Plastic Pollution: Evaluating the Effectiveness of a Circular Economy Solution

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Abstract

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In the coming decades, plastic production is expected to grow exponentially. On a global scale, we currently do not have sufficient waste management infrastructure or recycling capabilities to support the disposal of plastic products. As a result, most discarded plastic is placed in a landfill, incinerated, or makes its way into the natural environment. The production of plastic, manufacturing of plastic products, and disposal of plastic goods and packaging has serious impacts on the environment, ecosystems, and human health. Implementation of a circular economy model is a feasible solution to the plastics pollution problem. Under this economic model, products are reused and regenerated into new products, so the waste stream is eliminated. However, a circular economy solution will require cooperation between industry, governments, and scientific researchers. Each entity has different motivations and limitations, so the transition to a circular economy will require collaboration and mutual beneficence. From my research, there are three main barriers to the implementation of a circular economy. In existing discourse, there are few discussions about the differences in implementation across different countries, as solutions will vary depending on the location. Additionally, there is a need for industry to buy-in to circular economy principles such as Extended Producer Responsibility and Deposit Return Systems. Finally, there must be increased awareness and education about the benefits of a circular economy solution.

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Introduction

One morning, I examined my shampoo bottle. I had seen this bottle hundreds of times, but this time I looked at the bottle from a different perspective. The bottle was made of thick plastic covered by a thin plastic sticker, with a plastic lid that easily opened and closed. There was an obvious commonality in the packaging—everything was made of plastic. As I began to think more critically about this bottle, I wondered how it came to reside on the shelf in my shower. I wondered about the processes that it took to produce and mold the plastic into various forms to create the different components of the bottle. Looking at the small portion of shampoo remaining, I also thought about what would happen to the bottle after I "responsibly" disposed of it in the recycling bin. While I was not naïve to the magnitude of the plastics pollution problem, I sought to understand how different aspects of the plastics industry impact people and the environment.

Since 1950, plastic pollution has grown from two million metric tons (Mt) to 400 Mt in 2020 (ISO, 2020). Additionally, plastic production is expected to double by 2040 and increase by 2.5 times by 2050 (ISO, 2020). Unless we change our methods of producing and discarding plastic, the plastic pollution problem will continue to grow. This thesis is focused on the problems surrounding plastic pollution and insufficient recycling programs, and the viability of a circular economy solution. While there are many interpretations of this issue in the news and academic literature, I will examine the issue from various perspectives, considering the most recent developments by corporations, governments, and researchers to address plastic pollution.

One solution to this problem is the concept of a circular economy, which is defined as an economic system based on the reuse and regeneration of products or materials (Ellen MacArthur Foundation, n.d.). In the plastics industry, a circular economy would eliminate unnecessary plastic items, innovate plastics that are more environmentally friendly, and circulate all plastic items so they do not become waste. While a circular economy sounds practical in theory, it faces many obstacles from an economic, policy, and scientific perspective. Additionally, the implementation of a circular economy solution varies significantly depending on scale and location. This thesis addresses the following questions:

1. What effects do plastic production and insufficient recycling programs have on humans, the environment, and climate change?
2. What efforts (or lack of) are being made by companies in the plastics industry to be more sustainable, what policy is regulating plastic pollution worldwide, and what scientific research is being conducted to improve plastic recycling?
3. How viable is a circular economy solution?

In the first portion of this thesis, I will examine the entire lifecycle of plastics—from their production using fossil fuels to their disposal in recycling streams, landfills, or the marine environment. While plastics have become a ubiquitous aspect of modern life, plastic production and disposal is contributing to climate change, harming terrestrial and marine species, and impacting human health. Plastic generation is expected to grow exponentially over the next decades, and we currently do not have the systems in place to effectively manage plastic waste streams, especially in developing countries.

Plastic pollution is a negative externality driven by a market that favors fast production and subsequent fast consumption and disposal. The second portion of this thesis focuses on the plastics production and consumer goods industries. I will evaluate some of the largest companies involved in the plastics industry, and examine their contributions to the problem, while also recognizing their work towards a solution. Ultimately, no singular stakeholder contributing to the plastic pollution problem is entirely responsible.

Governments also have a major role in addressing this problem. As more environmental policies are enacted globally to address climate change, governments are writing policies to specifically combat plastic pollution. Much of this legislation is focused on single-use plastics, but there are also efforts to incentivize using recycled content and creating reusable packaging. I will specifically focus on legislation in three regions—North America, Europe, and Asia—to demonstrate how government policy varies dramatically based on location. Additionally, I will examine the newest international resolution within the United Nations (UN) working to end plastic pollution.

Scientific researchers are also working to address plastic pollution by designing products from alternative materials and implementing physical and chemical elimination technologies. Specifically, I will examine three areas of research—physical elimination, chemical elimination, and biodegradation. While there are promising solutions within scientific research, the technology will require large-scale implementation to make a significant difference in the current plastic waste management system.

After considering the various entities involved in this problem, I will evaluate the viability of a circular economy solution. Some companies are already operating under a circular model and profiting from a system that values the re-use and re-generation of materials over extracting raw materials. However, a circular economy model will look different from industry-to-industry and country-to-country. Before this model can be feasible on a larger scale, some important limitations must be addressed and will involve the intersection of industry, consumers, governments, and science.

<u>Chapter 1: Plastic Pollution Throughout Its Lifecycle</u>

We produce, use, and discard an enormous amount of plastic as a society. To be specific, plastic waste worldwide has more than doubled, from 156 million metric tons in 2000 to 353 million metric tons in 2019 (OECD, 2022). At its end life, 9% of plastic waste was recycled, 19% was incinerated, almost 50% went to sanitary landfills, and the remaining 22% was disposed of in uncontrolled dumpsites, burned in open pits, or leaked into the environment (OECD, 2022). While plastic waste is undeniably a problem, the entire lifecycle of plastic has a detrimental impact on the environment. From its initial production using fossil fuels to the final disposal of the (often single-use) product, the plastic industry results in significant carbon emissions, environmental consequences, and human health impacts. The figure below shows the flows of plastic production, plastic waste, and plastic in the environment.

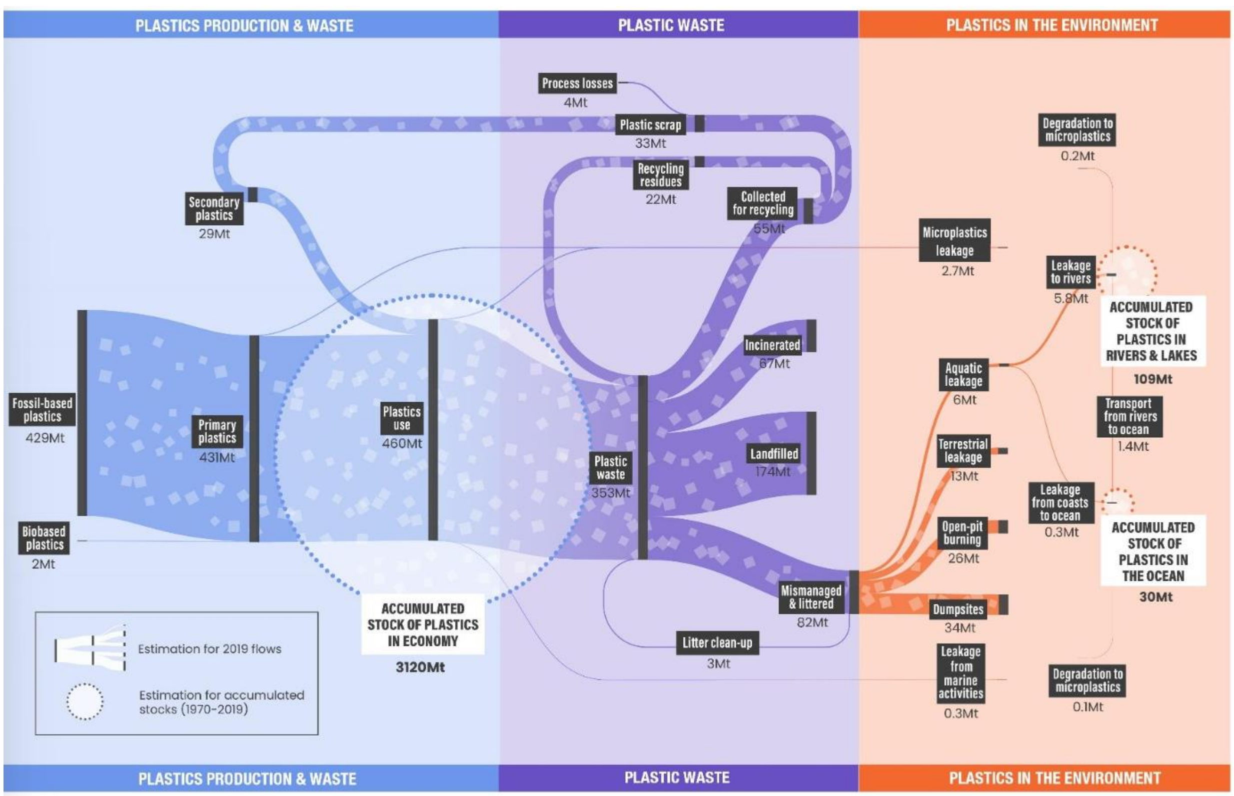

Figure 1: Plastic flow diagram showing global accumulation and waste (OECD, 2022)

Plastic Production Process

The production of synthetic plastics begins with crude oil, natural gas, or coal. During the refining process, crude oil is separated into different petroleum products that are useful monomers (a molecule that is the building block of a polymer). Next, in a process called polymerization, gases such as ethylene, propylene, and butylene (monomers) are converted into higher molecular weight hydrocarbons (polymers) by chemically bonding the monomers. Plastics are high molecular weight organic polymers that can be mixed with other substances, called additives, to take on various properties (Baheti, n.d.). Of the 3.4% of total greenhouse gas emissions attributed to the plastics industry, it is estimated that 90% are from the production and conversion of plastics from fossil fuels (OECD, 2022). If the entire lifecycle of plastic were a country, it would be the fifth largest emitter of greenhouse gases in the world (Break Free From Plastic, 2021). Additionally, the petrochemical industry faces controversy over environmental justice, as plastic production often takes place in low-income communities and disproportionally impacts people of color (Crunden, 2022). As plastic demand continues to increase, greenhouse gas emissions from the plastics industry will inevitably grow.

