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Patents for tomorrow’s plastics

Global innovation trends in recycling, circular design and alternative sources

October 2021

Foreword

How can we find a path towards a more sustainable planet? With pollution posing a major hazard to our health and the environment, innovation will play a crucial role in the search for solutions. This study focuses on the future of plastics and how new technologies can help to forge a more sustainable future.

While plastics are essential to the economy, plastic pollution is threatening ecosystems all over the planet. Over 50 million tonnes of plastics were produced last year alone, whilst at the same time up to 25 million tonnes of plastic waste went into landfill and up to 23 million tonnes of waste could have gone into rivers, lakes and oceans.

The good news is that innovation can make a difference. By improving waste management and plastic recycling, new technologies can accelerate the transition to a fully circular model that keeps materials flowing in a "closed loop" system, rather than being used once and discarded.

Drawing on the EPO's cutting-edge patent data, this study offers policymakers and investors key insights into potentially game-changing chemical and biological recycling methods for producing virgin-like plastics from waste. It also highlights Europe’s contribution to innovation in this sector. European universities and public research organisations are pioneering a range of technologies that foster the reusability, recyclability and bio-degradability of plastic products. But the major challenge faced by many is turning their research findings into inventions and bringing them to market.

Intellectual property (IP) rights can help them to commercialise their findings. In Europe, industries that make intensive use of IP rights account for 45% of the EU’s GDP and 39% of employment (EPO and EUIPO, 2019). IP rights also make it easier for innovative start-ups and spin-offs to attract venture capital and pursue licensing agreements.

As the European Commission’s Green Deal to make the EU carbon neutral by 2050 takes shape, helping innovative players to flourish is essential. This study not only offers a unique source of business intelligence on promising technologies for decision-makers in government and industry. It also sheds light on how innovation, coupled with regulation and cross-border collaboration, can create a smarter, more sustainable future for plastic-reliant industries.

António Campinos
President, European Patent Office

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List of abbreviations

AI	Artificial intelligence
CO_2	Carbon dioxide
CANs	Covalent adaptable networks
EPC	European Patent Convention
EPO	European Patent Office
FDCA	Furandicarboxylic acid (precursor material to make PEF)
GHG	Greenhouse gas
HMF	Hydroxymethylfurfural
IPF	International patent familiy
LCD	Liquid crystal display
L-PC	Linear chain polycarbonates
MF	Melamine-formaldehyde
MMF	Methoxymethylfurfural
PEF	Polyethylene furanoate
PET	Polyethylene terephthalate
PBT	Polybutylene terephthalate
PHA	Polyhydroxyalkanoates
PPE	Personal protective equipment
PROs	Public research organisations
PVC	Polyvinyl chloride
R&D	Research and development
RTA	Revealed technology advantage
SUPs	Single-use plastics
UF	Urea-formaldehyde

List of countries

AT	Austria
BE	Belgium
CH	Switzerland
CN	People's Republic of China
DE	Germany
DK	Denmark
ES	Spain
FI	Finland
FR	France
IL	Israel
IT	Italy
JP	Japan
KR	Republic of Korea
NL	Netherlands
SA	Saudi Arabia
SE	Sweden
SG	Singapore
TR	Turkey
TW	Chinese Taipei
UK	United Kingdom
US	United States

Executive summary

Our heavy reliance on single-use plastics (SUPs) has long been of growing concern. The COVID-19 pandemic triggered a massive deployment of masks, gloves, disposable test kits, swabs, syringes and medical packaging – all made from SUPs. This is just one of many instances illustrating the tension between the social benefits of plastics and the pollution that they cause.

Over the past 70 years, plastics have become an essential material for many industries and indeed for the economy. However, there is growing awareness of the dire environmental cost of this economic success. Today, the bulk of plastic production ends up as waste dumped in the environment, posing a critical and often immediate threat for countless endangered species, ecosystems and dependent socio-economic systems all over the planet.

The systemic challenge raised by this environmental crisis lies at the heart of the EU Green Deal (European Commission EC, 2019) and of the United Nations (UN) 2030 Sustainable Development Goals. To cope with the growing volume of plastic produced, used and dumped in today's linear economy, the plastics industry has to transition into a fully circular model, where end-of-life plastic products are not discarded as waste but instead become a source of value creation.

Innovation, regulation and international collaboration are needed to enable this transition. Progress in technologies related to waste recovery and transformation is crucial to support the systematic recycling of plastic waste and to maximise the value derived from it. Dominant technologies in the plastics industry often reflect a linear-economy focus on performance and durability. Nevertheless, further innovation in alternative plastics and designs can also foster the reusability, recyclability and biodegradability of plastic products, or even eliminate the need for plastic usage.

Aim of the study

Aimed at decision-makers in both the private and public sectors, this report is a unique source of intelligence on these technologies and the technical problems they aim to address. The report draws on the latest patent information available and the expertise of European Patent Office (EPO) examiners to provide a comprehensive analysis of the innovation trends driving the transition towards a circular economy for plastics.

Patent information provides robust statistical evidence of technical progress. The data presented in this report shows trends in high-value inventions for which patent protection has been sought in more than one country (IPFs[1]). It highlights technology fields that are gathering momentum and the cross-fertilisation taking place. Trends in circular plastic innovation have never been more important to the sector's development. Therefore, it provides a guide for policymakers and decision-makers to direct resources towards promising technologies, assess their comparative advantage at different stages of the value chain and shed light on innovative companies and institutions that may be in a position to contribute to long-term sustainable growth.

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[1] Each international patent family (IPF) covers a single invention and includes patent applications filed and published at several patent offices. It is a reliable proxy for inventive activity because it provides a degree of control for patent quality by only representing inventions for which the inventor considers the value sufficient to seek protection internationally. The patent trend data presented in this report refers to numbers of IPFs.

Key findings

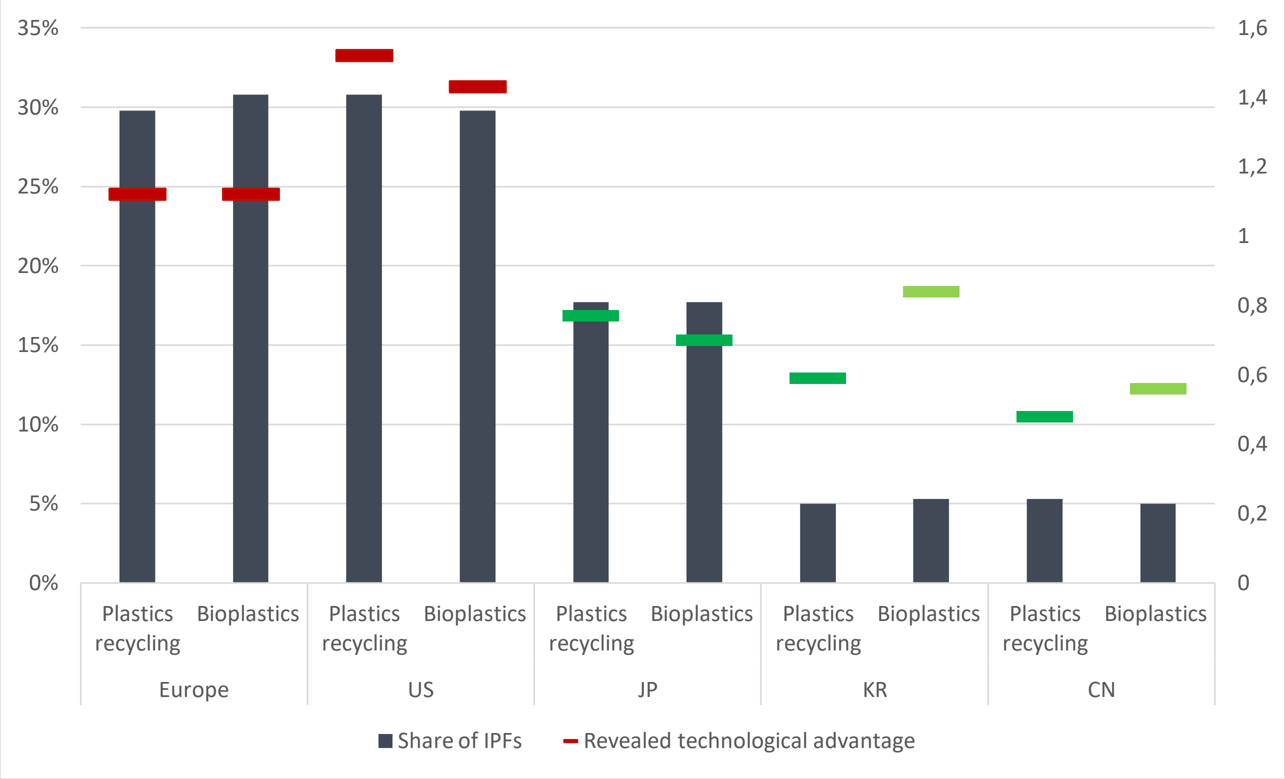
The US and Europe stand out as global innovators for a circular plastics industry

The US and Europe[2] are by far the main global innovators in terms of efforts to make the plastics industry circular, with about 30% each of IPFs related to the circular plastics industry between 2010 and 2019.[3] They are also the only major innovation centres truly specialising in these technologies. The US, in particular, shows significantly higher revealed technological advantages in both plastic recycling and bioplastic technologies.[4]

With about 18% of IPFs in 2010–2019, Japan is far ahead of the Republic of Korea and the People's Republic of China (each at about 5%). However, all three show a similar lack of specialisation in these technologies.

Within Europe, France, the UK, Italy, the Netherlands and Belgium stand out for their specialisation in both plastic recycling and bioplastic technologies. Although it posted the highest share of IPFs due to its larger economy, Germany lacks specialisation in these fields.

Figure E.1: Origins of inventions related to the circular plastics industry, 2010-2019



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[2] Unless specified otherwise, Europe and European countries refer in the study to all the 38 contracting states of the European Patent Convention (EPC). These countries include but are not restricted to the 27 member states of the European Union (EU).

[3] The date attributed to a given IPF always refers to the year of the earliest publication within the IPF.

[4] Specialisation is measured here using the revealed technological advantage (RTA) index. The RTA indicates a country's specialisation in terms of circular plastics innovation relative to its overall innovation capacity. It is defined as a country's share of IPFs in a particular field of technology divided by the country's share of IPFs in all fields of technology. An RTA above one reflects a country's specialisation in a given technology. Only the highest RTAs (approximately 1.5 or more) are reported in the chart.

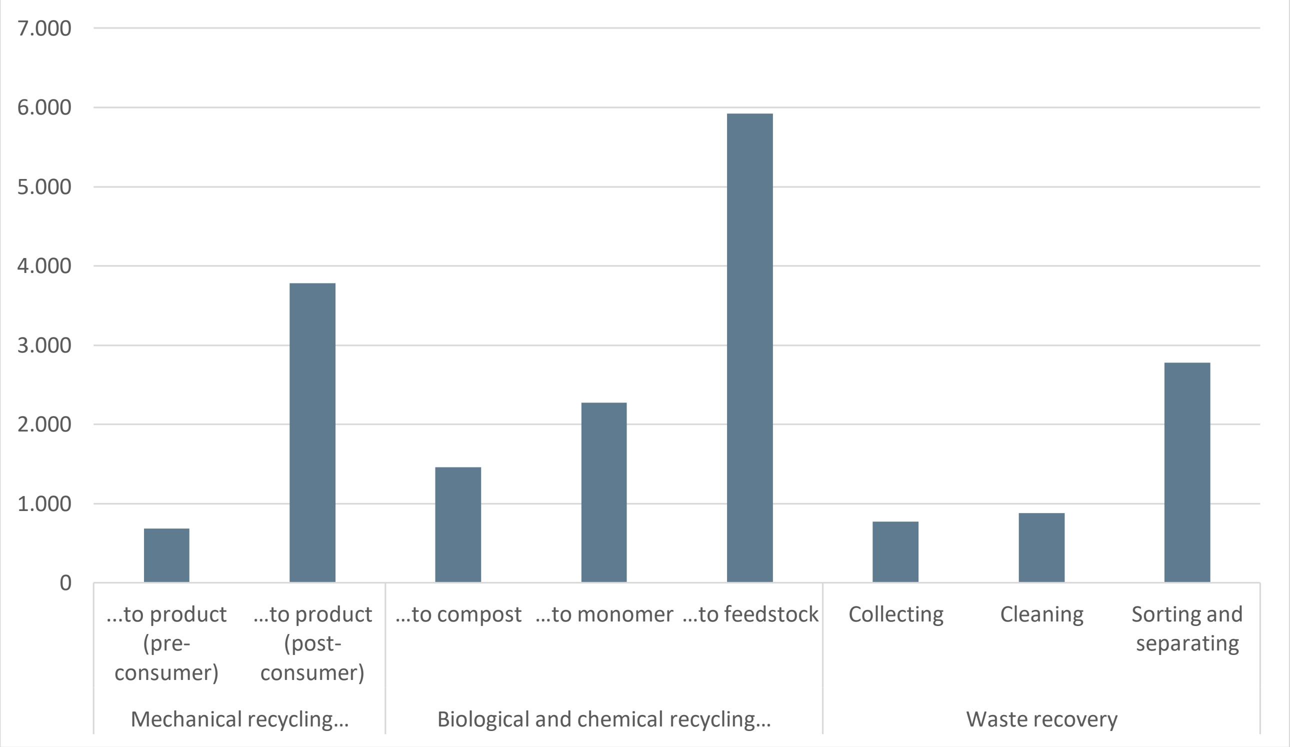
Chemical and biological recycling generated the highest level of patenting activities

Mechanical recycling is currently the simplest and most commonly used solution to transform plastic waste into new products. It generated nearly 4 500 IPFs from 2010 to 2019, with an increasing focus on addressing the quality degradation issues when recycling plastic waste that is collected post-consumer. However, with more than 9 000 IPFs over the same period, it is chemical and biological recycling methods that stand out in terms of the number of IPFs.

Chemical methods mainly consist of energy-intensive plastic-to-feedstock recycling processes (such as cracking and pyrolysis). Here, the chemical structure of plastic waste is converted into a mixture of basic chemicals, allowing for flexible reuse in the petrochemical industry. However, innovation in these technologies reached a peak in 2014. Emerging plastic-to-monomer recycling technologies now offer possibilities to break down polymers into their original building blocks, allowing for near virgin-quality material and a larger number of possible cycles. Likewise, recent biological plastic-to-compost recycling represents a comparatively small number of IPFs. This promising technology involves the use of living organisms to degrade polymers into compost.

All these methods require an effective recovery of plastic waste (about 3 400 IPFs from 2010 to 2019), where different categories of plastics are identified, separated and cleaned before recycling. Innovation efforts are mainly focused on the sorting and separating of waste, including the use of sophisticated technologies such as optical recognition and artificial intelligence (AI).

Figure E.2: Innovation in recycling technologies (number of IPFs, 2010-2019)



Note: Some inventions may be relevant to different technology fields resulting in the related IPFs being counted once in each field.

