "ban pre-emption" laws in at least fourteen states which restrict local governments from banning single-use plastics in their region (e.g. "bans on bag bans").[22]

c) Transitioning to a circular economy

Goods producers and plastics processors can address the plastics problem by transitioning to a circular economy model (Figure 4, box 2-2). Systems where capital is either linearly introduced to and then lost over a material's lifespan, or preserved through recapturing capital at a material's end-of-life are referred to as *linear* and *circular* economic models, respectively. In a circular economic model for single-use plastics, capital input into the plastics system would be recovered and recycled at many points over a material's life cycle. Plastics are sourced from renewable organic sources to create a carbon-neutral material. All compostable plastics are disposed of to commercial facilities to return carbon to and recycle carbon through the environment. All recyclable plastics are captured and reprocessed. Plastics which can't be composted are broken down into their constituent monomers are their end of life, which can then be re-synthesized to plastics. Transitioning to a circular economy requires cooperation from national and local governments to create and maintain needed infrastructure and enact supportive regulation; consumers to properly separate and dispose of single-use plastics; and goods producers and plastic processors to engage in this model and educate consumers.

If the exponential growth of single-use plastics production and consumption continues unchecked, a number of environmental problems ranging from deteriorating animal health to escalating carbon emissions to nonrenewable resource depletion will be exacerbated by a material designed primarily for human convenience. These impacts directly affect people through harm to economies, climate, and health. Curbing the single-use plastics crisis requires a coordinated implementation of diverse interventions including all stakeholders, from governments to citizens, NGOs to industry groups, and retailers to plastic producers. Today's ubiquitous use of plastics, though unimagined with its discovery in the 1950s, demands a response proportional to its costs and persistence for generations beyond its creation.

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Components, Interactions, and Interventions

Human components	Technical components	Environmental components
Monomer producers Plastics processors Goods producers End-use consumers	Monomers Single-use plastics Manufacturing techology Incinerators Recycling plants Composting facilities Landfills	Fossil fuel reservoirs Renewable monomer sources Atmosphere Waterways Ecosystems

Institutional components	Knowledge components
Markets National plastics laws Regional and local plastics laws Corporate partnerships	Methods of plastics production and processing Emissions inventories Health dangers of microplastics

Figure 1. Components in the single-use plastics system.

Knowledge

Institutions

	1. Human	2. Technical	3. Environmental
1. Human	(1-1) **Monomer producers, plastics producers, goods producers, and end-use consumers interact in markets**	(1-2) **End-use consumers dispose of single-use plastics, which go to landfills, incinerators, recycling plants, or composting facilities**	(1-3) Monomer producers extract raw materials from fossil fuel reservoirs and renewable sources; End-use consumers release single-use plastics into the environment
2. Technical	(2-1) Plastic products provide benefits to consumers and revenue to producers	(2-2) Monomers are converted into single-use plastics; Recycling plants capture plastics and process them into pellets for reuse; Incinerators burn plastics to capture stored energy	(2-3) Manufacturing technology releases GHGs during plastics production and processing; Recycling plants and incinerators release GHGs during plastic disposal; Landfills leak plastic waste into the environment
3. Environmental	(3-1) Microplastics in the atmosphere and waterways may affect human health	(3-2) Fossil fuel reservoirs and renewable sources provide raw materials for monomer production	(3-3) Environmental processes break down single-use plastics and create microplastics; Atmosphere and waterways transport microplastics; **Plastics in the environment harm ecosystems**

Figure 2. Interaction matrix for the single-use plastics system.

