
# INNOVATIVE SOLUTIONS ADDRESSING PLASTIC POLLUTION

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**Following on the heels of Net Zero momentum is a push for a reduction in global Plastic Pollution, particularly with respect to single-use plastics (SUP). Plastics "users", be they consumers (pull) or corporates (push) selling to them, are unfortunately still slow to change. On the other hand, innovators are addressing the problem, most impactfully via alternative materials and recycling processes. Hopefully, the next 5-10 years – driven by consumer awareness, innovation, funding and legislation - will witness a major transition away from fossil fuel derived single-use plastic.**



## I | PLASTICS POLLUTION BEING RECOGNISED AS A MAJOR PROBLEM

As a planet and a species, mankind is awash in plastic. But just 60 years ago, plastic hardly existed. It was in the 1967 film classic *'The Graduate'* that Mr. McGuire advised the protagonist Ben Braddock (played by a young Dustin Hoffman) "there's a great future in plastics". With all its potential and advantages (convenience, versatility, durability, cost), till recently he wasn't wrong.

Two generations later, plastic is ubiquitous. While plastic has brought us durable, long-lasting products (medical devices, car bumpers, keyboards), of all plastic produced ~40% is made for single-use, much of it in the form of packaging that serves a function for six months or less and then is discarded.

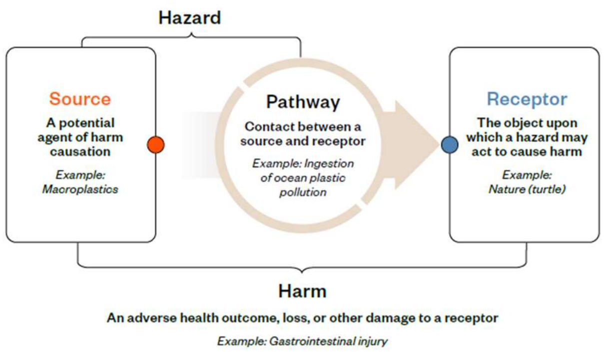
The ensuing problem has actually been known for some time: plastics waste, degrading into ever-finer (becoming invisible) particles ('**microplastics**'), is polluting our earth, rivers, oceans and even air. Via those pathways – particularly in the case of rivers and seas where it becomes hyper-mobile – plastic waste is affecting living organisms, either externally (picture those turtles caught in fishing nets) or even internally, the latter creating a vector for entering the human food chain and hence our bodies.

According to one study[1], under business-as-usual (BAU) the annual flow of plastic into oceans specifically will nearly triple by 2040, to 29M metric tonnes per annum (equivalent to 50kg of plastic per metre of coastline worldwide).

Why does all this matter? The current and emerging science is robust and unequivocally stated in over 5,000 papers: plastic-related pollution harms humans, other living organisms, nature more generally as well as economies.

[1] The Pew Charitable Trusts

**Plastic Pollution Causes Living Organism Harm**




*Source: Minderoo Foundation*

## II | A SHORT PRIMER ON PLASTICS

A plastic is a polymer ('poly' = many) made up of a repeating chain of monomers ('mono' = one). Plastics vary in weight, colour, melting point, density and barrier properties (i.e. permeability to oxygen or moisture), among other things. These properties depend on which monomers are used, their chemical structure, order of assembly as well as presence of any other chemicals (such as additives). The vast majority of monomers used to make plastics, such as ethylene and propylene, are derived from fossil hydrocarbons (oil & gas).

Plastic packaging is created from a variety of polymers, polyethylene terephthalate (PET) being the most used base material (representing ~95% of plastic bottles and containers). However, there are many others, including polyvinyl chloride (PVC), polypropylene (PP) and polystyrene (PS).

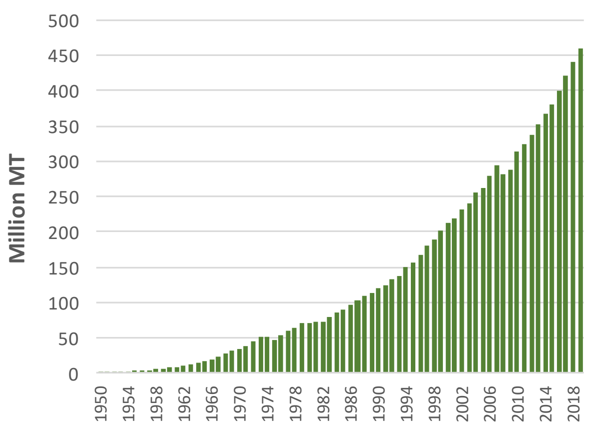
**Main Single-Use Plastics Types**

| Acro-nym | Chemical Name | Applications | Code[2] |
|---|---|---|---|
| PET | Polyethylene terephthalate | fruit juice & soft drink bottles | 1 |
| HDPE | High-density polyethylene | shampoo / milk bottles | 2 |
| PVC | Polyvinyl chloride | cordial, juice or squeeze bottles | 3 |
| LDPE | Low-density polyethylene | garbage bins & bags | 4 |
| PP | Polypropylene | lunch boxes, take-out food & ice cream containers | 5 |
| PS | Polystyrene | foam hot drink cups, plastic cutlery, containers, yogurt | 6 |
| Other | e.g. polycarbonate | | 7 |

*Source: Industry sources*

Worldwide plastic production rose from 2M tonnes in 1950 to **around 400M+ tonnes (depending on the source) in 2021** (representing a US$525B industry[3]). The industry is projected to double volumes by 2040.

**Global Plastic Production Volumes [M MT]**



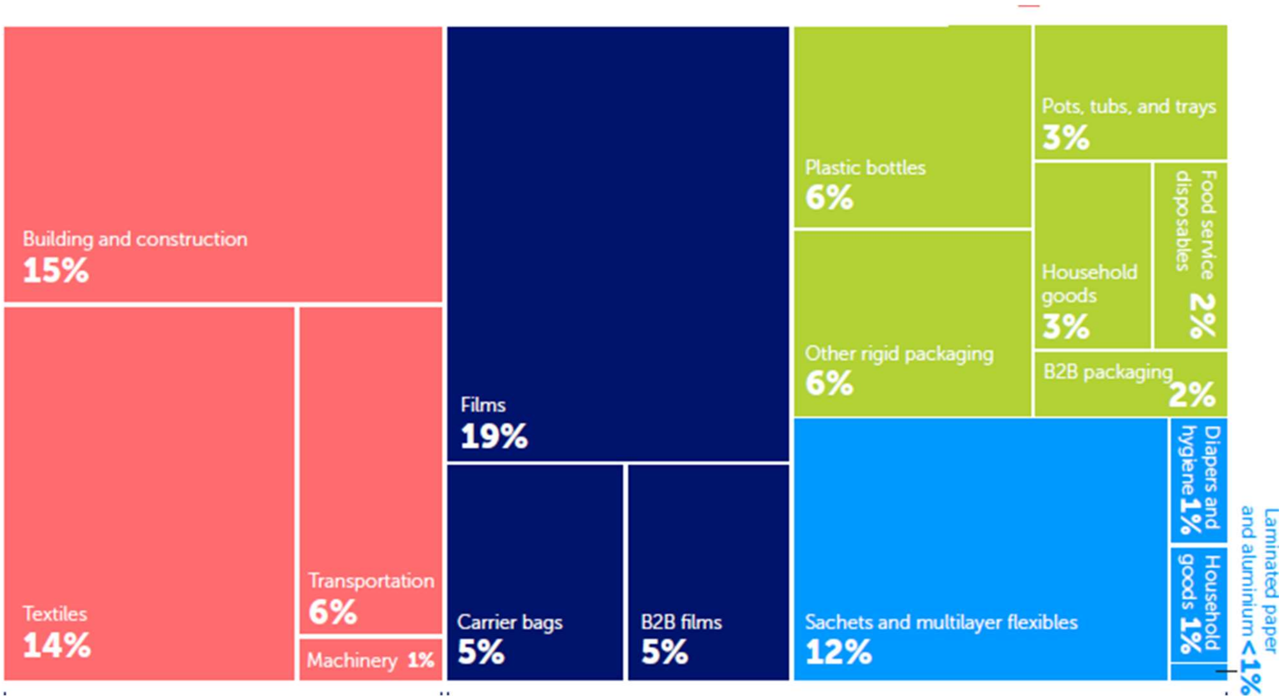

*Source: OurWorldInData.org*

The **global plastic packaging sector (all segments) was estimated to be valued at US$355B in 2020, growing at a 4.8% CAGR to reach US$586B by 2030**[4], with food & beverage applications accounting for roughly half of that.

[2] Resin identification code to aid recycling plants sort materials
[3] The Pew Charitable Trusts

