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Biodegradable Plastics: Standards, Policies, and Impacts

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Plastics are ubiquitous in our society. They are in our phones, clothes, bottles, and cars. Yet having improved our lives considerably, they now threaten our environment and our health. The associated carbon emissions and persistency of plastics challenge the fragile balance of many ecosystems. One solution is using biodegradable plastics. Ideally, such plastics are easily assimilated by microorganisms and disappear from our environment. This can help reduce the problems of climate change, microplastics, and littering. However, biodegradable plastics are still only a tiny portion of the global plastics market and require further efforts in research and commercialization. Here, a critical overview of the state of the art of biodegradable plastics is given. Using a material flow analysis, the challenges of the plastic market are highlighted, and with it the large market potential of biodegradable plastics. The environmental and socio-economic impact of plastics, government policies, standards and certifications, physico-chemical properties, and analytical techniques are covered. The Review concludes with a personal outlook on the future of bioplastics, based on our own experience with their development and commercialization.

1. Introduction

Discrete historical and economic events trigger innovations.[1] In the 19th century, the demand for ivory skyrocketed in Europe and America, driving up both price and exclusivity.[2] To substitute this, a semi-synthetic plastic, Parkesine, was invented in 1862.[3] In the following decades, synthetic plastics were researched intensively, culminating with the invention of Nylon in 1938. Together with other synthetic fibers, Nylon influenced the outcome of World War II,[4] marking the dawn of the new plastic age. In 1950, each person used on average 1.7 kg of plastics.[5] By 2007, annual consumption per capita rose to 100 kg. Today the figure is $>$140 kg.[6]

Plastics have several advantages over metal and paper. Their low energy requirement in production, low maintenance, corrosion resistance, lightness, and durability have made them ubiquitous. Polymer foam insulators, for example, have improved the energy efficiency of buildings by a factor of 200.[7] In the food sector, plastic packaging increased the shelf life of products without using preservatives.[8] Yet it looks like mankind's long-term romance with plastics is starting to decline. Today, traditional plastics face public scrutiny because of their effects on human health and on the environment. To keep this multi-billion-dollar market rolling, the industry is looking to develop plastics with new properties or raw materials. The magic terms in this context are "bio-based" and "biodegradable". Such new plastics are set to substitute the current persistent ones in the packaging, single-use, agricultural, and fishing sectors.

Yet moving from traditional plastics to eco-friendly ones is a tricky challenge. The very definitions of "bio-based" and "biodegradable" are unclear. Adjectives such as "green", "circular", or indeed "eco-friendly" are even vaguer. Producers, consumers, and policy-makers are faced with a plethora of choices and approaches, where relevant information is hard to come by. This Review will try and put things in the right perspective. We will examine various aspects of biodegradable plastics, ranging from socio-economic and environmental impacts to hands-on approaches on assessing biodegradability including certifications and policies. Hopefully, these facts, definitions, and figures will help people make better-informed decisions about plastics in the future.

1.1. (Bio)degradability of Plastics in the Environment

Allegedly, the first plastic sample ever made has still not degraded.[9,10] Yet an end-of-life can be identified for products even without degradation. Plastics can be recycled, landfilled, or end up in the environment with or without modification.[11] In 2013, 32% of the 78 million tonnes of plastics produced ended up in the environment.[12] The latest estimates[13] put the number of plastic micro-pieces in the oceans at 5×10^{12}. Such particles are categorized as either primary (*1°*) or secondary (*2°*). Primary microplastics denote as-synthesized products (e.g., plastic microbeads added to cosmetic products). Secondary ones are microplastics formed by the degradation of the plastic product. Major sources of microplastics are the wear and tear of automotive wheels (60–140 ktpa, *2°*), followed by industrial loss of plastic pellets during transport (5–80 ktpa, *1°*) and the wash of synthetic clothing (10–25 ktpa, *2°*). Intentionally-added microplastics range between 50–500 tpa (*1°*).[14] Still, the compounded weight of these microplastics is infinitesimal compared to the annual global production (see below). The high amount of mismanaged plastic waste, however, will eventually form microplastics that will build up in the environment.[15] The dynamic character of our environment also causes each ecosystem to be contaminated by plastics and become part of human/animal food chains.[16,17] Thus, reducing *any* type of microplastics will bring large benefits.

All plastics undergo some degradation, either physicochemical and/or biological. Physicochemical processes include weathering (degradation due to sunlight, wind, or waves) and hydrolysis/oxidation. These processes affect all plastics and are the primary cause of microplastics.[18] Plastics that are designed to degrade by oxidation or hydrolysis processes are called oxo-degradable and hydro-degradable plastics, respectively.[19] They are usually non-biodegradable as-is and require modification. Oxo-degradable plastics are commonly fossil-carbon-derived plastics (e.g., polyolefins) with a mixture of additives. These

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additives are both prooxidants and antioxidants, the combination of which induces time-controlled oxidation. Prooxidants are often metal stearates (e.g., iron stearate) and are balanced by phenolic or phosphite antioxidants.[20,21] Photodegradable plastics are a sub-category of oxo-degradable plastics, where the oxidation process is induced by UV light (≈4% of natural sunlight).[22] Hydro-degradable plastics are often a blend of petro-based plastic with a natural polymer, such as starch.[23] Polyacrylamide (PA) is also considered as a hydro-degradable plastic given its water-holding capacity and eventual degradation into biomass.[24–27] These plastics rely on the hydrophilic nature of the polymer for their decomposition into smaller oligomers. However, both oxo- and hydro-degradable plastics are considered to cause microplastics in their end-life.

Conversely, the degradation of biodegradable plastics is caused by microorganisms (bacteria; fungal enzymes).[28] Biodegradability may vary depending on humidity, temperature, and other conditions. Ideally, plastics can degrade by aerobic and anaerobic organisms all the way to CO_2, methane, water, and edible biomass/compost. Most commercial biodegradable plastics are converted into compost rather than gaseous products. For a plastic to be compostable, the organic matter formed should be harmless to animal or plants. The compost can form either at room temperature with food waste or, more commonly, in industrial facilities at controlled temperatures (typically 58 °C). This is known as industrial compost and requires appropriate collection and sorting of the plastic waste.

Consumers often confuse biodegradable plastics with bio-based plastics (see overview in Table 1). The latter are plastics made from biomass, generally related to the use of plants as feedstock. Given their natural origin, one could erroneously assume that these plastics are also biodegradable. However, biodegradability depends on the properties of the plastic at hand, including chemical structure and crystallinity (see below). Similarly, some petro-based plastics are also biodegradable. Bio-based plastics can be considered green as they are made from renewable resources.[29] At the waste management step, a plastic is termed circular if its components are reused or recycled. Inasmuch as that plants use CO_2 for growth and CO_2 is emitted in aerobic degradation, bio-based and biodegradable plastics are circular.

Bio-based but not biodegradable plastics often structurally mimic petro-based plastics. These plastics are considered drop-in solutions as they possess the same properties as their petro-based counterparts. Some examples include bio-polyethylene terephthalate (bio-PET), bio-polyethylene (bio-PE), or bio-polyamides (bio-PA or nylon). However, these plastics often have low feedstock efficiency or still include petro-based monomers.[30] For instance, current bio-PET production only includes 32% of bio-derived monoethylene glycol (MEG) while the remaining 68% is fossil-carbon-derived terephthalic acid. These low efficiencies are given by the inherently different chemical structures of fossil-carbon- and plant-derived feedstocks. In fact, the highly oxygenated nature of biomass will hinder the synthesis of linear alkyl plastics (e.g., bio-PE). The development of polyethylene furanoate (PEF) by the Dutch company Avantium gives another approach for high-performing bio-plastics.[31] PEF is analogous to PET, with the aromatic ring substituted by a furan ring. In this way, less oxygen is removed from the original feedstock, allowing better yields. The use of CO_2 as feedstock can also be seen as "bio-based". In fact, CO_2 is both a renewable material and industrial waste. However, current productions of CO_2-based plastics are still reliant on petro-based co-polymers or only use CO_2 as foaming agent.[32]

Polybutylene adipate terephthalate (PBAT) and polyvinyl alcohol (PVA) are examples of commercial petro-based biode-

Layla Filiciotto is a sustainability enthusiast from a small town in Sicily with 50% Swedish DNA. After learning chemistry in the U.S., she studied Industrial Chemistry at the University of Messina (BSc) and Catalysis at Cardiff University (MSc). She was then awarded a Marie Skłodowska-Curie Fellowship in a European Industrial PhD project (HUGS) between the University of Córdoba and the Dutch company Avantium. Currently, she works on a multi-industry project (BRECSIT) at the University of Amsterdam. Her research interests include air pollution, natural pesticides, biomaterials and plant-based chemicals, as well as the recycling and biodegradation of new chemical products.

Gadi Rothenberg was born in Jerusalem in 1967, and immediately (well, 26 years later) was awarded a BSc in chemistry *cum laude* from the Hebrew University of Jerusalem. Instead of getting a real job, he continued for a PhD in Applied Chemistry, also *cum laude*, and decided to become an academic. Since 2008 he is Professor and Chair of Heterogeneous Catalysis and Sustainable Chemistry at the University of Amsterdam. Rothenberg teaches courses on catalysis and workshops on scientific writing and innovation. He has published three books and over 200 papers in peer-reviewed journals, invented 16 patents and co-founded the companies Sorbisense, Yellow Diesel, and Plantics. The Chinese translation of his textbook Catalysis: Concepts and Green Application was recently published by the Chinese Ministry of Education. His current research interests include porous materials for clean energy, biomass conversion, and creating value from waste. Since 2020 he is also the Technical Director CO_2 and Circular Economy of the Shanghai Institute for Cleantech Innovation.

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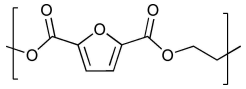
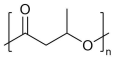
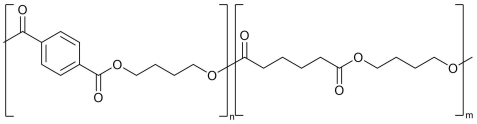
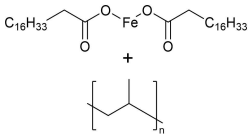
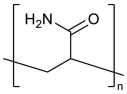
Table 1. Definitions, examples, and chemical structures of bio-based, biodegradable, and oxo- and hydro-degradable plastics.

