CHALLENGES AND OPPORTUNITIES IN THE PLASTICS INDUSTRY

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Introduction

Plastics are ubiquitous and, because of their low cost, versatility, and many physical properties, ideal materials for everything from food packaging to automotive parts and building materials. However, the paradox of plastics is that their most useful material attributes—durability, lightness, ease of manufacturing, and chemical diversity—are directly related to their lack of sustainability:

- Durability leads to persistence in the environment over hundreds of years.
- Ease of manufacturing, inexpensive feedstocks, and the light weight of the end product encourage the production of disposable, single-use products.
- Chemical diversity and amenability to modification by additives translate into a need for multiple recycling methods and require multiple recycling methods and sorting the materials ahead of time.

Consumers utilize many plastic products daily, but the convenience of single-use, disposable plastics comes with a heavy sustainability burden that we are only now beginning to address.

Fortunately, there is a growing multi-sector commitment to a circular economy, including the increasing use of tools, like life cycle assessment (LCA), to guide decision-making and policy generation, as well as strong consumer demand for sustainable plastics and packaging. Public and private investment in new materials and processes is beginning to yield innovations that will help us eliminate plastic waste within the next decade.

Sustainability challenges

While the debate around the sustainability of plastics is long-standing, there is new data on the scale and scope of the problem, which has led to a growing sense of urgency to address these issues. This report offers the most recent data and understanding of plastic's sustainability challenges.

Nearly 400 million tons of plastic are produced each year,[1] with a cumulative production of over 8 billion metric tons since plastics were introduced to the marketplace.[2] However, only 9% of all plastics produced have been recycled, while another 12% have been incinerated.

The remainder, a whopping 79% of all plastics produced, has accumulated in landfills or escaped into the natural environment (Figure 1). Even in countries with advanced waste management infrastructure, plastic recycling rates rarely exceed 35%.[3] The projected cumulative plastic waste is expected to grow to 26 billion metric tons by 2050, with a devastating impact on the "triple planetary crisis" of climate change, biodiversity loss,[4] and pollution.[5]

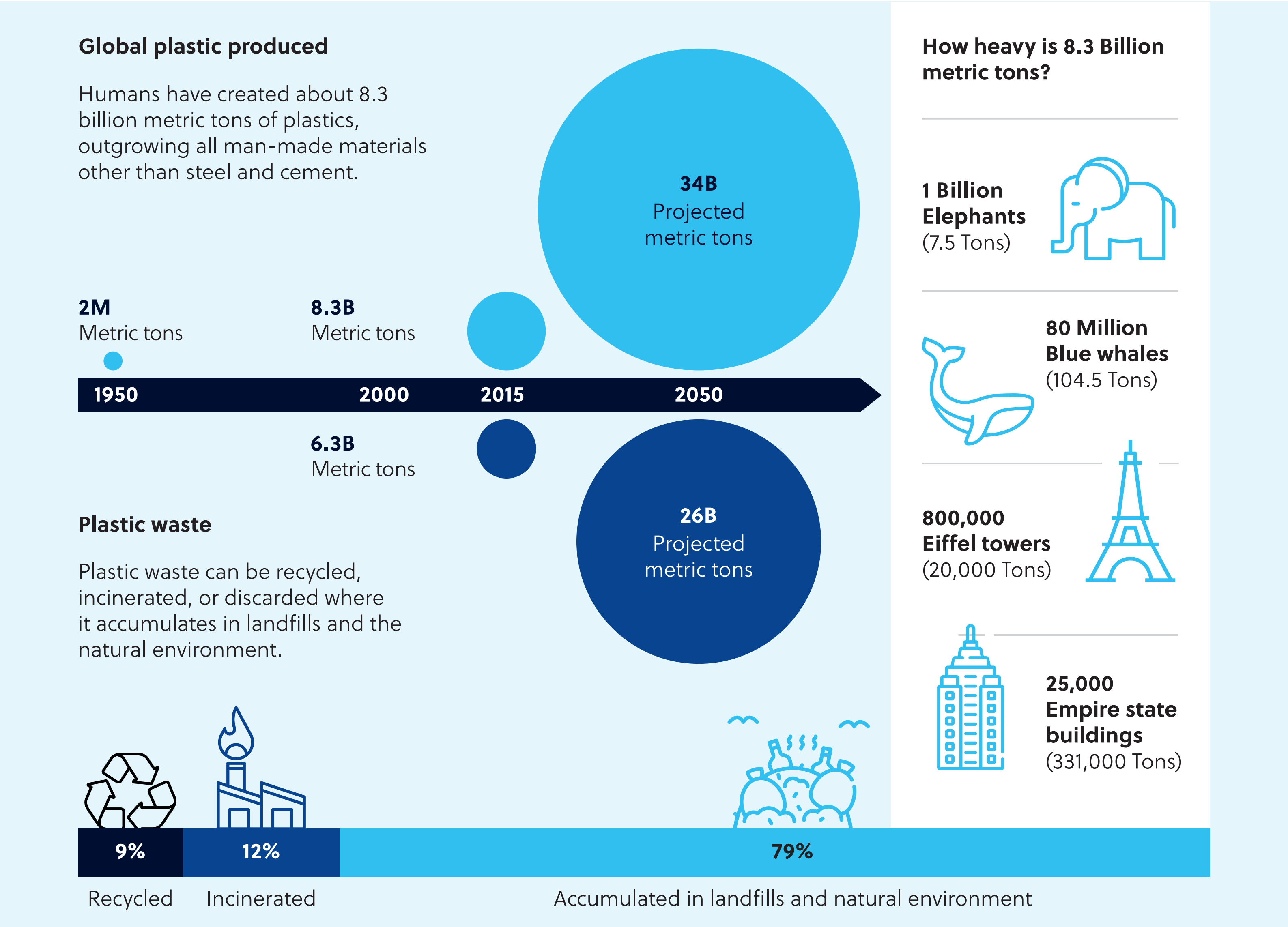


Figure 1. A comprehensive analysis of global plastic production and the fate of plastic waste.