The final products leaving a plastic production plant are nurdles, which are the building blocks of all plastic products. Nurdles are small pellets, about 1 to 5 mm in diameter, that are melted down in factories and poured into molds to produce almost any kind of product, from water bottles to sewage pipes. Due to their light weight, around 20 milligrams each, they can be easily transported by road, train, or ship. However, the environmental damage caused by nurdle spills is essentially unregulated, as they are not generally classified as pollutants or hazardous materials. When nurdles spill during transport, such as when loading the nurdles into containers, from train cars that are not properly sealed, or from ships that wreck during transport, they contaminate the surrounding environment. As a result, it is projected that 10 trillion nurdles will infiltrate marine ecosystems around the world each year (Dhanesha, 2022). To make matters worse, nurdles do not biodegrade, and instead, break down into even smaller microplastics that contaminate the oceans and harm marine life (Dhanesha, 2022).

The companies producing these nurdles do not usually have a pressing obligation to clean up nurdle spills (like they would for an oil spill) because they are not considered a contaminant, even though nurdles are produced from the same raw material (Dhanesha, 2022). If no action is taken to change the policy regarding nurdles, or better yet, move away from the production of plastic, nurdles will continue to accumulate and adversely impact marine environments. As seen from the figure below, oil spills have decreased over the past 50 years, while plastic debris (the end product of nurdles) discharged into the ocean has increased. While this burden should not be placed entirely on the companies producing plastic, nurdles are the second-largest source of ocean microplastics after tire dust (Pew Trusts, 2020).

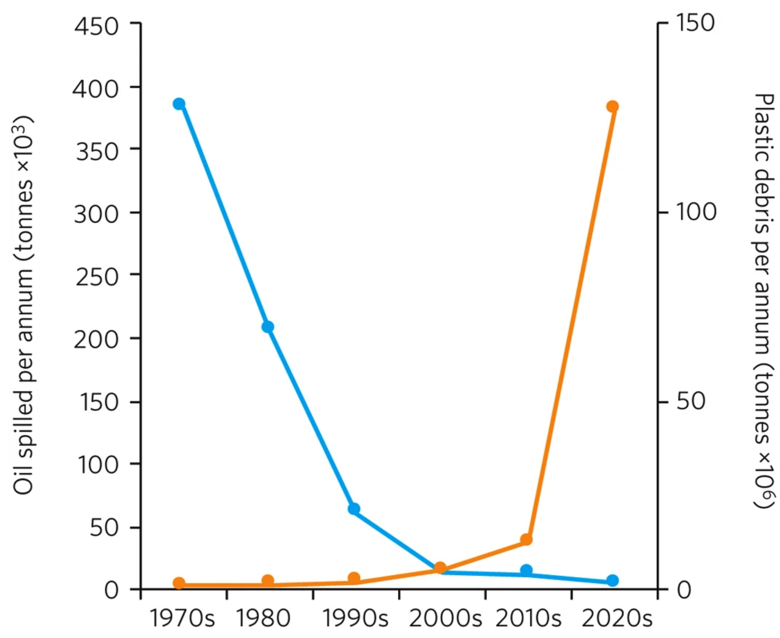

Figure 2: Amount of crude oil spilled (blue) compared with terrestrial plastics (orange) in the ocean (Galloway et al., 2017)

Plastics in the Environment

In the past 65 years, plastic production has outpaced the growth of any other manufactured material (Rhodes, 2018). Plastics are durable, resist degradation, and have extremely versatile properties that are difficult to find in natural materials. However, humans have continued to produce more plastic without an effective management strategy for the end life of these products, resulting in billions of metric tons of material accumulating in the natural environment. One of the defining properties of plastic–its slow degradation–poses a great challenge, as any plastic released into the environment will take hundreds of years to decompose (Rhodes, 2018). During physical decomposition, plastic steadily breaks into smaller fragments until it reaches the molecular level where it can be metabolized by microorganisms. Certain microorganisms can either oxidize the carbon molecules in polymers into carbon dioxide or incorporate the carbon into biomolecules (Rhodes, 2018). However, in both land and marine environments, the conditions are not favorable for degradation. In the ocean, there is limited oxygen available and slow rates of hydrolysis (which involves the splitting of polymers when they react with water molecules). In landfills, the conditions are mostly anaerobic, so there is not enough oxygen for effective plastic degradation. When the plastics do decompose, they can release toxic pollutants such as benzene, toluene, and bisphenol-A (BPA) (Rhodes, 2018).

Plastic leakage into the environment is widespread and has negative impacts on the affected ecosystems. Land-based plastic pollution (from populations within 50 km of the coastline) is the largest contributor to marine plastic pollution, comprising 80% of the plastic that accumulates in the ocean (Almroth and Eggert, 2019). Some models indicate that most plastic enters the marine environment through rivers, while others contend that the majority of plastic enters the marine environment through stormwater runoff, wind dispersal, and littering. One study suggested that 90% of the riverine input comes from eight large rivers in Asia and two in Africa (Almroth and

Eggert, 2019). Plastic undoubtedly enters the marine environment through all of these modes, even if the relative contributions of each mode are still uncertain.

Plastic pollution effects have been studied most closely in marine environments. It is projected by 2050 there will be more plastic (by mass) in the ocean than fish (Rhodes, 2018). In aquatic environments, the most visible negative effects include organisms becoming entangled in plastic debris such as fishing nets or plastic bags, and increased mortality due to ingesting microplastics (OECD, 2022). Microplastics are defined by the US National Oceanic and Atmospheric Administration as plastic pieces less than 5 mm in diameter (CAS, 2021). Primary microplastics include nurdles, "scrubbers" used in exfoliating cleansers, particles used for air blasting, and microplastics in fleece, nylon, and polyester clothes. Secondary microplastics are those that fragment from larger plastic pieces, sometimes with diameters smaller than that of human hair (CAS, 2021).

Microplastics are particularly concerning because they are easily consumed by animals within the marine food web. Research indicates that marine organisms ingesting microplastics can lead to blocked intestinal tracks, hormone disruption, inflammation, reproductive impact, and behavioral changes (Almroth and Eggert, 2019). Some marine wildlife, including zooplankton, are more likely to ingest plastics as they are attracted to plastics that have been coated with a layer of algae. When the algae decompose, they release dimethylsulfideal (DMS), which is an infochemical odorant for natural trophic interactions (meaning it "smells" like food). There have been recorded instances of turtles mistaking plastic bags for jellyfish, and subsequently dying from obstruction of the esophagus, or beached whales found with large amounts of plastic in their stomachs (Rhodes, 2018). Additionally, chemical additives used in plastic production can cause endocrine disruption, reproductive abnormalities, and developmental disorders in fish and marine mammals (Almroth and Eggert, 2019).

Outside of the ocean, seabirds have also been impacted by plastic in the environment. For example, seagulls living around the North Sea had 30 pieces of plastic in their stomach on average (Rhodes, 2018). This is due to them mistaking plastic pieces for prey or ingesting other organisms containing plastic. In seabirds, plastic in the digestive system can cause physical damage or a false sense of satisfaction, which could lead to starvation and eventually death. Additionally, additives can discharge into their muscle tissues and impair immune system responses, reproductive ability, and hormone balances (Rhodes, 2018). The documentary *Albatross*, which follows the lives of albatross birds on Midway Island in the Pacific Ocean, shows in graphic detail the cause of death for many of the birds—stomachs filled with every type of plastic item. The film's creator described the experience as "devastating, not only for what it meant for the suffering of the birds, but also for what it reflected back to us about the destructive power of our culture of mass consumption, and humanity's damaged relationship with the living world" (Albatross, n.d.).

Due to our close relationship with marine environments, there has been growing research into the effects of microplastics on human health. Microplastics can enter humans by consuming marine life that is contaminated. Plastic additives such as polybrominated biphenyls (PBBs), which are used as flame retardants, can have biological effects such as endocrine disruption or carcinogenicity. Additionally, exposure to BPA has been correlated with disrupting fertility, reproduction, or other health effects. Daily exposure to these toxins is usually within accepted safety limits; however, more research is needed to evaluate potentially adverse human health impacts (Rhodes, 2018). While marine life can act as vectors to transfer chemicals in plastics to humans, the greatest source of human exposure to toxins in plastics is through food packaging (Almroth and Eggert, 2019).

Ineffectiveness of Recycling

For the past 50 years, the main solution to plastic pollution has been recycling. However, the rates of plastic recycling in Europe and the United States in 2018 were only 32.5% and 9%, respectively (European Parliament, 2018; EPA, 2021). Although there are economic benefits to recycling–one study estimated that if all plastic waste were recycled, the equivalent of 3.5 billion barrels of oil could be saved, amounting to 176 billion dollars (at $50 per barrel)–recycling has not been implemented effectively (Rhodes, 2018). Some barriers to effective plastics recycling include upstream sorting challenges, maintaining material quality, and economic viability.

In the United States, the recycling industry has been strained by China implementing an import ban in 2017. Before the ban, higher-income countries in the Organization for Economic Cooperation and Development (including the United States) exported 70% of their plastic waste to China and lower-income countries in the Pacific (Brooks et al., 2018). This ban decreased the value of plastic waste as it created more supply while keeping the same number of recycling facilities in the United States. Following China's lead, other Asian countries have limited plastic waste imports, further straining the recycling industry. Compared to Europe and other countries like South Korea, there is not as much incentive to recycle in the United States because landfill tipping fees (cost to dispose of waste in a landfill) have remained low. The fees have only increased from $53.04 to $55.11 per ton from 1994 to 2018 (Vogt et al., 2021). With limited recycling facilities and low landfill costs, there has not been an economic incentive to invest in the recycling industry.

A key aspect of the recycling process is effectively sorting the different types of plastic. In general, polymers are immiscible, so they must be sorted properly so they do not contaminate other polymers that will be used again as post-consumer recycled content (Vogt et al., 2021). In high-income countries, the formal system of collection, transportation, and sorting of waste is managed by the government. However, these upstream steps are costly, and the sorting uses capital-intensive processing (OECD, 2022). Most plastics are sorted by polymer type using optical techniques, but there are imperfections in this process. For example, black plastics common in food trays are difficult to sort by this method as they absorb most of the light. Additionally, there is a wide range of additives used to manufacture plastic, and the chemical composition of the polymers could change as a result of degradation or adsorption from the environment. This further complicates the separation of plastics in recycling facilities. To address this problem, technologies are emerging to remove additives due to their differences in solubility with respect to the polymer. However, this process is expensive and results in significant amounts of solvent waste (Vogt et al., 2021).