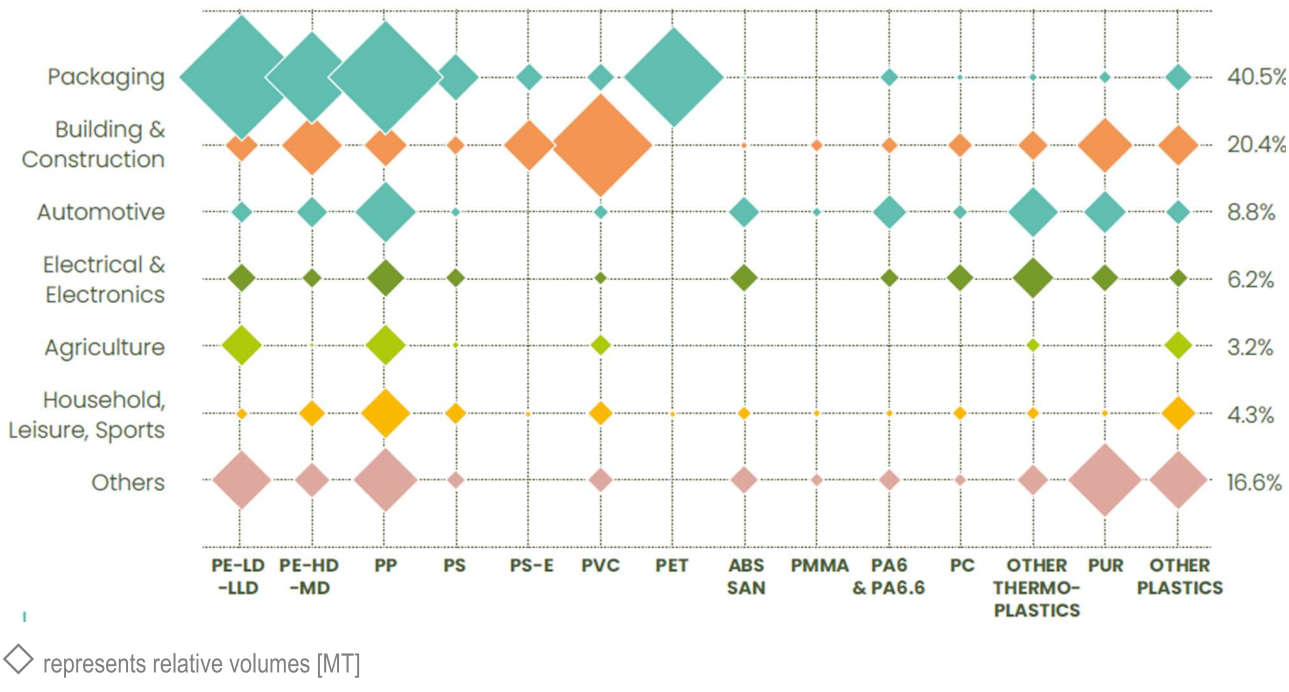
[4] GrandView Research

**Plastics Demand by Application**




*Source: The Pew Charitable Trusts*

**Typical Applications of Plastics by Plastic Type[5]**



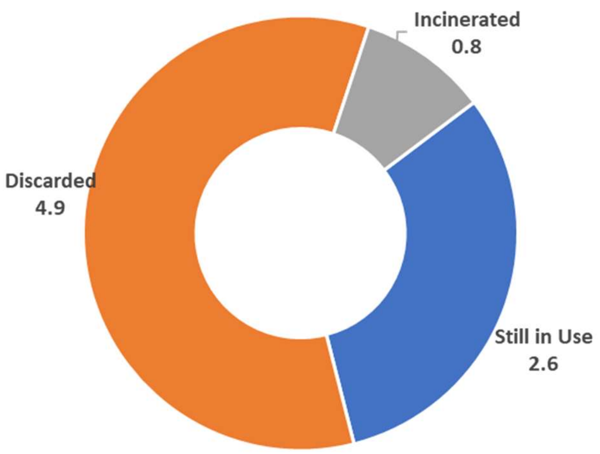

*Source: Plastics Europe (2021)*

Approximately 60% of the plastic ever produced – for all uses and applications – is estimated to have already been discarded into the environment. So even if we stopped producing and consuming plastic tomorrow, this ~5B tonnes of waste plastic is still going to find pathways via which to degrade to

[5] EU 27 + 3 converters plastic demand

microplastics and cause further harm to living organisms and the environment more generally. Likewise, the 2.6B tonnes "still in-use" will need to be managed appropriately at its end-of-life, to not further add to the problem.

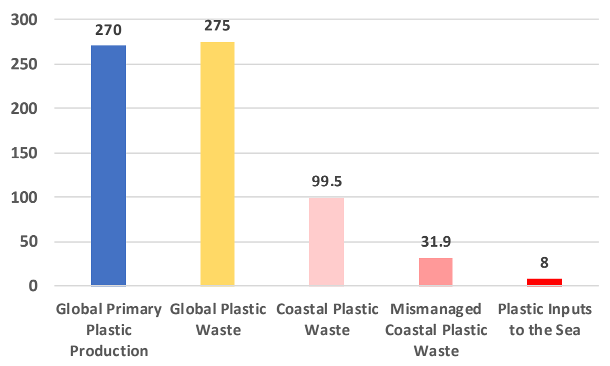
**Plastics "Fate" Since 1950 [B tonnes]**




*Source: Science Advances*

According to data, over one-third of plastic produced annually ends up in coastal areas and as much as 3% (or 8M tonnes) ends up in the sea, each year. Under BAU the amount of plastic waste produced globally is expected to triple by 2060 and, if nothing changes, those ratios will persist or even deteriorate.

**Annual Plastic Volumes (2014) [M tonnes]**

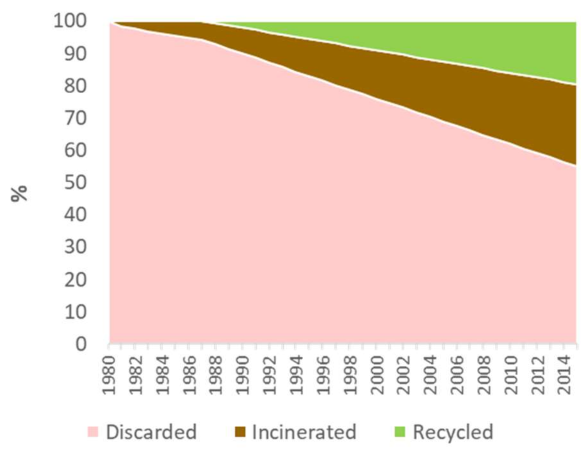



*Source: OurWorldInData.org*

For plastic waste which is actually collected, there are essentially three different fates for it today (in order of merit):

- Recycling / reprocessing: Waster plastic can be recycled or reprocessed into a secondary material, but this delays, rather than avoids, final disposal - it reduces future plastic waste generation only if it displaces primary plastic production. Furthermore, contamination and the mixing of polymer types generate secondary plastics of limited or low technical and economic value, so optimal sorting becomes critical. Around **8%-12% of global plastic waste is recycled today**.
- Thermal destruction: The only way to permanently eliminate plastic waste is by destructive thermal treatment. To-date virtually all thermal destruction has been by incineration (with or without energy recovery), the environmental and health impacts of which strongly depend on emission control technology as well as incinerator design and operation. Around **12% of global plastic waste is disposed of via incineration today**[6].
- Landfill: Plastics can be discarded and either contained in a managed system, such as sanitary landfills, or left uncontained in open dumps or in the natural environment. According to the OECD, today around half of the planet's plastic waste ends up in landfill of some sort.

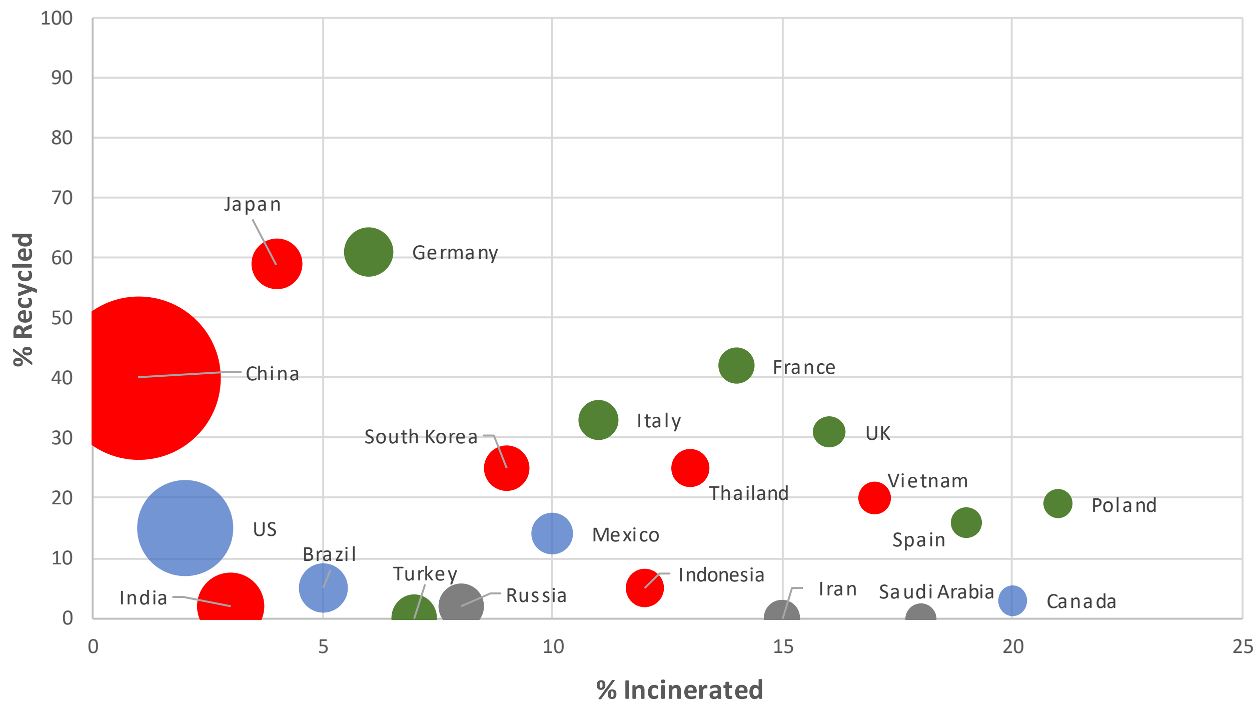
**Plastic Waste Fate [M tonnes]**




*Source: OurWorldInData.org*

[6] Science Advances

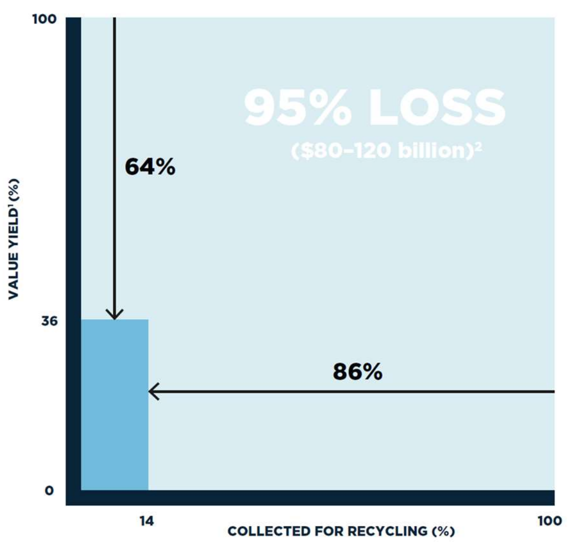
**Current Plastics Managed End-of-Life (2020)**




*Source: OurWorldInData.org*

While incineration and landfill disposal are environmentally deleterious, they also represent a major loss of value: with the bulk of plastic waste being burnt or dumped, 95% of plastics value is lost after one use, costing up to US$120B annually[7]. Plastic recycling therefore represents a real business opportunity, estimated to reach US$14.7B by 2024.

**Plastic Packaging Material Value Loss After 1 Cycle**




*Source: World Economic Forum*

## III | THE SCOURGE OF MICROPLASTICS

The unfortunate reality of fossil fuel derived plastics is that as non-readily degradable polymers they are persistent in the environment and can accumulate over time, similar to other stock pollutants such as persistent organic pollutants (POPs) or heavy metals. Not only that, depending on the specific plastic, they can disintegrate over time into ever smaller particles, making any effort at collection ever more futile. Microplastics are formed through degradation and fragmentation, in some cases intentional in others incidental:

– Plastic pellets, flakes and powders: Microplastics produced for the use in manufacturing of plastic products (from virgin fossil- or bio-based plastic materials or recycled polymers).