Plastic	Definition	Example[a]	Chemical structure	Ref.
bio-based	a plastic made from renewable resources, namely biomass or waste	PEF		[31]
bio-degradable	a plastic that can be assimilated by bacteria and/or fungi to give environmentally friendly products	PHB (bio-based)		[30]
		PBAT (fossil-carbon-based)		[30]
oxo-degradable	a plastic whose degradability is induced by additives that initiate oxidation reactions	Oxo-PP		[20, 21]
hydro-degradable	a plastic whose degradability is induced by the polar groups susceptible to hydrolysis	PA		[24–27]

[a] PEF = polyethylene furanoate; PHB = poly-4-hydroxybutyrate; PBAT = polybutylene adipate terephthalate; Oxo-PP = oxo-degradable polypropylene; PA = polyacrylamide.

gradable plastics.[30] These products are used as mulch films or dishwasher tablet packaging. Given the high water-solubility, PVA could be also considered a hydro-degradable plastic. Both of these plastics can be potentially produced by bio-routes if monomers are developed industrially. For instance, Novamont developed in collaboration with Genomatica a fermentation route to bio-1,4-butanediol, one of the monomers of PBAT.[33]

Notable bio-based and biodegradable plastics are polyhydroxyalkanoates (PHAs) and polylactic acid (PLA).[30] Out of the PHAs, poly-3-hydroxyvalerate (PHV) and poly-4-hydroxybutyrate (PHB) are the most known. The hydrophilic nature of these polymers enables also hydro-degradation. PHAs and PLA are produced by bacterial fermentation of sugars. This process runs at ambient temperature and pressure, using water as solvent. However, the sugars are still derived from crops that compete with food sources.[34] Future development of lignocellulosic sugar processes will increase the sustainability of these plastics (and might also impact the food sector, see below).

Figure 1 gives an overview of the life cycles of plastics. In the best-case scenario, a plastic will degrade independently of the environment at hand. However, biodegradability is strictly related to the biochemical interaction between materials and microorganisms. Furthermore, lab degradation studies often overestimate natural biodegradability rates. Colder environments, ecosystem dynamics, and mobility between eco-compartments can hinder biodegradation. Microplastics could thus form with partial biodegradation.

All things considered, biodegradability is the most appealing property of new materials when tackling (micro)plastics pollution. It can partially make up for littering and waste management problems. Moreover, carbon emissions can be reduced if plants are used as feedstock.[35,36] Today, bio-based and biodegradable plastics are predominantly used in food

Figure 1. Various fates for petro-based and bio-based plastics, including landfill, recycling, and environmental degradation.

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packaging.[37] Regardless of whether they stem from petrol or biomass, the clear end-of-life of biodegradable plastics gives an environmental advantage, especially in microbeads and packaging materials.

2. The Environmental Impact of Plastics

From an environmental point of view, the implementation of biodegradable plastics should be analyzed very carefully. Of the various indicators, the major contributing factor is the so-called global warming potential (GWP). This looks at the CO_2 footprint of the process at every stage.

Plant-based biodegradable plastics are often considered a priori with a zero or negative carbon footprint. However, when carbon emissions are calculated in life cycle assessments (LCAs), the losses (e.g., land use, by-products) and the carbon emissions during manufacturing are often disregarded.[38] Spierling et al. analyzed various LCAs for bio-plastics, showing the variability of the results depending on the choice of the upper or lower GWP.[39] Using multiple datasets can give more accurate LCA results.[40] Nevertheless, LCAs rely heavily on assumptions. Especially in the waste management of (biodegradable) plastics, LCA uncertainties can be cumbersome. In a Novamont study,[41] the GWP of biodegradable mulch films was 2–3 times lower than landfill and incineration, respectively. Another study stated that composting and anaerobic biodegradation have higher environmental impacts than incineration with energy recovery.[42] The variability of results reflects the difficulties in the environmental assessment and stresses the importance of a critical viewpoint. Even so, a significant reduction of the carbon footprint is commonly recognized for bio-plastics compared to petro-based ones.[43,44]

The feedstock used for producing biodegradable plastics will also have different impacts on society. Most of today's bio-based and biodegradable plastics are made from food crops. This creates concerns on the water-land nexus of bio-based chemicals. Yet according to European Bioplastics, the proportion of land required for bio-materials is 2% of the overall land use. This includes materials other than plastics. In perspective, the land used for plastics represents a mere 0.016% in 2019 and is estimated to increase to 0.021% by 2024. Land use for bio-fuels is 60 times larger.[45,46] In this sense, the land take indicator (in km^2 per year)[47] and/or soil sealing (in km^2; also known as imperviousness)[48,49] can also impose the limits of developing bio-based plastics (soil sealing represents the physical area covered by anthropological constructions, land take is the annual rate of soil sealing). These indicators describe the availability of land for construction and/or agricultural practices. The higher the values of these indicators, the less natural land is available. One of the UN sustainable development goals (SDG 15)[50,51] aims at having a zero net land take by 2050 to favor natural habitats and improve agricultural practices. Yet even if constructions on arable lands have slowed down in the EEA-39 region, the land take was 12.5 times higher than the re-cultivated land between 2000 and 2018. This reflects also population growth, which is projected to increase even further until 2050.[52,53]

The use of waste products to make biodegradable plastics might offer a so-called cushion solution that has zero impact on land use. According to the UN Food and Agriculture Organization (FAO), one-third of all food resources worldwide were wasted in 2011.[54,55] A recent study in our group for the city of Amsterdam shows how the major source of organic waste is households, even more than food industries, services, and production combined.[56] Even facing this dramatic datum, food waste continues, particularly in developed countries. In fact, EU citizens produce approximately 70 kg of waste per capita[36] (albeit that the leading waste management system in the EU is energy recovery from waste[57–60]). Converting waste into plastics creates product value from zero, which is economically and socially attractive. Some possible plastics from food waste were reviewed by Sanchez-Vazquez et al.[61]

That said, the major challenges of plastics lie in the current waste management logistics. In particular, sorting different wastes and the presence of hazardous mixtures challenge the current recycling efforts.[62] Undegradable plastics in landfills are likely to leak into the environment and cause microplastics. Worldwide, the values of landfilled plastic are 45–75%.[63–67] The high mobility of microplastics causes worldwide water contamination, affecting human and animal health.[68] In this sense, environmental analyses should consider the potential release of microplastics. However, studies on the potential release of microplastics from different types of plastics (e.g., bio-based) are rare, underestimating the issue. In fact, biodegradable microplastics were found to have negative effects on both freshwater[69] and marine species,[70] yet still with fewer ecological effects compared to petro-based ones. Furthermore, the molecules making the plastics have a significant impact on life. For example, polyvinyl chloride (PVC) was found to be more harmful compared to high-density polyethylene (HDPE) and polylactic acid (PLA). This hints to the usual toxicity of halogen-containing molecules. In this sense, plastics made with safe monomers will have a lower effect on (micro)organisms. The degradation of biodegradable plastics was found to be much slower in turtles compared to the claimed biodegradability. The 100% biodegradability claim resulted in a degradation of up to 8.5% in the turtles' digestive tract.[71] Even so, biodegradable plastics will still have an undeniably positive impact on uses that are prone to enter the environment.

3. The Socio-Economic Impact of Plastics

The socio-economic impact of plastics is vast. Global plastics production of plastics was of 360000 Mtpa in 2018[72] and is projected to surpass 600 Mtpa by 2050.[73] This data excludes plastic fibers, which could represent an approximately 10% increase of the total production ($\approx$40 Mtpa). In Europe alone, the 2018 annual turnover was of more than €360Bn with a production of about 62 Mtpa, contributing approximately €30Bn in taxes.[63,64] This represents only 17% of the worldwide production of plastics, preceded by Asia & Oceania (51%) and

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North America (18%) (Figure 2). Worldwide, China is the biggest player, with 30% of the total plastic production.

Plastics are used across sectors in numerous applications. The lead market share in Europe is taken by the packaging sector (Figure 3).[63,64,74] Compared to current options, plastic packaging is lighter and more durable.[75] However, the short lifetime of packaging (typically <6 months) creates much waste. Biodegradable packaging can minimize the overall environmental impact. Similarly, using biodegradable plastics for agricultural applications (e.g., mulch films) could strongly reduce soil microplastics.[76] These two sectors (150 Mtpa in total) could be potentially substituted by biodegradable plastics. In other applications, durability is the deciding factor, rather than biodegradability. If biodegradability could be tuned in a similar fashion to oxo-degradability, more sectors could be benefit. Overall, biodegradable plastics could take over approximately 50% of the total plastics production.

Over 20000 tons of plastics end up in the oceans every day.[73,77] This is caused by leaks from landfills, losses of plastic pellets during pre-product logistics (e.g., transportation), and littering. Transportation of industrial pellets causes economic losses of €70–105Bn. Of the collected plastic waste in Europe, a quarter is still landfilled (worldwide landfilling is higher, averaging between 45–75%).[63] Based on Europe's turnover for plastics (€360Bn), this translates to another €90Bn per annum. Minimizing these losses will benefit both the environment and the economy.

The total global production of both bio-based and biodegradable plastics in 2019 was only 2.1 million tonnes. The estimated production growth is a remarkable 14% over 4 years.[46,72] However, this means that if plastic production remained constant in the next 10 years, bio(degradable) plastics would rise to about 2% of the total plastic market. A good overview of market data, feedstocks, processes, and market leaders is given in the 2018 Eunomia report.[30]

The increase of gross domestic product (GDP) will affect plastics production, as people typically use more plastics as their income levels rise. The temporary reset caused by the covid-19 pandemic notwithstanding, the world economy is expected to grow steadily over the coming decades. The US market is expected to increase from $44000 at purchasing power parity ($PPP) to 81000 $PPP, and the EU-OECD countries from 30000 to 60000 $PPP. For China, Indonesia, and India the increase is estimated at a factor of 5–6 from a cumulative baseline of approximately 14000 $PPP (70000–84000 $PPP).[78,79] The economic growth in Asia will further increase the global demand for plastics. Given this high demand, most polymers will be still produced from fossil-carbon resources (today over 95% of plastics are produced from fossil-carbon resources).

The advent of fracking has fueled plastic production by allowing an increased supply of fossil-carbon resources.[74] At

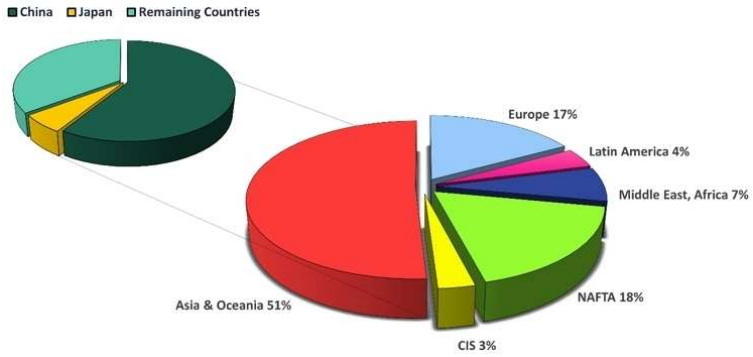

Figure 2. Plastic production by country in 2019. NAFTA: North America Free Trade Agreement (Canada, Mexico, and United States); CIS: Commonwealth of Independent States (Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Russia, Tajikistan, Turkmenistan, Ukraine, and Uzbekistan).