The most widely used recycling process is mechanical, where the polymer is recovered through a process of washing, shredding, melting, and remolding. Often recycled plastic is mixed with primary plastic (plastic produced from fossil fuel sources) of the same type so it can be used to produce new plastic goods. However, this approach only works with some types of plastics (polyethylene terephthalate and polyethylene specifically), which only account for 46% of all plastics produced (Rhodes, 2018). Additionally, the process of compounding and product fabrication with recycled polymers often decreases the average molecular mass of the plastic, which reduces its mechanical performance (Vogt et al., 2021). This downcycles the plastic from high-value to low-value applications, which reduces the economic viability of the recycled product.

Historically, recycled (secondary) plastic has been used as a low-cost substitute for primary plastic. Therefore, the price of secondary plastic correlates to the price of primary plastic, even though it costs more to produce recycled plastic (when the sorting, collection, and processing are considered). As a result, the secondary plastic market is left vulnerable to the fluctuations of the primary plastic market. Often secondary plastics producers are smaller, less capital intensive, and have fewer sales, so they are not as resilient to market changes (OECD, 2022). While the secondary plastics market has quadrupled in the last two decades, it is still a relatively small market compared to primary plastics, so there has not been a fundamental shift from primary to secondary plastic production (OECD, 2022).

Another developing method of secondary plastics production is chemical recycling, which can be used with additional resins and polymer types. This process involves breaking down the polymers into their monomers (a process known as depolymerization), which can be purified to produce plastics that are indistinguishable from primary plastics. The conversion back to monomers closes the loop of plastic production, as all the plastic can be repurposed into new products. This high-quality material can be used in food applications, unlike most mechanically recycled plastic. However, various challenges prevent this recycling process from being viable on a large scale. Similar to mechanical recycling, additives present a problem as they can deactivate the catalysts that enable depolymerization (Vogt et al., 2021). The process is also very energy intensive and produces toxic by-products, so it is not always environmentally friendly. Some large companies such as ExxonMobil are investing in chemical recycling, but some critics argue that it is the fossil fuel industry's "Plan B" as renewable energy is becoming more competitive. ExxonMobil's Vice President of New Market Development, Dave Andrews, responded to this criticism by saying “we’re going as quickly as we can because we see this as a profitable growth business that delivers benefits to society” (Wolman, 2022).

A Plastic Waste Crisis

The other option for plastic waste disposal is incineration. In sophisticated plants, the plastic is burned with enough heat to produce steam to turn turbine blades and generate electricity. These waste-to-energy plants divert waste from landfills or the ocean and produce useful energy in the process. However, they are also expensive to build, emit high rates of greenhouse gases, and release toxins such as dioxins, acid gases, and heavy metals (Royte, 2019). Additionally, some scholars contend that using plastic for energy does nothing to curb the demand for new plastic products, and instead contributes more to climate change (Royte, 2019).

Although there are various options for the end-life of plastic that do not include a landfill, these alternatives will not address the current production rates or keep up with the projected increase in plastic production, as seen in Figure 3.

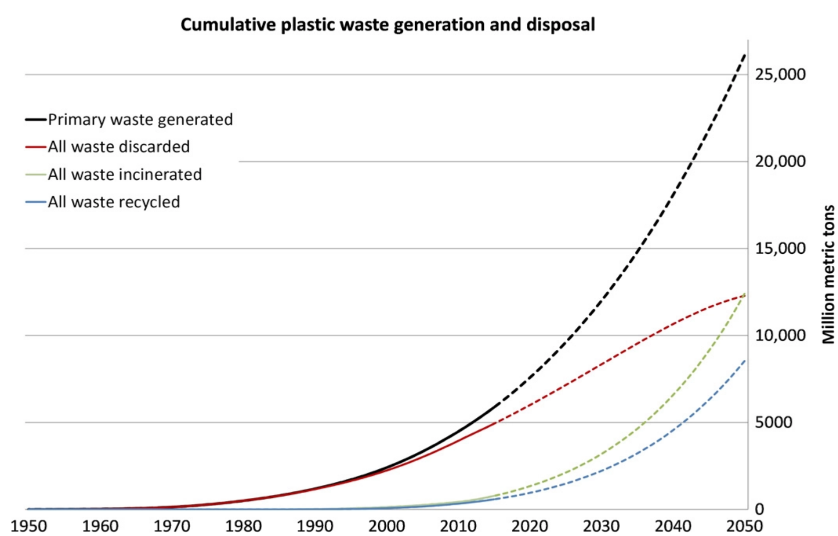

Figure 3: Global plastic waste generation and disposal, including projections based on historical trends (Geyer et al., 2017)

As seen in this figure, plastic production will continue to grow rapidly into 2050. While incineration and recycling rates are projected to increase and discard rates decrease, neither recycling nor incineration rates will be enough to divert all plastic waste from landfills.

There are many challenges facing the current recycling and incineration systems, as neither provides a cost-effective, environmentally friendly solution to the plastic pollution problem. Therefore, other options must be considered to substantially reduce the amount of plastic waste entering our environment. Feasible solutions must incorporate the intersection of industry, policy, and science to work towards a world free of plastic pollution.

Chapter 2: Economics of Plastics and the Effectiveness of Industry (In)action

The UN projects that plastics manufacturing will double from 2022 to 2040, and the International Energy Agency has predicted that the plastics industry will outpace coal-fired carbon emissions within the coming decade (United Nations, 2022; International Energy Agency, 2020). As the industry continues to grow, the plastics pollution problem can be framed by economics. Currently, the companies producing plastic and manufacturing plastic products have limited economic incentives to curb plastic pollution, beyond consumer or stakeholder pressure. There is no legislation in the United States restricting single-use plastics, so corporate pledges to curb plastic pollution are not driven by legal sanctions (Earth Day Network, 2022). The responsibility to curtail pollution is not placed on the producers or manufacturers, but instead falls on waste management systems, which are unable to effectively handle the amount of plastic being discarded. Substantially reducing plastic pollution will require that production and manufacturing companies take more responsibility over the entire life cycle of plastics, along with a significant decrease in primary plastic production.

The Plastic Production Industry

Petrochemical companies are making some strides towards reducing their environmental impact related to plastic. Specifically, I will evaluate the initiatives by some of the largest plastic producers: Dow Chemical, ExxonMobil, and Saudi Basic Industries Corporation (SABIC) (Minderoo Foundation, 2021).

Dow has pledged to “deliver circular economy solutions” by investing in bio-circular feedstocks from vegetable waste, designing products for recyclability, and incorporating post-consumer plastic waste into their new polyolefin portfolio (Dow Inc., n.d.). In 2022, they unveiled a series of partnerships intended to work towards its goal of “collecting, reusing, or recycling 1 million metric tons per year of plastics waste by 2030” (Dow, 2022). One of the largest collaborations is with the British firm Mura Technology, which uses steam to chemically break down plastics such as flexible polyethylene into products that can be used in petrochemical plants to produce new plastic (Dow, 2022). Dow was also a founding member of the Sustainable Packaging Coalition, which is responsible for the “How 2 Recycle” label that standardizes the recycling labeling on over 30,000 products. However, this label has been criticized for its lack of transparency about the actual recyclability of the plastics (Changing Markets Foundation, 2021). In the United States, the chasing arrows symbol is followed by the number 1-7, indicating the type of plastic. In reality, the recycling rates (the amount of plastic that is recycled by municipalities) for plastics 3-7 are close to zero (Changing Markets Foundation, 2021).

Dow was involved in developing the Alliance to End Plastic Waste, a coalition of 70 companies across the plastics industry that has the “goal of raising $1.5 billion over the next five years to develop and scale solutions that manage plastic waste and promote post-use solutions of plastic” (Alliance to End Plastic Waste, n.d.). While these are valuable initiatives, $300 million per year (split among the 70 member companies) invested in curbing plastic waste seems insignificant in comparison to Dow’s $57 billion annual revenue in 2022 (Macrotrends, 2023).

Other major plastic producers, ExxonMobil and SABIC, are also part of the Alliance, which has received criticism over the years. The Alliance grew out of the American Chemistry Council, a plastics industry lobbying group, so the interests of the group are focused on downstream solutions as opposed to limiting plastic production (Baker et al., 2022). Additionally, four years after its creation, it has diverted 34,000 tons of waste from landfills, which is only 0.2% of its original target (Baker et al., 2022).

In December 2022, ExxonMobil announced the successful startup of an advanced (also known as chemical or feedstock) recycling facility in Baytown, Texas. Advanced recycling involves converting plastic back to its original polymer so it has identical properties to primary polymers and can be used in commercial applications. This type of recycling is especially useful for plastics that cannot be recycled mechanically. The process breaks down “hard-to-recycle” plastics into raw materials that can be used for new products, with the capability of processing 80 million pounds of plastic waste per year (ExxonMobil, 2022). ExxonMobil has plans to build advanced recycling plants globally, with the goal of recycling 1 billion pounds of plastic annually by 2026 (ExxonMobil, 2022). However, according to one study (Figure 4) ExxonMobil is the top contributor to single-use plastic waste, contributing 5.9 million metric tons in 2019 (Minderoo Foundation, 2021). Accounting for the conversions between pounds and metric tons, processing 1 billion pounds of plastic waste annually would only account for about 8% of ExxonMobil’s annual contribution to single-use plastic waste. It is clear that ExxonMobil is focusing on recycling instead of addressing the root of the plastic pollution problem: reducing primary plastic production. As plastic production continues to grow, recycling rates will be unable to keep up with the rates of production, even with petrochemical companies investing in advanced recycling technology.