– Intentionally added primary microplastics: Microplastics purposefully designed to be small in size for their application and use (e.g. microbeads in cosmetic products, glitter, industrial abrasives, rubber in-fill materials or polymer encapsulated agricultural products).

[7] World Economic Forum

– Use-phase secondary microplastics: Microplastics generated during intended product use (e.g. microfibres from synthetic textiles, polymers from tyre, road and brake wear, as well as the degeneration of paints). It's interesting to note that the environmentally-positive transition from ICE vehicles to electric vehicles is greatly aggravating vehicle tyre plastic emissions due to the latter's far greater weight.
– Degradation-based secondary microplastics: Microplastics originating from the degradation and weathering of larger pieces of plastics after deposition in landfills or when lost in the environment.

**Microplastic Flakes**

*Source: Minderoo Foundation*

Several studies have attempted to quantify the scales of different microplastic sources. For the EU, approximately 14M tonnes of microplastics were estimated to be released from selected important sources in the period 2013-2017 (of which 4.05M tonnes were released to surface waters)[8].

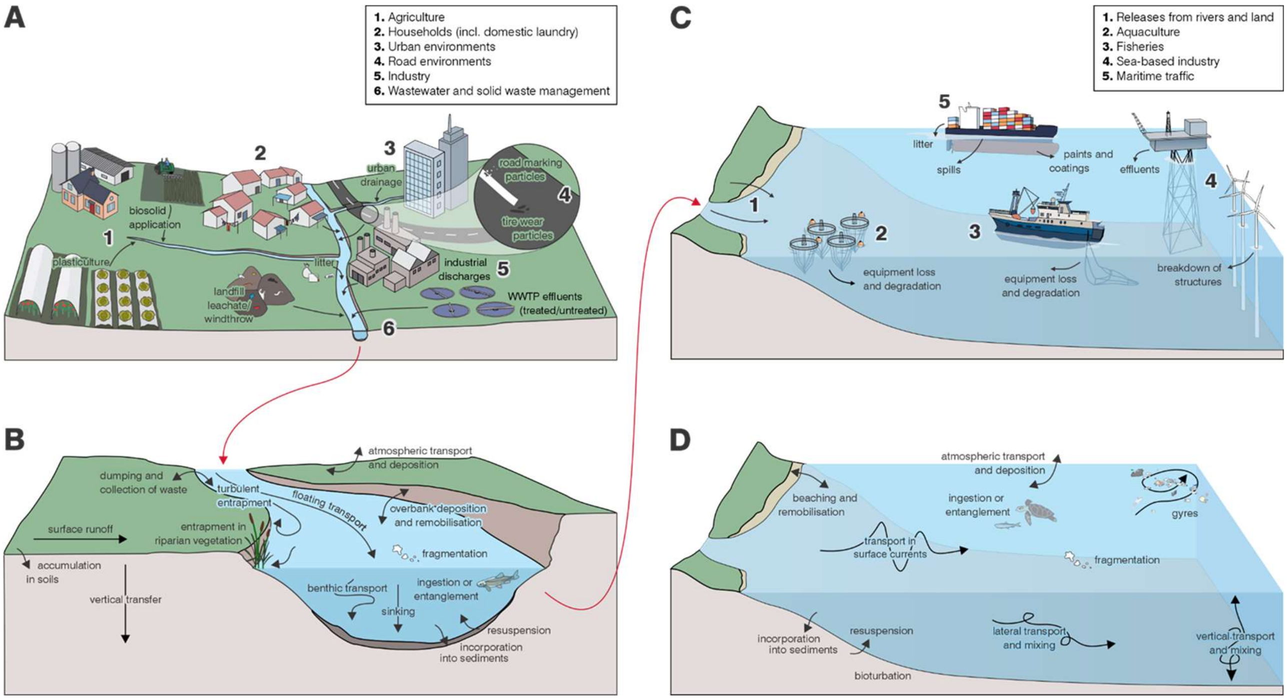
Depending on the size of the plastic particle, organisms interact with microplastics through: 1) ingestion; 2) inhalation; 3) absorption; 4) physical contact/entanglement; or, 5) trophic transfer[9].

Living organisms interact with microplastics differently because microplastics are particulate and can cause harm through particle toxicity in addition to chemical toxicity. As well as their direct impact, microplastics' effects on organisms can be indirect; e.g., the presence of microplastics may alter the habitat in which organisms operate, resulting in indirect effects on their viability.

[8] Norwegian Institute for Water Research

[9] The consumption of an animal having consumed plastic, by another, causing ingestion by the latter

### Major Sources & Pathways of Microplastics in Freshwater, Terrestrial & Marine Environments




*Source: Nordic Council of Ministers*

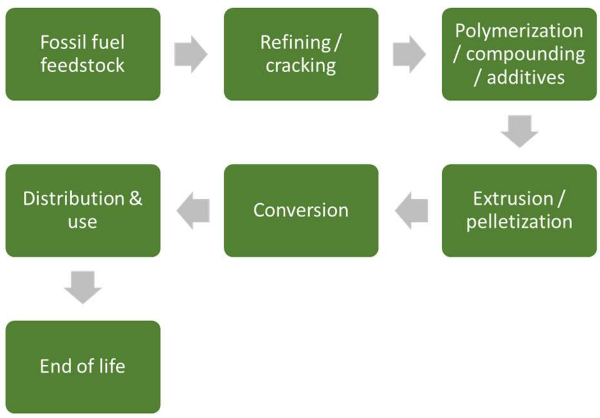
## IV | PLASTICS & CLIMATE CHANGE

As energy and transportation shift away from fossil fuels ('peak oil'), plastics beckon to many oil and gas producers as one of the few opportunities to retain demand (today 14% of global oil is consumed in the production of plastics[10]). However, this won't solve their net zero problem: it varies by feedstock and type of plastic, but on average, **1.89 metric tonnes of CO2e is produced for every metric ton of plastic made[11]**, with some experts calculating that 1 tonne of plastic causes as much as 5 tonnes of greenhouse gases (GHG) over its lifetime.

At every stage in their lifecycle, plastics contribute to climate change:

- Drilling for the fossil fuels that plastic is derived from is a GHG-releasing process; in particular fracking for natural gas, a main source of plastic-making fuel, releases methane - an extremely potent greenhouse gas - into the atmosphere.
- Refining those fossil fuels (be it natural gas, oil or coal) into plastic, ranks among the most energy-intensive and carbon-polluting industrial processes.
- As plastic waste piles up, the practice of incinerating that waste is a growing source of GHGs.

### Plastics Lifecycle




*Source: CleanTech Capital Advisors*

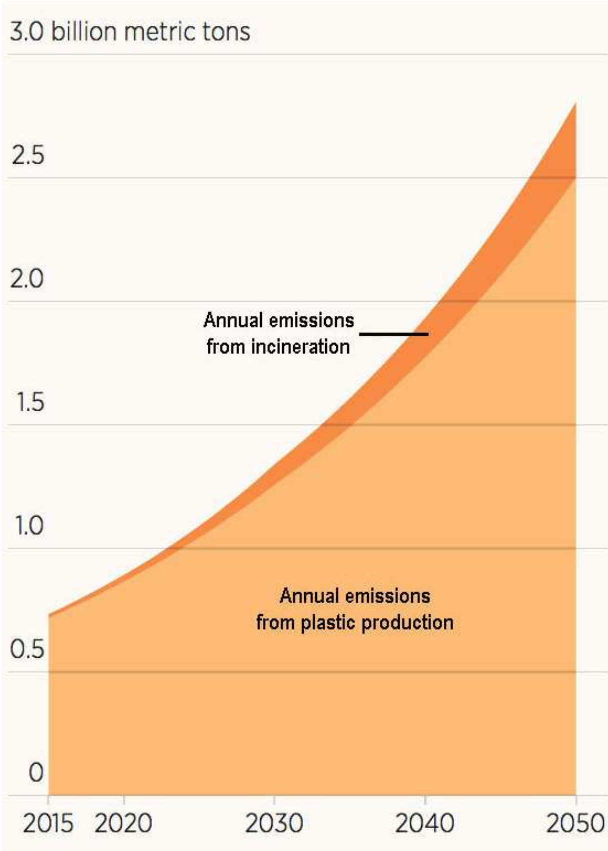
Research published in Nature found that plastics now account for 3.8% of global GHG emissions - nearly double the emissions of the aviation sector. If plastics production were a country, it would be the sixth-highest emitter in the world. At this rate, **emissions from plastic production alone will account for 15% of global emissions by 2050**. Overall, plastic use and disposal could create 56 gigatonnes in cumulative

[10] International Energy Agency

[11] Center for International Environmental Law (CIEL)

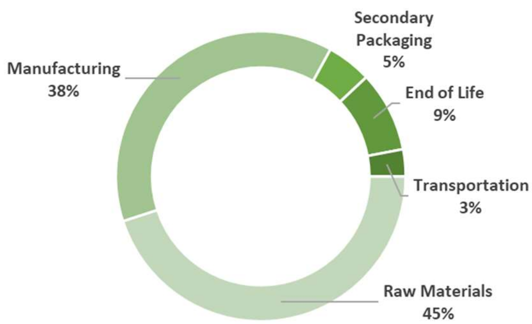
GHG emissions by 2050 (10%-13% of the Earth's remaining carbon budget to keep global warming under 1.5°C[12]).

**Annual Plastic CO2 Emissions to 2050 [B MT]**




*Source: CIEL*

**Plastic Carbon Footprint**




*Source: Journal of Cleaner Production*

## V | MOMENTUM IS BUILDING

Recent years have seen the emergence of far greater awareness of the detrimental impacts of single-use plastic and microplastics, so that gradually the various stakeholders are mounting an effort to address the problem.

### GOVERNMENTAL

Governments globally are increasingly proactive in tackling plastic pollution, with more than 50 governments having banned at least some types of single-use plastics. China, the world's largest producer of single-use plastics, announced in 2020 that it would ban non-recyclables other than degradable bioplastics by 2025. India and several other countries have imposed levies and taxes on the manufacture of such products. With the EU's 2021 **Single-Use Plastic Directive**[13] and Germany banning single-use plastic already in 2021, other European countries are following (e.g. France in 2022, the UK in 2023). New EU rules - first proposed by the European Commission in November 2022 - aim to support overall goals to reduce packaging waste in 2030 by 5% (compared with 2018 levels) and 15% by 2040.