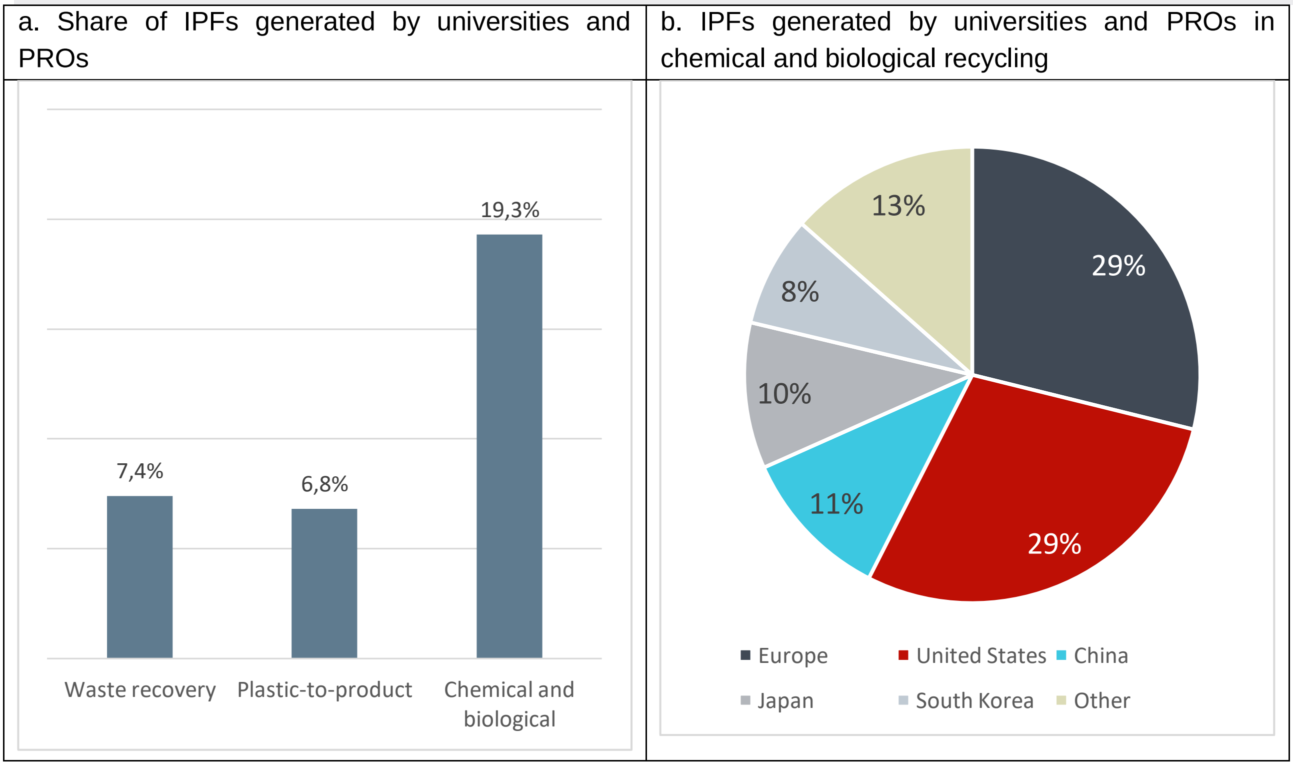
Fundamental research is key to further progress in chemical and biological recycling. Europe's good performance in this respect shows potential to bring new technologies to market.

Chemical and biological recycling methods rely far more on upstream fundamental research than other recycling technologies, with nearly 20% of IPFs stemming from universities and public research organisations (PROs) in the period 2010 to 2019. Innovation in waste recovery and plastic-to-product recycling frequently relies on available technologies and existing engineering approaches, which explains the lower shares (7.4% and 6.8%, respectively) of IPFs produced by research institutions in these fields.

European countries and the US demonstrate a clear lead with chemical and biological recycling methods, each with 29% of the IPFs stemming from research institutions. Europe is the only major innovation centre that contributes more to IPFs in upstream research than to all IPFs in the field (26%). By contrast, the US's and Japan's contributions to upstream IPFs (29% and 11%) are lower than their respective shares in all IPFs (36% and 17%).

This suggests that Europe, despite being particularly active in fundamental research, is not exploiting its full potential when it comes to transferring these technologies to industry. A closer analysis of the IPFs originating from start-up and scale-up companies supports this finding. Although the number of such IPFs increased in the same proportions in both regions between 2010 and 2019, US start-ups and scale-ups generated four times as many IPFs than their European counterparts (338 versus 84) over the decade.

Figure E.3: Upstream research in recycling technologies, 2010–2019


a. Share of IPFs generated by universities and PROs

b. IPFs generated by universities and PROs in chemical and biological recycling

Note: The geographic origins of the IPFs in Figure E.3b are based on the country of the applicants.

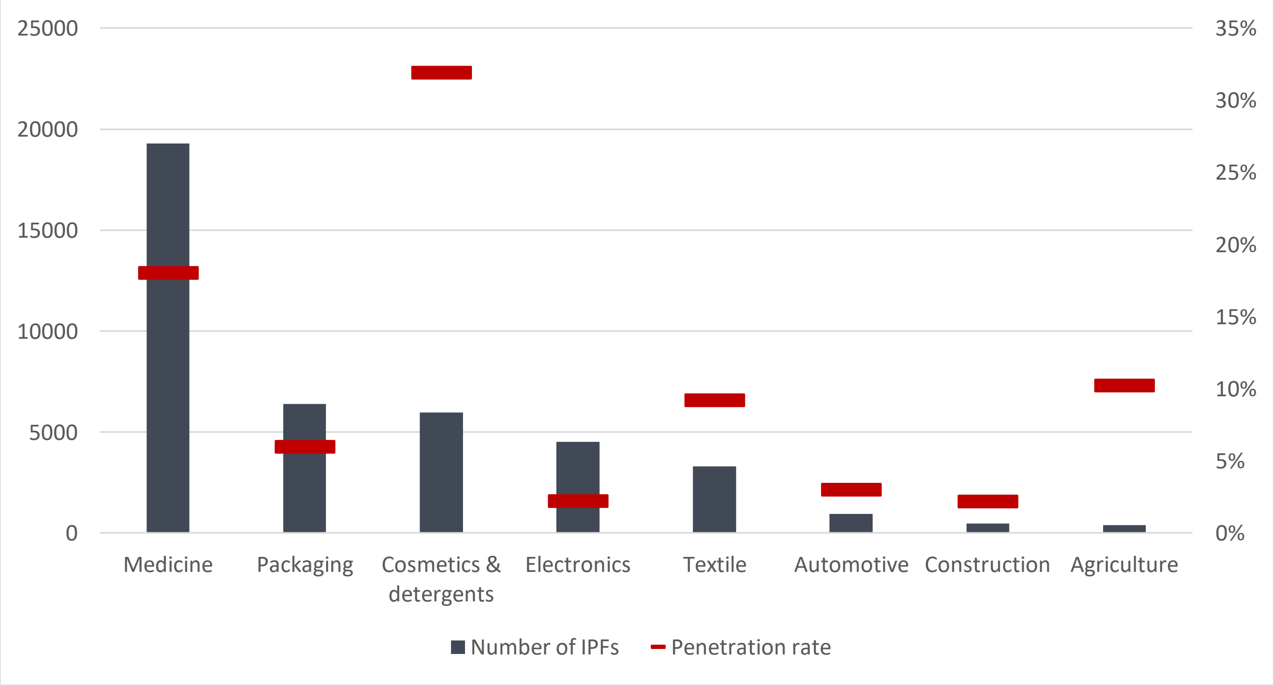
Bioplastics provide alternatives to conventional fossil raw materials

Bio-based and/or biodegradable plastics show potential for enhancing circularity and reducing the carbon emissions generated by the use of conventional fossil raw materials. Patenting activities in these bioplastics took off in the late 1980s and since then have followed a growth trend similar to that of conventional plastics technologies.

Of these materials, chemically modified natural polymers (such as modified cellulose) generated the largest share of patenting activities over the past decade. However, polymers from bio-sourced monomers have been the fastest-growing field. Most of the patents in this field relate to so-called "drop-in plastics" (i.e. Bio-PE, Bio-PET) which, although not biodegradable, allow for a reduced consumption of non-renewable resources and CO_2 emissions at the production stage. Among the smaller fields, industrial natural polymers show potential for creating reusable, recyclable plastics that can be readily broken down by microorganisms.

Despite accounting for less than 3% of the total demand for plastics in Europe (PlasticsEurope, 2020), healthcare is by far the most important industry in terms of the number of IPFs in bioplastics, with more than 19 000 IPFs recorded from 2010 to 2019. Meanwhile, cosmetics and detergents show the highest rate of innovation in bioplastics. In that sector, IPFs related to bioplastics are at 32% of the level of IPFs for conventional plastics. Packaging, electronics and textiles are also significant contributors to innovation in bioplastics, with 6 400, 4 500 and 3 300 IPFs, respectively, from 2010 to 2019. Agriculture shows a high penetration rate (10%) and posted 2.5 times more IPFs for bioplastics in 2019 than in 2010.

Figure E.4: Innovation in bioplastics for selected sectors



Note: The penetration rate is defined as the ratio of the number of IPFs in alternative plastics to the number of IPFs related to conventional plastics in the same sector

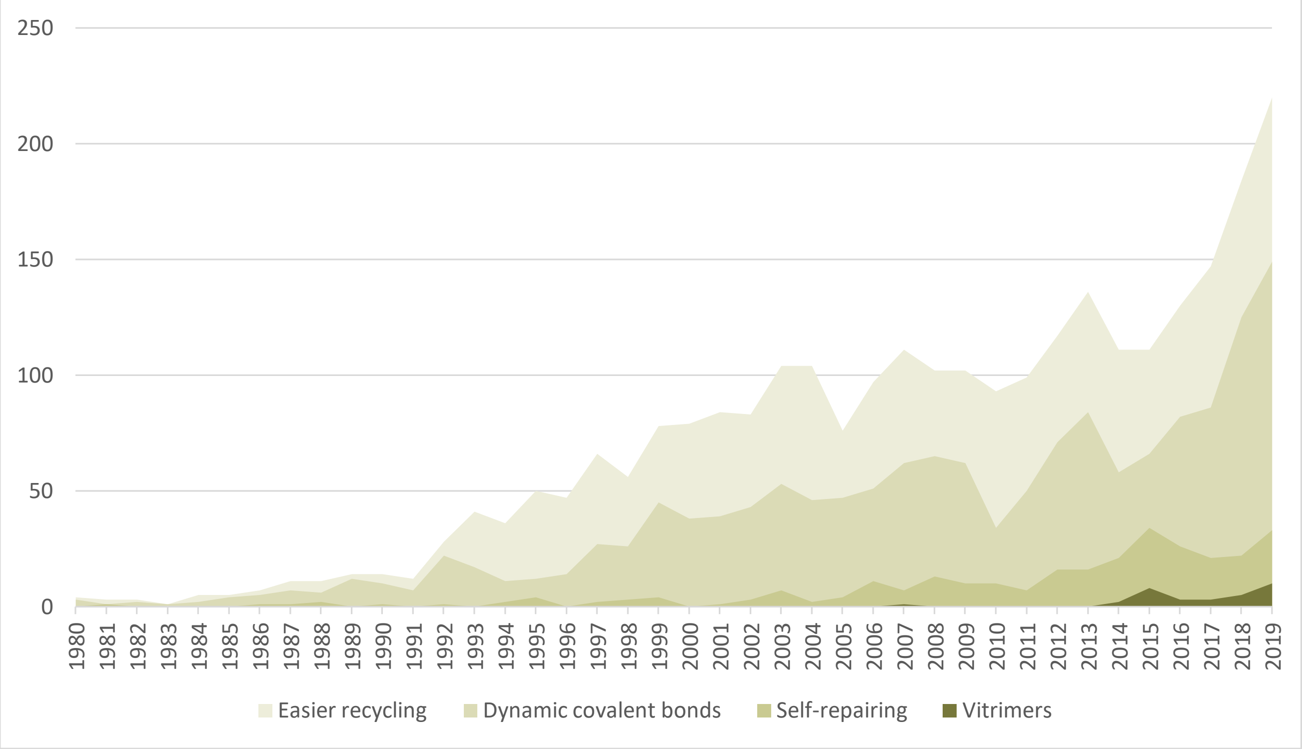
Rapidly emerging technologies allow for novel designs of durable plastic materials

In the early 1990s, technologies focused on plastic design for easier recycling started to emerge and these have been developing exponentially ever since. The rapid growth of patenting in these fields is driven by progress in dynamic covalent bonding, a synthetic strategy employed to form 3D networks of macromolecular chains that can break and reform via reversible chemical reactions. This dynamic reversibility can overcome difficulties encountered in the processing and recycling of the many polymers used in aerospace, construction, transport and microelectronics.

Among recent developments, vitrimers are a promising type of covalent adaptable network (CAN). Vitrimers are strong, stable and intrinsically self-healing, with potential for replacing thermoset plastics in high-performance and lightweight applications, such as the production of composite parts for aircraft, automotive, sports equipment and wind turbine blades.

Japan demonstrates a strong lead in technologies using dynamic covalent bonds, with nearly half (49%) of related IPFs from 2010 to 2019. The US follows with 24%, while European countries contribute only 17%. However, most of the IPFs originating from universities and PROs are from European and US research institutions (40% and 30%, respectively), while Japan has only 7%. Japan leads overall despite a small presence in university research, in stark contrast to Europe, which contributes nearly twice as much to upstream university research than to related patenting activities.

Figure E.5: IPFs related to design for easier recycling, dynamic covalent bonds, self-repairing polymers and vitrimers, 1980–2019



1. Introduction

Over the past 70 years, plastics have become an essential material for many industries and indeed for the economy. However, there is growing awareness of the dire environmental cost of this economic success. Today, the bulk of plastic production ends up as waste dumped in the environment, posing a critical and often immediate threat for countless endangered species, ecosystems and dependent socio-economic systems all over the planet.

The systemic challenge raised by this environmental crisis lies at the heart of the EU Green Deal (EC, 2019) and of the UN 2030 Sustainable Development Goals. To cope with the growing volume of plastic produced, used and dumped in today's linear economy, the plastics industry has to transition into a fully circular model, where end-of-life plastic products are not discarded as waste but instead become a source of value creation.

Innovation, regulation and international collaboration are needed to enable this transition. Progress in technologies related to waste recovery and transformation is crucial to support the systematic recycling of plastic waste and to maximise the value derived from it. Dominant technologies in the plastics industry often reflect a linear-economy focus on performance and durability. Nevertheless, further innovation in alternative plastics and designs can also foster the reusability, recyclability and biodegradability of plastic products, or even eliminate the need for plastic usage.

Aimed at decision-makers in both the private and public sectors, this report is a unique source of intelligence on these technologies and the problems they aim to address. The report draws on the latest patent information available and the expertise of EPO examiners to provide a comprehensive analysis of the innovation trends driving the transition towards a circular economy for plastics.