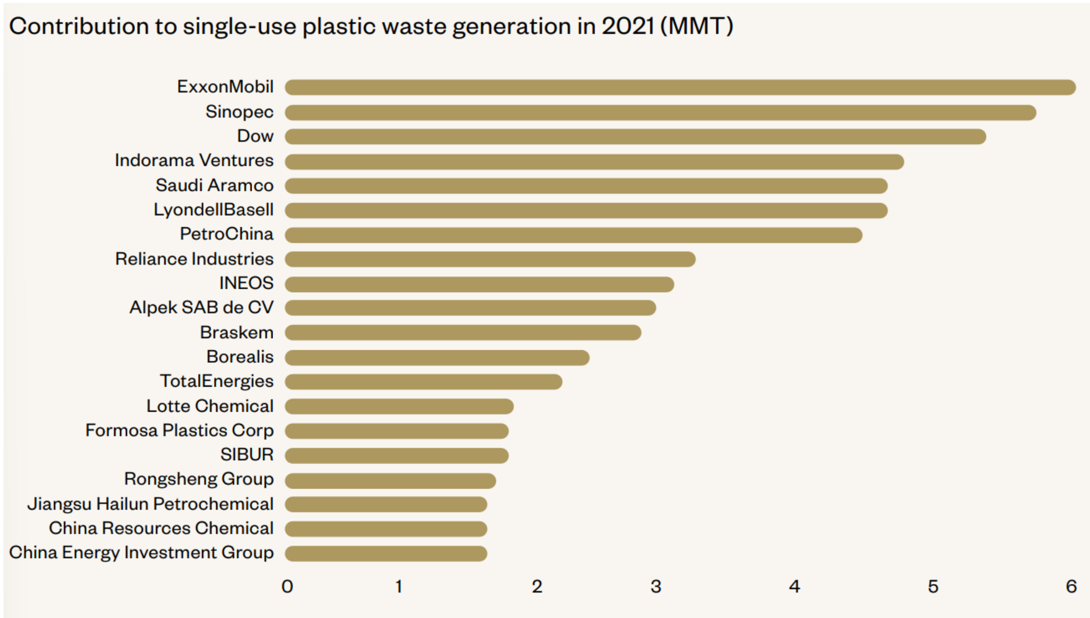

Figure 4: The top 20 petrochemical companies contributing to single-use plastic waste (Minderoo Foundation, 2021)

According to the same study by the Minderoo Foundation, Saudi Aramco (which merged with SABIC in 2020), contributed 4.3 million metric tons of single-use plastic waste (Figure 4). SABIC claims to be "first petrochemical company in the world to scale-up high-quality processes for chemical recycling" (SABIC, 2023). SABIC has created a new program called TRUCIRCLE, which has products and services focused on achieving a circular economy. Some of these initiatives include resins produced from chemical recycling, bio-based feedstocks, and products with improved recyclability characteristics. SABIC claims that their circular products have the same properties and specifications as their primary products, so they are an "easy drop-in solution to current production processes" (SABIC, 2021). At the World Economic Forum in January 2023, SABIC announced their goal to produce 1 million metric tons of TRUCIRCLE products annually by 2030. While this is a step in the right direction, it is still a small percentage of SABIC's 58 million metric tons of annual plastics production. In SABIC's press releases and sustainability reports, they express a "long-term ambition to fully transition to feedstock recycling and to create a circular economy for plastics" (SABIC, 2023). While this is an admirable statement, it does not specify the end date of this "long-term" goal and is not backed by substantial and visible company action. Especially after being acquired by Saudi Aramco, the largest oil and gas company in the world, it is unlikely that SABIC will be transitioning away from fossil-fuel derived chemicals and plastics anytime soon.

Across most of the petrochemical industry, there is growing interest in producing recycled plastics, but it is marginal in comparison to their primary plastic production. In 2020, 98% of single-use plastics were produced from fossil fuel feedstocks (Minderoo Foundation, 2021). Industry analysts forecast plastic production to be the biggest growth market for oil demand over the next decade (International Energy Agency, 2020). However, there are some outliers in the petrochemical industry, including ten major companies pledging to have 20% of their plastics production sourced from recycled products by 2030 (Minderoo Foundation, 2021). For example, Indorama Ventures, a Thai petrochemicals company, produced 6% recycled polymer in 2021 and has committed to increasing its capacity to one-third recycled polymer by 2027. Along with Far Eastern New Century, the two companies represent 20% of global polyethylene terephthalate (PET) bottle recycling capacity (Minderoo Foundation, 2021). With the existing infrastructure, resources, and industry connections, petrochemical industries are best situated to pave the way for mechanical and chemical recycling as the world transitions to a circular economy.

Unfortunately, most companies have long-term recycling commitments that lack specificity or intermediate deadlines. Additionally, many projects are still in the research and development stage and might not be feasible in a large-scale operation. The companies that are implementing policies that support the economics of recycling are only in certain regions—Europe, the United States, and some parts of Asia—mostly due to more progressive policies and consumer demands in these markets. Outside of these regions, most companies do not have financial incentives to commit capital towards recycling projects that will deliver lower financial returns than primary polymer production.

With respect to recycling, most petrochemical companies have focused on chemical recycling initiatives, but this process has faced criticism in recent years. Critics have focused on its lack of large-scale viability, required energy inputs, and the associated emissions. While companies claim that chemically recycled products can undergo “repolymerization” into a new product, this process is expensive and technically challenging. In a process known as plastic-to-fuel, the products produced in chemical recycling can be converted into fuels such as diesel and kerosene and then burned like any other fossil fuel, further contributing to carbon emissions (Changing Markets Foundation, 2021). Compared to mechanical recycling, this requires larger energy inputs and thereby creates more greenhouse gas emissions. Along with greenhouse gas emissions, the process releases toxic chemicals, including carcinogens, so there is still uncertainty around the safety of this process. In the United States and Europe, petrochemical companies have lobbied to weaken environmental regulation around chemical recycling by classifying the facilities as manufacturing as opposed to waste-disposal facilities, or allowing fuels derived from plastics to be characterized as renewable energy (Changing Markets Foundation, 2021).

The Manufacturing Industry

The companies that manufacture plastic items have few incentives to change their raw material source. As previously mentioned, the use of most secondary plastics is not economically feasible as compared to primary plastics when the collecting, sorting, and processing costs are considered for secondary plastics. Additionally, increased primary plastic production will further drive down the price of primary plastics. However, some of the largest consumer goods companies, namely Unilever, Procter & Gamble (P&G), and Coca-Cola, have made commitments to reduce their primary plastic usage, among other goals.

For example, Unilever has pledged to halve their use of primary plastic in packaging by 2025 and to design all their products to be "fully reusable, recyclable or compostable" (Unilever, n.d.). Additionally, they are a founding member of Business Coalition for a Global Plastics Treaty, a group of 90 business and financial institutions pushing for an effective and legally binding UN treaty on plastic pollution. The treaty aims to reduce the production and use of primary plastic, improve plastic recycling efforts, and prevent plastic leakage into the environment (Business Coalition for a Global Plastics Treaty, n.d.). On their website, Unilever claims that "we must move away from this finite and linear approach to a restorative and regenerative 'circular' economy" (Unilever, n.d.).

In 2020, Unilever's CEO Alan Jope announced that Unilever would be phasing out the tiny plastic sachets used to sell single servings of shampoo, toothpaste, and other basics (Brock and Geddie, 2022). The sachets are popular in developing countries as the single servings can be sold easily in small shops and convenience stores. However, the sachets are not biodegradable and are almost impossible to mechanically recycle. Across the industry, 855 billion plastic sachets are sold every year, and Unilever is one of the largest manufacturers of this packaging (Brock and Geddie, 2022). In 2021, Sri Lanka implemented new regulations to phase out these sachets in an effort to curb plastic pollution on the island and placed a ban on sachets sized 20 mL or smaller. In response, Unilever side-stepped this by relabeling the package to indicate that the 6 mL sachets should not be sold individually (Brock and Geddie, 2022). After Sri Lankan officials threatened legal action, Unilever stopped selling the 6 mL packets, but millions of larger sachets are still being sold in Sri Lanka. According to a Reuters investigation, Unilever also lobbied against sachet bans in India and the Philippines over the past few years, leading to the proposed bans being dropped (Brock and Geddie, 2022).

Similar to the petrochemical companies producing primary plastic, there are few economic incentives for consumer goods companies to limit their plastic usage. For context, Unilever makes 58% of its revenue from emerging markets in developing countries (Brock and Geddie, 2022). Prior to the development of sachets in the 1980s, many stores in developing countries would measure out portions of soap and other basics to customers who would bring their own containers, a buying culture known as “tingi” in the Philippines. However, the development of sachets allowed big brands like Unilever to promote loyalty to their products. Unilever claims that these single-use sachets are necessary for lower-income customers, as they might not be able to afford a larger container of the product. Unfortunately, these customers end up spending more on the single-use sachets (per unit volume), as opposed to saving up for a larger container (Brock and Geddie, 2022). Therefore, having lower-income markets dependent on single-use products is more economically beneficial for consumer goods companies.

Between 2016 and 2018, an environmental nonprofit called Global Alliance for Incinerator Alternatives (GAIA) collected nearly 50,000 pieces of “non-recyclable” plastic from households in 15 areas across the Philippines, with the aim of identifying which companies generated this waste. Non-recyclable plastics include cling film, blister packaging, plastic-coated wrapping paper, composite plastic, and polycarbonate (SL Recycling, 2022). A third of the branded waste was from Nestle, Unilever, and Procter & Gamble, with Unilever listed as the second-largest polluter overall (GAIA, 2019).

One of Unilever’s biggest competitors, P&G, is committed to similarly lofty sustainability goals. In particular, P&G has pledged to make 100% of its packaging recyclable or reusable and reduce its use of primary plastic by 50% by 2030 (P&G, 2022). The company has already reduced packaging between 2010 and 2020, resulting in "a material avoidance of over 200,000 metric tons" (P&G, 2022). Along with Dow, P&G is also part of the Alliance to End Plastic Waste and has supported the use of the "How 2 Recycle" label to provide customers information about the recyclability of certain packaging. Additionally, they support a circular economy investment management firm called Circulate Capital. From 2020 to 2022, Circulate Capital invested $80 million in 14 companies working to prevent plastic leakage into the environment and advance a circular economy (Circulate Capital, n.d.). The management firm claims to have diverted over 100,000 metric tons of plastic leakage and predicts that they will prevent 10 million metric tons of plastic pollution by 2030 (Circulate Capital, n.d.). Circulate Capital is focused primarily on building infrastructure in Southeast Asia, where a lack of capital for waste management systems has been a barrier to addressing plastic leakage. P&G also supports other programs to improve the recycling of film and flexible packaging materials, which have historically been difficult to recycle (P&G, 2022).