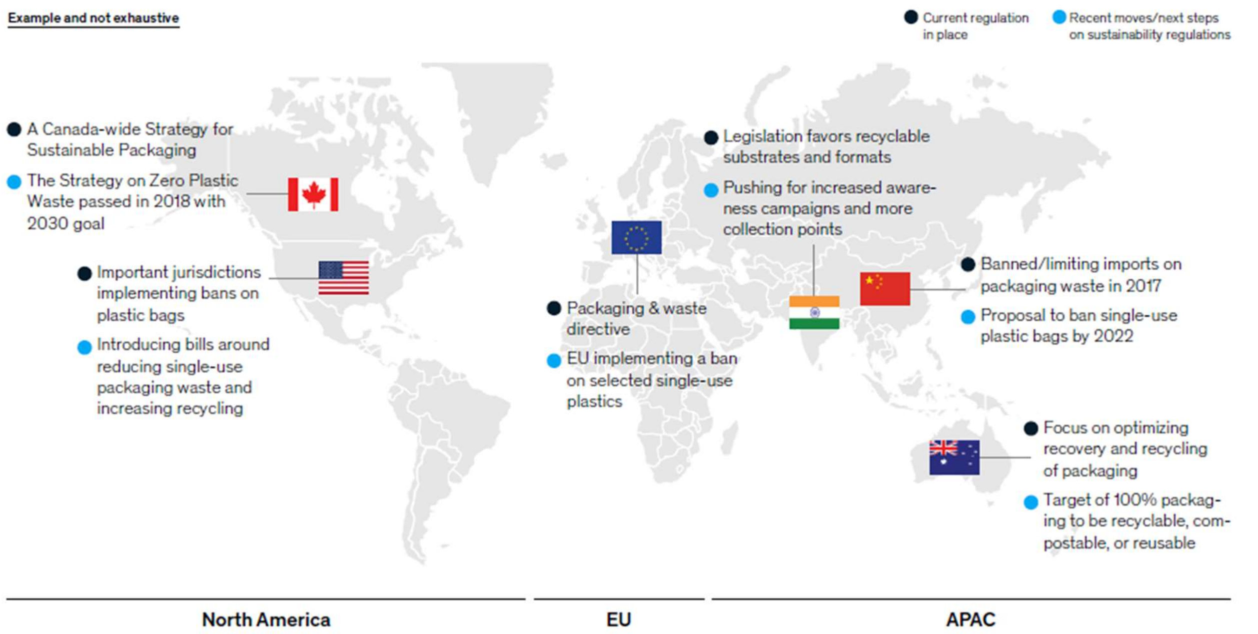
And governments' addressing of the problem may go beyond just laws and treaties: The French government's recent legal action with respect to white plastic pellets washing up on Brittany's beaches is strong testimony to that. In addition, governments can be expected to further incorporate sustainability considerations into their purchasing contracts.

At an inter-governmental level, in 2022 UN member states (the UN Environment Assembly) agreed to negotiate **a legally-binding global treaty on plastic pollution by the end of 2024**. This treaty is intended to tackle not only plastic pollution in the oceans but also the full lifecycle of plastics from production to disposal. Fingers crossed!

[12] Center for International Environmental Law (CIEL)

[13] Certain SUP fully banned, PET bottle recycling / recycled targets + EPR, labelling

**Plastics Regulatory Activity**




*Source: McKinsey*

### CONSUMER AWARENESS

Helped by respected campaigners like David Attenborough, consumer awareness of the pollution problem is rising around the world, although hasn't hit anywhere near the same degree of urgency as has climate change. It's time for Greta Thunberg to focus on PET bottles and not just pizza boxes [14]! In supermarkets, arms are reaching out for paper-packaged products instead of their plastic alternatives, and families are taking their waste sorting more seriously. For the most environmentally-proactive consumers, scattered outlets are allowing them shop with refillable containers. But broad-based consumer action will only emerge with greater awareness of the problem and when better alternatives are available.

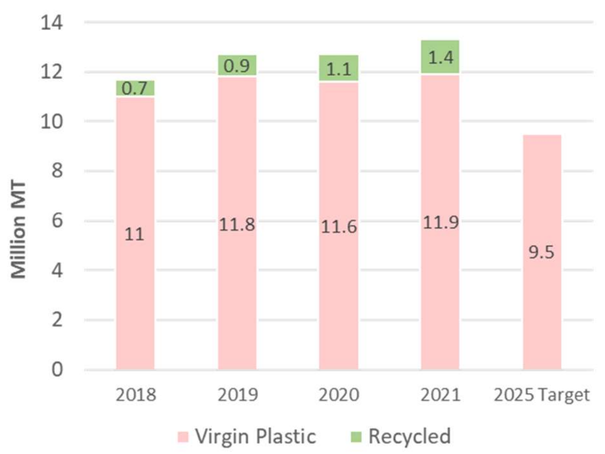
### CORPORATIONS

Many global fast-moving consumer goods (FMCG) companies have made ambitious recycling commitments: Evian water bottles will be manufactured with 100% recycled plastics by 2025; Unilever has pledged to make 100% of its plastic packaging recyclable by the same year; Walmart has announced that, by 2025, 100% of the packaging for its private-label products will be recyclable. In addition, several large recycling systems or companies (e.g. Veolia) have built strong businesses around recycling HDPE, PP or PET waste. In addition, chemical companies are also increasing their efforts to diversify their recycling portfolios and adapt more plastics to mechanical recycling as well as develop chemical recycling technologies. Lastly, an increasing number of companies are putting greater emphasis on designing for recyclability.

In 2018 many of the leading FMCG companies signed up to voluntary reduction targets under the **New Plastics Economy Global Commitment**. Targets include metrics on reducing fossil fuel based virgin plastic use (and increasing the recycled PET mix), as well as eliminating the most problematic plastics. However, in its 2022 report (reviewing 2021) the Ellen MacArthur Foundation data shows that progress has been slow, so that many companies will likely miss their targets and indeed some participants are even going backwards. For example, recycled material amounts to just 10% of plastic packaging used by pact signatories. Reusable containers, the most environmentally friendly form of packaging, amounted to only 1.2% of the total in 2021, and that figure has been declining.

[14] https://www.insider.com/greta-thunberg-mocks-andrew-tate-about-his-arrest-pizza-boxes-2022-12

**New Plastics Economy Global Commitments**




*Source: Ellen MacArthur Global Commitment 2022 Progress Report*

A major barrier to plastic packaging suppliers more aggressively reducing their plastic pollution is that today they are not actually responsible for the end-of-life of their product. Neither are the B2C companies that use the plastic to make or package their own products. Instead, the cost of collecting, sorting, and recycling plastic is borne by taxpayers. Hence the attractiveness of imposing some sort of '**Extended Producer Responsibility**' back up the supply chain.

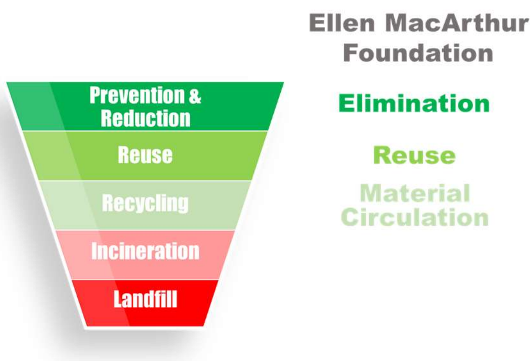
### LITIGATION

Like the challenge to Shell in 2021, when a Dutch court agreed with environmentalists that the oil major was not doing enough to reduce its carbon emissions, activists are targeting major FMCG companies in the courts for their lack of progress in reducing their plastics footprint. The most high-profile case is in France against Danone; French law imposes a duty of vigilance on larger companies over the environmental and social impact of their activities. Other multinationals are in the sights of activists: Unilever, PepsiCo, Coca-Cola, Mondelez, Diageo and Mars to name but a few. A recent study from the philanthropic group Minderoo Foundation suggested that liability risks for plastics-related companies could exceed US$20bn in the US alone over the 2022-2030 period and "orders of magnitude" beyond that.

## VI | WHAT ARE THE SOLUTIONS?

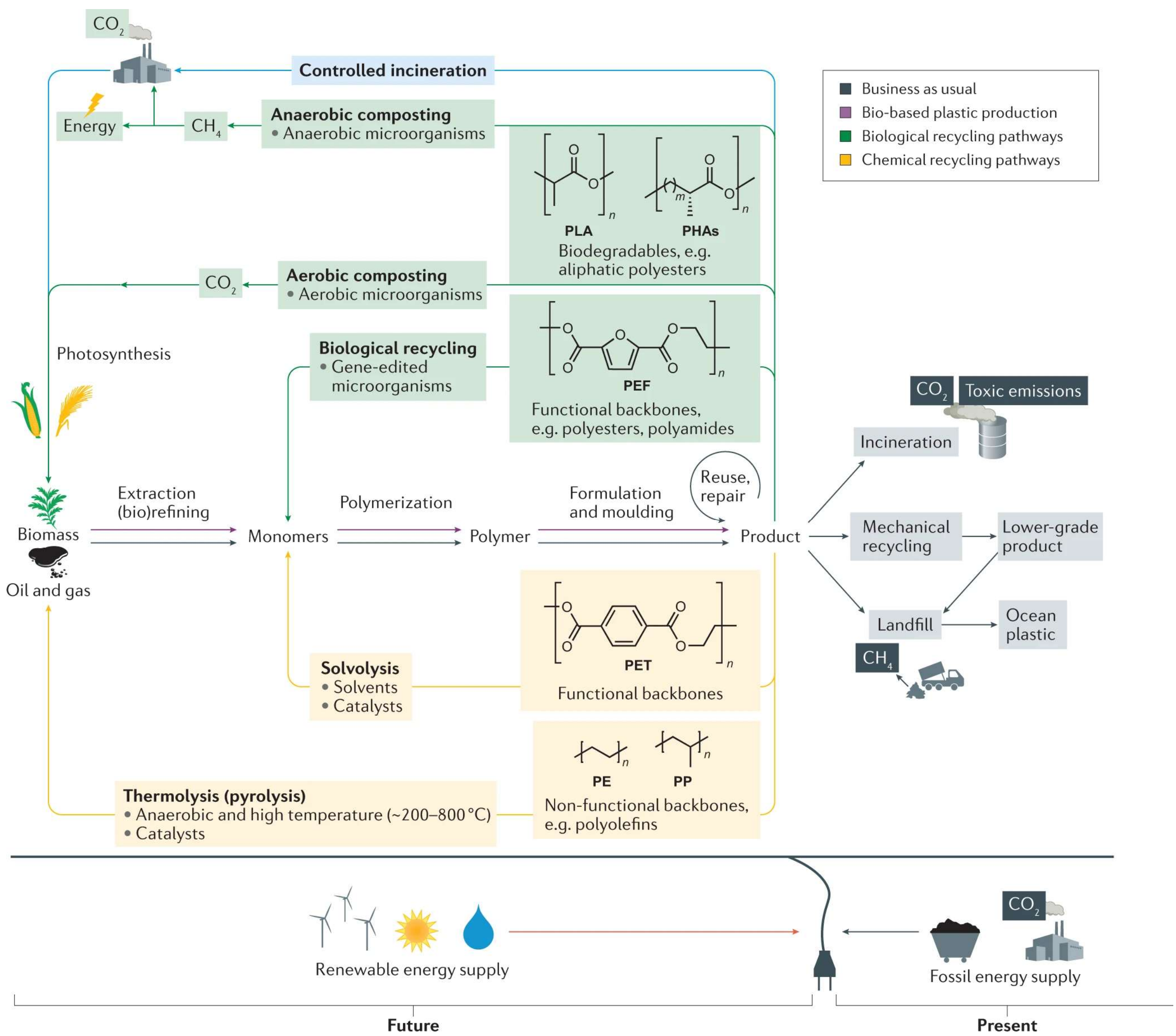
Meaningfully reducing plastic pollution will come down to deploying the various tiers of the classic waste "pyramid" (with a redefinition by the Ellen MacArthur Foundation of "recycling", as part of their extensive Circular Economy work, to 'Material Circulation'). The lower-most tiers - sending plastic waste to landfill or incineration - are the least desirable options, although they still represent mainstream approaches in the vast majority of countries today.