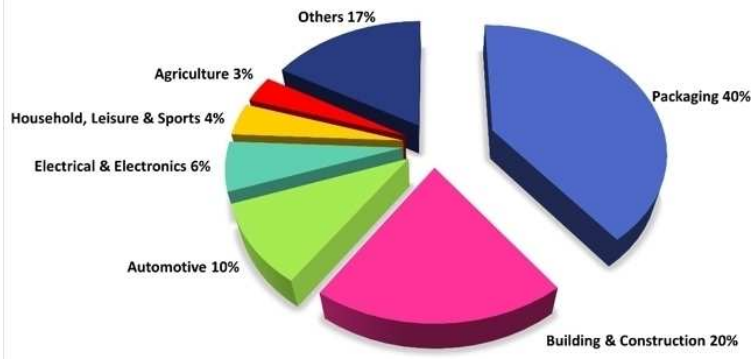

Figure 3. Plastic production by sector in Europe. Others include medical appliances, furniture, and machine building.

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the same time, only 4–6% of these resources are used to produce plastics worldwide and require less energy for their production, transportation, and use.[80] If non-renewable carbon resources were used solely for plastics, the lifespan of fossil-carbon sources would increase at least ten-fold. In this sense, the manufacturing capacity will also depend on renewable energy solutions. A model-based study estimated different scenarios of future energy demand per capita.[81] The alarming results of the worst-case scenario (i.e., continuous growth of GDP) require the use of all fossil-carbon resources and a significant growth of renewable energy to satisfy the population. In that scenario, petro-based biodegradable plastics could hinder economic growth by removing resources from fuels. Recycled and plant-based biodegradable plastics can undeniably contribute to satisfying the future world demand.

Human health and safety are interlinked to climate change, feedstock choice, and microplastic formation. For climate change, two indicators exist on the link between health and extreme temperatures[82] or inundations.[83,84] Excessive heat and floods cause premature deaths and are directly related to the emissions of greenhouse gases. Natural feedstocks (e.g., plants) may be perceived as safer, but they pose different risks compared to petro-based ones. For instance, mould inhalations and self-ignition of biomass were identified as the major risks in storage areas.[85] Similarly, dust explosions might occur if powder biomass is used. Some of the molecules derived from biomass are toxic, thus requiring safety studies regardless of their natural origin. Safe in use, microplastics are a post-consumer environmental hazard. Minimizing waste, improving waste management, and higher biodegradability can limit their impact.

Despite the increasing awareness of the dangers of microplastics, customers may advocate the preference for sustainable products while showing reluctance to change their consumer behavior.[86] A recent study shows that an industrial change might be a bigger driver for biodegradable plastics as opposed to customer choices. Unfortunately, the average consumer doesn't distinguish "bio-based" from "biodegradable".[61] In this sense, education on sustainable industrial practices might improve customers' viewpoint on plastics. A report by the European Academies' Science Advisory Council (EASAC) argues that shared responsibility between the manufacturer and the consumer can be introduced by increasing the price of plastic packaging.[87] However, fossil-carbon-derived plastics should not be considered at the same level of biodegradable and bio-based plastics. The low oil price[88,89] makes the competition with petro-based plastics difficult. A proper incentive, such as a higher carbon tax[90,91] could steer companies and consumers into making environmentally sensible choices.

Education on littering is crucial given the alarming amount of debris in the oceans.[92] Factors like the existence of small/single-use consumer goods (e.g., individual ketchup sachets in fast-food restaurants) and tourism have been identified as drivers of plastic littering.[74] A lack of easily recognizable sorting bins can hinder proper waste management. However, throwing trash in public shows marked neglect of pollution's consequences.[93] If we consider only mismanaged waste, Asian countries were identified as the biggest polluters worldwide.[94] Yet the US and EU are the biggest producers of plastic waste per capita, giving another perspective of the "biggest polluters". This hints to a lack of proper infrastructures in waste management and highlights the waste export industry: plastic is often shipped to developing countries for disposal.[95] The poorest people worldwide earn a living by collecting, sorting, and selling recyclable waste from landfills, bins, and streets.[74] This sad reality might be an inverse driver of waste management as it provides income to the poor. Yet if education and jobs opportunities are improved, waste management practices can be improved. Littering will decrease with an increased awareness of pollution and climate change.

Various socio-economic factors can be positively affected by bio-based and biodegradable plastics (Figure 4; note that several of these factors are co-dependent).

4. Material Flow Analysis of Plastics in 2019

By combining the information obtained from different sources,[15,67,72–74,77,94] we carried out a material flow analysis (MFA) for the year 2019 (see Figure 5). In particular, a "business-

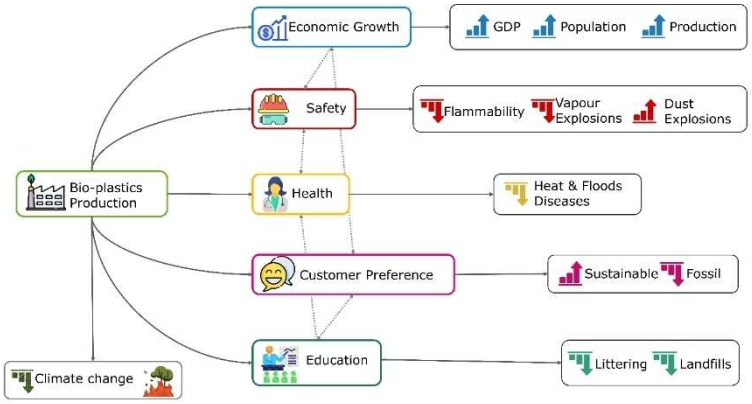

Figure 4. Socio-economic impact categories for biodegradable plastics and positive or negative change of different indicators.

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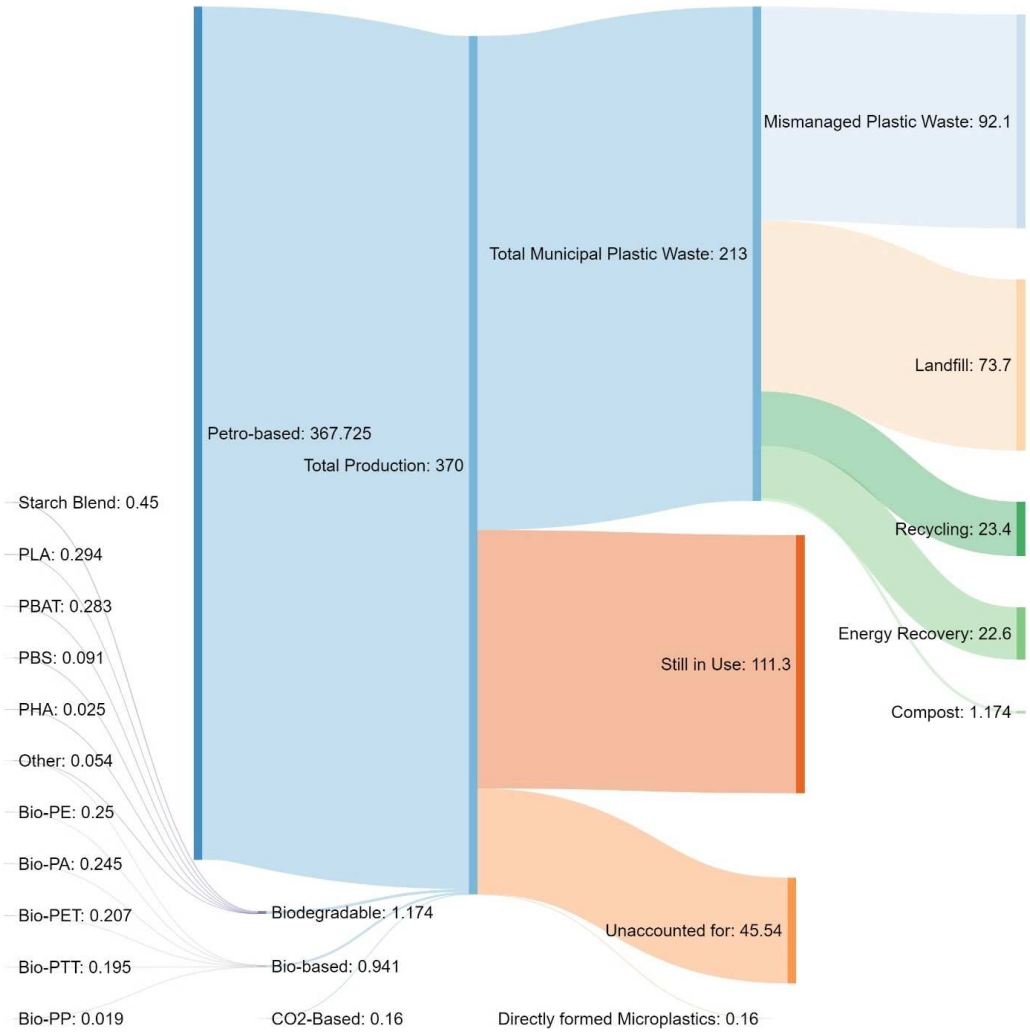

Figure 5. Sankey diagram showing the MFA for fossil-carbon-based, bio-degradable, bio-based, and CO_2-based plastics in 2019. All values are in millions of tonnes.

as-usual" scenario was considered, that is, a 3.2% yearly increase in plastic production worldwide.[74] From 359 million tonnes in 2018, more than 370 tonnes can be estimated for 2019. Compounding the data reported in 2019 for biodegradable/bio-based plastics[72] and CO_2-based plastics,[32] the contribution of sustainable plastics is nearly unnoticeable. Of the biodegradable plastics, an average of 200 ktpa are produced per type.[30] This value represents approximately 0.0005% of all plastics produced every year. This colossal difference demonstrates the effort needed to displace the fossil-carbon giant, but also the enormous market potential of biodegradable plastics.

Lebreton and Andrady provided projections for total and mismanaged quantities of plastic waste.[15] Including this 2015 data, we calculated the quantities of plastics that are landfilled, recycled, and whose energy is recovered in 2019.[66,67,74] Almost 60% of the yearly plastics production ends in waste management. Ideally, all of the municipal plastic waste will be then either recycled, burned for energy, or composted. Nevertheless, it is clear from the MFA diagram that the majority of waste is either mismanaged or landfilled, amounting to 78% of all municipal waste. Biodegradable plastics were assumed to form compost. However, most biodegradable plastics are still incinerated due to the high cost of industrial composting facilities.[74]

Landfills and mismanaged waste are the major causes of microplastics in the environment. Between 15–40% of mismanaged plastics enter the oceans from coastal cities.[94] Most of the microplastics that form in these conditions (soil, coastlines) are difficult to quantify.[96] Estimates of microplastics released in the soil in Europe are comparable to those reported for the oceans in the same region.[73,76] Other microplastics are formed before entering the waste management system. These are caused by wear and tear of rubber and synthetic clothing or during pellet transportation.[14] In the MFA diagram these are considered as production losses (directly formed microplastics, Figure 5). The cumulative quantity of these "pre-waste" microplastics is similar to the world production of CO_2-based plastics, that is, extremely small. But the real challenges of microplastics are not based on

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their relative quantity, rather on their effect on all living species and their persistency.