Data source: (7) Geyer R, Jambeck JR, Law KL. Production, use, and fate of all plastics ever made. Sci Adv. 2017;3(7):e1700782. doi:10.1126/sciadv.1700782
Graphic source: (6) Reckoning with the U.S. Role in Global Ocean Plastic Waste. National Academies Press; 2022. doi:10.17226/26132

Environmental fate of plastics

Due to their strong molecular bonds, plastics can persist in the environment for centuries. A study found that the half-life of high density polyethylene (HDPE) ranged from 58 years for bottles to 1,200 years for pipes.[6] Every year, an estimated 14 million tons of plastic waste ends up in the oceans.[7] If current trends continue, there could be more plastic than fish (by weight) in the ocean by 2050.[8]

In recent years, we've seen shocking images of beaches and rivers choked with plastic bottles and bags, but plastic pollution is not just unsightly, it is lethal to wildlife who ingest it or become entangled in plastic debris. Plastic pollution is driving biodiversity loss and habitat destruction, particularly in developing countries that don't have the infrastructure to manage the volume and complexity of these waste streams.

Microplastics are everywhere

Microplastics – tiny particles from 10 nm to 5 mm caused by the breakdown of plastics – are a growing concern.[9] Microplastics have been found everywhere, from Antarctica[10] to the Arctic[11–13] and from the depths of the Mariana Trench[14] to the pristine summit of Mt. Everest.[15] They have been found in rain[16] and the air,[17] carried by the hydrologic cycle and winds to every place on earth. In the ocean, they are ingested by marine life and concentrated in the food chain.

While we might think that the natural environment is "out there" and separate from our bodies, the reality is that the environment is inside of us due to the water, food, and air that we ingest or breathe. It is estimated that a person consumes from 0.1 to 5 grams of plastic every week,[18] or 74,000 to 211,000 microplastic particles per year,[19] which amounts to 40 pounds of plastic ingested and inhaled over a lifetime.[20,21]

Within the past year, microplastics were found for the first time in the blood and lower lung tissue of living humans. Other recent studies have found microplastics in the feces of newborn infants[22] and adults,[23] as well as the liver[24] and placental tissue.[25] The emerging human health impacts of microplastics are far from understood, but there is cause for concern. Preliminary studies have found correlations with cytotoxicity, inflammatory response, oxidative stress and cell barrier behavior,[26] inflammatory bowel disease (IBD),[27] and carcinogenicity.[28]

Climate impact of plastics production and recycling

Plastics are a significant contributor to climate change, as every step of the plastics lifecycle, from the extraction of raw materials to getting the finished product to the consumer, generates greenhouse gases (GHGs). Emissions due to plastics production are projected to reach 2.1 gigatons of carbon dioxide equivalent ($GtCO_2e$), or 19% of the global carbon budget by 2040.[29] Moreover, plastics that end up in the environment or landfill release GHGs as they break down. A recent study found that common plastics emit methane and ethylene when exposed to sunlight and that these emissions increase over time and continue even in dark conditions.[30]

Because our economy operates on a linear cradle-to-grave model and most plastics are designed for single use, it will take both political will and technological innovation to reduce these "locked-in" plastics-related GHG emissions.[31]

Better sorting and recycling systems are desperately needed

A recent *Atlantic* article argued that plastic recycling doesn't work and it never will.[32] The authors suggest that policies such as banning single-use plastics, plastic bags, and difficult-to-recycle plastics will have a greater impact than trying to improve recycling rates. Though they admit it's not because consumers aren't doing their part, paper recycling rates are as high as 68%. The difference is that the thousands of different types of plastics compositions and additives can't be recycled together, creating an impossible sorting problem that results in most plastics being landfilled. Recycling processes themselves are costly, energy-intensive, and generate GHGs. As long as oil prices remain low, it will be cheaper to make new, disposable plastic products instead of recycling.

Life cycle assessment can guide decision-making

Life cycle assessment (LCA) can be a powerful tool for evaluating environmental impacts associated with a product's life from cradle to grave, helping guide business, investment, and policy decisions towards less harmful materials and processes. However, *caveat emptor* applied to LCA studies would caution decision-makers to take a closer look at the system's boundary conditions, impact metrics, and end-of-life assumptions. Otherwise, there is a risk of making decisions based on incomplete or even misleading information.

LCA is an evolving approach, and studies from even a few years ago may be misleading due to inconsistent application of the methodology,[33] variable system boundaries,[34] omitting externalities such as human health impacts and microplastics,[35] end-of-life fate,[36] or excluding critical information due to knowledge gaps.

Like statistics, LCAs can be manipulated to draw a range of conclusions that support any number of narratives. For instance, many LCA studies claim that plastic packaging has a lower environmental impact than other materials, such as glass, metals, or paper.[37,38] When you look deeper, you'll find that these LCAs are misleading because they either assume that all plastics are collected, recycled, or re-used in their end-of-life phase, or they don't address the end-of-life phase at all.

When the impact of plastic pollution, microplastics, biodiversity loss, and human health are included, plastics have a much greater environmental impact than other materials.[39,40,41,42] That said, LCAs with appropriate system boundaries, inclusion of externalities, and realistic end-of-life scenarios can still provide useful answers to the biggest questions in the plastics debate.