Patent information provides robust statistical evidence of technical progress. The data presented in this report shows trends in high-value inventions for which patent protection has been sought in more than one country (IPFs[5]). It highlights technology fields that are gathering momentum and the cross-fertilisation taking place. Trends in circular plastic innovation have never been more important to the sector's development. Therefore, it provides a guide for policymakers and decision-makers to direct resources towards promising technologies, assess their comparative advantage at different stages of the value chain and shed light on innovative companies and institutions that may be in a position to contribute to long-term sustainable growth.

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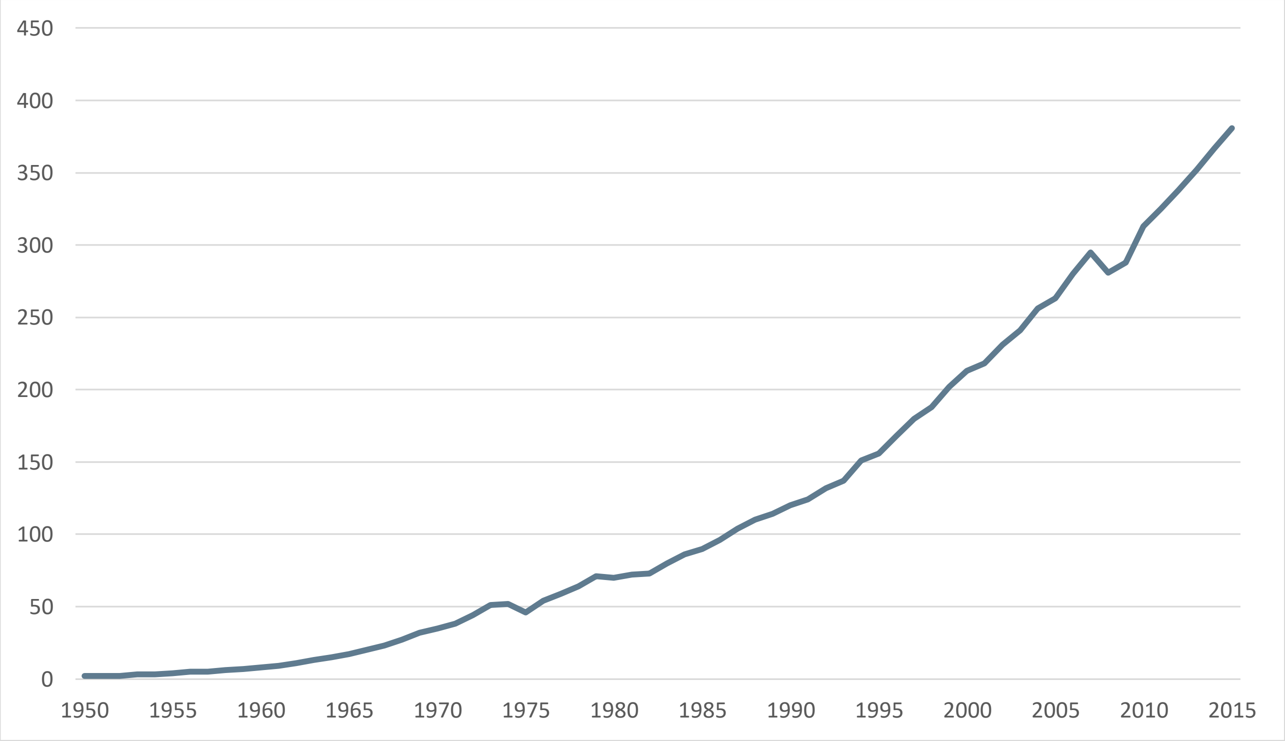
Plastics are everywhere in the economy

Industrial-scale plastics production began in earnest in the 1940s and rapidly increased in the 1950s (Figure 1.1). Growth has subsequently outpaced any other manufactured material (Geyer et al., 2017), with more than 8 billion tonnes of plastics produced worldwide from 1950 to 2015. Today, the plastics industry employs 1.56 million people in Europe alone, and ranks seventh in Europe in industrial value-added contribution (PlasticsEurope, 2020). Innovation in new plastic materials and production processes has been one of the key drivers of this success. Roughly a century after the creation of polyvinyl chloride (PVC), thousands of different kinds of plastics are now available.[6]

Figure 1.1: Global production of polymer resin and fibre, 1950–2015 (million tonnes per year)



Source: Geyer et al., 2017

With 50.7 million tonnes of plastics produced in 2019, Europe accounts for about 16% of global production, behind North America (19%) and Asia (51%) (PlasticsEurope, 2020). This production includes a large variety of plastics, including pure polymers, as well as mixtures of polymers, additives,[7] colourants and fillers. Over 90% of raw plastic is synthesised from fossil feedstock (oil or natural gas). However, chemically modifying renewable feedstock can also produce polymers.

As a material, plastics provide various technical benefits such as outstanding strength-to-weight ratio and permanency (they do not require extensive maintenance and are mostly resistant to corrosion). The physical properties of polymers can be easily tailored: plastics can be hard and

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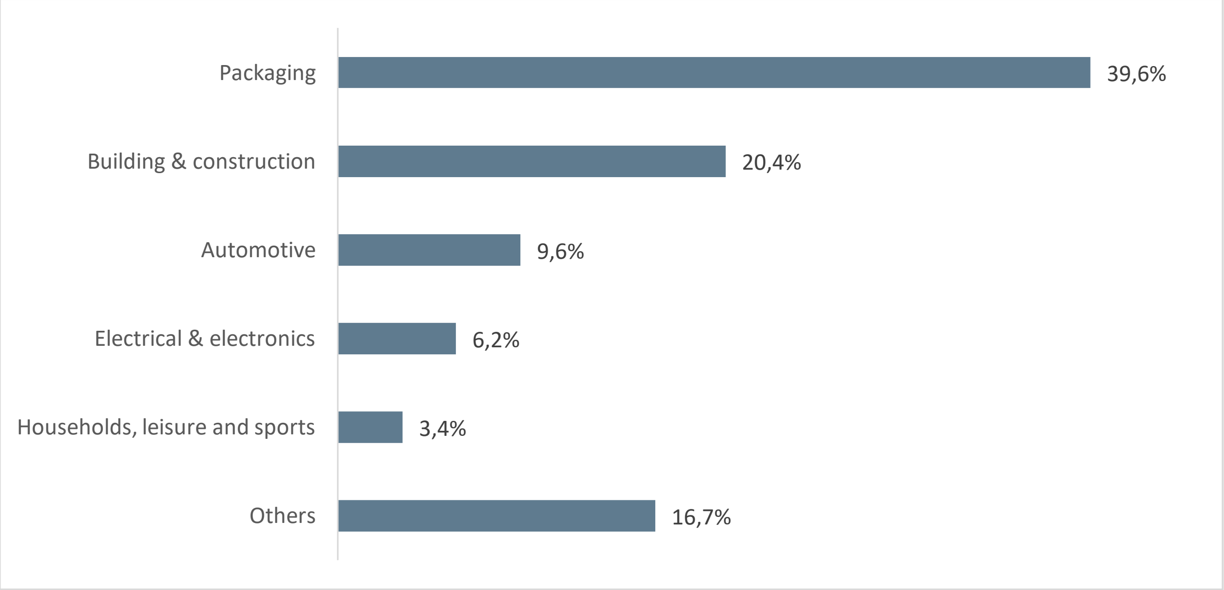
[6] The first patent on PVC was granted in 1913 to German inventor Friedrich Klatte for his process of vinyl chloride polymerisation using sunlight. In the 1920s, Waldo Semon took Klatte's invention and found a way to produce PVC in a solid, plasticised form as a substitute for natural rubber.

[7] Additives can render polymers bacteria- or fire-resistant, give them a rainbow of colours, make them flexible, fill them with bubbles to make them better insulators or even add fibres to make high-tech composites.

shatter-resistant or soft and flexible. This is achieved by optimising their chemical structure or by using functional additives, colourants or fillers resulting in multicomponent plastics. This versatility, combined with the low cost of plastic production, is the major reason why plastics are currently used in almost every economic sector (Figure 1.2).

Indeed, plastics can be found in mobile phones, televisions, computers and other electronic equipment that make modern life possible. They are used to make toys, textiles and car airbags. They are present in the roofs, walls, flooring and insulation that make homes and buildings energy efficient. Plastics are also in many products that people would not even recognise as plastic, such as cosmetics, paints, protective coatings and linings. Last but not least, they are ubiquitous in packaging.

Figure 1.2: Plastic demand by segment in Europe, 2019



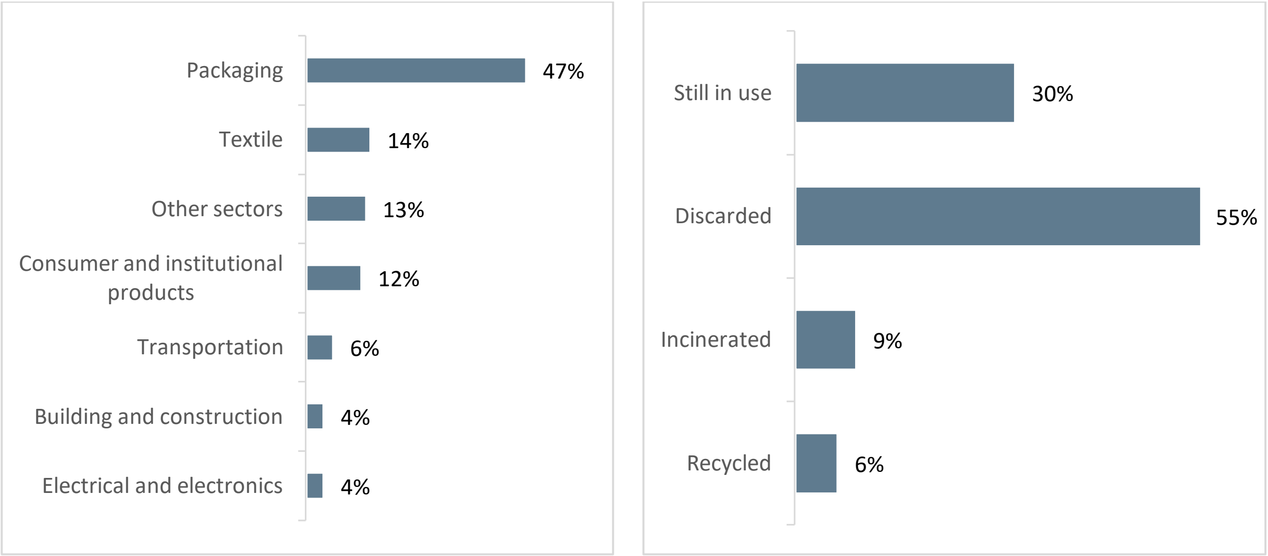
Source: PlasticsEurope, 2020.
Note: Europe is defined here as including the EU27, Norway, Switzerland and the UK

Such uses often reflect key properties that only plastics can provide at an affordable cost. For instance, the use of lightweight and innovative plastics has played a critical role in reducing the mass of cars, aircraft, ships and trains, thereby enabling considerable cuts in energy demand and CO_2 emissions. In healthcare, plastics are used for single-use medical tools, packaging and even for medical surgery and transplants. Most recently, the combined use of bio-compatible plastic materials with 3D printing technologies has opened up new avenues for medicine, providing yet another example of this material's vast innovation potential.

The global threat of plastic waste

Paradoxically, plastic's very success causes major concern in the light of the massive quantities of plastic waste generated and the global threat for the environment. Plastic pollution is present around the world. It is estimated that more than half of all the past production of plastics has been discarded, while only 15% has been recycled or incinerated (Figure 1.3).[8] And every year, another 9 to 23 million tonnes of plastic waste ends up in rivers, lakes and the ocean, while 13 to 25 million tonnes are dumped on land (MacLeod et al., 2021).

Figure 1.3: Origins of plastic waste



Global plastic waste production by sector

Status of the global stock of plastics

Source: Smith and Vignieri, 2021

The material's durability and resistance means that plastic waste remains in the environment, taking from decades to centuries to naturally decay. Plastic pollution is hard to reverse when manufacturing, use[9] or the weather causes plastic to fragment into microplastic and nanoplastic particles that are not visible to the human eye. Evidence points to it playing a predominant role in the loss of biodiversity and altering of ecosystems, including wildlife's ingestion of plastics or microplastics, habitat changes within soils and ecotoxicity (MacLeod et al., 2021).

Despite growing awareness of these threats, current forecasts point towards the issue simply getting worse. The emission rates of plastic waste is expected to approximately double from 2016 to 2025 (MacLeod et al., 2021), and as much as 12 000 million tonnes will have accumulated in landfills or the natural environment by 2050 (Kakadellis and Rosetto, 2021). Waste disposal infrastructure varies by location, and plastic ends up in the environment via leakages from waste collection, recycling and disposal systems or the absence of those systems in general. In the EU, only 42% of plastic waste is collected for recycling (Partridge and Medda, 2019), about half of which is sent abroad, where it often ends up in illegal landfills (d'Ambrières, 2019).

Towards a circular economy for plastics

Given our deep-rooted economic reliance on plastics, the challenge of managing plastic waste is a systemic one. Besides the elimination of plastic waste in the environment, it calls for the reduction of plastic use and the reuse of plastics, whenever possible. Estimates suggest that increased

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[8] Another study published in 2017 (Geyer et al., 2017) estimates that approximately 6.3 billion tonnes of plastic waste had been generated as of 2015, of which less than 10% had been recycled (with less than 1% being recycled more than once) and 12% incinerated. The vast majority, 79%, was accumulated in landfills or the natural environment.

[9] Microplastics are in some cases intentionally added to certain product categories (such as cosmetics, detergents, paints), dispersed during the production, transport and use of plastic pellets or generated through the wear and tear of products such as tyres, paints and synthetic textiles.

waste management capacity alone cannot keep pace with projected growth in plastic waste generation by 2030 (Borelle et al., 2020).

Unless growth in plastic production is stopped, we will need to fundamentally transform the plastic economy into a circular framework, where plastic waste can be fed back into the economy as a source of value. This would significantly reduce CO_2 emissions as the use of recycled plastics prevents the emissions generated by the production of new plastics. Such a systemic shift, however, necessitates a holistic approach combining strong regulatory frameworks, as well as international and industry collaboration (Kakadellis and Rosetto, 2021; Simon et al., 2021).

Likewise, we require a new approach to innovation and technology, away from the dominant linear model where fossil resources are extracted to make products that are discarded after use. In general, it is easier and cheaper to manufacture new, disposable plastics from virgin fossil-based feedstocks than to sort and reuse reprocessed material. The vast majority of plastics is still designed for performance and durability rather than for degradability or recyclability. The use of complex multicomponent plastics creates a barrier to recycling because of the need for separation prior to reprocessing.

Contents

This study focuses on technologies that offer a pathway to a more circular plastics industry. Drawing on the latest patent information available and on the expertise of EPO examiners for the identification of key technology fields,[10] it analyses the latest trends, benchmarks them against conventional plastic technologies and documents the global innovators in circular plastic technologies.

We have identified two broad categories of technologies, each of which has been dedicated a main section of the study, complemented by case studies illustrating a range of related inventions.