**Plastic Pollution Reduction Strategies**




*Source: Industry sources; Ellen MacArthur Foundation*

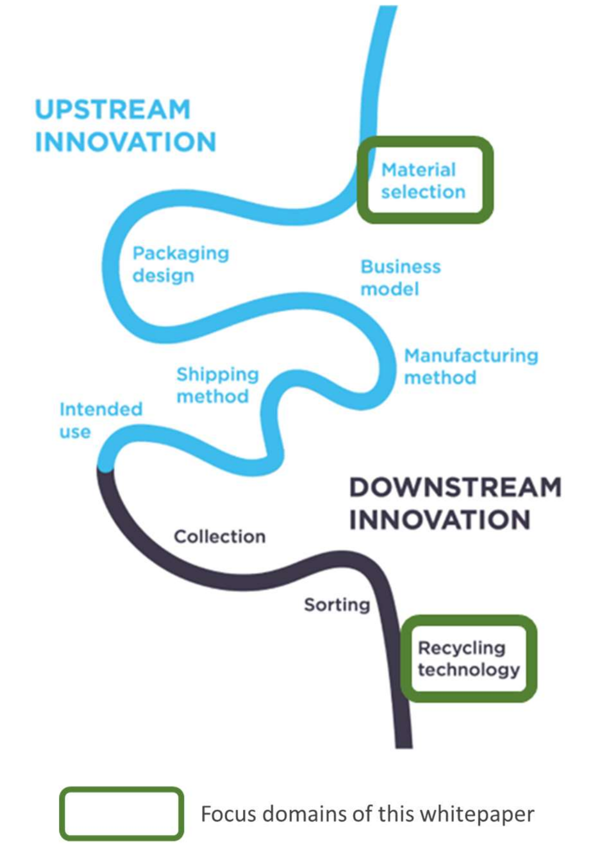
## The Circular Plastic Economy




*Source: Nature.com*

The Ellen MacArthur Foundation divides areas of "innovation" tackling plastic pollution into upstream and downstream portions. In relation to CleanTech Capital Advisors' activities and clients, the '**Material Selection**' and '**Recycling Technology'** domains are what we focus on here with respect to "solutions".

**Plastics Pollution Reduction Innovation**




*Source: Ellen MacArthur Foundation*

### PREVENTION & REDUCTION

Most single-use plastics are (by definition) discarded after their first use; the most effective solution for reducing such plastic waste is therefore to reduce its consumption. Efforts are already being made in that respect: retailers are eliminating the use of plastic shopping bags, takeouts are promoting refillable cups and traditional "silverware", plastic straws are being banned. These are significant steps, but it is not realistic to expect near- or medium-term transformations - plastics are too cheap and convenient, and the plastics waste problem has yet to work its way up the priority list in many jurisdictions. Moreover, even in the long-term, too many plastics are used for crucial single-use applications: think about their critical role recently in combatting COVID-19. So, while efforts are essential here, the complete elimination of single-use plastics seems highly unrealistic.

### REUSE

After reducing consumption, reuse is the next best alternative. Reuse maintains the integrity and purpose of the product and has minimal environmental impact because washing is typically the only processing required. Plastics manufacturers are producing an increasing number of reusable containers that are designed expressly for long-life and increased utilisation. But the application of reuse is limited, especially for containers that hold food, drinks, as well as chemical or toxic substances. Certain refillable hard plastic bottle systems are in use, but especially for applications such as food grade packaging, reusability is still difficult to apply.

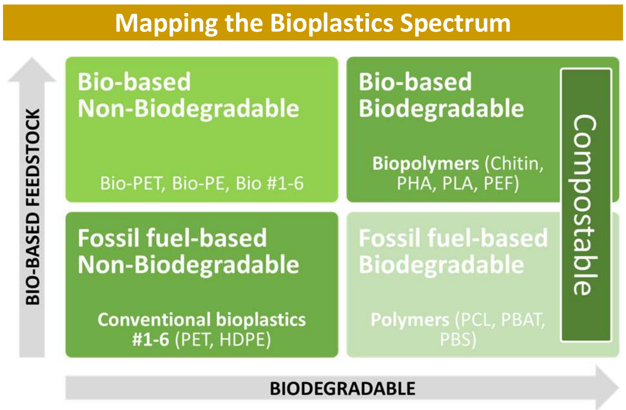
### MATERIAL SELECTION

So, if we cannot completely eliminate single-use plastics and with reuse being challenging, how about adopting more sustainable feedstock materials for their supply? This is currently an area of significant start-up activity.

Before diving into alternative materials though, how strong is the case for replacing single-use plastics with those time-honoured solutions, glass and paper / cardboard? The success of plastic as a packaging material over the past half century comes down to its impressive characteristics across a vast range of applications; after all, like for so much, packaging material choice is a trade-off. What has changed though is that the criterion of plastic pollution (and carbon footprint) – which didn't factor before – now weighs very heavily in packaging material selection. As a result, the comparisons improve for both glass and paper / cardboard; nonetheless, in many applications they just cannot meet (alone, more on this below) either the performance requirements (a "deal-breaker") or costs of plastic (important but less critical). So there is no escaping it: alternatives must be found with the qualities of plastics without the environmental downsides: this opens up the opportunity for more environmentally sustainable plastics, commonly referred to as bioplastics.

### BIOPLASTICS

'**Bioplastic**' can mean that a material is 'biobased' (refers to its feedstock) or '**biodegradable**' (refers to its end of life); furthermore, '**compostability**' is a subset of biodegradability. Therefore, a petroleum-based plastic that is biodegradable (e.g., PBAT) counts as a bioplastic, as does a biobased plastic that is not biodegradable (e.g. bio-PET). The majority of bioplastic innovators bridge the intersection of biobased and biodegradable, seeking to maximise the bio-benefits.




*Source: CTVC*

– Bio-based: Over the past 20 years there has been significant innovation with respect to bio-based feedstocks. The first wave (1st Generation) of such 'white biotech' innovation – applying to both biofuels and biomaterials (including plastic) - was with carbohydrate-rich feedstocks such as cereals, plant oils, sugarcane or other comestible matter. Bio-based polymers similar to conventional polymers are produced by bacterial fermentation processes by synthesizing the building blocks (monomers) from such renewable resources. However, given fine supply-demand equilibrium in food markets – despite only limited volume crossover to biofuels / biochemicals[15] – usage of 1st generation feedstock has been seen to present an unacceptable risk to global food supply (the so-named "Fuel vs. Food" debate). While 2nd generation (non-comestible) feedstocks such as lignocellulosic biomass (starch and cellulose), fatty acids and organic waste are seen as an improvement, through their being harvested from agricultural land does still present trade-offs. As a result, bio-based polymers, which are found "naturally", such as proteins (casein), nucleic acids and polysaccharides (collagen, chitosan, etc.) have generated enormous interest in recent years in terms of technological developments and their commercial applications.

– Biodegradability: Biodegradable plastics are plastic materials that are capable of being biodegraded, i.e., completely or partially converted to water, carbon dioxide or methane, energy, and/or new biomass by microorganisms such as bacteria or fungi. "Compostable" plastics are a subset of biodegradable plastics that break down under specific conditions (i.e. elevated temperatures and a controlled environment that is typically achieved during industrial composting). Some biodegradable materials (e.g. PBAT) are fossil fuel derived, and therefore may face increasing regulatory challenges as more bio-based biodegradable materials emerge. Today, in some cases the former and latter are blended to meet regulatory thresholds vis-à-vis bio-based feedstock content but also the techno-economic requirements of the application. Due to incidences of over-hyped biodegradability and compostability, regulators are increasingly establishing strict standards and certification procedures. For example, in the EU, certified industrially compostable materials must meet four requirements:

1. Disintegrate into fragments that are no longer visible;
2. Biodegrade and convert into carbon dioxide, water vapour and biomass;
3. Leave no trace of heavy metals or fluorinated chemicals;
4. May not contain by-products with harmful effects on plants.

### NATURAL PLASTICS

The EU's SUP Directive (2019/904) mentions in Article 3 the definition of "plastic" and "natural polymer" (as opposed to "chemically modified polymer") in order to identify materials that would be subject to exclusions from the SUP Directive. The ECHA[16] guideline states: "**Natural polymers are understood as polymers which are the result of a polymerisation process that has taken place in nature, independently of the extraction process with which they have been extracted**", differentiating them from any plastics which have been derived from fossil fuel feedstocks, whether biodegradable or not. Such natural polymers / plastics include:

[15] Currently, 0.02% of global agricultural land use is devoted to producing precursors for bioplastics [BCC Research], although the proportion is far higher for biofuels

[16] The European Chemicals Agency

- proteins (polymers of amino acids and nucleic acids)
- DNA / RNA (comprised of nucleotides)
- Starches / carbohydrates, natural polymers formed from glucose
- chiton, found for example in the external skeleton of crabs and spiders
- glycogen
- natural rubber

Much of the more recent innovation to replace fossil fuel derived plastics relates to such "natural" plastics.