One of the benefits of LCAs is that they highlight tradeoffs between different impacts, such as showing that bio-based plastics have lower GHG emissions than fossil-based plastics but revealing that they may have undesirable land use change, biodiversity, and eutrophication impacts if natural forests are cleared to create agricultural land.[34,43] As long as best practices to mitigate land use impacts and sustainable agricultural practices are employed, bio-based plastics can have a significantly positive impact. Coca-Cola's bio-Polyethylene terephthalate (bio-PET) PlantBottle is one such success story that is estimated to have reduced carbon dioxide (CO_2) emissions equivalent to 1 million vehicles being removed from the streets since its commercialization in 2009.[44]

If you want to find credible LCAs, the best approach is to search for review articles that compare a number of similar studies to identify common conclusions. From reviews such as these, many answers can be gleaned:

- Recycled-content plastics consistently demonstrate lower GHG emissions than virgin plastics.[45,46]
- Mechanical recycling remains the preferred method for plastics that are easy to recycle. However, the fate of mixed plastic waste (MPW) is more complex, as it would otherwise most likely be landfilled or incinerated.[47,48] For such plastics, chemical recycling (pyrolysis) is the better option,[49] with one study showing 50% lower CO_2 emissions than incineration of MPW.[48] It is important to note that there is still some critique of these LCAs.[50]
- Compared to processes that use virgin fossil-based feedstock, advanced recycling technology can be used to produce in-demand chemicals and plastics with a global warming potential (GWP) ranging from an increase of 22% to a decrease of 185%, with the majority of the data indicating a reduction in GWP.[51]
- Pyrolysis is often compared favorably with mechanical or chemical recycling, but only in high-efficiency combustion conditions where it replaced fossil fuels. However, more data is needed to ensure pyrolysis is better than other chemical recycling pathways, such as gasification, depolymerization, and hydrocracking.[47]
- In one comparison of mechanical vs. chemical recycling approaches for PET, the former and glycolysis delivered the best economic (9%–73% lower than competing technologies) and environmental (7%–88% lower) impacts, while dissolution, enzymatic hydrolysis, and methanolysis provided the best recyclate material qualities (2%–27% higher).[52]
- A study of fossil-based polypropylene (PP) versus bio-based PLA found that the use of PLA resulted in 63% economic gains and a reduction of 14-60% in all emissions categories.[53]

Addressing the sustainability challenges of plastics will require a multifaceted approach. Efforts to reduce plastic usage, improve recycling rates, and develop more sustainable alternatives are all important. Innovations in areas such as bio-based and biodegradable plastics and chemical recycling offer promising potential. However, these technologies are still in their early stages and come with their own challenges and trade-offs, which is where well-designed LCAs can help industry and policymakers make the best decisions.

Forces driving change

Consumer demand

U.S. consumers are increasingly aware of sustainability issues for plastic packaging and are willing to pay more for products incorporating Environmental, Social, and Governance (ESG) guidelines such as animal welfare ("cage-free," "cruelty-free," "not tested on animals"), environmental sustainability ("compostable," "eco-friendly"), organic certification, plant-based ("plant-based," "vegan"), social responsibility ("fair wage," "ethical"), and sustainable packaging ("plastic-free," "biodegradable"), according to a joint study by McKinsey and NeilsenIQ.[54] Furthermore, products making these claims enjoyed 28% cumulative growth over the past five years, compared to 20% for products that made no ESG claims.

A joint study with Trivium and Boston Consulting Group surveyed 15,000 consumers in the U.S., Europe, and South America and found that 67% of consumers consider themselves environmentally aware and believe sustainable packaging is important.[55]

Millennial consumers are more likely to buy sustainable products, while Gen Z consumers are willing to pay the most for sustainable products. This report indicated that consumers have begun connecting the dots between plastics being "harmful" (55%) and "connected with ocean pollution" (63%).

The Ellen MacArthur Foundation, in collaboration with the UN Environment Programme, has created The Global Commitment 2022 to end plastic pollution by targeting 100% reusable, recyclable, or compostable plastic packaging by 2025.[56]
Over 500 signatories are tracking and reporting their progress toward the goals, including companies representing 20% of all plastic packaging produced globally, such as L'Oréal, Mars, Nestlé, PepsiCo, Coca-Cola, Unilever, and Walmart. These companies are listening to consumers and making measurable steps toward a circular economy.

> **"Today marks a triumph by planet earth over single-use plastics. This is the most significant environmental multilateral deal since the Paris Accord. It is an insurance policy for this generation and future ones, so they may live with plastic and not be doomed by it.**
>
> Inger Andersen,
> Executive Director of UNEP

Government regulations

Under existing national regulations and voluntary measures, the problem has only become worse, affecting every corner of the planet. An international effort to control the plastics problem is needed. Finally, the time has come – in a landmark resolution in early 2022, 175 United Nations member states committed to forging a new international treaty to govern single-use plastics by 2024 by adopting UN Resolution 5/14, titled "End Plastic Pollution: Towards an international legally binding instrument."[57] Studies have shown that a shift to a circular economy can "reduce the volume of plastics entering oceans by over 80% by 2040; reduce virgin plastic production by 55%; save governments USD $70 billion by 2040; reduce greenhouse gas emissions by 25%; and create 700,000 additional jobs – mainly in the global south."[58]

Negotiations are currently underway, with a range of potential policy instruments to advance a circular economy, including single-use plastics bans, Extended Producer Responsibility (EPR) schemes, material and/or additive bans, minimizing virgin plastics with recycled content mandates, and recycling targets for plastics. There is also an innovation fund and investments in recycling infrastructure to support the industry in making the transition.

What is EPR?