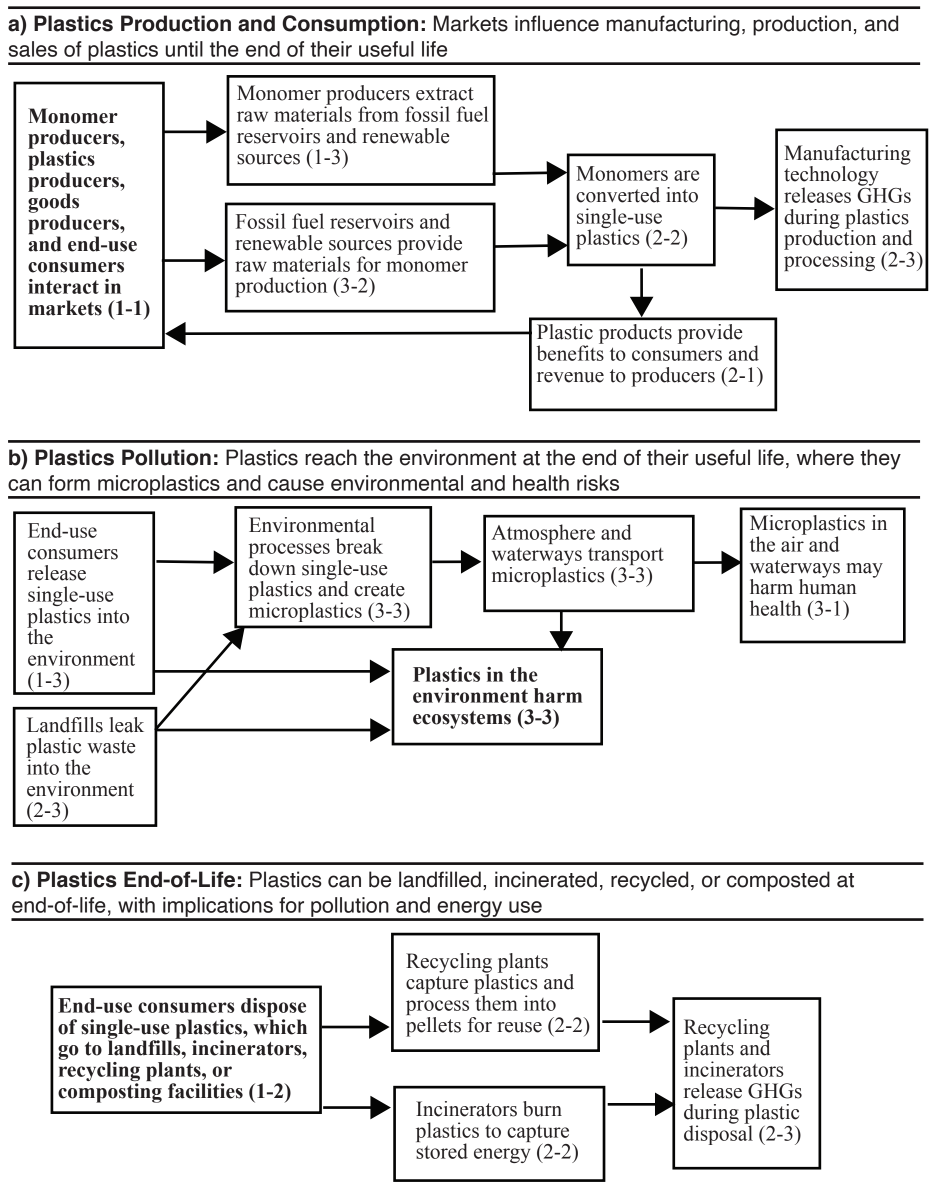

Figure 3. Pathways of interactions in the single-use plastics system.

Knowledge

Institutions

	1. Human	2. Technical	3. Environmental
1. Human	(1-1) Environmental organizations influence consumer purchasing; Consumers limit single-use plastic consumption	(1-2) National and local governments encourage composting, recycling, and associated infrastructure development	(1-3) Goods producers and environmental organizations pressure monomer extractors and plastics processors to meet sustainability criteria
2. Technical	(2-1) National and local governments ban or tax use of single-use plastics	(2-2) Multi-stakeholder groups implement plastic use and waste reduction strategies; National and local govern-ments ban or tax the production of single-use plastics; Goods producers and plastics processors transition to a circular economy model	(2-3)
3. Environmental	(3-1)	(3-2)	(3-3)

Interveners
National and local governments, international organizations, industry groups, environmental organizations; goods producers, plastics processors, consumers

Figure 4. Intervention matrix for the single-use plastics system.