The first section is dedicated to technologies that can be used in the recycling of plastic waste. Besides the waste recovery and mechanical methods used to recycle plastic waste into new products, it includes alternative chemical and biological solutions, which make it possible to recycle polymers into their constituting basic units or to degrade them into compost.

The second section focuses on alternative types of plastics, such as bioplastics, which can facilitate the degradation or recycling of plastic waste. It discusses the respective merits of the various categories of plastics. The study also examines patenting trends in new plastic designs and additional strategies to boost resource efficiency to plastics.

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[10] Further details on the identification methodology are provided in Annex 2 of this report.

2. Plastic recycling

This first section focuses on the technologies enabling a circular economy for plastics – from the recovery of post-consumer plastic waste to the various processes available for its recycling. It emphasises emerging innovation trends within these different technology fields.

2.1. Relevant technologies

Europe may be advanced in matters of plastic recycling, yet in 2018, only about a third of the 29.1 million tonnes of plastic waste collected there was recycled (PlasticsEurope, 2020).[11] The underlying collection and recycling processes are complex, with many regulations (d'Ambrières, 2019).[12] They also draw on a diverse set of technology solutions (Figure 2.1.1), which need to be developed to deploy a circular plastics industry.

Plastic recycling needs the right infrastructure and the right waste collection rules. This is a relatively easy task when pre-consumer plastic scraps are directly recovered during a manufacturing process. However, the recovery of post-consumer products is far more complex. The diversity of plastic waste is a critical obstacle to post-consumer plastic recycling. It is not sufficient to simply separate waste collection. Indeed, different categories of plastics need to be identified, separated and cleaned before applying recycling methods. This makes the recycling of products made of multilayer plastics particularly difficult. Innovation technologies facilitating the sorting, separating and cleaning of plastic waste are therefore critical in fostering a circular plastics economy.

As a second step, a variety of methods can be employed to recycle collected plastics, each of which involves specific technical conditions and valuation. Mechanical plastic-to-product recycling is the simplest, most common solution. It is typically based on the melting and reforming of thermoplastics or on the use of scraps in the composition of new products. Technical constraints, such as the need for virgin-like feedstock and the degradation of the polymers' quality during the recycling process, limit its potential

Against this backdrop, chemical and biological recycling methods offer promising alternatives. Feedstock recycling methods, such as cracking, gasification and pyrolysis, typically involve thermal treatments to decompose recovered plastics into shorter molecules.[13] These can then serve as virgin feedstock for new chemical reactions or for energy generation. Plastic-to-monomer recycling aims to recover the monomers, i.e. the building blocks of the polymer, allowing for the production of plastics with 100% recycled content with virgin-like properties and a larger number of reuse cycles. Biological recycling methods involve the use of enzymes or living organisms to degrade polymers to compost or monomers to synthesise useful compounds by biochemical transformation.

Finally, incineration provides an energy recovery solution for waste plastics that cannot be sustainably and efficiently recycled, due for example to the difficulty of properly sorting and cleaning them. As such, it provides an alternative to landfilling. In 2018, up to 42.6% of the plastic waste collected in Europe was incinerated (PlasticsEurope, 2020).

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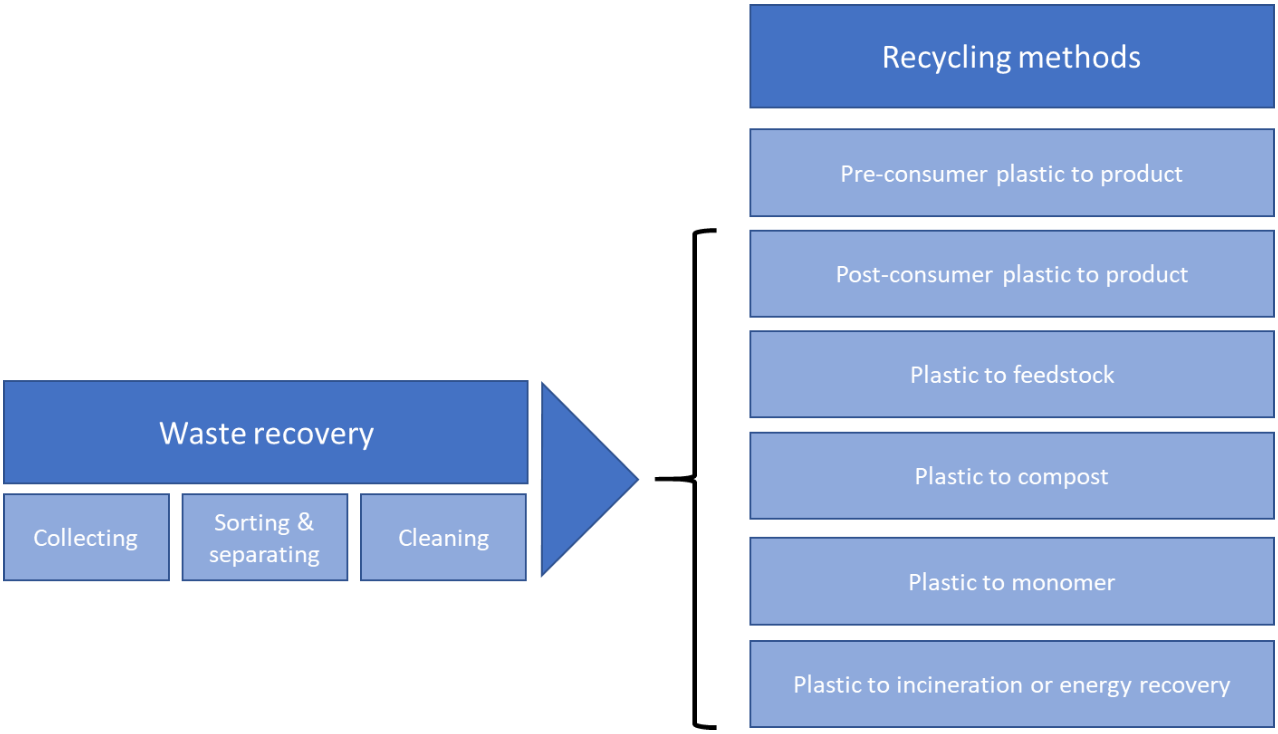
[11] Including here the EU27, Norway, Switzerland and the UK.

[12] The most stringent of which can be found in Europe and Japan.

[13] Typically, a mix of hydrocarbons, which can be separated into the individual fractions. Oils are used to produce fuels. Waxes can be used to produce lubricants. Oligomers and monomers can be used to produce new polymers. The other hydrocarbons can be used to produce new chemicals.

Figure 2.1.1: Overview of plastic recycling technologies

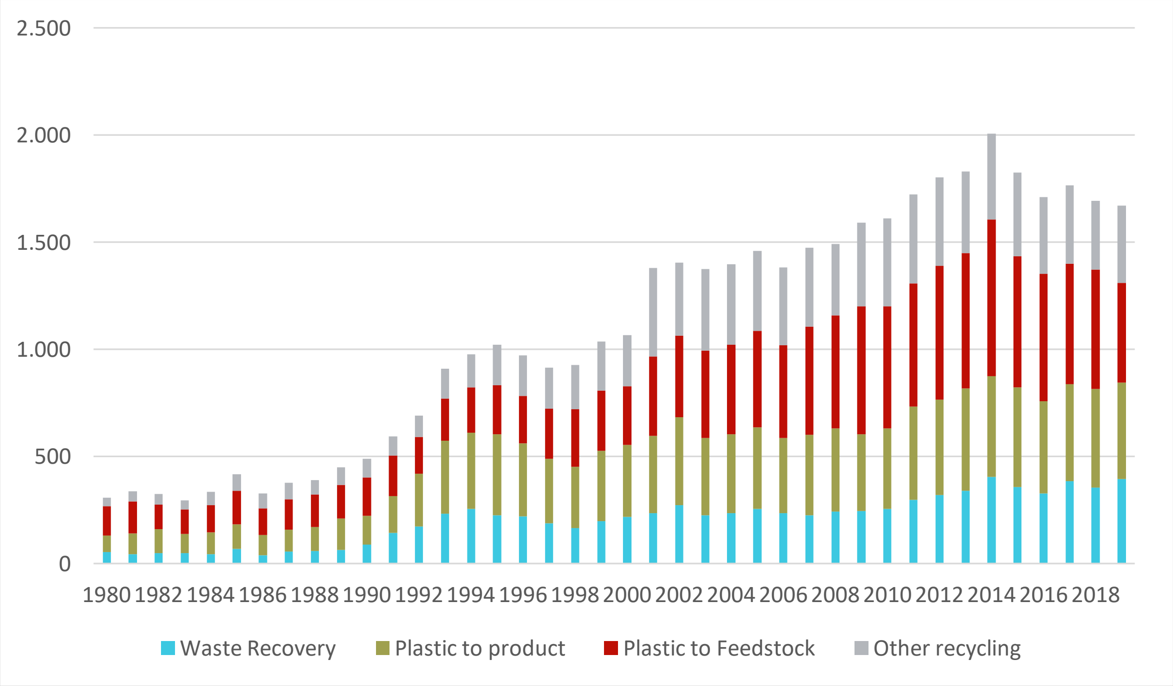


2.2. Overview of technology trends

Patenting activities related to plastic recycling took off in the mid-1980s and subsequently experienced two major periods of growth from 1997 to 2002 and from 2006 to 2014. However, after peaking in 2014, the patenting of these technologies declined (Figure 2.2.1). This negative trend is not visible in conventional plastic innovation, which posted a positive growth of IPFs between 2016 and 2019 (Figure 2.2.2). It is mainly due to a fall in patenting of plastic-to-feedstock recycling. This field alone represented a third of all IPFs since 2010, and decreased by 8.3% on average between 2014 and 2019.

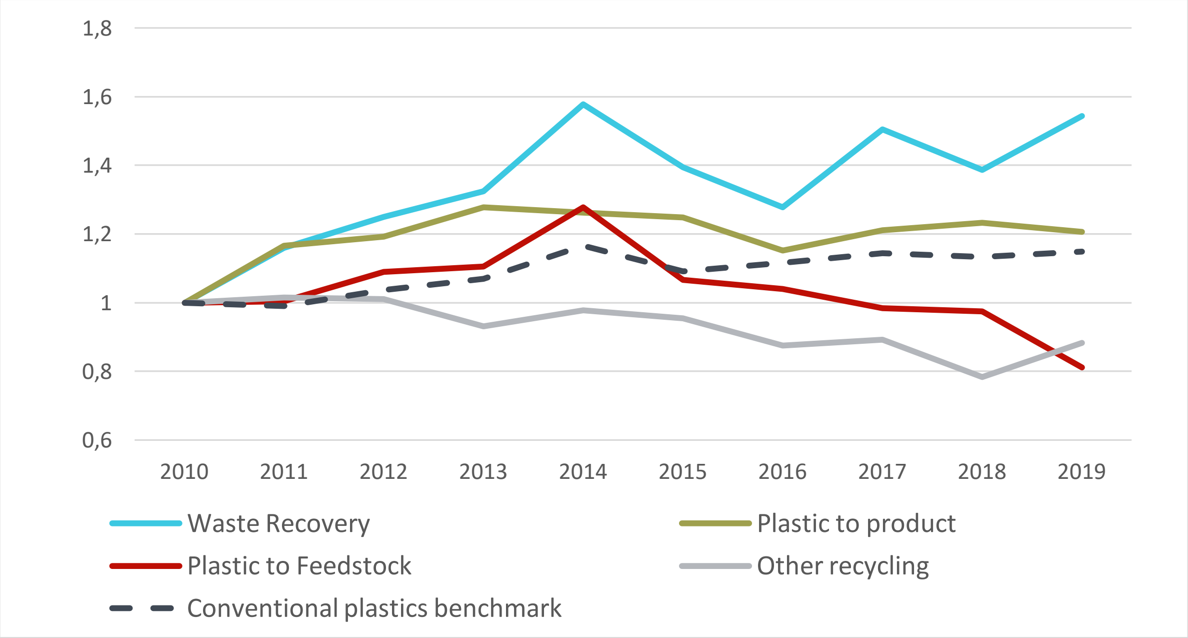
By contrast, innovation in plastic-to-product recycling and waste recovery (which represented 25% and 19% of IPFs from 2010 to 2019) posted positive growth over the same period. Other recycling technologies (encompassing emerging technologies in plastic-to-compost and plastic-to-monomer as well as plastic-to-incineration or energy recovery) contributed to the overall decline of patenting activities.

Figure 2.2.1: Long-term trends in IPFs related to plastic recycling, 1980–2019



Note: Some IPFs may be relevant to two or more of the four listed fields. In such cases they are counted once in each field.

Figure 2.2.2: Growth of plastic recycling technologies, 2010–2019 (base 1 set in 2010)



The geographic origins of the IPFs, calculated based on the location of inventors, are reported in Table 2.2.1. The US and Europe (defined here as the 38 member states of the EPC) clearly dominate the ranking, each with about 30% of all IPFs from 2010 to 2019. They are followed by Japan, with about 18% of all IPFs, while China and the Republic of Korea each post a modest 5%. Of these five major innovation centres, the US and Europe are the only two to show a real specialisation in plastic recycling technologies. The US has a revealed technological advantage (RTA) and a higher number of IPFs per capita. By contrast, Japan, China and the Republic of Korea all show a lack of specialisation in plastic recycling technologies.

Table 2.2.1: Origins of IPFs related to plastic recycling, 2010–2019

	Number of IPFs 2010-2019*	Share of IPFs 2010-2019*	IPFs per mio capita*	RTA 2010-2019**
US	4 640	30.8%	13.95	1.52
EPC	4 492	29.8%	6.77	1.12
EU27	3 829	25.4%	8.60	1.13
JP	2 665	17.7%	21.30	0.77
DE	1 242	8.2%	14.82	0.83
CN	801	5.3%	0.57	0.48
KR	749	5.0%	14.53	0.59
FR	644	4.3%	9.86	1.19
NL	440	2.9%	25.69	2.27
UK	436	2.9%	6.42	1.12
IT	349	2.3%	5.78	1.26
BE	219	1.5%	18.93	2.44
ES	151	1.0%	3.23	1.30
CH	141	0.9%	16.28	0.77
DK	105	0.7%	18.11	1.21
SE	89	0.6%	8.80	0.48

* The number of IPFs per country is calculated based on the location of the inventors, using fractional counting in case of multiple inventors for the same IPF.

** The revealed technological advantage (RTA) index indicates a country's specialisation in terms of bioplastics technology innovation relative to its overall innovation capacity. It is defined as a country's share of IPFs in a particular field of technology divided by the country's share of IPFs in all fields of technology. An RTA above one reflects a country's specialisation in a given technology.