While these goals are moving the company in a positive direction, P&G has been criticized for "changing the goalposts on its voluntary commitments" in the past (Changing Markets Foundation, 2021). For example, in 2010, the company made a commitment to replace 25% of its petroleum-based products with renewable materials by 2020. However, the company did not report any progress towards the target and changed the wording in their 2015 sustainability report to "create technologies by 2020 to substitute top petroleum-derived raw materials with renewable materials as cost and scale permit" (Changing Markets Foundation, 2021). P&G claimed to achieve this goal in 2018 but did not mention the original 2010 pledge. In their most recent report from 2022, P&G shared that currently 79% of their consumer packaging is designed to be reusable or recyclable, and there has been an 8% reduction of primary plastic in packaging from a 2017 baseline (P&G, 2022). The company has developed technology to improve the quality of recycled polypropylene plastic that is used in 20% of their packaging. In a process branded as VersoVita, imperfections are removed from the resin, and it is used again in P&G products (P&G, 2022). While this is a significant technological advancement, it may not be enough for the company to reduce their primary plastic use to 50% by 2030.

The food and beverage industry also contributes to the plastic crisis. In a 2021 brand audit conducted by Break Free From Plastic, Coca-Cola was listed as the top corporate plastic polluter. The study collected over 300,000 pieces of waste from 45 countries around the world and recorded the percentage of branded waste corresponding to each company. This is further reinforced by a brand audit published by the Bangladeshi Environment and Social Development Organization, which ranked Coca-Cola as the top polluter through a similar process of collecting branded single-use plastic waste (Break Free From Plastic, 2021). While Coca-Cola has pledged to collect and recycle one bottle or can for every bottle or can sold by 2030 (The Coca-Cola Company, n.d.), their packaging products are still very prevalent in the environment.

Additionally, Coca-Cola has a history of directly attempting to limit reuse of their products, specifically by lobbying against Deposit Return Systems (DRS) in Scotland. DRS allows large volumes of empty containers in clean waste streams to be collected for recycling or used in refill systems. Over 40 countries and states have implemented this system, allowing millions of people to return their cans and bottles. In the system, a retailer buys the product from the distributor and pays a deposit in addition to the product price. When a customer purchases the product, they pay a small deposit in addition to the price of the product. After using the product, the consumer is incentivized to return the container to the retailer, as their deposit is refunded. A system administrator, usually a non-profit organization or stakeholder in the industry, arranges for the containers to be recycled or refilled with the same product. The system is paid for by unredeemed deposits, sales of recyclable materials, and licensing fees paid by the consumer good companies. DRS is a highly cost-effective and reliable way to achieve a high collection rate of containers (Changing Markets Foundation, 2021). While it is currently utilized primarily in the beverage industry, it could also be expanded to the beauty and personal care sectors.

In 2017, Coca-Cola changed its opposition to DRS after weeks of negative press when a leaked internal document displayed plans to “fight back” against deposit systems in Europe. The document, which placed business impact and likelihood to materialize on either axis, positioned “EU scheme for deposit systems” at a high business impact which was likely to materialize (Changing Markets Foundation, 2021). Once again, the largest beverage and consumer goods companies are reluctant to invest in strategies to mitigate plastic pollution, as it poses a high cost to the company. A Greenpeace investigation also revealed years of quiet lobbying by Coca-Cola; the company spent close to $1 million lobbying the EU Commission and meeting with senior government officials to remove DRS from future policy considerations (McClenaghan, 2017).

Taken as a whole, the plastics industry has attempted to delay, distract, or derail the shift from primary plastics to more sustainable alternatives. As shown in the previous examples, many companies have made voluntary commitments to changing their production or manufacturing processes, but these goals are not enforced by legislative requirements. Corporations make commitments to their customers and shareholders, but they are also at liberty to change the scope or timeframe of their goals if they feel like the target will not be met. While this might result in negative publicity, it is unlikely to significantly impact their business performance. Additionally, data surrounding collection and recycling can be manipulated to give the impression that more products are being recycled than what is truly happening. For example, some numbers can include chemical recycling in their recycling quotas, even if the plastic is being used for fuel instead of being recycled back into a product. As shown in the examples with Unilever and Coca-Cola, the largest plastic manufacturers have made concerted efforts to delay legislation that will place specific restrictions or targets on their industries. The previous examples illuminate how many companies involved in the plastics industry have been hesitant to make changes in their operations.

Another tactic used by industry leaders has been to distract the public with clean-up solutions or by promoting the viability of recycling. Several companies, including P&G and Coca-Cola, have launched products made from recycled marine plastics (Changing Markets Foundation, 2021). While these initiatives provide great publicity for the brand, they fail to address the principal cause of the problem—ever-increasing primary plastic production. Most companies have committed to making 100% of their products recyclable, reusable, or compostable, but many materials cannot be recycled or composted at scale. Claiming that a product is “recyclable,” even if it has very low recycling rates, shifts the responsibility away from the manufacturer and onto the consumer and the waste management infrastructure. The plastics industry has also largely remained silent about the harms associated with upstream production and chemical recycling by using distraction tactics to promote the usefulness of plastics.

Through direct or indirect lobbying, the plastics industry has attempted to derail legislation that will restrict their plastic usage. While companies have directly lobbied politicians, others use indirect lobbying through seemingly independent recycling groups. For example, major supermarket chains in Austria, Spain, and the Czech Republic have pressured governments to limit plastic restrictions through the Green Dot organization, as the companies have influence within this organization (Changing Markets Foundation, 2021). The Green Dot organization places a symbol on products belonging to companies that have made a financial contribution towards recycling.

Plastic is undeniably an important material source—for example, it allows for safe food packaging and disposable items used in the medical field for hygiene purposes. However, corporations and consumers must be willing to dramatically shift their reliance on single-use plastic items. To truly transition towards a world without plastic pollution, corporations must be required to reveal the specifics of their plastic usage, significantly reduce that amount of plastic used in their products and change their product delivery to reuse and refill systems.

Chapter 3: The Politics of Plastics

Plastic production and manufacturing companies are heavily influenced by regional, national, and international legislation. While many companies have their own sustainability initiatives due to consumer or stakeholder pressures, industry changes also are heavily driven by policies and regulations. In this chapter, I will focus on the main policies within North America, Europe, and Asia because these regions are the top contributors to plastic pollution. While various policies have been introduced over the last two decades, some have been more successful than others. I will make note of which policies have been the most effective and suggest how they can be further adapted. Additionally, I will examine the UN's plastic pollution treaty and its impact on the future of plastic. While there has been an increasing number of public policy responses to plastic pollution over the last decade (Karasik et al., 2020), the problem will require international co-operation and a comprehensive global approach while considering the different waste management infrastructures in various regions.

North America

In North America, there has been some legislation to reduce plastic pollution over the past few decades. In 2006, Congress passed the Marine Debris Research, Prevention and Reduction Act, which authorized a program to "identify, determine sources of, assess, prevent, reduce, and remove marine debris" (NOAA Marine Debris Program, n.d.). Over the years, the act was amended to authorize cleanup for severe marine debris events like hurricanes or tsunamis, develop education strategies to address sources of marine debris, and enhance infrastructure to prevent marine debris (NOAA Marine Debris Program, n.d.). Additionally, the United States has taken measures to ban the use of microbeads in rinse-off applications and limit the distribution of single-use plastic items such as straws and shopping bags. In 2015 and 2016, the United States and Canada, respectively, passed legislation to ban plastic microbeads (defined as plastic beads less than 5 millimeters in size) that are used in toiletries (Karasik et al., 2020). While there is currently no national policy on single-use plastic, cities in California, New York, and Texas have placed bans on straws and plastic bags. For example, in 2018, a California bill banned restaurants from providing single-use straws to customers unless requested by the customer (Karasik et al., 2020). In 2020, New York banned plastic bags for most uses, but it has been criticized for its poor enforcement across stores in New York City (Kinniburgh, 2022). In Austin, the city banned single-use carry out bags in 2013, only allowing businesses to sell or provide reusable bags (Karasik et al., 2020). While these bans have been somewhat effective, they only address certain types of single-use plastics and are limited to specific states or cities. Additionally, they depend on enforcement from local agencies, which can be slow to respond to violations of the ban.

In 2021, the Break Free From Plastic Act was introduced to Congress by Senator Merkley from Oregon. The bill is designed to amend the Solid Waste Disposal Act by pausing new or expanded plastic production, reducing single-use plastics, and improving recycling rates (Break Free From Plastic, 2021). While this bill would be groundbreaking legislation to combat plastic pollution at multiple stages of its lifecycle, it has only been referred to the Committee on Finance, with no indication of when it might be passed (U.S. Congress, 2021).

North America, and the United Stated in particular, has disjointed policy regarding plastic pollution, with laws varying from state to state and city to city. To address this problem, the federal government must be willing to enact legislation that targets all aspects of the plastic lifecycle, particularly focusing on regulating the plastics production and manufacturing industry. This could include suspending or denying permits for new or expanded plastic production facilities, updating the Clean Air Act regulations for plastic facilities to reflect new standards, ending loan and guarantee financing programs that subsidize the petrochemical industry, and setting minimum recycled content standards for certain consumer goods (Break Free From Plastic, 2021).

Europe

Over the past decades, there has been an increase in regional policies in Europe that address plastic pollution and a shift in policies to define the problem in more complex terms, such as focusing on different types of plastic pollutants. Most of the policies focus on plastic waste management and prevention, recycling, and Extended Producer Responsibility (EPR) requirements. In 2004, the European Union (EU) issued a directive on packaging and plastic waste, calling for minimum recycling targets for different types of waste. The directive called for a 22.5% by weight recycling target for plastic by 2008 (Karasik et al., 2020). Currently, 32.5% of plastic waste in EU countries is recycled, with the goal of increasing this rate to 55% by 2030 (European Commission, 2022).

In late 2019, the EU presented the Green Deal, with the goal of transitioning the EU economy to a sustainable economic model and becoming a climate neutral continent by 2050. As part of the Green Deal, the EU has proposed a Circular Economy Action Plan (CEAP) which aims to transition Europe to a circular economy by 2050 (European Commission, 2022). The core themes in the CEAP include making sustainable products the norm, empowering consumers by providing transparency about the sustainability of products, improving the circularity of products in seven high-impact sectors, and ensuring less waste through recycling regulations and incentives (World Business Council for Sustainable Development, 2020). Specifically regarding plastics, the EU issued a Single-Use Plastics Directive that focuses on the ten most commonly found plastic items found on beaches: cotton bud sticks, cutlery, plates, straws and stirrers, balloons and sticks for balloons, food containers, cups for beverages, beverage containers, cigarette butts, plastic bags, packets and wrappers, wet wipes and sanitary items. From late 2021, the EU has been phasing in bans on plastic cotton bud sticks, cutlery, plates, straws, stirrers, balloon sticks, and polystyrene cups (OECD, 2022).