Extended producer responsibility (EPR) was originally defined as "a policy principle to promote total life cycle environmental improvements of product systems by extending the responsibilities of the manufacturer of the product to various parts of the entire life cycle of the product, and especially to the take-back, recycling and final disposal of the product."[59]

In EPR systems, municipalities generally take responsibility for waste collection, sorting, and transportation, while the producers pay for the recycling of the waste. Based on learnings from existing EPR systems in Europe, Japan, and Canada, the basic principles of EPR generally include:

- A legal basis for assigning producers (inclusive of first importers) responsibility for the recovery of recyclable packaging materials.
- Recovery and recycling targets that producers must meet collectively.
- Authorization of an independent recovery organization to manage the collection of materials on behalf of the producers.
- Material fees based on recovery costs and material type.
- Penalties or other mechanisms to eliminate non-compliance and free-riders among producers.

As of 2016, there were about 400 EPR systems in the world, covering waste items, including packaging, rechargeable batteries, electronics waste, and more.[60]

Europe

In late 2022, the European Union proposed new rules for all plastic packaging to be made recyclable or reusable by 2030.[61] The main target is to reduce packaging waste by 37% overall in the EU through reuse and recycling. The policy options on the table include bans on single-use packaging for food and beverages when consumed in a restaurant or cafe, creating mandatory deposit return systems, mandatory rates for recycled content and packaging, better labeling and design to help consumers sort plastics, and clarifying the confusion around bio-based, biodegradable, and compostable plastics. The plan is expected to reduce GHG emissions, conserve water, and create more than 600,000 jobs.

In the UK, a packaging EPR system took effect on January 1, 2023, and will be fully implemented by 2027. This new law makes producers responsible for the packaging they introduce to the marketplace, including through the end-of-life stage.[62]

North America

The U.S. EPA published the National Recycling Strategy in November 2021 and reaffirmed the goal to increase the U.S. recycling rate to 50% by 2030, with three main objectives:

- Reduce pollution during plastic production.
- Improve post-use materials management.
- Prevent trash and micro and nano-plastics from entering waterways, and remove escaped trash from the environment.[63]

In addition, the EPA publishes an annual report, "Advancing Sustainable Materials Management: Facts and Figures," with details about Municipal Solid Waste (MSW) generation, recycling, composting, and combustion, along with energy recovery and landfilling.64 A full list of federal agency programs and initiatives addressing plastic pollution can be found on the U.S. State Department website.[65]

In 2022, Canada banned single-use plastics (checkout bags, straws, stir sticks, and cutlery) and is targeting zero plastic waste by 2030.[66] The full range of government programs to develop a circular economy can be found on the Zero Plastic Waste Agenda website.[67]

In 2019, the largest companies in Mexico's plastics industry signed the National Agreement for the New Plastics Economy, a non-binding pact with the federal government by which all parties commit to reducing single-use plastic production, promoting recycling, and eliminating unnecessary or problematic plastic packaging. According to the agreement, all plastic containers and packaging must be 100% reusable, recyclable, or compostable by 2030.[68] Two dozen states and cities have instituted bans on single-use plastics, with Mexico City taking the lead in banning plastic bags in December 2020, and the widest range of single-use products since January 2021.[69]

Asia Pacific

As a global destination for plastic pollution, there's a growing trend in APAC countries toward more stringent regulations, though the policies vary significantly from country to country. Japan, South Korea, and Taiwan have EPR systems in operation. In Japan and South Korea, producers can create an individual recycling system to do it themselves.[70]

China, the world's largest producer and consumer of plastic products, has taken significant steps towards controlling plastic pollution within its borders. In 2018, China's National Sword policy banned foreign imports of residential recycled materials, sending shockwaves through the global waste management industry and forcing over 90 exporting countries, especially the Top 3 – Japan, the United States, and Germany – to confront the full scope of managing their own waste.[71,72] Following the ban, the destination of many of these exports shifted to Southeast Asia, India, and Africa, where they were completely unequipped to manage the tidal wave of plastic waste.

In 2020, China's National Development and Reform Commission (NDRC) issued a new policy to phase out the production and sale of single-use disposable plastic straws and bags. By the end of 2020, non-degradable bags were banned in major cities, and by 2022, the policy is expected to be extended to all cities and towns.[73]

Japan, the world's second-largest generator of plastic waste per capita, has introduced the concept of the "Sound Material Cycle Society," which aims to achieve zero waste. Japan has achieved 85% recycling of plastic bottles, with the aim to reach 100% by 2030. However, recycling rates for all other plastics and materials are around 20%, according to Statista.[74,75] A zero-waste city, Kamikatsu, has demonstrated 80% recycling of all materials.[76]

Singapore has implemented "Zero Waste Singapore," where the government has enforced regulations with innovative strategies of rewards and penalties. Consequently, Singapore managed to achieve 60% recycling in 2015.[77]

Australia's National Packaging Targets, announced in 2018, aim to make all packaging reusable, recyclable, or compostable by 2025.[78] Also, 70% of plastic packaging is to be recycled or composted, and problematic and unnecessary single-use plastic packaging is to be phased out.