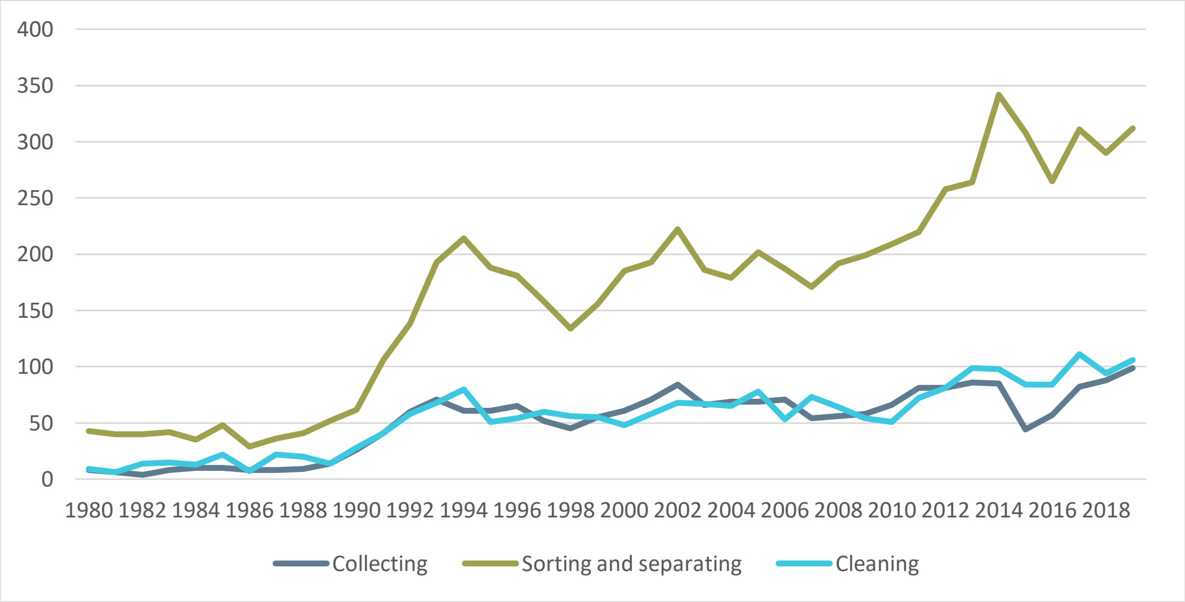
Within Europe, the large number of IPFs posted by Germany reflects the size of its economy rather than a real specialisation in plastic recycling technologies (RTA<1). France, the UK and Italy show some specialisation in the field. Among smaller European countries, the Netherlands and Belgium have particularly high (above 2) RTAs, denoting a strong technological specialisation in plastic recycling.

2.3. Waste recovery

Waste recovery has been the fastest-growing field in plastic recycling technologies since 2010. The recovery and preparation of plastic waste is an obvious prerequisite to its recycling, and, as such, a major challenge to achieving a circular economy of plastics. While all the main steps of recovery, namely the collecting, sorting and separating, and cleaning of plastics, involve significant industrial challenges, the sorting and separating step is the most innovation-intensive, as revealed by the high, fast-growing number of related IPFs (Figure 2.3.1).

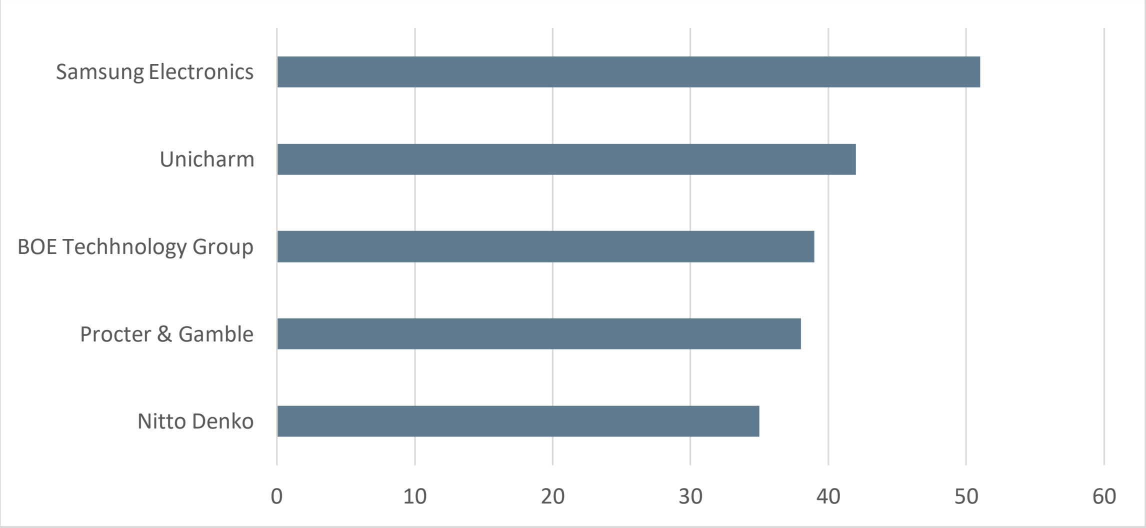
Inventions related to sorting and separating are needed to cope with the diversity of plastic waste and to route each type of waste to the appropriate recycling method. These inventions range from identifying and sorting plastics from waste streams, generally based on optical identification, to the separation of different components of plastic articles (delaminating layered product, separation based on density difference or separation using gravity, such as wind sifter and electrostatic separation for instance).

Figure 2.3.1: Number of IPFs related to waste recovery, 1980-2019



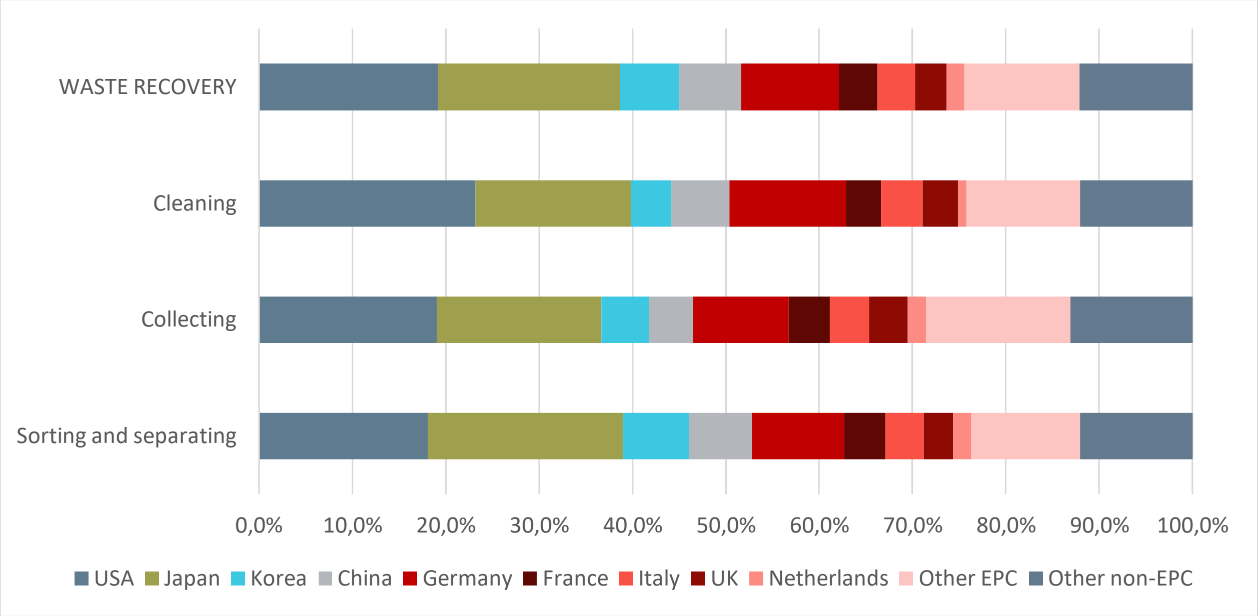
There are a large number of different applicants in waste recovery. The top applicant, Samsung Electronics, accounts for only 1.5% of all IPFs from 2010 to 2019, and the top five applicants for a mere 6%. This fragmentation is reflected in the diversity of the top applicants' profiles. Samsung, a major Korean conglomerate and one of the global leaders in consumer electronics, is directly followed by Unicharm, a Japanese company that manufactures disposable hygiene and cleaning products. Next comes BOE Technology Group, a Chinese electronic components producer. Procter & Gamble, an American multinational consumer goods group, and Nitto Denko, a Japanese company that produces tapes and vinyl among other products, complete this ranking.

Figure 2.3.2: Top five applicants in waste recovery, 2010–2019



Europe shows a strong lead in the distribution of IPFs in all fields of plastic waste recovery. In sorting and separating technologies, European countries generated 38% of all IPFs from 2010 to 2019. Japan and the US follow, with about 19% each. Europe posted a similar 38% share of IPFs in waste cleaning technologies and up to 40% of IPFs in plastic waste collecting.

Figure 2.3.3: Origins of IPFs related to waste recovery, 2010–2019



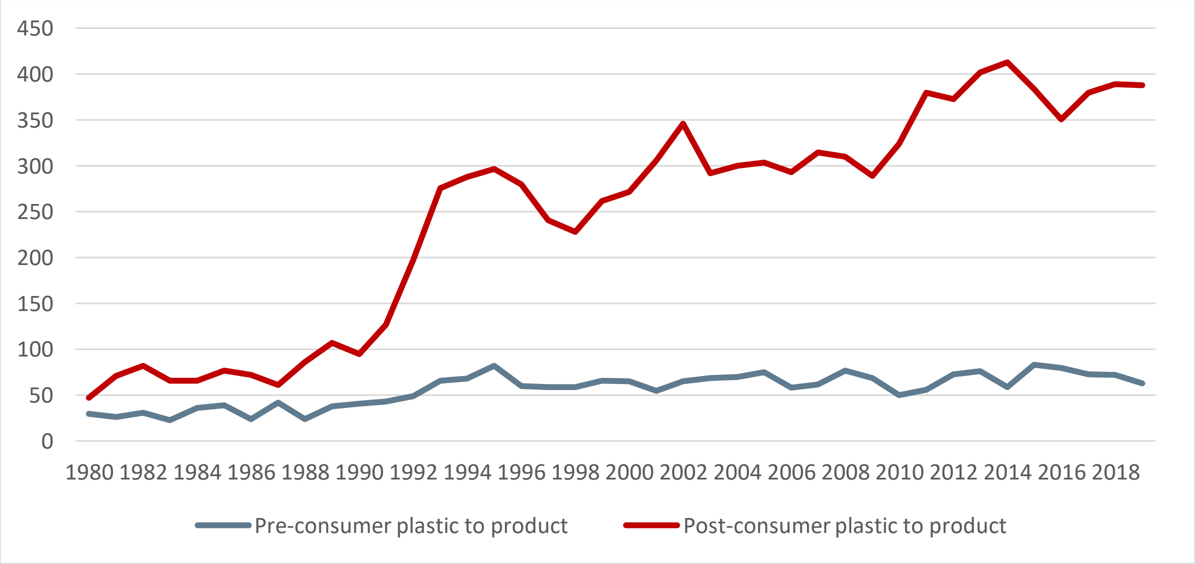
2.4. Recycling methods: plastic to product

Plastic-to-product recycling technologies are currently the simplest and most common recycling solution. These are typically employed to recycle thermoplastics, namely plastics that can be re-melted and reformed for the manufacturing of new products. The operation is simple but the likely presence of impurities or contaminants limits its application fields. Even though the technologies are available on a large scale, specific challenges due to thermomechanical or lifetime degradation of the polymer materials, and constraints related to the presence of other polymers or additives, limit the number of possible cycles. In terms of patenting, plastic-to-product was the dominant plastic recycling technology until the 1990s. Subsequently, plastic-to-feedstock recycling technologies using chemical methods (Figure 2.2.1) overtook this recycling method.

As reported in Figure 2.4.1, this technology field can be further broken down into two distinct categories. Pre-consumer plastic-to-product recycling typically consists of re-extrusion or closed-loop processes within factories, where scrap plastics with similar features to the original products are recycled. This process requires single types of scrap polymer with virgin-like material and similar features to the original products, making it difficult to apply to post-consumer plastic waste. It has generated a stable annual flow of 50 to 100 IPFs since the mid-1990s.

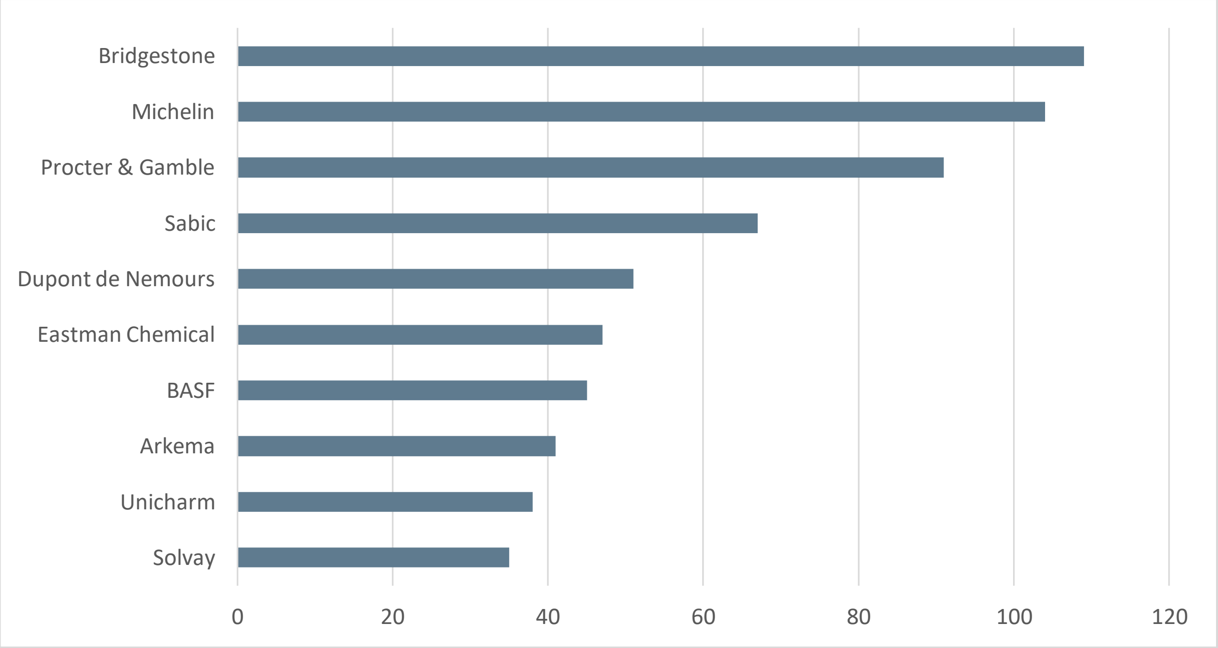
By contrast, post-consumer recycling technologies aim at using recovered post-consumer plastic waste for the manufacturing of new products. Patenting activities in that field increased dramatically in the late 1990s and subsequently continued to grow. As a result, they accounted for the bulk (86%) of IPFs in plastic-to-product recycling in 2019. Innovation in that field typically aims to address the problem of quality degradation caused by the recycling process.