In November 2022, the European Commission proposed new rules on packaging, to ensure reusable packaging options, reduce unnecessary packaging, and provide clear labels to support recycling. They set out a goal to reduce packaging waste by 15% per Member State by 2040 and foster the reuse or refill of packaging (European Commission, 2022). Additionally, certain types of plastic packaging will be banned, including packaging for food when served inside a restaurant, miniature packaging for toiletries in hotels, and single-use packaging for fruits and vegetables. The measures aim to make packaging fully recyclable by 2030 by setting design criteria for packaging and creating mandatory deposit return systems for plastic bottles. Clear labels on packaging will help consumers determine which items can be recycled and how to properly dispose of biodegradable, biobased, and compostable plastics. To limit greenwashing, the products will indicate how long an item takes to biodegrade, how much biomass was used in the product, and if the product can be composted at home (European Commission, 2022). While these labeling options can be instructive, the products still must be designed and disposed of correctly to achieve environmental benefits.

While some of these initiatives have yet to be enacted into legislation, the EU has already placed some financial pressure on Member States with regard to their recycling rates. As of January 2021, each Member State must pay a uniform rate of €0.8 for each kilogram of plastic packaging waste that is not recycled, with a process in place to prevent less wealthy countries from contributing excessive amounts (European Commission, n.d.). While this fee intends to motivate national governments to prioritize recycling, it will require the collaboration of industry and recycling municipalities. In fact, a new study by the European Investment Bank found that an "investment gap of €6.7-8.6 billion must be closed to achieve Europe's pledged goal of placing on the EU market each year 10 million tons of plastic [recycled content] in final products by 2025" (European Investment Bank, 2023). The study provides policy recommendations to place restrictions on composite packaging (such as packaging made from plastic and paper), boosting public awareness campaigns, providing loans to municipalities, and providing funds to support research and innovation projects (European Investment Bank, 2023).

Even though the UK is no longer part of the EU, they have set their own ambitions to "end plastic pollution by 2040" (UK Government, 2021). In the UK, there is tax on packaging that contains less than 30% plastic, a ban on microbeads, and restrictions on single-use plastic items such as straws and drink stirrers. Additionally, through the Environment Act, the government plans to introduce DRS, place charges on single-use items, create more consistency in the recycling system, and better control the export of plastic waste (UK Government, 2021).

Compared to other regions, Europe has made the most strides towards limiting plastic pollution, improving recycling rates, and setting ambitious goals for the future of plastic products. This is largely due to the majority of Europe being part of the EU, which has legislative power over the Member States and can enact regulations. Even with the UK's exit from the EU, they have introduced their own policies to mitigate plastic pollution. However, to meet these goals, there must be strict enforcement of the regulations and transparency from industry. A recent study found that, overall, European supermarket retailers have minimal transparency about their plastic footprint, low ambition to reduce plastic packaging, and lack support for government policies such as DRS and mandatory reuse targets (Changing Markets Foundation, 2021). While the most recent proposals by the European Commission are a step in the right direction, they still require approval by the European Parliament and EU governments to become law. When this new legislation takes effect, careful monitoring of industry will be required to ensure that the ambitious targets are met.

Asia

Of the world's top 20 countries contributing to marine debris, eight are from Asia—China, Indonesia, the Philippines, Vietnam, Sri Lanka, Thailand, Malaysia, and India (Akenji et al., 2020). As this region is experiencing rapid economic growth and development, there is also a large increase in their consumption of single-use plastics. While many of these countries face challenges with their waste management infrastructure, they are developing policies in response to the growing plastics problem. In general, most of these policies are focused on downstream solutions such as recycling and waste management as opposed to upstream changes in business patterns, product design, and consumer behavior.

As one of the world's largest generators of plastic waste, China has ramped up their policies to reduce plastic pollution. In 2021, the National Development and Reform Commission (NDRC), China's central economic planner, released a five-year plan to phase out single-use plastics, improve recycling, and promote alternatives to plastic (Xue, 2021). Part of the plan includes a plastic ban which prohibits restaurants and hotels from providing single-use plastic items and stores from providing plastic shopping bags. Also, the sale of products containing microbeads was banned at the end of 2022 (U.S. Department of State, 2022). Additionally, the country aims to have at least 10 million reusable boxes in circulation for express deliveries by 2025. The policies will be enforced by fines, which could reach up to approximately $15,000 for those failing to comply with the restrictions (U.S. Department of State, 2022).

In Southeast Asia, the Philippines and Indonesia are large contributors to marine plastic waste. While these countries have several policies in place, there is a shortage of data regarding plastic consumption and the effectiveness of recycling operations. In 2001, the Philippines enacted the Ecological Solid Waste Management Act, which is still the main basis for plastic waste management in the country. The main components include universal waste collection services at the local level, regular waste characterization, and a shift from dumpsites to controlled landfill disposal as the main mode of waste treatment. While this law focuses almost exclusively on establishing basic waste management practices, only 36% of local government units were in compliance with all of the terms by 2016 (Akenji et al., 2020). However, at the local level, city governments have issued regulations to reduce the use of single-use plastic items, and there is an informal network of plastic bottle recycling in urban areas (Akenji et al., 2020).

In June of 2107, Indonesia launched the National Action Plan on Marine Debris, which included the target to reduce 70% of marine plastic debris (from a 2017 baseline) by 2025. The country has also pledged $1 billion towards projects to clean its rivers and seas from waste and placed a tax on single-use plastic bags in 2020 (OECD, 2018). The national government has shown a commitment to tackle the plastics issue, but most local governments do not meet their responsibilities for waste management. Additionally, most recycling is based in the informal sector, so local governments are struggling to establish a formal recycling system.

While the Philippines and Indonesia have made progress towards plastic waste management, many of the policies are not being adequately translated into practice because there is a disconnect between the national and local governments. Without adequate skills and knowledge about waste management at the local level and centralized data on waste generation, it will be difficult for these countries to make strides towards achieving their sustainability ambitions (Akenji et al., 2020).

India has recently taken steps to mitigate the environmental impact of plastic. In July 2022, a ban on most single-use plastics went into effect (Goel, 2021). While this is an important first step, the government needs to address issues such as promoting the use of plastic alternatives, strengthening recycling infrastructure, and improving waste segregation. Similar to other countries in Asia, most of the recycling is in the informal sector. Independent waste-pickers collect plastic waste from landfills or in the environment and sell the plastic to recycling centers or plastic manufacturers for a fee. Unfortunately, much of the plastic is downcycled, where high quality plastic is turned into a new plastic of lower quality, reducing the life of the plastic (Goel, 2021). India also launched EPR guidelines in 2022, which outlines responsibilities for all of the stakeholders in the plastics industry and includes fines for violations. However, many companies have failed to register for the centralized data tracking system that will track their progress towards EPR targets and the average weight of plastic manufactured, imported or purchased (Deshpande, 2022).

On a regional level, the 10-member Association of Southeast Asian Nations (ASEAN) has taken steps over the past decade to address plastic pollution in the ocean. Most recently, at the 34th ASEAN Summit, the countries vowed to "strengthen actions at the national level as well as through collaborative actions...to prevent and significantly reduce marine debris" (Tanakasempipat and Wongcha-um, 2019). In 2021, ASEAN launched a Regional Action Plan focused on reducing primary plastic inputs, minimizing leakage into the environment, and creating value for recycled waste (World Bank, 2021). However, critics contended that implementation of this action plan will be difficult, as the member countries have a code of non-interference so each nation will be required to make its own policies (Tanakasempipat and Wongcha-um, 2019).

In general, Asia has increased their policies to address plastic pollution and improved waste management capacity. However, many of the responses are voluntary initiatives through public and private partnerships or lack the proper monitoring system to enforce regulations (such as single-use plastic bans or EPR initiatives). To start, countries must improve their monitoring system to better understand the flows of plastic in both the formal and informal sectors and raise public awareness on plastic pollution issues. From a policy perspective, many countries would benefit from establishing partnerships between the formal and informal waste management sectors, reducing knowledge gaps between national and local authorities, and focusing on upstream engagement with producers and consumers along with downstream solutions (Akenji et al., 2020).

International Policy

In 2022, the United Nations Environment Assembly (UNEA) approved the resolution titled "End Plastic Pollution: Towards an international legally binding instrument." The UNEA is the world's decision-making body on environmental issues and is composed of all 193 Member States in the UN. The agreement must be ready for ratification by 2024, after the details are established by an intergovernmental negotiating committee. It will be similar to the Paris Agreement on climate change in structure and intent, with the broad aims of promoting sustainable plastic production and consumption, encouraging cooperation between relevant regional and international parties, and specifying arrangement for technological and financial assistance among countries (Filho et al., 2022). While this agreement cannot be enforced until it is approved and endorsed by Member States, the Resolution was unanimously endorsed by 175 of the UN's member states, solidifying the world's commitment to ending plastic pollution (Filho et al., 2022).

Each region of the world has different policies regulating the production, manufacturing, and disposal of their waste. The policies vary depending on their enforcement capabilities and existing infrastructure. For example, in Europe, there is a large focus on regulating upstream production by requiring that products are designed to be reusable or made of a certain percentage of recycled content. In contrast, in Southeast Asia, there are more efforts to regulate downstream issues by improving basic waste management capabilities and placing bans or taxes on single-use items. The UNEA Resolution marks the first global commitment to address plastic pollution, but it will require careful consideration of the existing political, economic, and social structures in each region of the world and strategies to maximize impact based on the capabilities of each country.

Chapter 4: Promising Scientific Innovations

As the plastics problem has continued to grow, the scientific community has responded with various remediation technologies for plastic pollution. In this chapter, I will focus on three types of plastic remediation technologies: physical elimination, chemical degradation, and biodegradation. While these technologies are promising, they face challenges that have prevented them from being scaled up to larger operations. Some of these challenges include high operating costs, large energy inputs, and low process efficiencies. Even though these technologies have been proven in a laboratory setting, they have not been widely implemented within industry. I will evaluate specific examples of these remediation technologies and provide recommendations for problems that need to be addressed before the technology can become a viable solution.