**Plastics Feedstock Comparison**

| | Petroleum-based Polymers | Bio-based Feedstock | |
|---|---|---|---|
| | | Partial or Fully Bio-based Polymers | "Natural" Polymers |
| **Description** | Synthetic polymers like PET, PP, nylon, PS and epoxy (commonly known as 'plastic') are derived from petroleum hydrocarbons. | Bio-based as original feedstock comes from agriculture.<br>Polymers not directly extracted from a plant / bacterium but synthesized by using (bio)chemical processes from partial or full bio resource.<br>Chemical structure of biomass feedstock not maintained. | No chemistry step - direct use of biomass as polymeric material.<br>Polymers are synthesized by living organisms or obtained by the fermentation of living organisms. |
| **Examples** | PS, PP, PET | PLA, Bio-PET | CareTips[17], Ooho[18] |

*Source: Industry sources*

**Bioplastic Feedstock Generations**

| | 1st | 2nd | 3rd |
|---|---|---|---|
| **Description** | Rich in carbohydrate and can be consumed by humans & animals | Crops & plants unsuitable for human / animal consumption (e.g. cellulosic, waste vegetable oil) | Emerging feedstocks |
| **Pros** | ▪ High yield & efficiency<br>▪ Mature technology / processes | ▪ No food competition | ▪ No agriculture / food competition |
| **Cons** | ▪ "Food vs. Fuel" competition | ▪ Agricultural land competition | ▪ Relatively immature |
| **Examples** | Corn, wheat, sugarcane, potato, sugar beet, rice and plant oil | Wood & short-rotation crops (poplar, willow, miscanthus), wheat straw, bagasse, corncobs, palm fruit bunches, switch grass | Algae, seaweed, proteins (e.g. casein) |

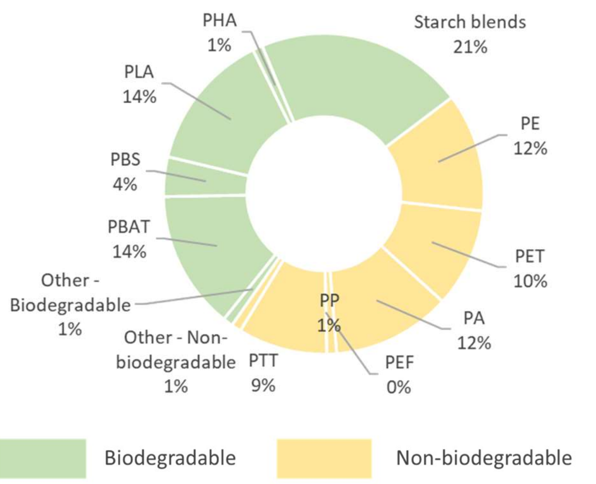
*Source: Industry sources*

According to European Bioplastics 2.4M tonnes of bioplastics was made globally in 2021, with biodegradable bioplastics accounting for almost 60% of that. This volume is expected to triple to around 7.5M tonnes by 2026 (though still represent less than 2% of global plastic production).

[17] From Lactips

[18] From Notpla

## Bioplastic Production Capacity by Material[19] (2019)

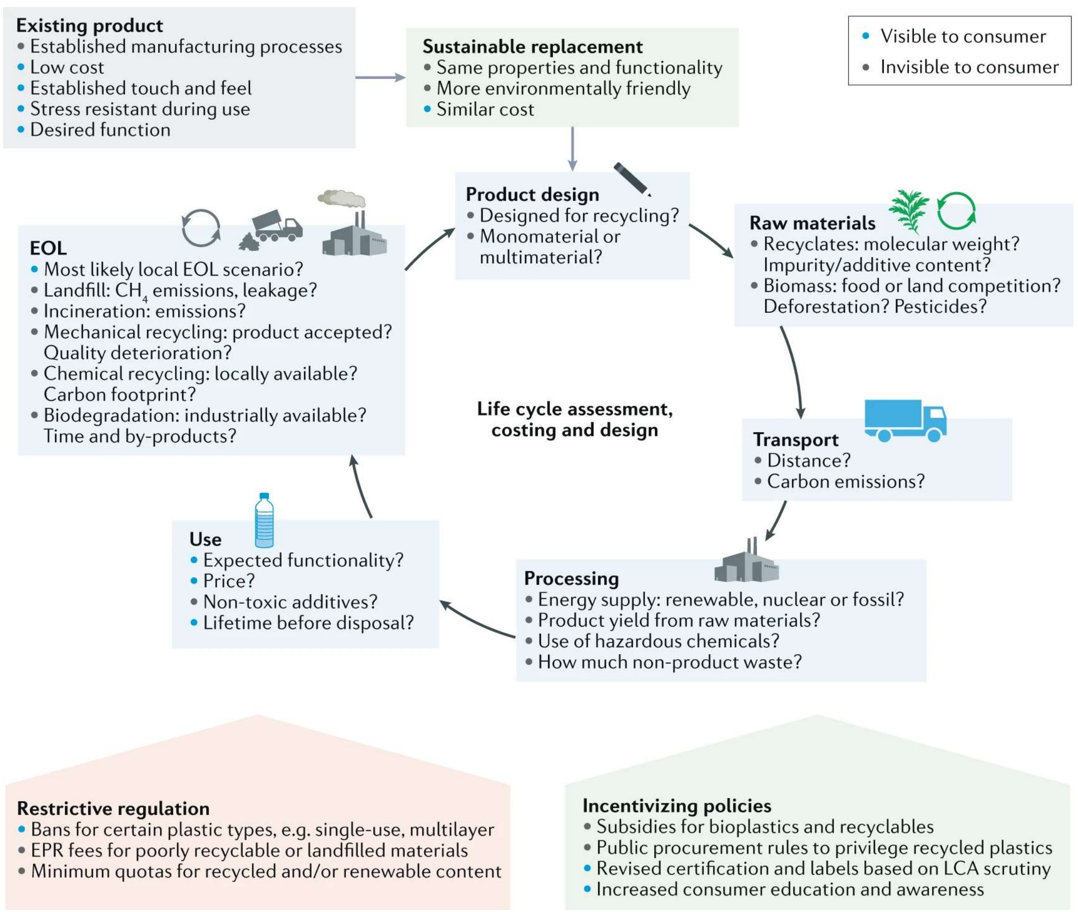



*Source: European Bioplastics*

Despite all of the new material development underway, the reality today is that alternative bioplastics that don't involve some other functional compromise aren't yet available for <u>all</u> applications, at least cost-competitively and / or at scale. But that situation will improve over time. One usage to allow newer bioplastics technologies achieve initial penetration and scale over time is as a barrier layer in paper packaging, where paper would otherwise not have been a functionally realistic alternative. Paper is inherently porous and hydrophilic (attracts moisture) and therefore for perishable products only provides limited barrier and strength; plastic on the other hand can provide a high oxygen and moisture barrier as well as structural integrity.

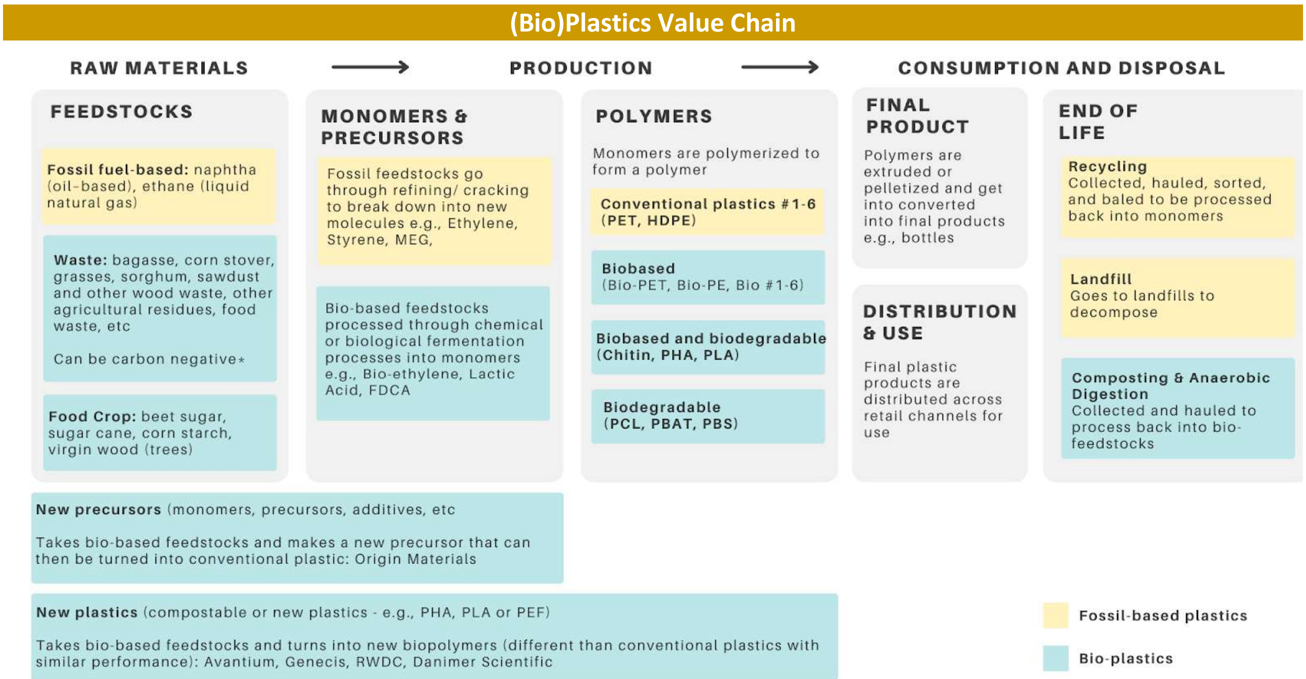
In addition to techno-economic performance, an imperative for any supplier and user of bioplastics is to conduct full lifecycle analyses of the feedstock as well as the broader impact of its adoption on the respective supply chains: is the feedstock (and any associated additives) truly sustainable (not diverted from another essential use)?, does it have a negative CO2 impact (transport, processing …)?, is its end-of-life sustainable (biodegradable, recyclable …)?

## Implementation Framework for Companies Switching to Sustainable Materials / Plastics




*Source: Nature.com*

[19] Only bioplastic versions of polymers (e.g. bio-PET, not PET)




*Source: CTVC*

## RECYCLING TECHNOLOGY

Efficiently recycling plastic by conventional means is notoriously difficult, and only 9%[20] of all plastic ever made has been recycled into new plastics. This dismally low rate stems from a variety of factors, including the nature of the plastics themselves, the efficacy of the collection and sorting processes, availability / proximity of capable recycling sites. All of these impediments will have to be addressed to meaningfully raise recycling rates.

Much of the plastic that could economically be recycled, e.g. PET used for bottles, ends up in landfill due to poor collection and / or sorting; it is estimated **that 30%-35% of potentially recyclable material is lost due to collection and sorting inefficiencies**. The most popular PET for recycling is colourless and without printing, as it is more versatile in terms of reuse.