Figure 2.4.1: Number of IPFs related to plastic-to-product recycling, 1980–2019



Together, the top five and top ten applicants in plastic-to-product recycling generated 10% and 14% of IPFs, respectively, between 2010 and 2019. While higher than those in waste recovery, these figures still show a relatively low concentration of innovation activity. Bridgestone and Michelin dominate the ranking. Both tyre companies are particularly innovative in tyre retreading technologies. Consumer goods company Procter & Gamble also stands out as a major applicant in the field. Apart from Unicharm, all other applicants belong to the chemical industry.

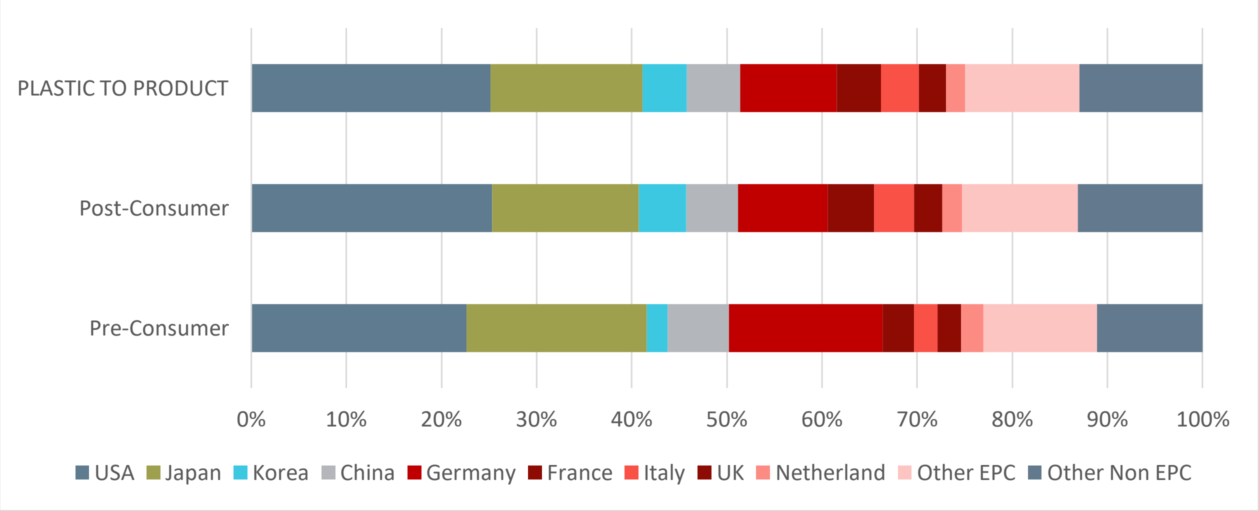
Figure 2.4.2: Top 10 applicants in plastic-to-product recycling, 2010–2019



Statistics on the geographic origins of IPFs highlight the leadership of European countries in plastic-to-product technologies, with combined shares of 34% and 35% of IPFs in pre- and post-consumer recycling technologies between 2010 and 2019. The US ranks second in post-consumer recycling with 26.5%, followed by Japan with 19%. Both countries have a stronger presence in pre-consumer recycling (Japan has 25% and the US 24%), though fall well behind EPC countries. The Republic of Korea and China have modest shares of 2% to 4% in each field.

Germany is the main contributor among EPC countries, showing a particularly high share of IPFs in pre-consumer (16%) as compared with post-consumer (10%) recycling. This may reflect the importance of the industrial production sector in its economy. France and Italy also show a significant contribution to post-consumer recycling, each with 4% of IPFs in that field.

Figure 2.4.3: Origins of IPFs related to plastic-to-product recycling, 2010–2019



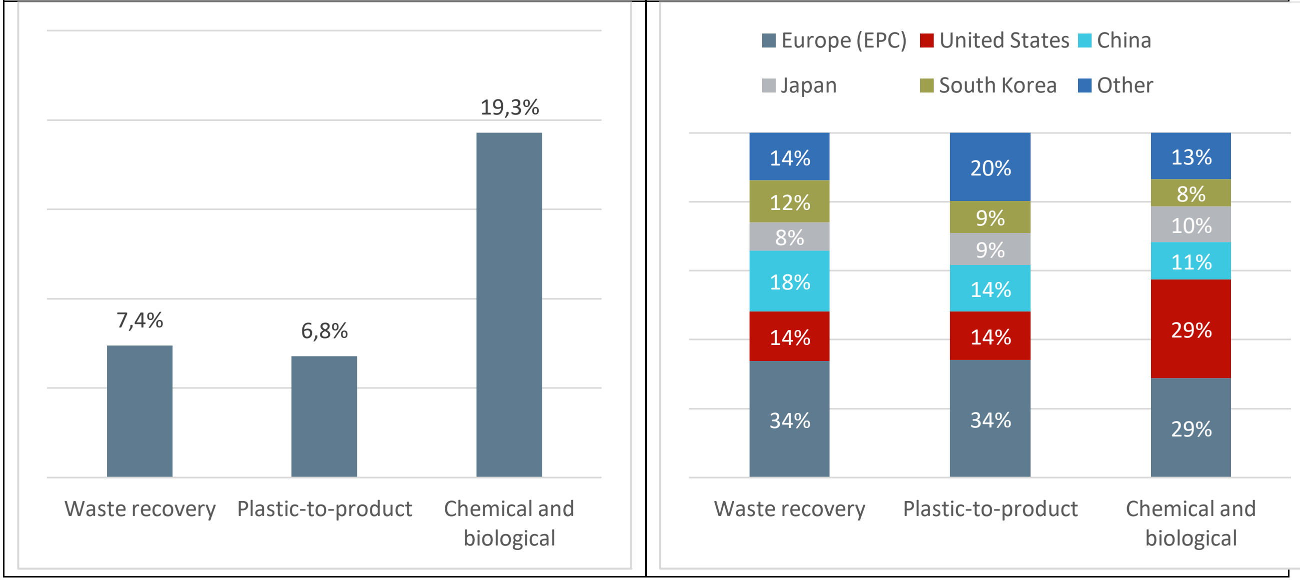
Box 1: University research on plastic recycling

As illustrated in Figure B1.1, upstream research in plastic recycling is mainly focused on chemical and biological processes, where universities and PROs contributed nearly 20% of all IPFs between 2010 and 2019. In comparison, the proportion of IPFs stemming from upstream research was only 7.4% and 6.8%, respectively, in waste recovery and plastic-to-product recycling. This reflects the fact that innovation in both fields typically relies on more standard and well-established technologies. Europe contributes by far the largest share (34%) of university IPFs in these two fields.

In terms of chemical and biological recycling methods, the geographic location of the universities and PROs is interesting. Figure B1.1b shows that European countries and the US have a clear lead, with 29% each of the IPFs stemming from upstream research from 2010 to 2019. Europe is the only major innovation centre to contribute more to IPFs in upstream university research than to all IPFs in the field (26%, see Figure 2.5.3). By contrast, the US's and Japan's contributions to upstream IPFs (29% and 11%) are lower than their respective shares in all IPFs (36% and 17%).

This suggests that Europe, despite being active in related research, is not exploiting its full potential when it comes to transferring these technologies to industry. A closer analysis of the IPFs originating from start-up and scale-up companies also supports this finding (Figure B1.2). Although the number of such IPFs increased in roughly the same proportions in both regions between 2010 and 2019, US start-ups and scale-ups generated four times as many IPFs than their European counterparts (338 versus 84) over the decade.

Figure B1.1: Upstream research in recycling technologies, 2010–2019

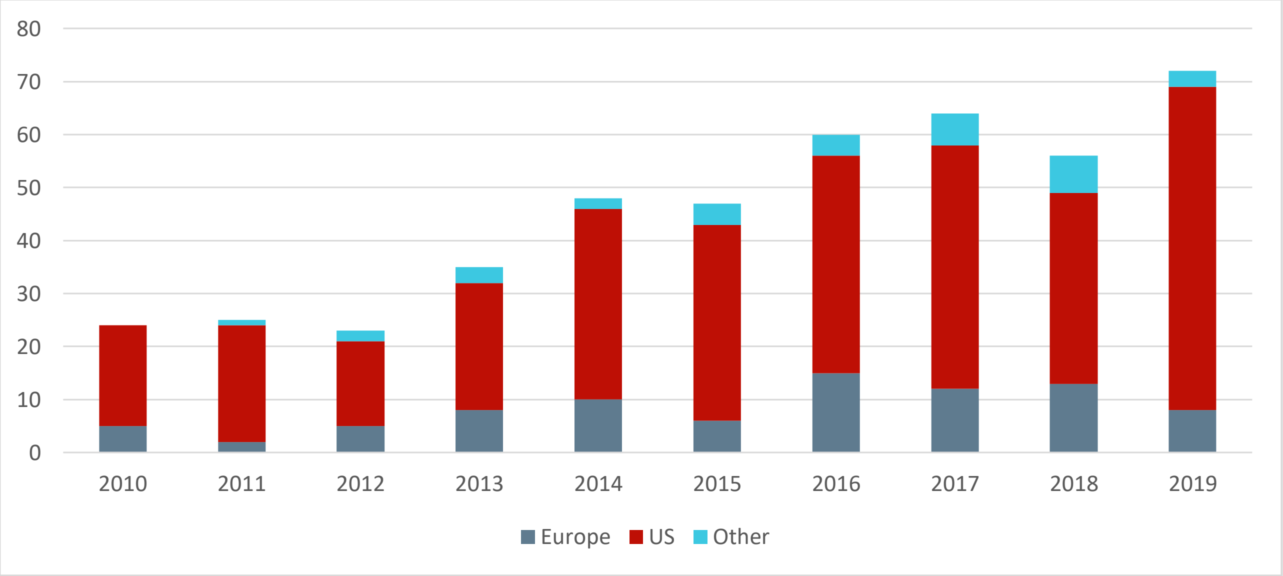


a. Share of IPFs generated by universities and PROs

b. Geographic origins of IPFs generated by universities and PROs

Note: The geographic origins of the IPFs in Figure B1.1b are based on the country of the applicants.

Figure B1.2: IPFs originating from start-up and scale-up companies in chemical and biological recycling, 2010–2019



Source: Crunchbase and the EPO.

Note: The figure reports on start-up and scale-up companies listed on Crunchbase that have filed at least one IPF related to chemical and biological recycling technologies in 2010-2019. Only companies founded after 2000 with fewer than 10 000 employees in their latest Crunchbase reporting have been considered.

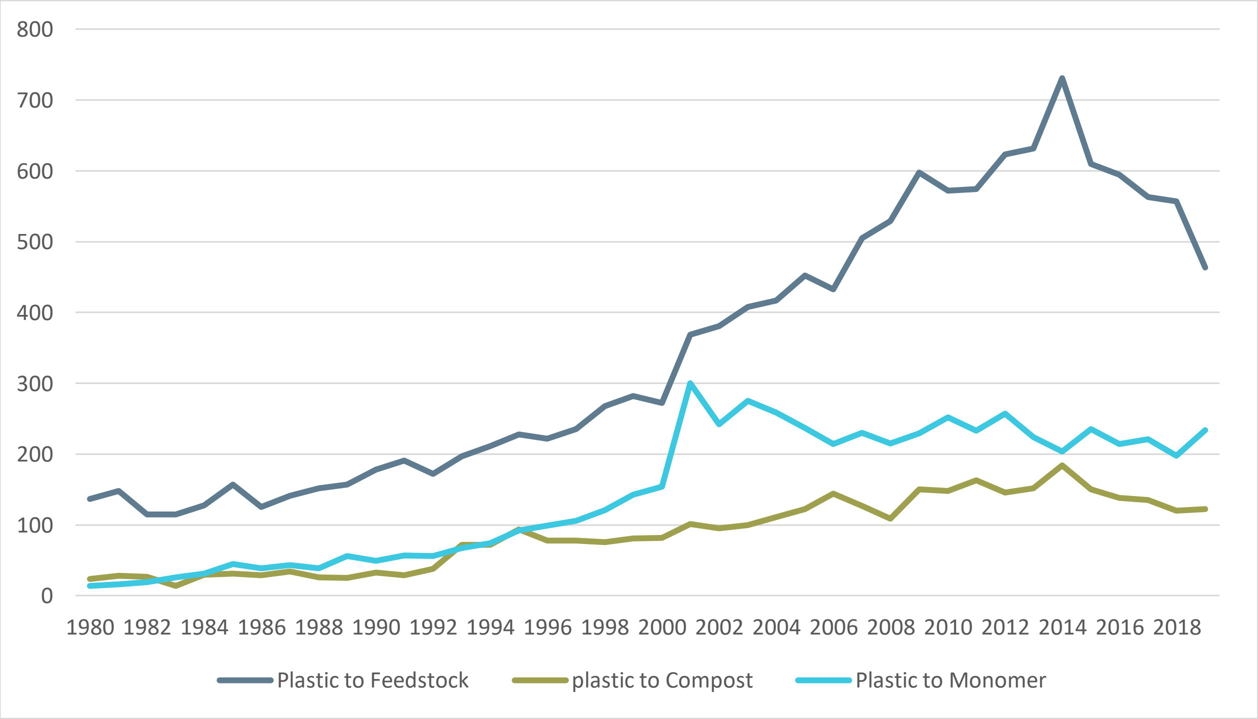
2.5. Recycling methods: chemical and biological recycling

Chemical and biological recycling technologies stand out as the most important subfield of plastic recycling technologies in terms of the number of IPFs over the past two decades. Chemical plastic-to-feedstock technologies, such as cracking and pyrolysis, dominate here. Such techniques make it possible to change the chemical structure of plastic waste and convert it into a mixture of basic chemicals, allowing for its flexible reuse in the petrochemical industry.[14] They are generally energy-intensive and involve a large number of processing steps for separation and purification.

Innovation in plastic-to-feedstock technologies reached a peak in 2014, before declining rapidly. By contrast, the number of IPFs related to plastic-to-monomer recycling technologies, albeit smaller, remained relatively stable over this period. These technologies can break long-chain polymers into their constituting basic units, allowing for repolymerisation with virgin-like quality and increased recycling rates. They can be applied to a broad variety of plastics, including polyamides, polyesters and rubbers.

Biological plastic-to-compost recycling processes recently emerged and represent a comparatively small number of IPFs. These technologies are promising for full circularity. They refer essentially to the use of enzymes or living organisms to degrade polymers to compost or to synthesise useful compounds by biochemical transformation. As shown in Box 2, this technology can also be used to achieve depolymerisation through biological processes.