Physical Elimination

There are various technologies that address the removal of plastics already existing in the environment. Plastic that does not make it to a landfill often makes its way into rivers and eventually reaches the ocean. To address marine waste, a Dutch start-up launched the Great Bubble Barrier in 2018. Fitting its name, the technology is a barrier of bubbles that redirects plastic in rivers or canals so that it does not reach the ocean. A tube filled with holes is placed at the bottom of the riverbed and high-pressure air is pumped through the tube, creating a curtain of bubbles that rise to the surface. Ships and aquatic life can pass through the bubbles, but plastic is redirected to the side of the riverbed for collection (Rushe, 2018). Based on their pilot data, the barrier catches 86% of plastic waste in the water (The Great Bubble Barrier, n.d.). While the technology has only been implemented in Europe, the team has plans to expand their operations to rivers in Asia to address some of the most polluted rivers in the world (Rushe, 2018).

A non-profit known as The Ocean Cleanup is working to eliminate plastic waste that is already in the ocean, with the aim to remove 90% of floating ocean plastic (The Ocean Cleanup, 2023). The technology is a 600-meter tapered mesh pulled by boats to form a U-shaped barrier. By maneuvering the boats at a relative speed difference to the plastic, the waste is guided towards a retention zone where it is extracted. The collected plastic is then returned to land where it is recycled (The Ocean Cleanup, 2023). In 2020, the non-profit removed 103 tons of plastic waste from the ocean (Ji et al., 2022). These novel technologies are working towards removing existing waste in the environment and are promising solutions for the future. However, if plastic production continues to grow, these remediation technologies will need to scale-up quickly to meet the demand of discarded waste. Given that this technology is not currently widespread, we must incorporate other technological solutions to address plastic pollution.

Chemical Degradation

As mentioned in previous chapters, chemical degradation, also known as advanced recycling, breaks down plastics into single units known as monomers. The recycled plastic can be used to make primary plastic or as a fuel source. Unlike mechanical recycling, chemical recycling enables the removal of hazardous substances and ensures that legacy substances such as dioxin are not transferred to new products (Qureshi et al., 2020). The two main categories of chemical degradation are thermal degradation and oxidation degradation. In a thermal process called pyrolysis, the plastic is heated to high temperatures in low-oxygen conditions. Depending on the operating conditions, the product of pyrolysis is a liquid or wax that can be refined into chemicals or fuels (Qureshi et al., 2020). Another form of thermal degradation is gasification, which uses high temperatures combined with air or steam to degrade plastic into a gas called "synthesis gas." The resulting gas can be processed into fuels or chemicals (Qureshi et al., 2020).

In 2022, researchers at the University of Texas at Austin published groundbreaking research to address plastic pollution through enzymatic degradation. Their research demonstrates the potential for the degradation and resynthesis of polyethylene terephthalate (PET), which currently accounts for 12% of solid global waste (Lu et al., 2022). Enzymatic depolymerization involves using enzymes to break the bonds in PET down to its molecular form. Unlike previous research in this area, the team demonstrated that the process could be performed at lower temperatures (less than 50 °C), which makes the technology more promising for large scale applications (Lu et al., 2022). Additionally, the researchers repolymerized (combined the molecules back together) the degraded PET and created primary-like PET with 97% purity (Lu et al., 2022). The entire process of depolymerization and repolymerization of PET only took a few days, demonstrating the promising applications for this technology within industry. Thus, technology is available to support a circular plastics economy, but companies must invest in the scaled-up design and implementation of these processes.

Biodegradation

Biodegradation is the process by which microorganisms break down chemicals. In the case of the plastics industry, some companies are creating bioplastics that more easily biodegrade than traditional plastic. The term bioplastics can refer to plastics derived from biological sources (such as plants or microorganisms) or petroleum-based plastics that can be biodegraded. However, even if bioplastics are made from natural sources, they are not necessarily biodegradable or compostable. For example, Bio-polyethylene terephthalate (Bio-PET) is neither biodegradable nor compostable, but it is considered a bioplastic because it originates from plant material as opposed to fossil fuels (Ortiz, 2023). Bioplastics are marketed to be more environmentally friendly as their production releases significantly fewer greenhouse gas emissions, but some experts argue that they result in more pollutants due to the agricultural and chemical processing involved (Cho, 2017). Bioplastics that can be degraded often require high temperature industrial composting facilities to properly break down the plastic, and few cities have sufficient infrastructure. Additionally, if bioplastics are not discarded properly, they can contaminate normal plastic recycling streams, which can result in an entire lot reaching the landfill (Cho, 2017). Although bioplastics offer some promising solutions, there also needs to be investment in the proper infrastructure to biodegrade these materials.

In an effort to provide alternatives to plastic packaging, a company called Ecovative has released a line of packaging made from hemp hurd, a byproduct of the fiber hemp industry, and mycelium, which is a network of fungal threads. The product, named "Mushroom Packaging" is unique in that it can be composted at home in around 45 days (Ecovative, n.d.). The user simply needs to break up the packaging into smaller pieces and distribute it in garden soil or a compost bin, where moisture and microorganisms will decompose the packaging. This technology is an example of a circular product, as the material is derived from biological sources and returned to the natural environment after the product has been utilized. While it is unlikely that this material will become a substitute for plastic, it demonstrates an innovative way to use biological products for packaging purposes.

Most scientific research to remediate plastic pollution is focused on end-of-life solutions, through physical, chemical, or biological elimination or transformation technologies. Although these technologies are encouraging, they must be economically viable and commercially scalable to compete with the primary plastics market. Additionally, if alternative materials are to replace primary plastic, there must be proper infrastructure in place to ensure that the product can be properly recycled or degraded. In developing countries where basic waste management infrastructure is lacking, this would not likely be feasible, so these technologies should be focused in economic markets that can support proper disposal.

Chapter 5: Viability of a Circular Economy Solution

In recent years, there has been increased interest in the idea of a circular economy for the plastics industry. While the term "circular economy" can be applied to many different products, I will be discussing specifically how this concept can be applied to plastic products. One of the main voices in this conversation is the Ellen MacArthur Foundation, which launched a report on the business and economic benefits of a circular economy in early 2012 (McKinsey & Company, 2012). The report outlined a shift from a "take-make-waste" linear economy to a circular economy, where products and materials can be regenerated at their end of life into a new product. A circular model is regenerative by design, so it aims to keep materials at their highest value and utility through all stages of its lifecycle. While the circular economic model certainly has its advantages, it must overcome some limitations to be a feasible solution to plastic pollution. To be implemented successfully, circular economy solutions must account for geography, receive the support of industry, and be accompanied by an increase in awareness about the benefits of this system.

Linear to Circular Economy

Since the Industrial Revolution, most industries have developed under a linear economic model. Global Gross Domestic Product (GDP) grew twenty times from 1900 to 2000, allowing for more availability of consumer goods at increasingly lower costs (McKinsey & Company, 2012). In this system, resources are extracted for production and consumption with no plans to re-use or re-purpose any of the materials. The linear economy is extremely material- and energy-intensive because each product is being created from a raw material source; in the case of plastics, the raw material is fossil fuels. As the world becomes more interconnected, linear economies rely on complex global supply chains that serve to benefit one group: the consumer. As more countries increase their GDP, more people have the economic resources to participate in the consumer market. However, the disposal and/or recycling infrastructure has not increased along with these increased rates of consumption. While the linear economy resulted in large profits gains in the past, modern manufacturing processes have reached a stagnation in efficiency. Experts contend that competitive advantage and increased profits can be achieved if companies invest in a circular economy business model (McKinsey & Company, 2012). Below, a diagram depicting ways to transition from a linear to circular economic model is shown.

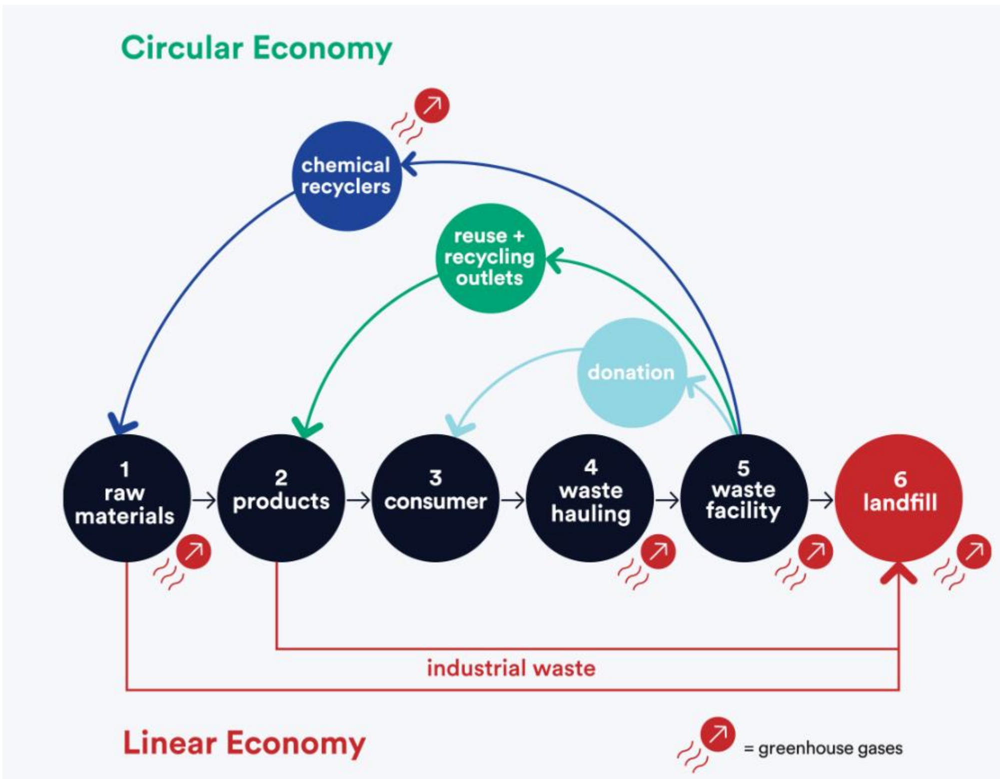

Figure 5: The transition from a linear to circular economic model (Recycle Track Systems, n.d.)