Other plastics – such as salad bags and other food containers – find their way to landfill because the economics of recycling (mainly handling and yield related) are poor or they are made up of a combination of different plastics / materials that can't be easily split apart in a recycling plant. While the latter such multi- (vs. mono-) layer packaging (e.g. chip bags or plastic packets) presents a challenge for recyclers, it is driving innovation with respect to delamination techniques. Plastic that's been printed on is also often unrecyclable or, at a minimum, degrades the value of the recycled plastic given the ink contamination.

More generally plastics other than PET (resin identification code #1), HDPE (#2) and PP (#5) – so PVC (#3), LDPE (#4), PS (#6) and "Others" (#7) - are unrecyclable by most municipal recycling facilities (MRFs) in most countries; this is due to either their poor recyclability or the very poor economics for doing so. The best case for these products frequently is that they are recycled into construction materials for roads and buildings or are used as fuel in industrial plants.

[20] Science Avances

**Composition of Plastic Waste Streams**

| Properties | Chemical Name |
|---|---|
| **Mono** | One polymer |
| **Mixed** | Blend of PE, PP, PET, PS, PVC, variety of minor components, or unknown polymers |
| **Multi-layer** | Often PP/ PA, PP/PET, PET/PE/aluminium foil, waste electrical & electronic equipment (WEEE) plastics |
| **Contaminated** | Organic and inorganic impurities, other polymers, other non-polymers (wood or paper), non-ferrous metals (e.g., aluminium), chemicals, PVC |
| **Composites** | Polymer matrix, thermoset or thermoplastic, fibre reinforced plastics (FRP), glass FRP, carbon FRP, glass fibre reinforced polypropylene (PP-GF) |

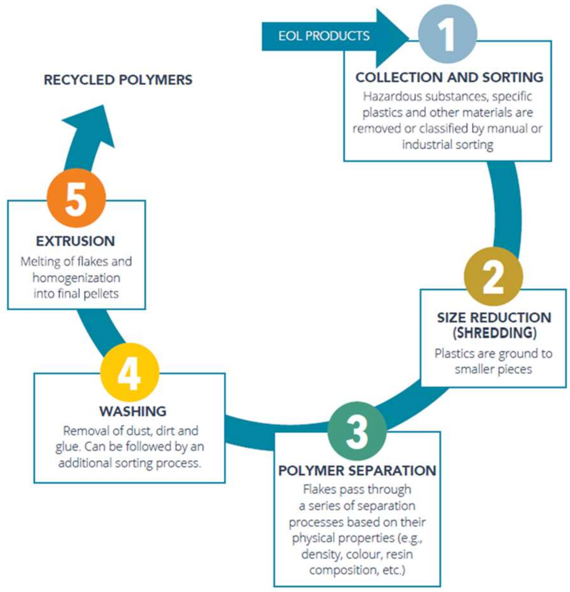
*Source: The European Chemicals Agency*

Demand for certain recycled materials has risen rapidly over the past few years, driven, among other factors, by FMCG companies' commitments to using a certain share of recycled raw materials. Other factors though constrain the use of new recycling technologies, e.g. **regulatory approval for food-grade plastics** as well as the **complexities of recycling complex (multi-layer) packaging**. Nonetheless, the recycled plastic market is starting to follow that of recovered paper (RCP) in being an international commodity market in its own right, especially for the #1 recycled plastic PET (becoming 'rPET'). rPET can be cheaper to produce than virgin PET, but because of its sustainable credentials can sell at higher prices.

## MECHANICAL RECYCLING

The simplest (and mainstream today) plastic recycling processes are "mechanical" and involve collecting, sorting, shredding, washing, melting and pelletising. During mechanical recycling, waste is recycled into secondary raw materials without changing the basic structure of the material. The actual particular processes vary based on plastic resin or type of plastic product.

**The Plastics Recycling Process - Mechanical**




*Source: EuRIC*

Ongoing innovations in recycling technologies have made the mechanical recycling process simpler and more cost-effective. Such technologies include reliable detectors (increasingly FT-NIR) and sophisticated decision and recognition software that collectively enhance the productivity and accuracy of automatic sorting of plastics.

Mechanical recycling today cannot process blended materials. Consequently, during the **product design phase**, the use of additives (such as glue) needs to be considered carefully. For some products, such as beverage containers and food-grade packaging, design and material standardisation has become the norm, but other types of plastics applications still lack explicit design standards for recyclability, which in turn prevents mechanical recycling from achieving its full potential. Newer technologies - such as 'purification' - that go beyond conventional mechanical recycling, are emerging. These work by dissolving plastics into solvents and extracting additives and dyes, leaving a decontaminated polymer. These technologies focus on the same materials as conventional mechanical recycling (i.e. PET, HDPE and PP) but have yet to see large-scale deployment.

Additionally, because some materials degrade when heated, such plastics can be recycled only once or twice before the next option is "downcycling" (the conversion into a lower value material).

### CHEMICAL RECYCLING

Beyond mechanical recycling, several new chemical technologies are emerging that address limitations in material applicability as well as the complexity of mechanical recycling processes. Such chemical recycling is a form of "**plastics regeneration**" in circular-economy terms: instead of a system where some plastics are rejected because they are the wrong colour or made of composites, chemical recycling could see all types of plastic fed into an "infinite" recycling system that "unmakes" plastics back into raw feedstock, so they can then be used to make plastic or other useful materials again. Chemical recycling can also potentially tackle complex mixed plastics wastes not sorted adequately in mechanical recycling facilities.

While a distinction can be made between plastics-to-fuels (PTF) and plastics-to-plastics (PTP), recent activity is notable for the level of engagement of chemical corporates and the interest in plastics-to-plastics technology.

- Plastics-to-Fuel (PTF): Plastics-to-fuel recycling converts plastics into the equivalent of crude oil or petrochemical feedstock that can be fed into refineries or chemical plants, respectively. PTF is realised through a variety of technologies, the most common being '**pyrolysis**'. Pyrolysis is based on the natural geological process that produces fossil fuels and uses heat to decompose materials in an oxygen-starved environment. The outputs are synthetic oil and gas, which have greater calorific value than coal and can be put to a variety of uses. One big attraction of pyrolysis is that its feedstocks are types of plastic that have no value for present-day recycling operations, i.e. codes 3, 4, 6.
- Plastics-to-Plastics (PTP): Plastics-to-plastics recycling involves decomposition, or 'monomer recycling', and is a perfectly circular option that reverses the original polymerisation process, transforming the plastics back into stable monomer molecules that can then be combined to create the same grade and type of plastic as the original waste.

Despite significant interest in chemical recycling, the technologies are not without their drawbacks. Like mechanical recycling, the presence of contaminants can make recycling more challenging and even biodegradable plastics in waste streams are reported to cause problems. Critics also refer to the relatively high energy requirements in more developed processes and the production of unwanted, potentially dangerous by-products (generated in pyrolysis).

The various PTF and PTP recycling technologies have their respective pros & cons but importantly, activity in the space is accelerating and in some cases demonstration-scale or even industrial scale plants are under construction. The lower costs and ease of application of PTF technology (such as pyrolysis) provide a viable alternative for treating plastic waste until the loop can be fully closed on all plastic materials via PTP.

**Plastics Chemical Recycling Technologies**

| Conversion \| Plastics-to-Fuel | Monomer Recycling \| Plastics-to-Plastics |
|---|---|
| ▪ Pyrolysis | ▪ Chemolysis |
| ▪ Fluid catalytic cracking | ▪ Hydrolysis |
| ▪ Hydrogen technologies | ▪ Methanolysis |
| ▪ KDV[21] process | ▪ Glycolysis |
| ▪ Gasification | ▪ Aminolysis |
| ▪ Hydrothermal liquefaction | ▪ Other methods |
| ▪ Other methods | |

*Source: Boston Consulting Group*

## VII | RELEVANT START-UPS IN EUROPE

As a global problem, innovation directed at tackling plastic pollution - involving new materials, tracking, sorting and recycling technologies - is accelerating worldwide. PitchBook has identified 120 companies globally addressing the sustainable packaging ("Material Selection" according to the terminology used here) space alone (not including "Recycling Technologies").

[21] KDV = chemical-catalytic pressureless conversion to oil

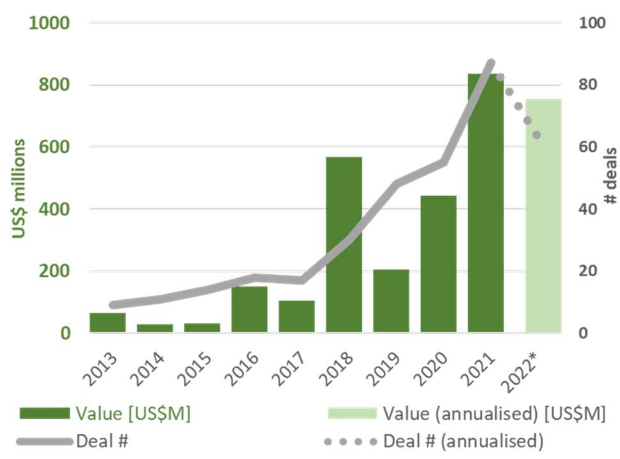
| Natural Plastics Comparison & Associated Start-ups | | | | |
|---|---|---|---|---|
| | **Pros** | **Cons** | **Comment** | **Examples** |
| **Natural proteins** | ▪ Water soluble<br>▪ Biodegradable<br>▪ Edible<br>▪ Recycling compatibility | ▪ Potentially competing with food usage | ▪ Various different sources (casein, peas …)<br>▪ Potentially more suitable for blends than standalone | ▪ **Lactips**<br>▪ **Xampla** |
| **Starch** | ▪ Edible | ▪ Food competition | ▪ Polysaccharide | ▪ Do-Eat<br>▪ Ecoshell |
| **Sugarcane** | ▪ Edible | ▪ No thermoplastic industrialisation<br>▪ No raw material supplier | ▪ Bioethanol extracted from sugarcane | ▪ Candy Cutlery<br>▪ Earth Renewable Technologies<br>▪ Renouvo |
| **Seaweed / Algae** | ▪ Water resistant<br>▪ Edible<br>▪ Biodegradable<br>▪ Rapid growth | ▪ Not drop-in for existing plastics supply chain<br>▪ Require chemical cross-linking | ▪ Polysaccharide | ▪ Evoware<br>▪ Loliware<br>▪ Oceanium<br>▪ **Notpla** |
| **Mycelium** | ▪ Moldable<br>▪ Lightweight<br>▪ Hydrophobic<br>▪ Biodegradable | ▪ Low TRL currently for packaging applications | ▪ Mushrooms / fungi | ▪ Ecovative<br>▪ **Magical Mushroom Company** |
| **Food waste** | ▪ No competitive use<br>▪ Potentially inexpensive | ▪ Feedstock stability<br>▪ Feedstock supply chain complexity | ▪ Various different food types – carrots, crab (shells) … | ▪ Genecis<br>▪ Shellworks<br>▪ Great Wrap<br>▪ Feltwood<br>▪ **EnvoPAP** |
| **Cellulose** | ▪ Ample supply<br>▪ Additives may not be sustainable | ▪ Not water soluble<br>▪ Not normally edible | ▪ Polysaccharide<br>▪ Often based on sawdust / waste wood | ▪ Origin Materials<br>▪ **NaturBeads**<br>▪ **Paptic**<br>▪ **Sulapac** |

**= European Company**

*Source: CleanTech Capital Advisors*

According to PitchBook, worldwide VC investment in Sustainable Packaging providers has grown steadily over the past decade, peaking at US$834M across 87 deals in 2021, with deal count up 58.2% y/y. Through the end of Q3 2022, Sustainable Packaging deal count retreated y/y on an annualised basis (47 deals for the first nine months), though full-year deal value may have less.