Figure 2.5.1: Number of IPFs related to chemical and biological recycling, 1980–2019



Chemical and biological recycling is the most concentrated field of waste recovery technologies, with 12% and 19% of all IPFs generated by the top five and ten applicants, respectively. It is characterised by a much stronger contribution in fundamental research, with nearly 20% of IPFs

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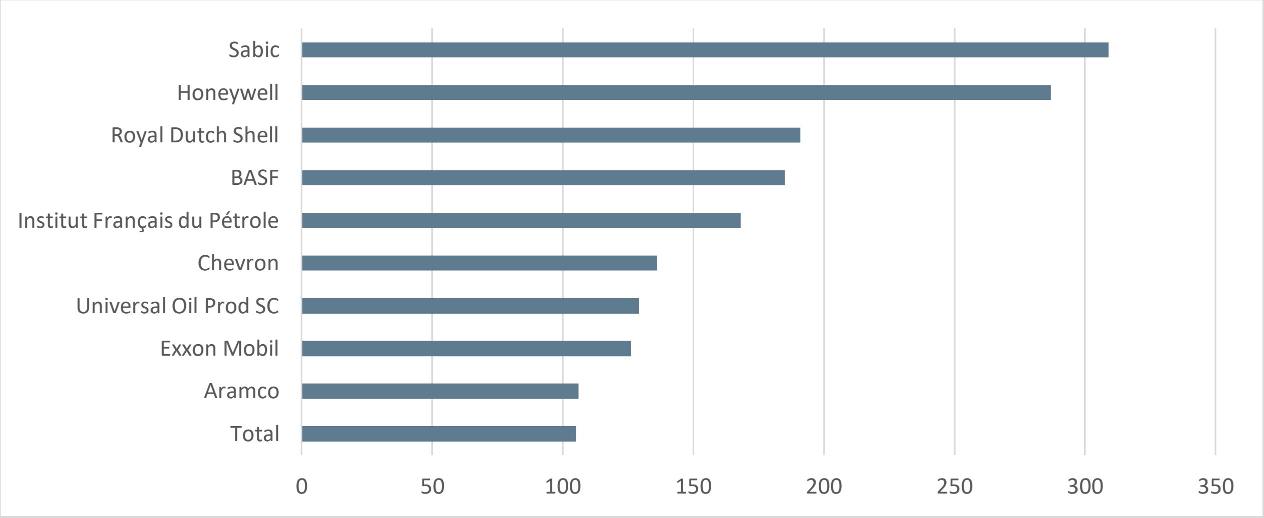
[14] Some basic chemicals are used to create new monomers but most of the mixture is typically used for synthesising other chemicals or is burned for energy recovery.

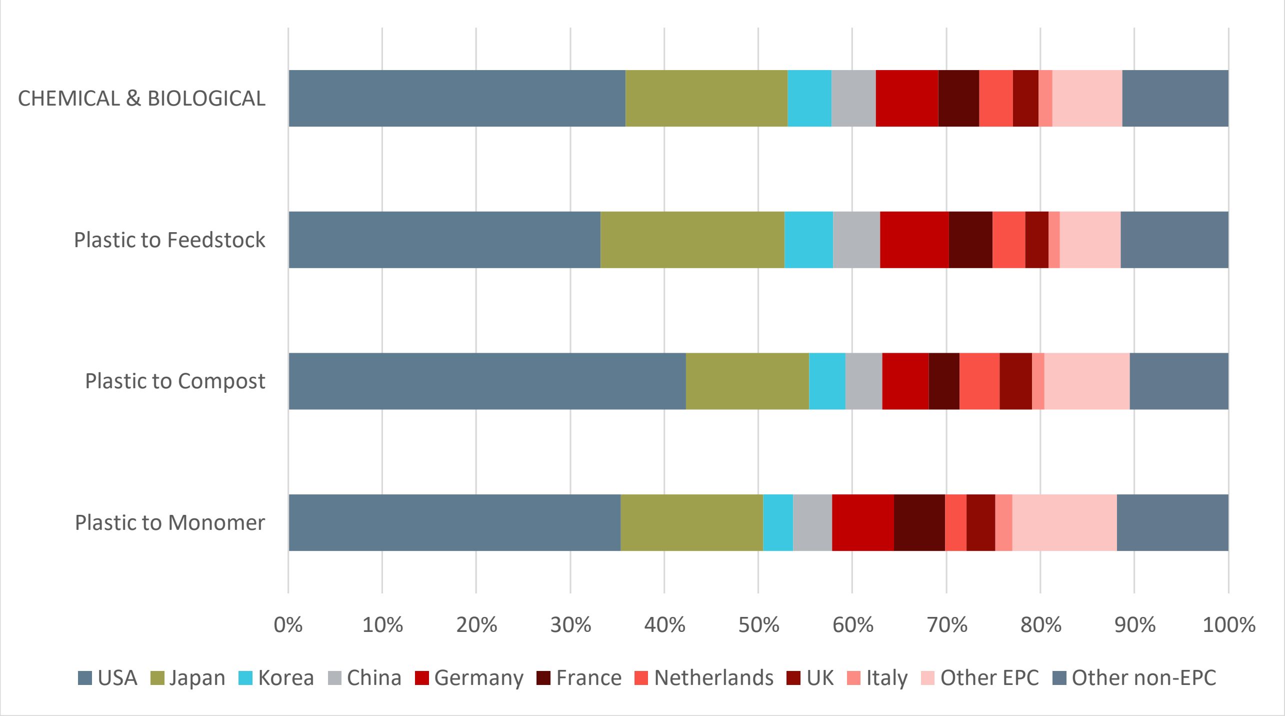
originating from universities and PROs in 2010–2019 (Box 1). Apart from German chemical company BASF, oil and gas companies or dedicated PROs heavily dominate the list of the top applicants.

Figure 2.5.2: Top 10 applicants in chemical and biological recycling, 2010–2019



From a geographical perspective, the US strongly dominates innovation in chemical and biological recycling technologies for plastic. The US alone contributed up to 36% of all IPFs from 2010 to 2019. In plastic-to-compost recycling, the US contribution amounted to 42% of all IPFs over the same period. With 26% of all IPFs in chemical and biological recycling, Europe remains the second innovation centre globally, closer to Japan (17%). This pattern can be observed in all subfields of chemical and recycling technologies. It is caused by Germany's modest performance, accounting for only 6.7% of these recycling technologies from 2010 to 2019, while generating up to 10% of IPFs related to waste recovery and plastic-to-product recycling over the same period.

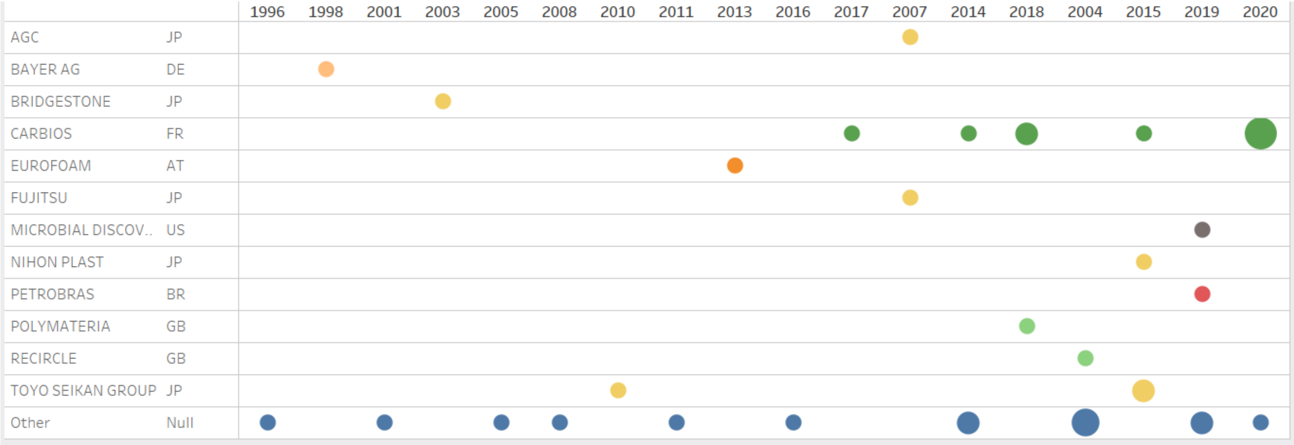
Figure 2.5.3: Origins of IPFs related to chemical and biological recycling, 2010–2019



Box 2: Enzymatic depolymerisation

Enzymatic depolymerisation is a new, promising approach to plastic recycling, based on the use of bacteria. The process employs enzymes initially produced by bacteria to selectively break down the polymers into monomers, which can be more easily reemployed. This approach overcomes the issue of degradation of polymer properties in conventional recycling and can be used on any type of PET plastic.

Figure B2: IPFs in enzymatic depolymerisation



Note: The IPF data reported for 2020 may not be entirely complete.

Only a few companies are currently exploring this technology. However, recent progress has made it possible for French company Carbios to initiate a commercial recycling programme. Carbios has developed a process to supercharge an enzyme naturally occurring in compost heaps that normally breaks down the leaf membranes of dead plants. By adapting this enzyme, Carbios has fine-tuned the technology and optimised it to break down any kind of PET-based plastics (regardless of colour or complexity) into its building blocks. These can then be turned back into virgin-quality plastics, which are like new. The recycling process works under mild conditions. Carbios claims that it could also lower the carbon footprint of PET waste treatment by saving 30% of CO_2 emissions compared to a conventional end-of-life mix of incineration and landfill, taking virgin PET production substitution into account.

Case study: Higher-performance plastic recycling

Invention: Counter current technology

Company: EREMA Group

Sector: Green technology

Country: Austria

There are few environmental issues more emotive than plastic waste. While recycling seems the obvious solution to a global problem, it is incredibly complex with no one-size-fits-all approach. Each polymer requires a specific method to reclaim reusable material. Moreover, sorting mixed plastics with precision is not an easy task. To further complicate matters, films can retain odours and printed plastics need to be de-inked. Manufacturers supplying the food and cosmetic industries have additional hurdles – strict regulations dictate the types of packaging that may be used with food or cosmetic products.

Klaus Feichtinger and Manfred Hackl (winners of the European Inventor Award 2019 in the Industry category) have dedicated their careers to solving such technical problems. For over 25 years, the Austrian inventors have worked at EREMA, a subsidiary of EREMA Group GmbH, leading the development of systems that enable industry to recycle and reuse an increasingly wide variety of plastic waste.

Go against the flow

The group manufactures recycling systems that perform a series of tasks. These include buffering material in a cutter/compactor, called a preconditioning unit (PCU), before plasticising it in an extruder featuring a screw. Counter current technology is one of the key innovations in these systems. In older recycling systems, the material inside the cutter/compactor would have been turned in the same direction as the extruder screw. With counter current technology, waste enters the extruder but is rotated in the PCU in the opposing direction to the flow of the extruder screw. The process is like collecting water from a stream by placing a cup against the movement of the water. Thanks to the improved material intake, the output stays at a consistently high level within a considerably broader temperature range in the PCU. The invention enables the extruder to process more waste material in less time at lower temperatures.

However, the complexity of plastic recycling means that multiple technologies are needed to overcome specific technical hurdles. Throughout their careers, Feichtinger and Hackl have developed several innovations to make recycling more economically viable and broaden the scope of recyclable materials. These include processes to degas liquid plastics, filter melted plastics, remove organic waste and minimise odour. When these processes are combined, complex materials can be reprocessed and the end result – plastic pellets – are indistinguishable from new plastic.

Closing the loop, growing the market

Currently, over 7 000 EREMA Group systems are in operation worldwide, producing over 14.5 million tonnes of plastic pellets every year. The group's turnover increased to EUR 250 million between 2020 and 2021 and they now employ over 660 people across five continents. Over the past three years, they have invested approximately EUR 60 million in modernising and expanding their facilities.

The market for plastic recycling is projected to reach EUR 54 billion by 2024 (PSI, 2019) due to several contributing factors. In 2018, China announced that it would stop accepting waste plastics shipped there from other countries. Furthermore, some 43% of the EU's plastic waste is incinerated and 32.5% ends up in landfills (PlasticsEurope, 2020). The EU's plastic strategy aims to improve these figures through regulation that will make all plastic packing recyclable by 2030. This combination of technology, market forces, policy and increased public pressure to reduce the impact of SUPs could pave the way to more sustainable, closed-loop plastic production.

Case study: Plastics from plant starch

Invention: Plant-based bioplastic

Company: Avantium

Sector: Green plastics

Country: The Netherlands

Polyethylene terephthalate (PET) is the fourth most commonly used plastic polymer, utilised in applications ranging from clothing to bottles. However, this versatility has an environmental cost: PET production requires petrochemicals made from oil and natural gas and the resulting polymer is non-biodegradable. Substitutes for PET have been proposed but a commercially viable option produced on an industrial scale remains elusive.

Gert-Jan Gruter (European Inventor Award 2017 finalist, SMEs category) overcame a long-standing challenge to enable the development of a plant-based alternative to PET. The Dutch scientist is currently Chief Technology Officer at Avantium, an Amsterdam-based company that develops technologies using plant-based carbon sources.

Solving the riddle of the century

Polyethylene furanoate (PEF), a plastic based on plant starches, is one alternative to PET. Many complex molecules or polymers are made from simpler, intermediate chemicals. Furandicarboxylic acid (FDCA) is the necessary intermediate for PEF. Its easy production eluded researchers for over a century. The approach most often used involved first creating a precursor called 5-(hydroxy)methylfurfural (HMF) in water and then oxidising it into FDCA, but this was never viable on an industrial scale. Gruter went in a different direction, making his precursor in alcohol solutions to create, for example, methoxymethylfurfural (MMF) in a solution of methanol. The resulting MMF was more stable and easier to oxidise into FDCA, an essential building block for PEF.

PEF offers several advantages over petroleum-based PET. Its greater strength means less material is needed to make a bottle of the same size, thereby lowering production costs. Additionally, it has better gas barrier properties. PEF bottles are ten times more effective at blocking oxygen from entering the container, keeping contents fresher for longer. They also release CO_2 more slowly, an essential property for carbonated drinks. The plant-based plastic offers several environmental benefits: the PEF manufacturing process requires 70% less energy and releases one third of the carbon emissions of PET production. Critically, PEF can be wholly recycled and unlike many other polymers, small amounts can be recycled alongside PET.

Green chemistry for a greener future

Avantium was initially spun off from petrochemicals multinational Royal Dutch Shell in order to accelerate catalysis research. In 2006, the company began to expand its plant-to-plastic innovations. Since then, their FDCA and PEF technology has drawn investment from several companies that recognise the potential for next-generation packing material, including The Coca-Cola Company and Danone. To meet potential demand, Avantium is planning investment in a flagship refinery in the Netherlands and exploring potential licensing agreements with chemical companies, converters and consumer brands.

The company continues to conduct research into polymers and develop new products and processes using green chemistry. These include: an efficient process to convert plant-based sugars into a building block for PET or PEF-based products; technology to convert waste or residual material, such as forestry branches and bark, into higher-value industrial sugars; and techniques to convert carbon dioxide into high-value chemicals.

Several industrial players including Procter & Gamble, Evian and Canon have been exploring the use of PEF in hygiene articles, packaging and film. Once it has been shown that production can be scaled up to be cost-effective, PEF could achieve a rare feat: satisfying the demands of both industry and conscientious consumers.

3. Alternative plastics

This section focuses on alternative plastics which encompass bio-based, biodegradable and compostable plastics, as well as plastics designed for easier recycling, such as vitrimers (covered in Box 3) or plastics made from CO_2 (Box 4).[15] These materials have been an active field of research since the late 1980s. They are interesting for the circular economy because they could potentially provide an alternative to fossil-based or non-biodegradable plastics.