The lifespan of plastic products can exceed 20 years. Thus, a portion of plastics (≈30%)[64,77] will still be in use each year. However, the sum of all the different fates still leads to about 20% of plastics that are unaccounted for. This could be a warning sign of the amount of littering, illegal exports, and underestimated values of plastic waste. Overall, a significant improvement in waste management worldwide is needed. Accelerating the development of sustainable plastics, such as biodegradable ones, will positively impact the plastic market.

5. Government Policies on (Micro)Plastics Use and Registration

Policies have the power to shift the companies' focus towards different approaches, either locally or as international protocols. Since the establishment of the United Nations' 17 sustainable development goals (SDGs),[51] many companies have advocated sustainable practices. According to the goals, plastics production will look at using renewable sources without impacts on humans' health (SDG3), climate change (SDG13), life below water (SDG14), and life on land (SDG15). Circularity should also be considered, tackling SDG11 (sustainable cities and communities) and SDG12 (responsible production and consumption). Yet even with the adoption of the SDGs, the transition towards environmentally friendly plastics is still slow and requires country-specific policies.

The biggest impact on the reduction of plastic waste was given by the Chinese waste import ban of 2017.[97] This pushed several countries to find other solutions for their plastic waste, implementing recycling processes and developing biodegradable plastics. Europe halved its monthly plastic waste export with these restrictions (from 300 to 150 ktons). Yet other countries still accept plastic waste. As mentioned above, sorting of plastics in landfills is an important source of income for a part of the world population. Countries like Malaysia (≈11%), Thailand (≈6%), and Vietnam (≈5%) are the biggest importers, while the US (≈16%), Japan (≈15%), and Germany (≈13%) are the biggest exporters. US exports of plastic waste in 2018 reached almost 9500 kton.[74] In 2019, the Basel Convention, now signed by 187 countries worldwide (excluding the US, among others), called for more domestic solutions in dealing with (hazardous) waste.[98] This new agreement will only come into effect in 2021. Meanwhile, the garbage export to Asian countries continues.

At the European level, the new EU Green Deal 2020 will target (illegal) waste exports to Asian countries. At the same time, a regulatory framework for biodegradable and bio-based plastics is set to be implemented. The ambitious plan will also look at the local improvement of waste management techniques, which could in turn push recycling processes forward, reducing the need for biodegradable plastics. Amelioration of rural areas with a new financial plan will incentivize both circular and bio-economies.[99] Although we discussed the limited impact of biodegradable plastics in land take, improvements of soil quality and availability can only be beneficial to this kind of plastics. In 2019, the EU imposed a ban on the production of oxo-degradable plastics thought to produce persistent microplastics in the environment.[100] This ban, however, excludes the knowledge transfer of this particular category to bio-based plastic. If oxidation is combined with a bio-plastic, enhanced biodegradability could be observed.

From the financial point of view, the 2018 EU regulation facilitates sustainable investment by setting clear criteria for assessing the green investment funds.[101,102] Fees to discourage plastic production are imposed in Europe under the extended producer responsibility (EPR).[103] According to the EASAC report, these fees are too low (€50–250 per tonne) and vary significantly between countries.[87] Nevertheless, said fees are not imposed worldwide, and a higher price could only reduce the European companies' competitiveness. At the same time, the economic burden to develop properly recyclable and/or biodegradable plastics can be significant for companies. For this, Europe allocates investment schemes for research under the Horizon 2020 and Horizon Europe programs.[104,105] In the latter, the investment focus now includes industrial digitalization and cybersecurity, reducing the funding available for climate-related technologies. Of the proposed budget (originally €100Bn, but still under debate) half is envisioned for public–private partnerships (PPPs). The majority of PPPs (70%, €35Bn) will be allocated to innovative small and medium enterprises (SMEs) for product development at low technology readiness levels (TRL1–5, ideation/product development). However, bio-based and biodegradable plastics often lack the economic push for commercialization (high TRLs) given the low price of petroleum feedstocks and long-established industrial processes.

The public uproar over microplastics has pushed policymakers to start acting on the matter. The UK already enforced a ban on microbeads used for cosmetic and cleaning purposes in 2018.[106] This ban was impelled by the release of up to 500 million microplastics per day despite an 80% retention rate in UK wastewater treatment plants.[71] At the EU level, politicians are evaluating reports to make an informed choice for new bills. For instance, the European Chemical Agency (ECHA) has recently provided a socio-economic assessment on intentionally added microplastics (e.g., microbeads in cosmetics).[107] These microbeads could be substituted with truly biodegradable materials, offering an eco-friendly solution. However, microbeads per se might superfluous, so their use should be closely scrutinized.

New and existing (bio)plastics with productions of over one tonne need to comply with chemical registration regulations. Such regulations exist worldwide to reduce the uncontrolled release of toxic substances. The REACH regulation at the EU level bans substances of very high concern [SVHCs, i.e., carcinogenic, mutagenic, or toxic for reproduction (CMR), persistent and/or bio-accumulative substances], which nowadays only account for 205 small molecules.[108,109] However, considering the cumulative and detrimental effect of (micro) plastics, these should be included in the SVHCs list. Yet the

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restriction process is also fairly lengthy and costly: prior to the review period (set to 45 days), the manufacturer must have all product and biodegradability testing done in a GLP-certified laboratory. In the future, the classification and management of hazardous substances in (new) waste streams might be improved by the EU Green Deal.[110]

Worldwide, the focus on sustainability is limited to international protocols rather than local bills. At the US level environmental policies appear to have a lower focus. To face littering, the US still enforces the 1972 Clean Water Act.[111] Concerning biomass, instead, the US government had released in early 2012 its National Bioeconomy Blueprint. This bill focuses on fuels produced from CO_2 and biodegradable plastics made from renewable biomass.[112] Currently, only California is setting up a law to phase out plastics that cannot be compostable or recyclable, and even this legislation faces bureaucratic resistance.[113] Other countries, such as China, also have limited policies on biodegradable plastics but support research via funding.[114] Rwanda is setting the example for African countries in banning imports and single-use plastics while improving the country's economy.[115] For more country-specific policies on bio-plastics, see the Organization for Economic Co-operation and Development (OECD) report.[114]

6. Standards and Certifications for Biodegradable Plastics

Regardless of their feedstock or durability, all plastics appear similar to the eye. Thus, a series of standardized tests, certifications, and corresponding labels are provided online. For biodegradability, a variety of tests exists with specified conditions. Standardized tests often strike a balance between a time-efficient testing (shortest 14 days, longest 24 months) and real-life conditions. In fact, higher temperatures than real conditions are often used to speed up the testing time. Companies developing new plastics need to invest significant resources in self-assessing product sustainability and in certification. The overall biodegradability assessment, including laboratory spaces and equipment, becomes costly and time consuming.

The first guidelines for testing chemicals were given by the OECD in the 1980s and sporadically updated thereafter.[116] These guidelines are offered free of charge online and include various methods. However, these guidelines are not recognized worldwide and act as self-certification. For a moderate fee (€50–100), certified standard tests are available worldwide. The International Standards Organization (ISO) offers a series of tests regarding biodegradability in various environments (e.g., soil, activated sludge, seawater, marine sediment), and these are regularly updated.[117] The organization is supported by the United Nations Standards Coordinating Committee (UNSCC), acting as a global harmonization attempt. At the EU level, the European Committee for Standardization (CEN) proposes a series of biodegradability tests for packaging and agricultural plastics (e.g., mulch films); for other applications, CEN refers to the ISOs.[118] At the US level, American Society for Testing and Materials (ASTM) standards use the imperial system and were recently updated.[119] These tests allow to compare biodegradability worldwide, but give no certification. A certification (with a label or conformity mark) can only be given by an accredited body, upon a one-time and/or annual payment.

In general, when comparing the different tests, various definitions of biodegradability also arise. Of the ones considered by an ECHA report, we can distinguish three categories for aerobic degradation: ready, inherent, and ultimate biodegradability. These tests vary in duration and percentage of biodegradation (measured as percentage of the theoretical O_2 demand).[107] Table 2 gives the differences in biodegradability terms.

All the tests are run in parallel against multiple blanks (microbiota in chosen media only) and a reference substance (e.g., aniline, microcrystalline cellulose). Pre-adaptation of the microorganisms to the test substance is not allowed. By using dissolved organic carbon (DOC, Zahn-Wellens) or biological oxygen demand (BOD, MITI II test) measurements, a material can be considered inherently biodegradable if it reaches at least 70% within 14 days.[120,121] A readily biodegradable material instead requires at least 60% in a 10 days window within 28 days.[122–124] The window begins when 10% biodegradation is reached. Ultimate biodegradation is obtained when the test substance degrades by 90% of the reference material. Duration of the test depends on the ecosystem and could last a maximum of 6 months in (sea)water.[125,126] For soil[127] and

Table 2. Differences between the three types of degradation.

Biodegradation	Minimum degradation [%]	Timeframe of degradation	Maximum test duration	Analytical method	Standard	Ref.
inherently degradable	70	within maximum duration	14 days	DOC or BOD analysis[a]	OECD 302B or 302 C	[92, 93]
readily degradable	60	10 days[b]	28 days	CO_2 evolved or O_2 demand	OECD 301, 306, 310	[94–96]
ultimately degradable	90	within maximum duration	6 months (aqueous); 24 months (soil, seawater/sediment)	CO_2 evolved or O_2 demand	ISO 14851, 14852 (aqueous), ISO 17556 (soil), ISO 19679, 18830 (seawater/sediment)	[97–101]

[a] DOC: dissolved organic carbon, BOD: biological oxygen demand. [b] Only after 10% degradation is reached.