## Global VC Activity in Sustainable Packaging




*Source: PitchBook*

Leading legislation globally on banning single-use plastics, Europe is a hotbed of innovation, with many technology pioneers emerging. Funding for the space is relatively robust, though less so than in other cleantech sectors such as 'ClimateTech' and the 'Hydrogen Economy'. Also, activity is far greater in Materials than Recycling, the latter perhaps experiencing the traditional investing challenges of the waste sector (CapEx intensity, plant complexity, limited corporate interest ...). Nonetheless, given the magnitude of the problem and the extent of innovation in Europe, we expect "Solutions to Address Plastic Pollution" to be a key theme for European investors in the years to come.

## Relevant Start-ups

| | Europe | Rest of World |
|---|---|---|
| Materials | CuanTec [UK] | Ecovative [US] |
| | Fiberwood [FI] | Loliware [US] |
| | **Lactips [FR]** | Mycel [KO] |
| | Magical Mushroom [UK] | MycoWorks [US] |
| | **Notpla [UK]** | Tipa [IL] |
| | Oceanium [UK] | |
| | **Papkot [FR]** | |
| | **Paptic [FI]** | |
| | **Pond [DK]** | |
| | **Sulapac [FI]** | |
| | **Xampla [UK]** | |
| Recycling | Carbios [FR] | Agilyx [US] |
| | DePoly [CH] | GreenMantra [CD] |
| | Iniqa [NL] | Licella [AU] |
| | Plastic Energy [UK] | Loop Industries [CD] |
| | **Polymateria [UK]** | PyroWave [CD] |
| | **QuantaFuel [NO]** | UBQ Materials [IL] |
| | **Recycling Technologies [UK]** | |
| | Saperatec [DE] | |

**= Company profile included**

*Source: CleanTech Capital Advisors*

French company **Lactips** ("plastic" rearranged, with a wordplay on "lac") is a pioneer in 'natural' plastics based on casein (a milk protein) which are compostable / biodegradable, water soluble, edible and usable in multi-layer solutions given their excellent barrier properties. The company was founded in 2014 by Marie-Hélène Gramatikoff (plastics engineer and business strategy specialist) and Frédéric Prochazka (lecturer-researcher at Saint-Etienne University), but has seen a change in leadership to Alexis von Tschammer in 2022. Also in 2022, the company completed construction of a 2,500m$^2$ facility to produce its 'CareTips' pellets. Current investors include BPI SPI, Mitsubishi Chemical, BASF and Demeter Partners.

UK-based **Xampla** uses 'supramolecular engineered protein' (SEP) technology to create bio-based products from plant protein (currently specifically peas). SEP technology untangles the plant-based proteins and reassembles them without altering the chemical structure of the molecules, so that they can be organized into plastic-like materials such as films, gels and capsules. Current investors include Amadeus Capital Partners and Horizon Ventures.

**Notpla** ("not plastic") creates advanced packaging solutions made from brown seaweed extract (alginates) and other natural materials (e.g. waste fibre from the seaweed) as an alternative to single-use plastic. Nature's way of wrapping liquids utilising membranes, from egg yolk to cells or fruits, as well as traditional food technologies like 'spherification' techniques for packaging, are the startup's motivation. Notpla's first breakthrough product 'Ooho' is a natural, flexible container for liquids (water, soft drinks, sauces, or even alcohol) that biodegrades in 4-6 weeks or may even be eaten. Current investors include Astanor Ventures, Horizon Ventures and Sky Ocean Ventures.

**Papkot** is a French start-up providing paper-based food & beverage products. The solution involves a molecularly-fine silica layer to bind the barrier layer to the paper substrate. The company currently works with tollers to create its packaging but is considering options to scale-up capacity. To-date Papkot has not taken in any VC funding.

**Paptic** ("paper" + "plastic") is a spin-out of Finland's VTT and was founded in 2015. As an alternative for plastic film, the firm uses fibre from wood pulp to produce a "paper-textile", providing (just) the advantages of plastic without the disadvantages of paper (for packaging applications). The firm also uses some bio-based, biodegradable, man-made fibre, and crucially does not use any fibres that traditionally make up plastic products. Paptic goes beyond just producing the material to also providing actual packaging products like e-commerce mailers and bags on repurposed paper machines, but with its patented foam-forming technology (which involves less wastewater than the traditional paper-milling process). The company reached 11M€ in revenues in 2022. Current investors include ITOCHU Corporation and Springvest.

**Pond** is a Danish startup producing bio-resin systems ('bio-binder') that are 95%+ biobased (starch), fully biodegradable and according to the company, usable with virtually any natural fibre (flax, hemp, pineapple, palm leaves, cotton, banana and jute) resulting in fully biodegradable products. The technical specifications vary depending on which natural fibers are chosen. The company targets various verticals including automotive, wind power, airplane, textile, construction and plastic packaging. In 2021 Pond signed an agreement with adidas on the development of a recyclable, high-performance material derived from plant waste.

Founded in 2016 in Finland, **Sulapac** creates fully biodegradable packaging materials from 'biocomposite' (a combination of wood pulp and natural binders) that can be molded, shaped and mass-produced on existing plastics conversion lines. These biocomposites are designed to break down within 29 days in an industrial composter (around the same rate as a piece of wood) and are marine environment biodegradable. The company had achieved particularly strong traction in the cosmetics vertical. Sulapac's current investors include Bonnier Ventures, Sky Ocean Ventures and Chanel.

**PolyMateria** is a British start-up incubated at Imperial College that develops enhanced biodegradable products based on its proprietary 'Biotransformation' technology (via a 2% by weight additive). The Biotransformation technology is designed to trigger a chemical conversion which attacks the crystalline and amorphous region of (traditional) plastic's polymer structure, turning it into a biodegradable wax-like substance (rather than leave, however minute, microplastic). The company is focusing initially on the packaging space but intends ultimately to address other verticals requiring truly biodegradable plastics. In 2020 PolyMateria completed a £15M funding round led by Planet First Partners, to support commercial rollout.

UK-based **Recycling Technologies** provides a plastics-to-fuel solution to chemically recycle end-of-life plastic back to a synthetic oil ('Plaxx'), for a number of different applications, ranging from Plaxx-8 (a feedstock for producing new plastics) to Plaxx-30 (for heavy fuel oil). Recycling Technologies' RT700 machine is capable of processing 7,000 tons of plastics per year and is built to be mobile, being installable on sites with limited infrastructure. The company hopes to have 1,300 stations in operation by 2027 in order to reach their target production of 7M tonnes of Plaxx. Having historically mostly been crowdfunded, the company's 2022 IPO was pulled due to the departure of its CEO.

Founded in 2009, **Ioniqa Technologies** in the Netherlands is commercialising its 'Smart Materials' and 'Separation Process' technology for the recycling of PET. The process first breaks coloured PET into a coloured liquid, after which the colourants are removed, leaving behind a usable raw material than can be recycled back into plastic. Ioniqa's process produces just 30% of the CO2 that would result from manufacturing one 1kg of virgin PET. The company is currently scaling up a 10,000 MT production facility. The company has been funded by Koch Industries (a 30M€ round in 2022) and Chemelot Ventures.

**Quantafuel** is a Norwegian company specialising in converting mixed plastic wastes into sustainable fuels and chemicals via pyrolysis (so chemical recycling). Its initial Skive plant is producing 20KT/yr synthetic fuel. While the company had initially put somewhat more emphasis on purification after the pyrolysis stage, the company has embarked on an ambitious capacity expansion with its partners and customers to meet very strong downstream demand for alternative to virgin feedstock. The company has commercial agreements with a number of leading chemicals multinationals, the most important of which is perhaps BASF. Having BASF as a strategic investor (€20M invested in 2020), the two companies intend to jointly build a broad supply base for BASF's 'ChemCycling™' products. Quantafuel also counts Vitol and Kirkbi (the Lego family holding company) among its shareholders.

**CleanTech Capital Advisors considers the "Innovative Solutions Addressing Plastic Pollution" theme to be a very attractive opportunity for financial and corporate investors, though clear distinctions must be made between the Materials and Recycling Technologies space. Given the breadth of chemistries and applications for plastics today, this will not have a winner-takes-all outcome; rather many differentiated players will be able to build sizable businesses, attractive for M&A or public market listings.**

## ACRONYMS

| | |
|---|---|
| **BAU** | business-as-usual |
| **CO2e** | carbon dioxide "equivalent" |
| **FMCG** | fast-moving consumer goods |
| **FRP** | fibre reinforced plastic |
| **FT-NIR** | Fourier Transform near-infrared |
| **GHG** | greenhouse gas |
| **HDPE** | high-density polyethylene |
| **ICE** | internal combustion engine |
| **LCA** | lifecycle analysis |
| **LDPE** | low-density polyethylene |
| **MRF** | municipal recycling facility |
| **MT** | metric tonnes |
| **PA** | polyamide |
| **PBAT** | polybutylene adipate terephthalate |
| **PC** | polycarbonate |
| **PET** | polyethylene terephthalate |
| **PHA** | polyhydroxyalkanoate |
| **PLA** | polylactic acid |
| **POP** | persistent organic pollutant |
| **PP** | polypropylene |
| **PS** | polystyrene |
| **PTF** | plastics-to-fuel |
| **PTP** | plastics-to-plastics |
| **PVC** | polyvinyl chloride |
| **RCP** | recovered paper |
| **SUP** | single-use plastic |

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