For durable goods, there have already been examples of businesses transitioning to a circular economy. For example, in the automobile industry, Renault launched Europe's first circular economy factory for vehicles in 2020. At the factory, they remanufacture vehicle components and create a second life for batteries to be used again in new vehicles (Renault Group, 2020). The remanufactured parts are 40 % less expensive than brand new parts and retain the same quality (McKinsey & Company, 2012). For single-use plastic goods, the transition to a circular economy has more complexities, yet it promises economic incentives. The Ellen MacArthur Foundation performed a product-level analysis on industries that represent 80% of the total consumer goods market—food, beverages, textiles, and packaging—and predicted $700 billion per annum in material savings if these industries invested in circular economy solutions (McKinsey & Company, 2012). As environmental regulations tighten, materials become scarcer, and consumers begin to value sustainable products, it will benefit businesses to shift towards a circular economy model.

Case Study: Interface Carpet Tiles

Interface, the world's largest manufacturer of carpet tiles, has demonstrated the business success of a circular economy company. Since 1994, the company has transitioned its operations to a circular model, where waste is used as the material source for the new product. In the past 15 years, this has resulted in $400 million in savings for the company (Australian Circular Economy Hub, 2022). The billion-dollar corporation uses discarded fishing nets from the Philippines and Cameroon to construct nylon yarn for its carpet tiles. Discarded fishing nets are responsible for 10% of marine litter, so this business strategy serves to re-purpose existing waste into a usable product (Khoo et al., 2021). Lifecycle analyses on nylon yarn estimate that 68% of the environmental impact is created at the raw materials stage, when the raw materials are extracted and processed. By using discarded nylon as its material source, the company is eliminating the need for extracting raw materials (Khoo et al., 2021).

Additionally, Interface has a "ReEntry" program that takes back old carpet tiles and repurposes them into new tiles so that none of their products reach a landfill. Customers can return their carpet tiles to Interface at little to no cost, which helps the customer lower their environmental footprint and save money on disposal fees (Interface, n.d.). Since 1996, the company has reduced the embodied carbon footprint of its carpet tile by 74% and demonstrated the economic feasibility of a circular economy business model (Australian Circular Economy Hub, n.d.).

Strategies for Circularity

While companies such as Interface have developed a circular economy model, it is important for companies to choose a strategy that aligns with their capabilities and resources. Specifically, plastic manufacturing companies can develop circular economy business models using a combination of three basic strategies: retain product ownership (RPO), product life extension (PLE), or design for recycling (DFR) (Atasu et al., 2021). Depending on the specific product, companies may use a combination of these strategies to transform their business models.

RPO is a strategy in which the producer is responsible for the products after the consumer has finished using them. In the classic version of this model, durable items, such as appliances or clothing can be rented by the customer and the company is responsible for maintaining the items. In the plastics industry, RPO could take the form of EPR by shifting the responsibility of end-of-life waste management from municipalities to the producers of the product. This system aims to create shared physical or financial responsibility for waste management and provides incentives for manufacturers to design resource efficient products (Plastic Smart Cities, n.d.). In developing countries, this system could help improve waste management infrastructure, as many of these countries are struggling to cover the costs associated with proper waste collection, sorting, and recycling. EPR programs are often implemented by governments with a set of regulations. Some have mandatory targets for collection, recycling, and post-consumer recycled content with penalties for not meeting these specifications, while others have non-binding targets but legal requirements for brands to report their mitigation performance (Plastic Smart Cities, n.d.). While this will not fully transition companies to a circular model, EPR is a first step as it requires producers to be responsible for the end-life of their products and incentivizes the design of products for recyclability or reuse.

PLE strategies aim to extend how long a product can be used for, with the goal of maximizing the products' utilization duration. In the plastics industry, PLE is especially relevant for product packaging. Most plastic packaging is created to safely store products until they are bought by the consumer but are discarded after the consumer uses the product. If the packaging is made with certain types of flexible plastic or is combined with another material such as paper or aluminum, it can be especially difficult to recycle. However, if packaging products could be designed to last for more than one use, this could significantly transform the consumer goods industry into a more circular model. Systems such as DRS, which relies on durable packaging that can be reused, will potentially benefit the company as it could discourage customers from switching to a rival brand.

While DRS has mostly been implemented in the beverage industry, a group of consumer goods companies have tested this re-use model through a partnership with TerraCycle. In the UK, customers at select Tesco grocery stores can purchase products from brands such as Heinz and Quaker packaged in refillable containers. The product prices are slightly higher to include a deposit that incentivizes the customer to return the packaging. After using the product, customers can drop off the empty container at a return point inside the store, and they are refunded their deposit through an app. The empty packaging is collected, professionally cleaned, and refilled to be sold again in the store. In the United States, a similar system has been established for household products to be delivered in refillable packaging through Walmart's home delivery program, but the service is only currently offered in Northwest Arkansas (Loop, n.d.). If more companies invested in re-use models, especially for household items such as non-perishable pantry goods, cleaning supplies, or cosmetics, this could result in large reductions in single-use plastic packaging waste.

The third strategy for circularity, DFR, involves designing products to maximize the recoverability of the materials to be used in new products. To transition towards circular economy thinking, producers must carefully consider the design of their products and how the product or packaging can be recycled, repurposed, or re-used at its end-of-life. Material science and selection will play a key role in product design as manufacturers consider the purpose and performance of the end-product. Products can be designed with only one material so that they can be easily recycled, made more from durable materials so that they can be re-used, or be created from biodegradable materials so that they can be returned to the natural environment.

There are several resources that can help producers transform their product designs. To ensure a product is recyclable, The Association of Plastic Recyclers (APR) has a Design Guide to help plastic designers "measure each aspect of a package design against industry-accepted criteria to ensure that it is truly recycling compatible." (Association of Plastic Recyclers, 2022). The content of the guide is regularly updated to reflect the recycling technology and infrastructure currently available in North America. However, the APR notes that although some products may be compatible with a recycling stream in terms of physical or chemical properties, there must also be sufficient collection systems and recycling markets. Additionally, the Ellen MacArthur Foundation and design studio IDEO have also created a Circular Design Guide that aims to "help innovators create more elegant, effective, creative solutions for the circular economy" (Ellen MacArthur Foundation, 2022). The guide provides educational resources to help designers better understand circular economy principles, provides examples of companies implementing circular economy solutions, and provides access to a network of circular design practitioners. Designing products for circularity will require a fundamental shift in research and development initiatives within industry, establishing systems to support recyclability and reuse, and a change in consumer behavior to limit reliance on single-use items.

Using these three strategies, companies can begin the shift towards a circular economy model. Although there may be initially higher manufacturing costs, the circular economy model has proven to be profitable in many cases as there is an elimination of raw material costs. If there is adequate consumer pressure, government incentives, and economically viable technology, industries can begin transitioning from linear to circular production methods. These different entities must be working in conjunction with one another to support the transition to a more sustainable economic model, or we will continue to face the consequences of plastic pollution into the future.

Conclusion

As demonstrated throughout this thesis, the plastics pollution problem is complex and there is no simple solution. We are producing more plastic year after year, and the waste management infrastructure is incapable of handling the increasing volume of waste. While many people believe that plastic items are recycled, most waste is returned to a landfill, incinerated, or makes its way into the natural environment. This has detrimental effects on the environment; people, animals, and ecosystems are disrupted by the emissions created during the production process, toxic chemicals released during incineration, and the prevalence of plastics that end up in the ocean. Especially in developing countries that are struggling with basic waste management infrastructure, increasing recycling capabilities is not a reasonable solution.

From an economic perspective, both the producers of plastic and manufacturers of plastic products benefit from a fast-paced consumer economy. Single-use plastic products can be made cheaply from primary plastic and sold for a large profit margin to the consumer. After using the product, the consumer disposes of it and needs to buy a new item, which further perpetuates this cycle. While the plastics industry creates products that are essential to our everyday lives, there must be a shift in consumer behavior and industry strategy to extend the utility of plastic items. This could include eliminating most single-use plastic items, expanding DRS programs, and increasing the use of secondary plastic or alternative materials in manufactured products.

Meaningful solutions to the plastic pollution problem will require significant government intervention. Depending on the country and their existing waste management infrastructure, policy will vary. Among the developed world, the European Union is leading in efforts to reduce plastic pollution by setting ambitious goals for reducing packaging waste, imposing penalties for not meeting recycling targets, and incentivizing research and development for new technologies. In developing countries, there should be a focus on working with local communities and the informal recycling sector to improve waste management and limit the amount of plastic that leaks into the environment. On a global scale, the UN resolution is a promising step in the right direction. Although it still requires ratification and eventual enforcement strategies, it demonstrates the commitment of the international community to work together towards ending plastic pollution.

As technology becomes more advanced, researchers are proposing solutions to address plastic pollution. Most of these technologies are focused on mitigating the impacts of plastic waste at its end of life through various physical, chemical, and biological elimination methods. While these projects are groundbreaking, they will require the financial support of governments or industry to be feasible on a larger scale. As a result, they will likely be focused within economies that can support the scale-up of these technologies. Nevertheless, these technologies will be essential to mitigate the environmental impacts of plastic waste as the global economy moves towards a circular model.

Through an integration of industry, government and scientific research, the circular economy can be a viable solution to the plastics pollution problem. If implemented correctly, it can help the environment, the economy, and consumers. Through studies evaluating the business rationale for transitioning to a circular economy, experts have found that a circular economy will decrease carbon emissions, result in substantial new material cost savings, allow for greater security in supply, and lower prices for customers (Ellen MacArthur Foundation, n.d.). However, there are some limitations to the system that need to be addressed before widespread implementation of a circular economy model will be possible. From my research, there is little discussion of how the circular economy will be implemented on an international scale. Transitioning to a circular economy will require international regulation and standardization, but the implementation of these policies will differ from country-to-country. Additionally, there must be voluntary, incentivized, or regulated buy-in from industry to shift their business models. Finally, there is a need for increased awareness by all stakeholders in the plastics industry (politicians, industry leaders, scientists, and consumers) about the benefits of a circular economy solution.

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Biography

Jillian Merritt is studying Chemical Engineering and Plan II Honors at the University of Texas at Austin. This summer, she is interning at Procter & Gamble (Gillette) in Boston in their Research & Development Next Generation Sustainability group. She has plans to study abroad in Madrid, Spain in Fall 2023 where she will take Spanish and engineering classes. Jillian has plans to work in the sustainability realm after graduating in May 2024.