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marine sediment or seawater/sediment interface,[128,129] the maximum test period is 24 months. For a critical review on biodegradability in freshwater, see the work of Harrison et al.[130]

The customer can recognize a biodegradable material only if a label is placed on the product. Some of the common certified labels are provided by organizations such as TÜV AUSTRIA, DIN Certco (of TÜV Rheinland), or the European Union.[131–133] The different conformity marks depend on the environment and type of plastic:

- Freshwater: The *OK Biodegradable Water* label certifies biodegradability in freshwater. This label requires detailed product description and biodegradability tests.
- Seas: The *OK Biodegradable Marine* label certifies biodegradability in seawater and includes ecotoxicity studies.
- Compost: Products that can be thrown in the food waste bear the conformity mark or label *OK home compostable*. Other products bear the certificate *OK compost IND*, related to industrial composting facilities. A *Compostable (Seedling)* label also exists. DIN Certco uses the *DIN Geprüft* logo and specifies the biodegradability category. These labels are based on a series of standards depending on the compost environment.
- Bio-based: Din Certco provides *Bio-based* $>85\,\%$, *OK Biobased*, and *USDA certified* biobased product (based on the standard EN16785-1). The Royal Netherlands Standards Foundation (NEN) has also launched a certification scheme in 2016 (NCS 16785) with a label indicating the percentage of bio-based content.
- Overall environmental protection: The *EU Ecolabel* looks at the sustainability of the whole manufacturing process of a product (e.g., amount of hazardous additives, circular waste streams, water recycling systems). The company must provide all relevant tests and pay both a one-time and an annual fee for using the label. This label can include biodegradable materials that are produced sustainably.

The variety of labels can cause confusion. For instance, the *Seedling* label strictly refers to industrial composting. However, the logo is vague and could be confused for materials degrading with food waste (i.e., home composting). Some products make false claims. For instance, a study on commercial biodegradable plastics shows that only four out of the six tested plastics were showing degradation.[134] Standardization of labels could help both travelers and migrants. Most importantly, ethical approaches should be at the base of biodegradability claims, ensuring a positive impact on society.

7. Analytical Techniques for Biodegradability and Microplastics

Most aerobic tests look at CO_2 evolution or O_2 demand as the necessary gases involved in microbial life. Similarly, in anaerobic digestion, the evolution of methane is measured. The uptake or release of gases can be measured by different methods and is used for all media (soil, water, and seawater). Many of the standardized tests (e.g., ISOs) suggest the use of respirometers.[135] Other methods may rely on simple manometric measurements by the use of BOD bottles or as in the MITI test proposed in the OECD guidelines.[121,122] Titrimetric measurements of the quantity of CO_2 adsorbed in a base [e.g., $Ba(OH)_2$] can be used too.[122] Using a DOC analyzer can also be an option, where the dissolved inorganic carbon is measured (e.g., Zahn-Wellens/EVPA tests).[120,123,136,137] Analogously, the total organic carbon (TOC) can be measured. All of the tests must be done in the dark with controlled conditions (temperature, humidity). Although differences exist in sensitivity of the analyses, the choice often relies on availability and standard used. All of these analytical techniques possess inherent measurement errors, especially if done manually. Proper assessment of biodegradability today requires a significant investment in equipment (e.g., the respirometer shown in Figure 6 costs $\approx$€65k).

Measurement errors arise given a big variability of the media respiration (without sample, e.g., soil respiration). In fact, multiple parallel blank measurements are required (at least 3) to assess the "base" respiration (i.e., of the water, soil, etc.). The sample too should be done in replicates. This means that analyzing a single substance requires six parallel reactors. Other techniques, for example, monitoring isotopic carbon, can be used according to OECD guidelines.[138–140] However, this is an expensive technique and usually used for potentially SVHC pesticides.

Compostable plastics are monitored by thermogravimetric analysis and calorimetry for home and industrial composting, respectively. Even if one of the requirements for a material to be compostable is no ecotoxicity, standardized tests (e.g., ISO 14855) exclude ecotoxicity studies.[141,142] Ecotoxicity was only included in a withdrawn ASTM test (D6692-01).[143] However, the test was based on the analysis of $^{14}CO_2$ from radiolabeled polymers (cost-ineffective). Nevertheless, when applying for a conformity mark, ecotoxicity must be evaluated.

Standardized tests suggest using small films (no larger than 5 mm $\times$ 5 mm) or the powder form (maximum 250 μm diameter) of the plastics. A study on the granulometry effect showed improved biodegradation when in the nano form.[144] This

Figure 6. Biodegradability equipment (Respicond™) at the Institute for Biodiversity and Ecosystem Dynamics (IBED) of the University of Amsterdam. The setup consists of 96 parallel respirometers in a temperature-controlled water bath under dark conditions. Photo by L. Filiciotto.

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approach excludes the first biodeterioration and/or weathering step of a bottle or similar. This deterioration could be monitored by analyzing the molecular weight of an actual plastic product. The available techniques are gel permeation chromatography (GPC) or matrix-assisted laser desorption ionization time of flight (MALDI-TOF); however, the solubility of the plastic is usually the issue. Sometimes, biodegradability is assessed on the pellets rather than the final product. This will also give a higher result as it ignores the thermal effect on the crystallinity of the materials (see below).

Photodegradation and accelerated weathering are assessed by UV/Visible (UV/Vis) spectroscopy and infrared (IR) analysis with the ISO 10640.[145] Nevertheless, UV/Vis is limited to plastics presenting chromophores (e.g., conjugated double bond). IR analysis can give complex spectra of difficult interpretation. Nuclear magnetic resonance (NMR) analysis can also be used. However, when considering new bio-based plastics, the final structure could have no clear repeating unit, which could complicate the final spectra. These analyses, in turn, are useful in monitoring released monomers or changes in the molecular structure.[146]

The formation of microplastics is overlooked by the standardized tests, and no standard is available for their analysis. On the same line, the recommended temperatures in the tests range between 15–28 °C (except for industrial composting facilities, which use 58 °C). However, the environment is usually at lower temperatures (seawater at 9 °C, freshwater and soil at 12 °C average).[71] Moreover, all the standardized tests are carried out in the dark, excluding the effect of solar light and meteorological conditions (e.g., wind). At the same time, instead of freshwater, activated sludge is suggested by standards. Activated sludge has more microbiota (also known as colony forming units, CFUs). In this sense, activated sludge is not indicative of the real environmental conditions for plastic litter. Furthermore, the tests overlook the microorganisms' ability to fight pollution and maintain the ecosystems' balance via adaptation.[147]

Generally, standards look at the microbial effect on the plastic, neglecting the possible released molecules that are not CO_2. Gas chromatography (GC) with a thermal conductivity detector (TCD) is often used to assess biodegradability. Human error can be eliminated with an automatic sampler or an online system (continuous sampling). Using a flame ionization detector (FID) or a mass spectrometer (MS) could help to analyze the monomers/oligomers coming from the degradation of plastics. As seen for PVC, certain molecules could be highly toxic and can be assessed in laboratory conditions.[70] The combination of a series of analytical methods could give a better estimate of biodegradation. There is a trade-off between proper assessment and time-efficient analysis. Figure 7 summarizes the commonly used analytical techniques and workflow.

8. Physicochemical Properties and Biodegradability

The design of biodegradable plastics is hindered by the complexity of the processes involved and the lack of consistent data. Several physical and chemical properties influence biodegradability. The surface area of the plastic product is proportional to its biodegradation. Hydrophilicity/hydrophobicity also influence biodegradation. Usually, hydrophilic microbes give higher biodegradation rates.[148] For example, the assimilation of traditional petro-based plastics (e.g., PE) improves if carboxylic acid groups are introduced.[149] Generalizing this, bio-based plastics containing heteroatoms will be more biodegradable. At the same time, factors like high crystallinity, melting temperature (T_m), glass transition temperature (T_g), and molecular weight can reduce biodegradability. In general, the higher the molecular weight, the lower the biodegradability. Some plastics (e.g., LDPE)[150] biodegrade faster thanks to their amorphous character given by branching. However, branching alone is not a guarantee for biodegradability.[149] If annealed after injection-molding, PLA becomes less biodegradable.[151]

Chemically, based on the knowledge derived from studies on small molecules (such as pesticides), the presence of oxygen-containing groups (e.g., ester, acid) is considered as an enhancer to biodegradation. In fact, the presence of oxygen will improve the polar interaction with water and thus hydrolysis.[152]

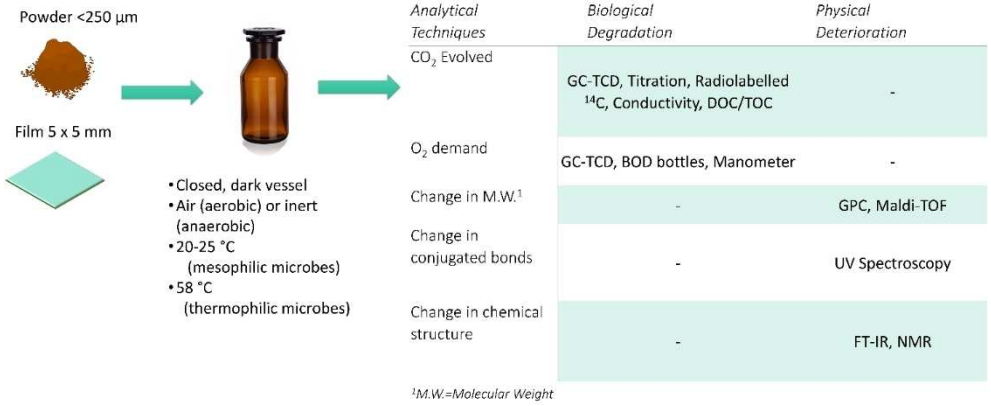

Figure 7. Sample form, conditions, and analytical techniques for assessing biodegradability of plastics.

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Introducing amine or amide groups may also favor biodegradability.[153,154] Halogens can decrease bio-assimilation given their toxicity.[155] The general low reactivity of aliphatic groups is a barrier to biodegradability. Part of sunlight, UV light will cause photodegradation of C–H bonds particularly in systems with conjugated bonds (including aromatics). Aromatic groups usually confer rigidity and radical scavenging properties which reduce biodegradability, even if prone to UV-initiated chain scission.[149] The addition of aliphatic esters can improve the biodegradability of aromatic groups.[156] This is the case of PBAT (see Table 1), which is considered a more rigid biodegradable plastic. Similarly, the presence of conjugated alkenes may cause photo-initiated cross-linking rather than degradation. For methods and mechanisms of (oxo/bio)-degradability of polyolefins, the reader is referred to the Review by Ammala et al.[157] The major factors and chemical groups affected during biodegradation are illustrated in Figure 8.

The lack of consistent information on biodegradability of different plastics hinders finding a clear correlation between physicochemical properties and their final fate. A good study on the biodegradability of some commercial plastics was published by Chamas et al.[158] Model-based analysis might be useful if applying quantitative structure-biodegradability relationships (QSBR). However, these models already present some incongruencies for small molecules.[152] Often, literature studies focus on monitoring one change [e.g., Fourier-transform (FT)IR structure] or only report CO_2 evolution, hindering the creation of a database. A complete database could predict the biodegradability of new plastics or aid the design of ad-hoc biodegradability. Repeating units, elemental analyses, physical properties (e.g., T_g and T_m), and thermal history should be correlated to biodegradability. Kinetic studies of biodegradability could also be a highly useful tool for comparing new plastics.