The ASEAN (Association of Southeast Asian Nations) member states also show a mixed but growing commitment to tackling plastic pollution. Several members, like Thailand, Vietnam, and Indonesia, have implemented or announced intentions to impose restrictions or taxes on single-use plastics. In recognition that plastic pollution doesn't respect international borders and the need to protect shared rivers and coastlines, the ASEAN announced the Bangkok Declaration on Combating Marine Plastics in 2019. In 2022, an ASEAN Regional Action Plan articulated 14 priority actions for member states. The World Bank has since approved a USD $20 million grant to support these regional policies.[79]

India has been tackling its plastic waste issue by implementing and reinforcing bans on single-use plastics. In 2016, the country's Plastic Waste Management Rules required, among other measures, explicit fees for plastic bags to discourage usage. In 2019, Prime Minister Narendra Modi called for a phase-out of single-use plastic by 2022.[80,81]

Other forces

In May 2023, the United States set an ambitious goal to reach 100% carbon-free electricity by 2035.[82] Under the proposal, new and existing natural gas power plants must install carbon capture and storage (CCS) equipment that reduces 90% of carbon emissions by 2035. Coal plants with planned operation past 2040 will be required to install CCS starting in 2030.

While this proposal doesn't directly impact the plastics industry, all of the captured CO_2 needs to go somewhere – such as in underground storage, in depleted oil reserves to enhance oil recovery, or potentially to make virgin plastics out of CO_2 feedstock, as described later in this report.

Innovation opportunities

Getting to a circular economy will not be a linear process. Plastics producers argue that recycled content mandates are difficult, if not impossible, to achieve given the available quantity and quality of recycled plastics. For example, recycled PET water bottles are not sufficient to be used in the production of new water bottles. Most often, recycled PET is downgraded to other things, like textiles or carpeting. However, the frontiers of innovation abound with game-changing technologies, processes, and new materials that solve these problems.

Enzymatic deconstruction of PET may be cost competitive with virgin PET

An NREL-led team participating in the BOTTLE Consortium,[83] has discovered enzymes that can chemically deconstruct all varieties of PET, including crystalline PET, which usually requires thermal treatment to "soften" it before recycling.[84] With a 48-hour treatment in a bioreactor, nearly 98% of the plastic waste (including PET carpeting and clothing, which are not recyclable with current technologies) was converted back into terephthalic acid (TPA) and ethylene glycol, building blocks for new PET bottles or advanced plastics. Even more astonishing, this enzymatic process could be done at a cost of less than $1 per kilogram. The cost of fossil-derived TPA is typically $1 to $1.50 per kilogram, making this new approach cost-competitive with virgin plastic production.[85] The team utilized state-of-the-art bioinformatics and machine learning in a sleuthing exercise to identify a set of 36 plastic-eating enzymes based on patterns and biological rules of enzymes known to be active against plastics. This work demonstrates the potential to radically transform the circular economy landscape with innovative technology and AI/ML.

Companies such as Loop Industries and Carbios have also been on the hunt for enzymes that break down PET into its original monomers. Loop's technology breaks PET down into dimethyl terephthalate (DMT) and monoethylene glycol (MEG) below 90 degrees with no added pressure.[86] Loop has attracted investment from SK Global Chemical[87] and is building a plant to manufacture recycled PET plastics in France. Carbios has developed a PET hydrolase based on enzymes derived from leaf-branch compost cutinase that outperform enzymes from the bacterium *Ideonella sakaiensis*, and can depolymerize 90% of PET into ethylene glycol and terephthalic acid in just 10 hours.[88]

Carbon dioxide is a promising building block

Coupled with e strong forces driving the adoption of CCS of carbon dioxide, there are new demonstrations of chemical building blocks manufactured from CO_2 feedstocks (Figure 2).[89] Polyurethanes have been successfully synthesized using CO_2, and the development of other polymers from CO_2 has good prospects.