9. Summary and Outlook: A Personal Viewpoint

The technological development of biodegradable plastics requires chemistry and chemical engineering knowledge, as well as proper assessment of environmental and socio-economic impacts. Yet even if it succeeds, this does not guarantee a commercial success. In this final section we present our personal critical insight on the challenges that biodegradable plastics face in entering the large-scale plastics market. This insight is based on our experience working for (and in one case, inventing and co-founding) bioplastic-producing companies.

Biodegradable plastics (and indeed all plant-based plastics) are an easy media sell. People love the stories: an eco-friendly plastic, a plastic that's made from plants, zero CO_2 footprint-all straightforward and clear messages that benefit everyone. But turning this into reality is a huge challenge. To date, no company has commercialized bioplastics on a large scale (there are some advanced stage plants starting in China and India, but these are still a far cry from the megatons that are needed for having an impact on the sector). A glance at the meagre material flows of bioplastics in the Sankey diagram in Figure 5 shows how much needs to change.

As far as we see it, there are three main reasons for this discrepancy between popular public opinion and industrial reality:

The first and foremost is the cost. Bio-based plastics are more expensive than petro-based ones. The plastics industry relies on legacy production facilities that depreciated long ago and turn-key processes that are safe for company boards to invest in while minimizing risk exposure. Companies may say nice things about sustainability on their websites, but their boards are obliged to maintain shareholders' profits. And biodegradability is not always desirable, as it can also encourage single-use and wastage. Biodegradable packaging makes sense, but plastic products such as LEGO bricks are good for decades and should remain so.

The second is that large-scale production of bioplastics comes with a host of technical challenges, from low reactor space-time yields to large variation in feedstock composition and structure. The result is an increase in by-products, which means added costs in separations, especially if one seeks drop-in replacements to conventional plastics. Because biomass, unlike crude oil, is already functionalized, it presents opportu-

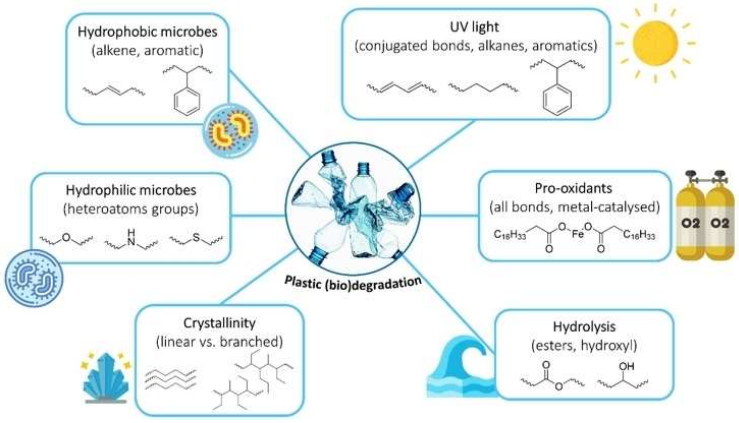

Figure 8. Key properties and processes that induce (bio)degradation of different chemical groups.

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nities for alternative solutions (new types of plastics), but these come with added complications.

Finally, perhaps the most crucial barrier is the human element. Not invented here (NIH) is an old yet highly relevant adage when it comes to bioplastics. The traditional plastics industry is conservative and risk-averse. Business unit managers shy from investing in truly new concepts, because if they fail, there goes their bonus (and maybe their job!), and if they succeed, the new business might disrupt their own position.

Yet we remain optimistic. Biodegradable plastics are being continually developed and have the potential for capturing healthy market shares in the coming decade. Tougher government regulations and higher carbon taxes are helping, as is the change in public opinion. Feedstock and product diversity also have an upside, namely more flexible processes and a different approach to consumer products. And globalization means that companies can benefit from cost differences: the Corbion Purac plant in Thailand produces 75 ktpa with a CapEx of approximately €60 M, compared to €200 M for the Total Corbion 100 ktpa PLA plant in France. Cost advantages may yet prove to be the driver for enhancing the spread of bio-based and biodegradable plastics in developing and emerging economies.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords: biodegradable · economy · policy · polymers · sustainable chemistry

[1] J. Taalbi, *Research Policy* **2017**, *46*, 1437–1453.
[2] R. W. Beachey, *J. Afr. His.* **1967**, *8*, 269–290.
[3] R. Mülhaupt, *Macromol. Chem. Phys.* **2013**, *214*, 159–174.
[4] J. G. Cook, in *Handbook of Textile Fibres: Man-Made Fibres*, Woodhead Publishing, Cambridge, **1984**, pp. 201–207.
[5] H. Lintsen, M. J. Hollestelle, R. Hölsgens, *The Plastics Revolution: How the Netherlands Became a Global Player in Plastics*, Foundation For The History Of Technology, Eindhoven, **2017**.
[6] PlasticsEurope, "The Compelling Facts about Plastics," can be found under https://www.plasticseurope.org/application/files/1515/1689/9283/2007CompellingFacts_PubOct2008.pdf, **2007**.
[7] PlasticsEurope, "Plastics - Architects of Modern and Sustainable Buildings, can be found under https://www.plasticseurope.org/application/files/3915/1714/0577/bc_brochure_111212.pdf, **2012**.
[8] A. White, S. Lockyer, *Nutrition Bulletin* **2020**, *45*, 35–50.
[9] "Every single piece of plastic ever made still exists. Here's the story," can be found under https://www.greenpeace.org/international/story/7281/every-single-piece-of-plastic-ever-made-still-exists-heres-the-story, **2017**.
[10] S. Freinkel, in *Plastic: A Toxic Love Story*, Houghton Mifflin Harcourt, Boston, **2011**, pp. 6–11.
[11] O. Horodytska, A. Cabanes, A. Fullana, in *The Handbook of Environmental Chemistry*, Springer, Heidelberg, **2019**, pp. 1–18.
[12] Ellen McArthur Foundation, "The New Plastics Economy: Rethinking the Future of Plastics," can be found under https://www.ellenmacarthurfoundation.org/publications/the-new-plastics-economy-rethinking-the-future-of-plastics, **2016**.
[13] M. Eriksen, L. C. M. Lebreton, H. S. Carson, M. Thiel, C. J. Moore, J. C. Borerro, F. Galgani, P. G. Ryan, J. Reisser, *PLoS One* **2014**, *9*, e111913.
[14] S. Hann, C. Sherrington, O. Jamieson, M. Hickman, P. Kershaw, A. Bapasola, G. Cole, *Investigating Options for Reducing Releases in the Aquatic Environment of Microplastics Emitted by (but Not Intentionally Added in) Products*, Eunomia, **2018**, https://www.eunomia.co.uk/reports-tools/investigating-options-for-reducing-releases-in-the-aquatic-environment-of-microplastics-emitted-by-products/.
[15] L. Lebreton, A. Andrady, *Palgrave Commun.* **2019**, *5*, 1–11.
[16] D. Eerkes-Medrano, R. C. Thompson, D. C. Aldridge, *Water Res.* **2015**, *75*, 63–82.
[17] K. L. Law, R. C. Thompson, *Science* **2014**, *345*, 144–145.
[18] N. Kalogerakis, K. Karkanorachaki, G. C. Kalogerakis, E. I. Triantafyllidi, A. D. Gotsis, P. Partsinevelos, F. Fava, *Front. Mar. Sci.* **2017**, *4*, 84.
[19] G. Scott, in *Degradable Polymers* (Ed.: G. Scott), Springer, Dordrecht, **2002**, pp. 1–15.
[20] A. U. Rahman, *Oxo-Biodegradable Additives for Use in Fossil Fuel Polymer Films and Once-Used Packaging*, **2012**, WO2012088585 A1.
[21] P. Zbořilová, J. Pác, *Oxo-Degradable Polyolefinic Material*, **2014**, CZ304315B6.
[22] J. M. R. da Luz, S. A. Paes, D. M. S. Bazzolli, M. R. Tótola, A. J. Demuner, M. C. M. Kasuya, *PLoS One* **2014**, *9*, e107438.
[23] S. Lambert, M. Wagner, *Chem. Soc. Rev.* **2017**, *46*, 6855–6871.
[24] S. Harrison, *Compositions and Methods for Resisting Soil Erosion and Fire Retardation*, **2008**, US7407993B2.
[25] D. M. Teegarden, in *Polymer Chemistry: Introduction to an Indispensable Science*, NSTA Press, Arlington, **2004**, pp. 20–21.
[26] B. Xiong, R. D. Loss, D. Shields, T. Pawlik, R. Hochreiter, A. L. Zydney, M. Kumar, *NPJ Clean Water* **2018**, *1*, 1–9.
[27] J. J. Mortvedt, R. L. Mikkelsen, *Micronutrient Delivery Systems Using Hydrophilic Polyacrylamides*, **1993**, US5221313 A.
[28] J. P. Greene, in *Sustainable Plastics*, John Wiley & Sons, Ltd, **2014**, pp. 71–106.
[29] P. Anastas, N. Eghbali, *Chem. Soc. Rev.* **2009**, *39*, 301–312.
[30] S. Hann, R. Scholes, R. Briedis, K. Kirkevaag, *Bio-Based and Biodegradable Plastics: An Assessment of the Value Chain for Bio-Based and Biodegradable Plastics in Norway*, Eunomia For The Norwegian Environment Agency, **2018**.
[31] E. de Jong, M. A. Dam, L. Sipos, G.-J. M. Gruter, in *Biobased Monomers, Polymers, and Materials*, American Chemical Society, **2012**, pp. 1–13.
[32] Y. Xu, L. Lin, M. Xiao, S. Wang, A. T. Smith, L. Sun, Y. Meng, *Prog. Polym. Sci.* **2018**, *80*, 163–182.
[33] M. M. Bomgardner, *Chem. Eng. News* **2016**, *94*, 13.
[34] E. de Jong, H. Stichnothe, G. Bell, H. Jørgensen, *Bio-Based Chemicals: A 2020 Update*, International Energy Agency, **2019**.
[35] European Bioplastics e.V., "Environment," can be found under https://www.european-bioplastics.org/bioplastics/environment/, **2019**.
[36] European Bioplastics e.V., *Bioplastics Facts and Figures*, Berlin, **2020**.
[37] T. Iwata, *Angew. Chem. Int. Ed.* **2015**, *54*, 3210–3215; *Angew. Chem.* **2015**, *127*, 3254–3260.
[38] P. Pawelzik, M. Carus, J. Hotchkiss, R. Narayan, S. Selke, M. Wellisch, M. Weiss, B. Wicke, M. K. Patel, *Resour. Conserv. Recycl.* **2013**, *73*, 211–228.
[39] S. Spierling, E. Knüpffer, H. Behnsen, M. Mudersbach, H. Krieg, S. Springer, S. Albrecht, C. Herrmann, H.-J. Endres, *J. Cleaner Prod.* **2018**, *185*, 476–491.
[40] E. J. M. van der Harst, Robustness of Life Cycle Assessment Results: Influence of Data Variation and Modelling Choices on Results for Beverage Packaging Materials, Environmental Systems Analysis PhD Thesis, Wageningen University, **2015**, https://edepot.wur.nl/360115.
[41] F. Razza, A. K. Cerutti, in *Soil Degradable Bioplastics for a Sustainable Modern Agriculture* (Ed.: M. Malinconico), Springer, Berlin, Heidelberg, **2017**, pp. 169–185.
[42] M. R. Yates, C. Y. Barlow, *Resour. Conserv. Recycl.* **2013**, *78*, 54–66.
[43] I. D. Posen, P. Jaramillo, W. M. Griffin, *Environ. Sci. Technol.* **2016**, *50*, 2846–2858.
[44] J. W. Levis, M. A. Barlaz, *Environ. Sci. Technol.* **2011**, *45*, 5470–5476.

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[45] European Bioplastics e.V., "Feedstock," can be found under https://www.european-bioplastics.org/bioplastics/feedstock/, **2019**.
[46] European Bioplastics e.V., nova-Institute, "Bioplastics Market Data 2019. Global Production Capacities of Bioplastics 2019–2024," can be found under https://docs.european-bioplastics.org/publications/market_data/Report_Bioplastics_Market_Data_2019.pdf, **2020**.
[47] "Land take in Europe," can be found under https://www.eea.europa.eu/data-and-maps/indicators/land-take-3/assessment, **2019**.
[48] "Imperviousness and imperviousness change in Europe," can be found under https://www.eea.europa.eu/data-and-maps/indicators/imperviousness-change-2/assessment, **2020**.
[49] S. Naumann, A. Frelih-Larsen, G. Prokop, S. Ittner, M. Reed, J. Mills, F. Morari, S. Verzandvoort, S. Albrecht, A. Bjuréus, G. Siebielec, T. Mituriski, in *International Yearbook of Soil Law and Policy 2018* (Eds.: H. Ginzky, E. Dooley, I. L. Heuser, E. Kasimbazi, T. Markus, T. Qin), Springer International Publishing, Cham, **2019**, pp. 83–112.
[50] "Goal 15: Sustainable Development Knowledge Platform," can be found under https://sustainabledevelopment.un.org/sdg15, **2019**.
[51] United Nations, *The Sustainable Development Goals Report*, UN, **2020**.
[52] "World population projected to reach 9.8 billion in 2050, and 11.2 billion in 2100 | UN DESA | United Nations Department of Economic and Social Affairs," can be found under https://www.un.org/development/desa/en/news/population/world-population-prospects-2017.html, **2017**.
[53] W. Lutz, S. KC, *Philos. Trans. R. Soc. London Ser. B* **2010**, *365*, 2779–2791.
[54] "Food Loss and Food Waste - FAO - Food and Agriculture Organization of the United Nations," can be found under http://www.fao.org/food-loss-and-food-waste/en/, **2020**.
[55] R. Ishangulyyev, S. Kim, S. H. Lee, *Foods* **2019**, *8*, 297.
[56] L. Viva, F. Ciulli, A. Kolk, G. Rothenberg, *Adv. Sustainable Syst.* **2020**, *2000023*, 1–17.
[57] "Diversion of waste from landfill," can be found under https://www.eea.europa.eu/data-and-maps/indicators/diversion-from-landfill/assessment, **2019**.
[58] "Waste recycling," can be found under https://www.eea.europa.eu/data-and-maps/indicators/waste-recycling-1/assessment-1, **2019**.
[59] European Economic Area (EEA), *Diverting Waste from Landfill. Effectiveness of Waste-Management Policies in the European Union*, European Union, Copenhagen, **2009**.
[60] J. Papineschi, P. Jones, R. Gillies, *Recycling – Who Really Leads the World?*, Eunomia, **2017**.
[61] S. A. Sanchez-Vazquez, H. C. Hailes, J. R. G. Evans, *Polym. Rev.* **2013**, *53*, 627–694.
[62] B. Didier, "Briefing of the European Parliament," can be found under https://www.europarl.europa.eu/RegData/etudes/BRIE/2015/559493/EPRS_BRI(2015)559493_EN.pdf, **2015**.
[63] PlasticsEurope, "Plastics-The Facts 2018," can be found under https://www.plasticseurope.org/application/files/6315/4510/9658/Plastics_the_facts_2018_AF_web.pdf, **2018**.
[64] PlasticsEurope, "Plastics-The Facts 2019," can be found under https://www.plasticseurope.org/application/files/1115/7236/4388/FINAL_web_version_Plastics_the_facts2019_14102019.pdf, **2019**.
[65] P. Agamuthu, *Waste Manage. Res.* **2013**, *31*, 1–2.
[66] Organisation For Economic Co-Operation And Development, "Environment at a Glance 2020," can be found under https://www.oecd-ilibrary.org/environment/environment-at-a-glance/volume-/issue-_4ea7d35f-en, **2020**.
[67] Conversio Market & Strategy, *Global Plastics Flow Study 2019*, Conversio Gmbh, **2020**.
[68] J. C. Prata, J. P. da Costa, I. Lopes, A. C. Duarte, T. Rocha-Santos, *Sci. Total Environ.* **2020**, *702*, 134455.
[69] S. Straub, P. E. Hirsch, P. Burkhardt-Holm, *Int. J. Environ. Res. Public Health* **2017**, *14*, 774.
[70] D. S. Green, B. Boots, J. Sigwart, S. Jiang, C. Rocha, *Environ. Pollut.* **2016**, *208*, 426–434.
[71] European Environmental Bureau, ClientEarth, ECOS, "Joint NGOs' comments to the Annex XV restriction report, proposal for a restriction of intentionally added microplastics," can be found under https://mk0eeborgicuypctuf7e.kinstacdn.com/wp-content/uploads/2019/09/Response-to-draft-microplastics-biodegradation-criteria.pdf, **2019**.
[72] European Bioplastics e.V., "Market," can be found under https://www.european-bioplastics.org/market/, **2019**.
[73] European Parliament, "A European Strategy for Plastics in a Circular Economy," can be found under https://www.europarl.europa.eu/doceo/document/TA-8-2018-0352_EN.html, **2018**.
[74] *Plastic Atlas 2019: Facts and Figures about the World of Synthetic Polymers*, Heinrich Böll Foundation, Berlin, **2019**.
[75] B. Brandt, H. Pilz, *The Impact of Plastic Packaging on Life Cycle Energy Consumption and Greenhouse Gas Emissions in Europe.*, Denkstatt & PlasticsEurope, **2011**.
[76] J.-J. Guo, X.-P. Huang, L. Xiang, Y.-Z. Wang, Y.-W. Li, H. Li, Q.-Y. Cai, C.-H. Mo, M.-H. Wong, *Environ. Int.* **2020**, *137*, 105263.
[77] R. Geyer, J. R. Jambeck, K. L. Law, *Sci. Adv.* **2017**, *3*, e1700782.
[78] OECD, "Economic Outlook No 95-Long-term baseline projections," can be found under https://stats.oecd.org/Index.aspx?DataSetCode=EO95_LTB#, **2014**.
[79] OECD, *OECD Economic Outlook, Volume 2014 Issue 1*, OECD Publishing, Paris, **2014**.
[80] E. Chiellini, S. Cometa, A. Corti, in *Encyclopedia of Polymer Applications, 3 Volume Set* (Ed.: M. Mishra), Taylor & Francis, **2018**, pp. 1907–1957.
[81] I. Capellán-Pérez, M. Mediavilla, C. de Castro, Ó. Carpintero, L. J. Miguel, *Energy* **2014**, *77*, 641–666.
[82] "Extreme temperatures and health," can be found under https://www.eea.europa.eu/data-and-maps/indicators/heat-and-health-2/assessment, **2016**.
[83] "Floods and health," can be found under https://www.eea.europa.eu/data-and-maps/indicators/floods-and-health-1/assessment, **2016**.
[84] R. S. Kovats, R. Valentini, L. M. Bouwer, E. Georgopoulou, D. Jacob, E. Martin, M. Rounsevell, J.-F. Soussana, in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects.* (Eds.: V. R. Barros, C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea, L. L. White), Cambridge University Press, Cambridge, **2014**, pp. 1267–1326.
[85] J. Mullerova, in *SGEM2014 Conference Proceedings*, SGEM2014, **2014**, pp. 261–266.
[86] L. M. Heidbreder, I. Bablok, S. Drews, C. Menzel, *Sci. Total Environ.* **2019**, *668*, 1077–1093.
[87] European Academies Science Advisory Council (EASAC) Secretariat, "Packaging Plastics in the Circular Economy," can be found under https://easac.eu/fileadmin/PDF_s/reports_statements/Plastics/EASAC_Plastics_complete_Web_PDF.pdf, **2020**.
[88] "US oil prices turn negative as demand dries up," can be found under https://www.bbc.com/news/business-52350082, **2020**.
[89] L. H. Ederington, C. S. Fernando, S. A. Hoelscher, T. K. Lee, S. C. Linn, *J. Commod. Mark.* **2019**, *13*, 1–15.
[90] European Commission, "EU Emissions Trading System (EU ETS)," can be found under https://ec.europa.eu/clima/policies/ets_en, **2016**.
[91] E. Narassimhan, K. S. Gallagher, S. Koester, J. R. Alejo, *Climate Policy* **2018**, *18*, 967–991.
[92] J. Lehmköster, in *World Ocean Review* (Ed.: T. Schröder), Maribus, **2010**, pp. 76–99.
[93] H. Ritchie, M. Roser, "Our World in Data," can be found under https://ourworldindata.org/plastic-pollution, **2018**.
[94] J. R. Jambeck, R. Geyer, C. Wilcox, T. R. Siegler, M. Perryman, A. Andrady, R. Narayan, K. L. Law, *Science* **2015**, *347*, 768–771.
[95] European Environment Agency, *The Plastic Waste Trade in the Circular Economy*, European Environmental Agency, Copenhagen, **2019**.
[96] J. N. Möller, M. G. J. Löder, C. Laforsch, *Environ. Sci. Technol.* **2020**, *54*, 2078–2090.
[97] A. L. Brooks, S. Wang, J. R. Jambeck, *Sci. Adv.* **2018**, *4*, eaat0131.
[98] United Nations (UNEP), *Report of the Conference of the Parties to the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal on the Work of Its Fourteenth Meeting*, Basel Convention, Geneva, **2019**.
[99] European Commission, "Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. The European Green Deal," can be found under https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF, **2019**.
[100] European Commission, "Directive (EU) 2019/ of the European Parliament and of the Council of 5 June 2019 on the Reduction of the Impact of Certain Plastic Products on the Environment," can be found under https://eur-lex.europa.eu/eli/dir/2019/904/oj, **2019**.
[101] European Commission, "Proposal for a Regulation of the European Parliament and of the Council on the Establishment of a Framework to Facilitate Sustainable Investment.," can be found under https://ec.europa.eu/transparency/regdoc/rep/1/2018/EN/COM-2018-353-F1-EN-MAIN-PART-1.PDF, **2018**.