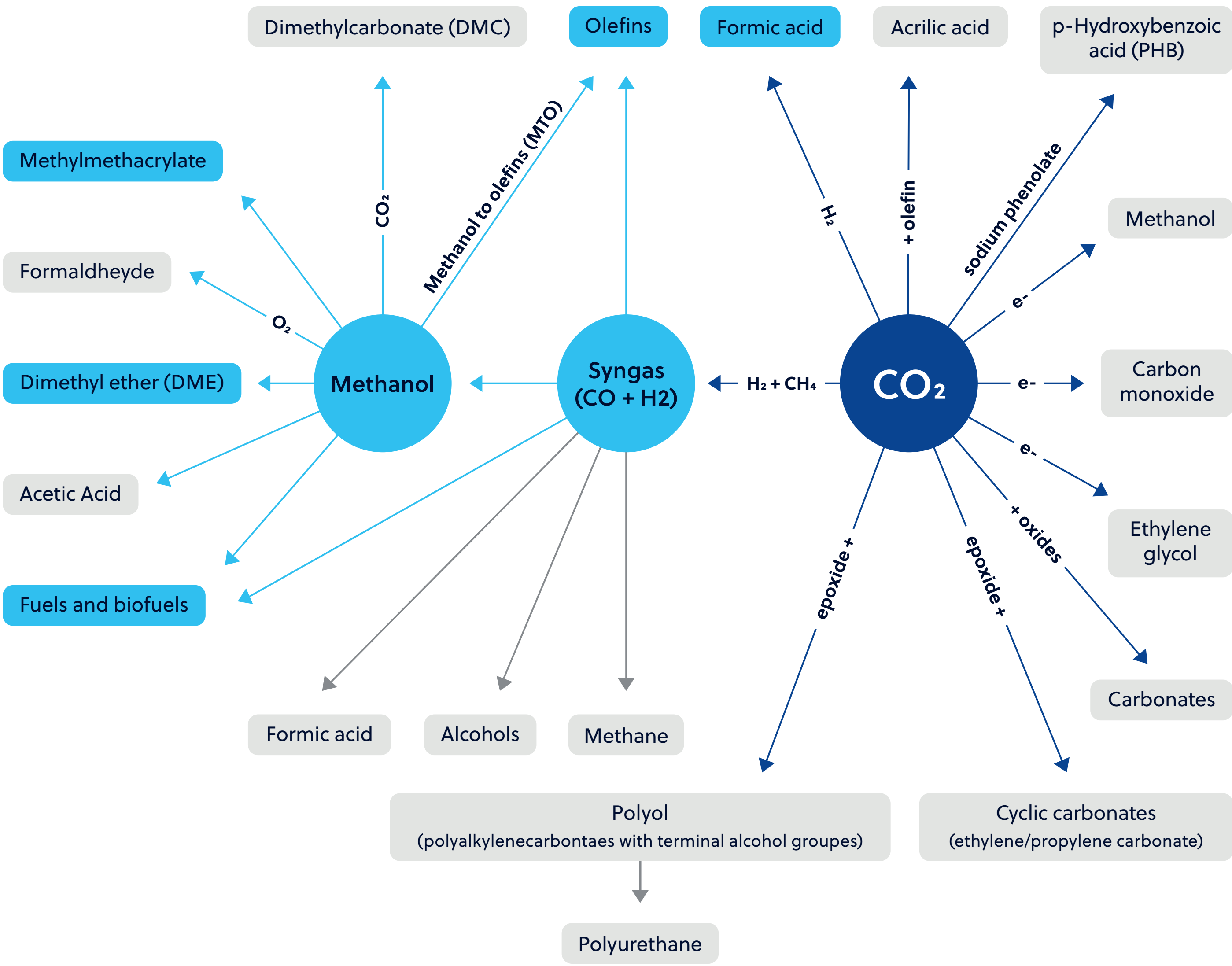


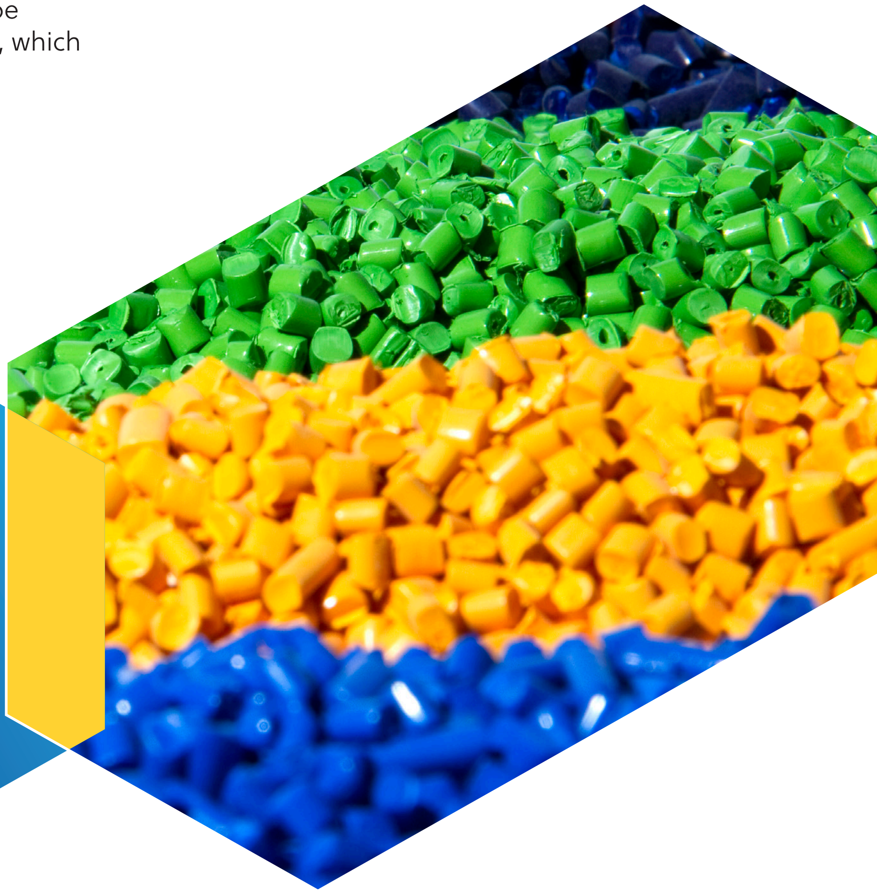
Figure 2. Carbon dioxide is a resourceful building block that can be converted into numerous chemical compounds.[89]

A bio-based counterpart to PET, polyethylene, furandicarboxylate (PEF), hasn't been commercialized due to an energy-intensive, lengthy production process. However, a group from Durham University in the UK has found that industrial CO_2 emissions can offer a cost-effective PEF alternative that reduces GHG emissions by up to 40.5% compared with PET. The cost of PEF production with the new pathway is about USD $2,435 t −1, versus the production cost of PET at USD $1,800 t −1, which doesn't currently take into account the expense of ~50% additional CO_2 emissions.[90]

Chemical recycling beats mechanical recycling

There are many new chemical recycling developments that could allow virgin-quality plastic and other valuable chemicals to be created from recycled plastics without petroleum feedstocks – a potential game changer for the circular economy. Catalysts and enzymes are crucial for enabling and accelerating chemical reactions in the recycling process, driving R&D efforts to find the most efficient and cost-effective solutions:

- Scientists at the U.S. Department of Energy's Ames Laboratory have discovered a catalyst that can break down polyolefins into high-value products at low temperatures.[91]
- Researchers at Argonne National Laboratory have developed a catalytic hydrogenolysis process that can turn plastic waste into high-quality liquid products, such as lubricants and waxes.[92]
- Researchers from the University of California, Santa Barbara, have developed a methanolysis method to break down polyethylene, one of the most persistent plastics, into readily usable molecules. They used a super-heated, catalyst-driven technique that breaks the polymer chains into smaller pieces that can be converted into liquid and gaseous hydrocarbons, which can then be reused in other products.[93]
- Pyrolysis is a process that can turn plastic waste into fuel, energy, and chemicals by heating it in an oxygen-free environment. Companies such as Agilyx[94] and Plastic Energy[95] are pioneering this technology. While this approach is technically not circular, and there are concerns about GHGs and toxic emissions, it may still have an important role in closing the loop on plastic waste.
- Waste plastic can be converted to hydrogen by gasification combined with carbon capture and storage for USD $2.26–2.94/kg, which can compete with fossil fuel hydrogen with carbon capture and storage (USD $1.21–2.62/kg) and current electrolysis hydrogen (USD $3.20–7.70/kg). The study authors also created a roadmap for reducing the average minimum hydrogen selling price from USD $2.60/kg to USD $1.46/kg, which can be further lowered to USD $1.06/kg if carbon credits are on par with the carbon capture and storage costs, along with low feedstock cost.[96]



Bio-based and biodegradable plastics are viable replacements

Bio-based raw materials are an excellent starting point to move away from fossil-based sources.[97,98] Figure 3 offers a summary to clarify the confusion around bio-based and biodegradable plastics and direct R&D efforts toward more sustainable options.[99] Two useful polymers, polylactic acid (PLA) and polybutylene succinate (PBS), can be found in the biodegradable quadrants, while PBS can be made from either fossil or bio-based feedstocks.[99]

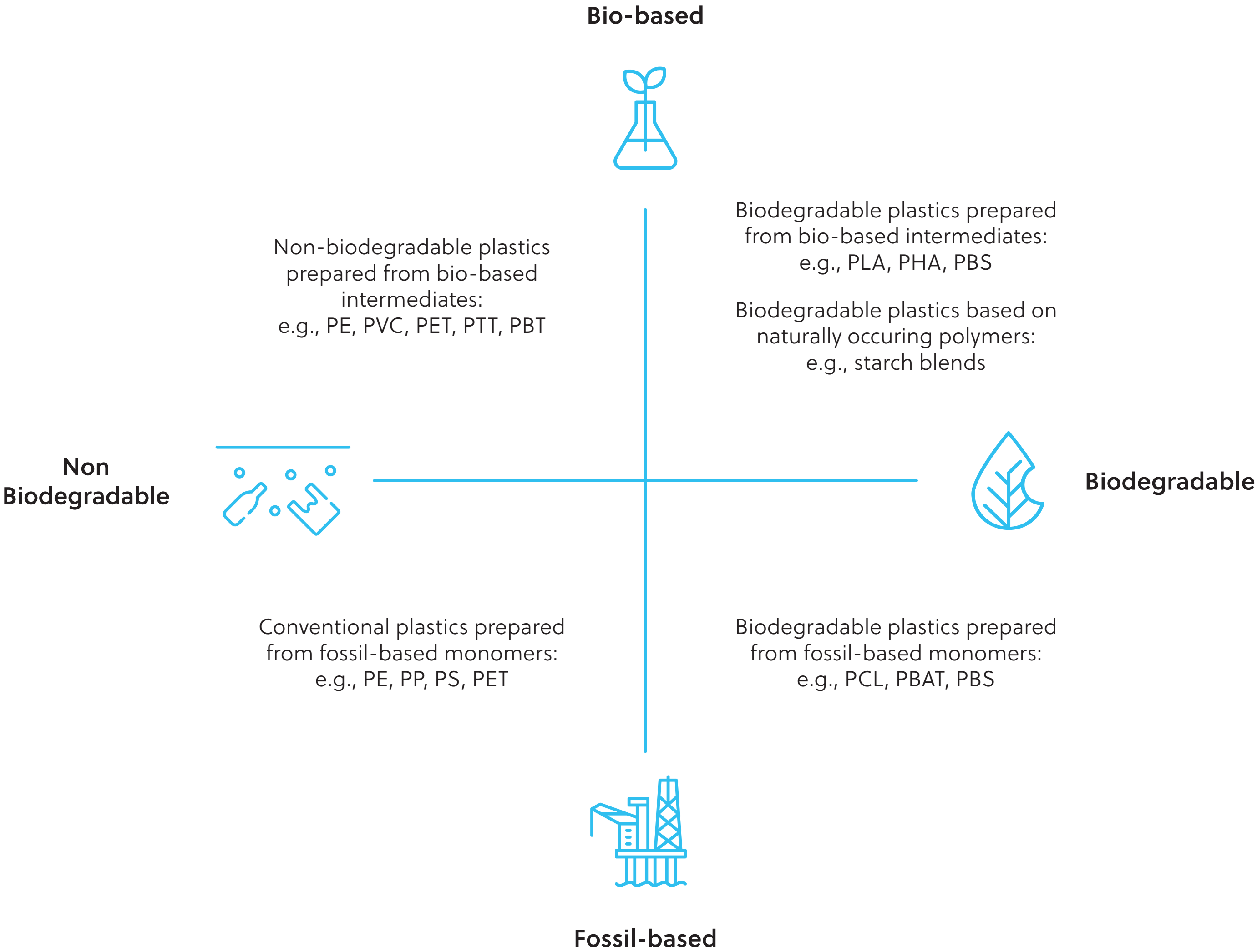


Figure 3: Simplified four-quadrant representation to clarify fossil, bio-based, and biodegradable plastic material types.