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[102] "Legislative train schedule," can be found under https://www.europarl.europa.eu/legislative-train, **2020**.
[103] V. Monier, M. Hestin, J. Cavé, I. Laureysens, E. Watkins, H. Reisinger, L. Porsch, "Development of Guidance on Extended Producer Responsibility (EPR)," can be found under https://ec.europa.eu/environment/archives/waste/eu_guidance/pdf/Guidance%20on%20EPR%20-%20Final%20Report.pdf, **2014**.
[104] European Commission, "Commission Staff Working Paper. Impact Assessment - Horizon 2020, the Framework Programme for Research and Innovation," can be found under http://ec.europa.eu/research/horizon2020/pdf/proposals/horizon_2020_impact_assessment_report.pdf#view=fit&pagemode=none, **2011**.
[105] European Commission, Directorate-General for Research and Innovation, "EU Budget for the Future: Horizon Europe," can be found under http://publications.europa.eu/publication/manifestation_identifier/PUB_KI0118590ENN, **2018**.
[106] United Kingdom, "The Environmental Protection (Microbeads) (England) Regulations 2017," can be found http://www.legislation.gov.uk/uksi/2017/1312/pdfs/uksi_20171312_en.pdf, **2017**.
[107] European Chemicals Agency (ECHA), "Annex XV Restriction Report: Proposal of Restriction for Intentionally Added Microplastics," can be found under https://echa.europa.eu/documents/10162/05bd96e3-b969-0a7c-c6d0-441182893720, **2019**.
[108] European Chemicals Agency (ECHA), "Authorisation-ECHA," can be found under https://echa.europa.eu/substances-of-very-high-concern-identification-explained, **2019**.
[109] M. Kubicki, *Guidance on the Preparation of an Application for Authorisation*, European Chemicals Agency, Helsinki, **2011**.
[110] European Commission, "A New Circular Economy Action Plan," can be found under https://ec.europa.eu/environment/circular-economy/pdf/new_circular_economy_action_plan.pdf, **2020**.
[111] United States of America, "The Clean Water Act and Trash-Free Waters," can be found under https://www.epa.gov/trash-free-waters/clean-water-act-and-trash-free-waters, **1972**.
[112] T. W. House, *Ind. Biotechnol.* **2012**, *8*, 97–102.
[113] M. Singh, "Most ambitious US law to tackle single-use plastics faces make-or-break moment", can be found under http://www.theguardian.com/us-news/2019/sep/13/california-plastics-legislation-single-use, **2019**.
[114] OECD, "Policies for Bioplastics in the Context of a Bioeconomy," can be found under https://www.oecd-ilibrary.org/science-and-technology/policies-for-bioplastics-in-the-context-of-a-bioeconomy_5k3xpf9rrw6d-en, **2013**.
[115] J. O. Babayemi, I. C. Nnorom, O. Osibanjo, R. Weber, *Environ. Sci. Eur.* **2019**, *31*, 60.
[116] Organisation for Economic Co-operation and Development, *OECD Guidelines for the Testing of Chemicals*, **1992**.
[117] "ISO - Standards," can be found under https://www.iso.org/standards.html, **2019**.
[118] "CEN - Advanced search - Publications and Work in Progress," can be found under https://standards.cen.eu/dyn/www/f?p=CENWEB:105::RESET::::, **2019**.
[119] "ASTM International - Standards and Publications," can be found under https://www.astm.org/Standard/standards-and-publications.html, **2019**.
[120] "Test No. 302B: Inherent Biodegradability: Zahn-Wellens/ EVPA Test," can be found under https://www.oecd-ilibrary.org/environment/test-no-302b-inherent-biodegradability-zahn-wellens-evpa-test_9789264070387-en, **1992**.
[121] "Test No. 302C: Inherent Biodegradability: Modified MITI Test (II)," can be found under https://www.oecd-ilibrary.org/environment/test-no-302c-inherent-biodegradability-modified-miti-test-ii_9789264070400-en, **2009**.
[122] "Test No. 301: Ready Biodegradability," can be found under https://www.oecd-ilibrary.org/environment/test-no-301-ready-biodegradability_9789264070349-en, **1992**.
[123] "Test No. 306: Biodegradability in Seawater," can be found under https://www.oecd-ilibrary.org/environment/test-no-306-biodegradability-in-seawater_9789264070486-en, **1992**.
[124] "Test No. 310: Ready Biodegradability - CO2 in sealed vessels (Headspace Test)," can be found under https://www.oecd-ilibrary.org/environment/test-no-310-ready-biodegradability-co2-in-sealed-vessels-headspace-test_9789264224506-en, **2014**.
[125] International Organization for Standardization, "ISO 14851:2019," can be found under https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/07/00/70026.html, **2019**.
[126] International Organization for Standardization, "ISO 14852:2018," can be found under https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/07/20/72051.html, **2018**.
[127] International Organization for Standardization, "ISO 17556:2019," can be found under https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/07/49/74993.html, **2019**.
[128] International Organization for Standardization, "ISO 19679:2016," can be found under https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/06/60/66003.html, **2016**.
[129] International Organization for Standardization, "ISO 18830:2016," can be found under https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/06/35/63515.html, **2016**.
[130] J. P. Harrison, C. Boardman, K. O'Callaghan, A.-M. Delort, J. Song, *R. Soc. Open Sci.* **2018**, *5*, 171792.
[131] "Product certification and certification marks | TÜV Rheinland," can be found under https://www.tuv.com/netherlands/en/product-certification.html, **2019**.
[132] "Certifications," can be found under https://www.tuv-at.be/green-marks/certifications/, **2019**.
[133] "EU Ecolabel - Environment - European Commission," can be found under https://ec.europa.eu/environment/ecolabel/, n.d.
[134] M. Nazareth, M. R. C. Marques, M. C. A. Leite, Í. B. Castro, *J. Hazard. Mater.* **2019**, *366*, 714–722.
[135] H. Spanjers, P. A. Vanrolleghem, in *Experimental Methods in Wastewater Treatment* (Eds.: M. C. M. van Loosdrecht, P. H. Nielsen, C. M. Lopez-Vazquez, D. Brdjanovic), IWA Publishing, London, **2016**, p. 133.
[136] "Test No. 302 A: Inherent Biodegradability: Modified SCAS Test," can be found under https://www.oecd-ilibrary.org/environment/test-no-302a-inherent-biodegradability-modified-scas-test_9789264070363-en, **1981**.
[137] "Test No. 303: Simulation Test - Aerobic Sewage Treatment – A: Activated Sludge Units; B: Biofilms," can be found under https://www.oecd-ilibrary.org/environment/test-no-303-simulation-test-aerobic-sewage-treatment-a-activated-sludge-units-b-biofilms_9789264070424-en, **2001**.
[138] "Test No. 307: Aerobic and Anaerobic Transformation in Soil," can be found under https://www.oecd-ilibrary.org/environment/test-no-307-aerobic-and-anaerobic-transformation-in-soil_9789264070509-en, **2002**.
[139] "Test No. 308: Aerobic and Anaerobic Transformation in Aquatic Sediment Systems," can be found under https://www.oecd-ilibrary.org/environment/test-no-308-aerobic-and-anaerobic-transformation-in-aquatic-sediment-systems_9789264070523-en, **2002**.
[140] "Test No. 309: Aerobic Mineralisation in Surface Water – Simulation Biodegradation Test," can be found under https://www.oecd-ilibrary.org/environment/test-no-309-aerobic-mineralisation-in-surface-water-simulation-biodegradation-test_9789264070547-en, **2004**.
[141] International Organization for Standardization, "ISO 14855-1:2012," can be found under https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/05/79/57902.html, **2012**.
[142] International Organization for Standardization, "ISO 14855-2:2018," can be found under https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/07/20/72046.html, **2018**.
[143] D20 Committee, *Test Method for Determining the Biodegradability of Radiolabeled Polymeric Plastic Materials in Seawater*, ASTM International, **2010**.
[144] S. Chinaglia, M. Tosin, F. Degli-Innocenti, *Polym. Degrad. Stab.* **2018**, *147*, 237–244.
[145] International Organization for Standardization, "ISO 10640:2011," can be found under https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/04/60/46024.html, **2011**.
[146] W.-F. Su, in *Principles of Polymer Design and Synthesis* (Ed.: W.-F. Su), Springer, Berlin, Heidelberg, **2013**, pp. 89–110.
[147] B. A. J. Poursat, R. J. M. van Spanning, P. de Voogt, J. R. Parsons, *Crit. Rev. Environ. Sci. Technol.* **2019**, *49*, 2220–2255.
[148] A. Krasowska, K. Sigler, *Front. Cell. Infect. Microbiol.* **2014**, *4*, 112.
[149] B. Gewert, M. M. Plassmann, M. MacLeod, *Environ. Sci.: Processes Impacts* **2015**, *17*, 1513–1521.
[150] A. Rudin, P. Choi, in *The Elements of Polymer Science & Engineering (Third Edition)* (Eds.: A. Rudin, P. Choi), Academic Press, Boston, **2013**, pp. 1–62.
[151] R. Pantani, A. Sorrentino, *Polym. Degrad. Stab.* **2013**, *98*, 1089–1096.

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[152] R. W. Okey, H. D. Stensel, *Water Res.* **1996**, *30*, 2206–2214.
[153] M. F. Ebbesen, C. Gerke, P. Hartwig, L. Hartmann, *Polym. Chem.* **2016**, *7*, 7086–7093.
[154] K. Luo, J. Yang, P. Kopečková, J. Kopeček, *Macromolecules* **2011**, *44*, 2481–2488.
[155] R. S. Boethling, E. Sommer, D. DiFiore, *Chem. Rev.* **2007**, *107*, 2207–2227.
[156] A. A. Shah, S. Kato, N. Shintani, N. R. Kamini, T. Nakajima-Kambe, *Appl. Microbiol. Biotechnol.* **2014**, *98*, 3437–3447.
[157] A. Ammala, S. Bateman, K. Dean, E. Petinakis, P. Sangwan, S. Wong, Q. Yuan, L. Yu, C. Patrick, K. H. Leong, *Prog. Polym. Sci.* **2011**, *36*, 1015–1049.
[158] A. Chamas, H. Moon, J. Zheng, Y. Qiu, T. Tabassum, J. H. Jang, M. Abu-Omar, S. L. Scott, S. Suh, *ACS Sustainable Chem. Eng.* **2020**, *8*, 3494–3511.

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