Plants rich in carbohydrates can be transformed into polylactic acid (PLA) through separation, polymerization, and microbial fermentation steps.[98,100] In terms of its structure, PLA is similar to PET, with excellent durability and good barrier protection, with gas permeability approximately 1,000 times lower than LDPE.
Therefore, PLA is a perfect replacement for PET used in the food-services industry as it provides an affordable product that will prevent oxygen and moisture ingress.[98,99,101]

In addition, PLA is compostable within a relatively short timeframe.[99,100] PBS is a good PP replacement due to its mechanical properties, excellent thermal properties, non-transparency, and greater rigidity than other bioplastics.

Blockchain and AI are at the cutting edge of the circular economy

Imagine picking up a plastic bottle on a beach in India and being able to identify its chemical composition, additives, origins, and all the stops it made along its journey. There are a number of studies and pilots involving blockchain technology that may enable this level of supply chain and waste stream traceability. There are several groups working at the intersection of blockchain technology and plastics waste,[104,105] including gamification and recycling incentives for consumers in the form of tokens.[106,107]

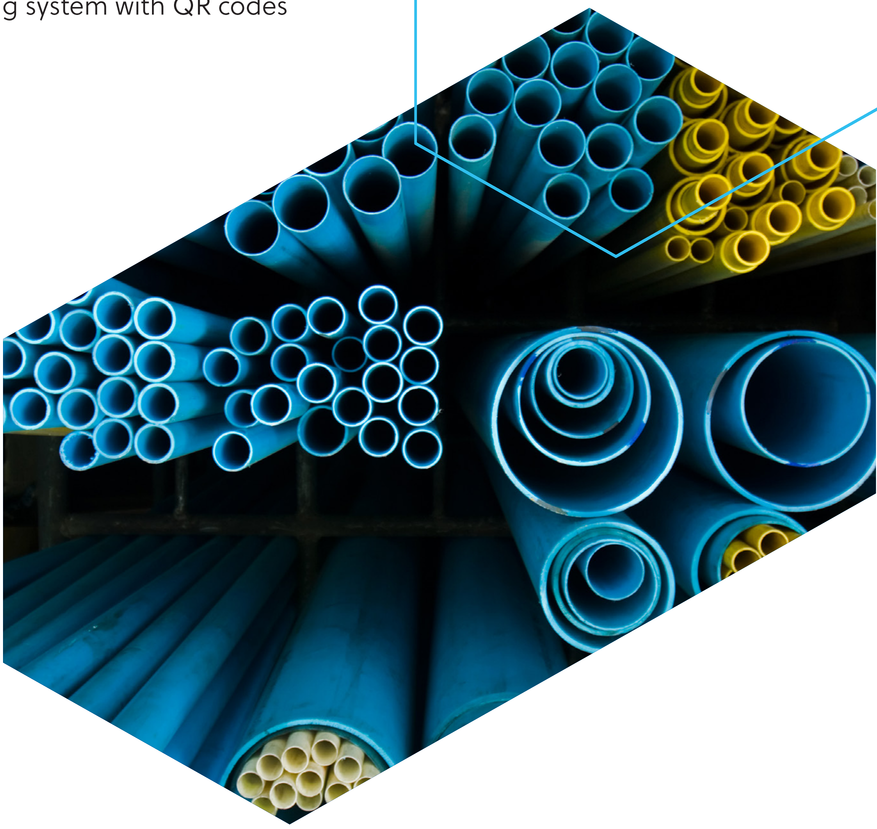
The HolyGrail 2.0 consortium led by Proctor & Gamble is integrating nearly-invisible digital watermarks into plastic packaging so that AI scanners can be used to solve the sticky problem of sorting,[108] and others are investigating this technology as well.[109,110] Some notable industry pilots and collaborations in this space include:

- Circulor has announced Project TRACKCYCLE, a partnership with TotalEnergies and Recycling Technologies, a chemical recycler of plastic, to develop a blockchain-enabled traceability solution for hard-to-recycle plastics (HTRP), with funding by Innovate UK. The goal of the project is to provide "a fully traceable and accurately labeled record of recycled materials, from the waste sourcing up to the use of recycled polymers in new production streams."[111]
- A partnership between Finboot, Plastic, SABIC, and Intraplas, which aims to make the recycled plastic supply chain more transparent.[112]
- PlasticFinder, an Italian company, has introduced a blockchain-based tracking system with QR codes on packaging.[113]

Designing for destruction

Perhaps one of the most significant developments in the design of new polymers that can be infinitely recycled is the creation of PDK (polydiketoenamine) plastics by researchers at Lawrence Berkeley National Laboratory. PDK plastics can be chemically recycled back into their original monomers with no loss of quality, enabling true circularity for these materials.[102]

An LCA study from the University of Stuttgart considered the influence of design considerations on plastics recyclability and found that generally, fillers, colors (especially black), insoluble adhesives, and large labels made of a material differing from the main packaging material should be avoided as they render packaging unrecyclable. They identified favorable design attributes to enhance recyclability and encourage packaging designers to utilize these recommendations.[103]



Doing our part in the circular economy

Sustainable development was originally defined in the 1987 Brundtland report "Our Common Future" as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs."[114] Over 35 years later, the concept of a circular economy is taking hold – "a systemic approach to economic development designed to benefit businesses, society, and the environment. In contrast to the 'take-make-waste' linear model, a circular economy is regenerative by design and aims to gradually decouple growth from the consumption of finite resources."[115]

Stakeholders across the plastics value chain, the public sector, and global governance are now uniting around a common cause to end plastic pollution. The insights provided in this report can guide the chemical and plastics industries to close the loop on plastics by keeping building block molecules in circulation for as long as possible. Despite the devastating impacts of plastic pollution, there is new hope for a future circular economy for plastics that can be realized by adopting innovations in process technologies and new polymer materials, combined with strong policy drivers and incentives for manufacturers.

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