3.1. About bioplastics

For the purpose of this study, the definition of bioplastics "includes all plastics that are either bio-based and/or biodegradable".[16] However, the terminology remains a challenge. The umbrella term bioplastics is generally used to describe different materials, and the terms bio-based, biodegradable and compostable are often wrongly used as equivalents.

The concept of bio-based plastics encompasses all plastics that are fully or partially made from biological resources and act as an alternative to fossil raw materials. They include plastic materials that are produced from renewable biomass sources and agricultural by-products, as well as from used plastics by using microorganisms. Also included under the term are chemically modified natural biopolymers and polymers resulting from biosynthesis through man-made cultivation and fermentation processes in industrial settings (termed in this study as “industrial natural polymers). Natural biopolymers are large, high-molecular weight molecules with long chain-like structures commonly found in nature. These form the building blocks of plant tissue (such as cellulose and lignin) and animal tissue (such as chitin). The chemical modification of natural polymers (after extraction) allows to tailor their properties.

Besides allowing for a reduction in the carbon footprint and greenhouse gas (GHG) emissions, some bio-based plastics have the potential to be a renewable resource through composting and biodegradation.[17] However, it must be underlined that not all bio-based plastics are compostable or biodegradable. The property of biodegradation, where microorganisms found in the environment convert the material into natural substances such as gases, water, biomass and inorganic salts, is linked to the chemical structure of the plastic rather than the source of the material. In other words, 100% of a bio-based plastic may not be biodegradable, while in some cases 100% of a fossil-based plastic may be biodegradable. Therefore, the full life cycle of bio-based plastics must be examined before concluding that bio-based plastics may be beneficial to the environment beyond the reduction in use of fossil resources.[18]

A distinct concept of "biodegradability" is used in the study to account for all inventions related to plastics (either made from bio-based or fossil-based materials) claiming some degree of

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[15] https://ec.europa.eu/environment/topics/plastics/bio-based-biodegradable-and-compostable-plastics_en

[16] A policy framework on bio-based, biodegradable and compostable plastics in the EU is planned, but not yet published (see: https://ec.europa.eu/environment/topics/plastics/bio-based-biodegradable-and-compostable-plastics_en).

[17] As they allow for the replacement of petrochemical feedstock by feedstocks that are renewable (including bio-based feedstocks or biomass), bio-based plastics have the potential to reduce the direct carbon footprint of plastics. However, a full assessment would also require taking into account their potential impact on land use whenever the feedstock is derived from biomass.

[18] This includes, for instance, the potential impact of plastics derived from bio-sourced feedstock on the otherwise wild or agricultural land that may be used to grow that feedstock.

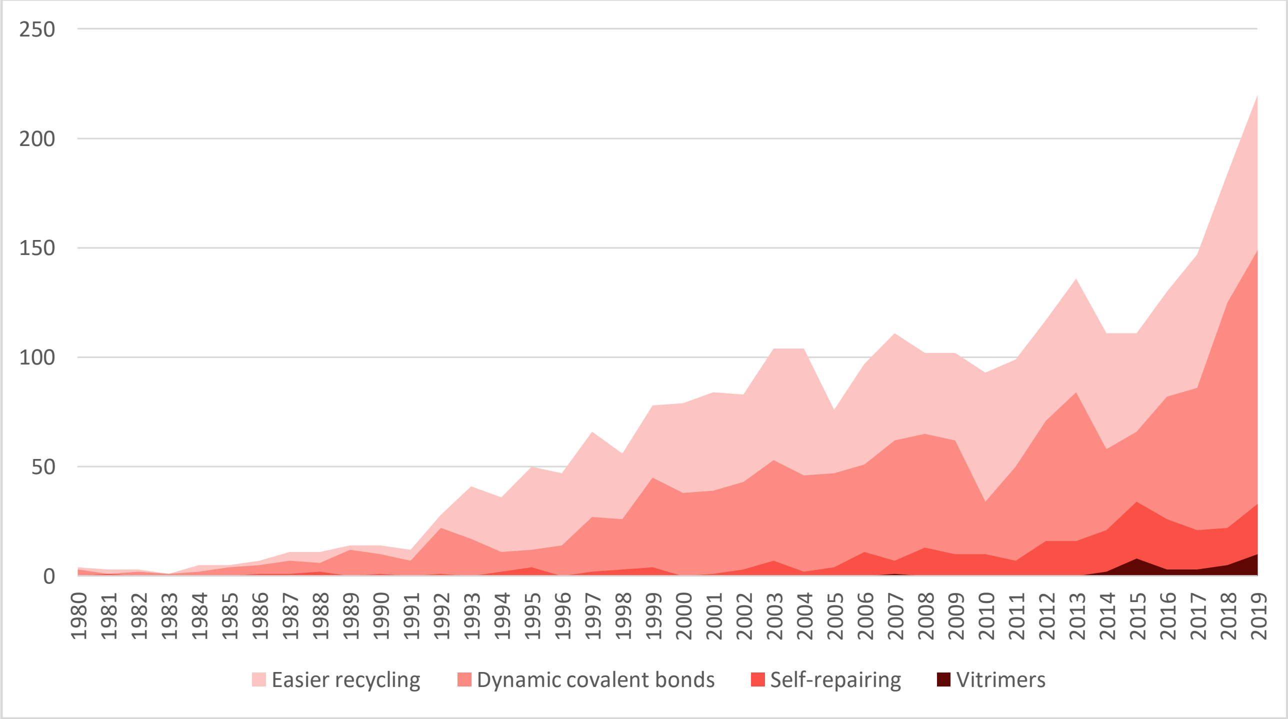
biodegradability, even if such degradability is only possible under specific conditions, such as high temperatures for instance.

Such biodegradable plastics can contribute to reducing "unavoidable" littering. However, they do not fully solve the littering problem as most currently available plastics labelled as biodegradable generally only degrade under specific conditions not easily found in the natural environment. Biodegradation in the marine environment is particularly challenging. Likewise, plastics that are labelled "compostable" are not necessarily suitable for home composting. A further important aspect is that some plastics claiming biodegradability properties, such as "oxo-degradable plastics", have been found to offer no proven environmental advantage over conventional plastics, while their rapid fragmentation into microplastics causes concern. These plastics should be used when it is not possible to reduce, reuse or recycle.

Box 3: New plastic designs for easier recycling

Another research avenue towards circularity is designing new polymers that can be recycled in an environmentally friendly way. This approach relies on polymer synthesis and the use of additives for easier recycling. It also includes new emerging technologies, such as covalent adaptable networks (CANs), including dynamic covalent bonds and vitrimers.

Figure B3.1: IPFs related to design for easier recycling, dynamic covalent bonds, self-repairing polymers and vitrimers, 1980–2019

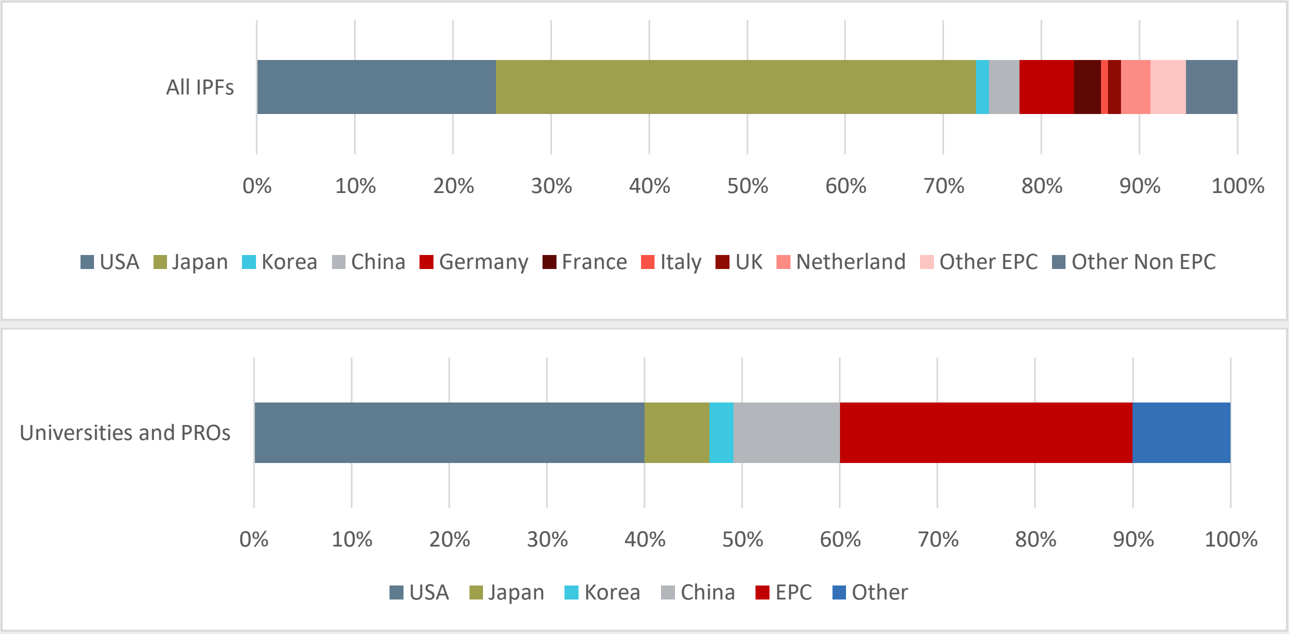


Technologies focused on plastic design for easier recycling started to emerge as a new research field in the 1990s and have been developing ever since. As illustrated in Figure B3, innovation in dynamic covalent bonding drives the rapid growth of patenting in these fields. This accounted for up to two-thirds of the IPFs related to design for easier recycling in 2019. Dynamic covalent bonding is a synthetic strategy employed to form 3D networks of macromolecular chains. These are similar to thermosetting polymers, with the difference that the cross-links are able to break and reform through reversible chemical bonding reactions. This dynamic reversibility can overcome the difficulties typically encountered in the processing and recycling of traditional thermosets widely used in aerospace, construction, transport and microelectronics.

Vitrimers are a recent and promising type of covalent adaptable networks (CANs) based on a polymer network that can shuffle chemical bonds through an exchange reaction. The permanent degree of network connectivity further increases the material's strength and stability, without sacrificing recyclability. In addition, intrinsically self-healing vitrimers could potentially reduce the obsolescence of damaged plastic products. This makes them a promising candidate for replacing thermosets in high-performance and lightweight applications. They could potentially revolutionise entire industries, including the production of composite parts for aircraft, automotive, sports equipment and wind turbine blades (see case study “Vitrimers”).

As shown in Figure B3.2, Japan has built a strong lead in dynamic covalent bonds, with nearly half (49%) of related IPFs from 2010 to 2019. The US follows with 24%, while European countries contribute only 17%. However, most of the IPFs originating from universities and PROs in the field originate from European and US research institutions (40% and 30%, respectively), whereas Japan has only 7%. The contrast is particularly striking between Japan, which leads overall despite a small presence in university research, and Europe, which contributes more than twice as much to upstream university research than to patenting activities overall in the field.

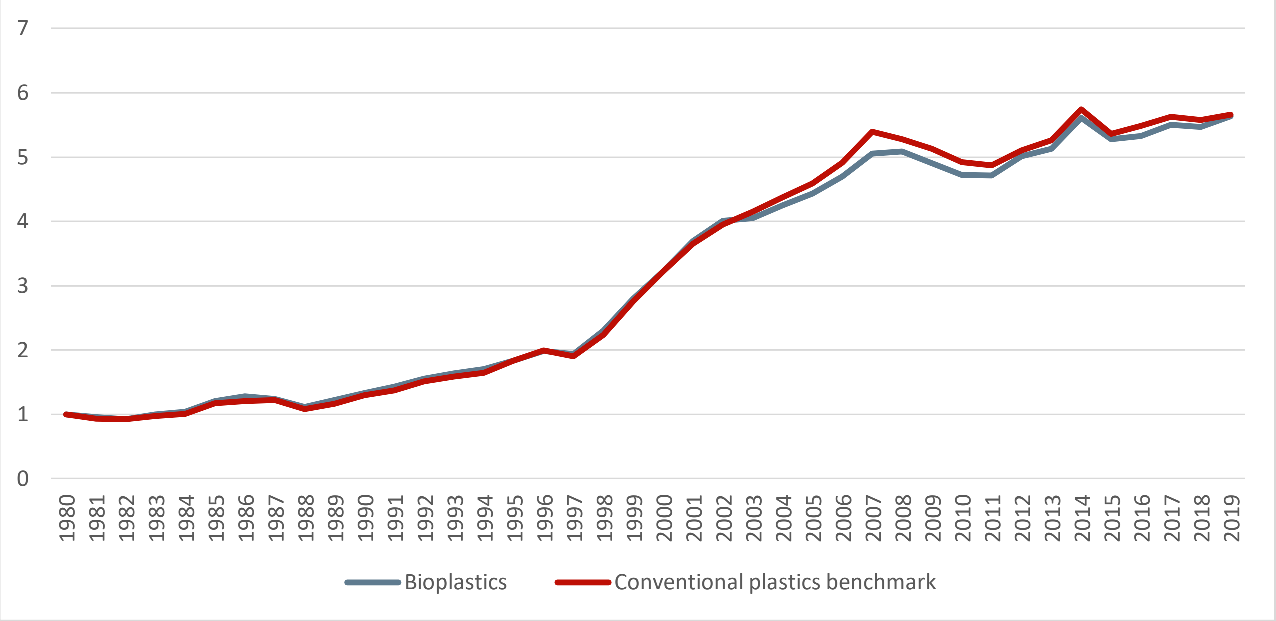
Figure B3.2: Origins of IPFs in dynamic covalent bonds, 2010–2019



3.2. Overview of technology trends in bioplastics

Innovation in bioplastics took off in the 1980s and rapidly grew until the 2008 economic crisis (Figure 3.2.1). Growth resumed in 2012, albeit at a slower pace, before peaking in 2014. This shows an almost perfect correlation with the trend of IPFs for conventional plastics, suggesting that the proportion of R&D dedicated to bioplastics has remained stable since the 1980s.

Figure 3.2.1: Growth of patenting in bioplastics versus conventional plastics, 1980–2019 (base 1 set in 1980)



A more granular analysis shows some divergences between the different categories of feedstock comprised in bioplastics (Figure 3.2.2). Chemically modified natural polymers generate the largest share of patenting activities, in particular modified cellulose, modified other polysaccharides and other modified natural polymers. Modified cellulose appears as a relatively mature field, with the largest number of IPFs and a relatively low share (9.2%) of IPFs stemming from research organisations. Progress in modified other polysaccharides and other modified natural polymers appears more dependent on fundamental research, with a respective 22.3% and 17.1% of IPFs stemming from universities and PROs (Figure 3.2.3).

Among other bio-based polymers, polymers from bio-sourced monomers have constituted the most important, fastest-growing field and the one closest to fundamental research over the past 20 years. Most of the patents in this field relate to so-called "drop-in plastics" (i.e. Bio-PE, Bio-PET, Bio-PA or Bio-PP), which are not biodegradable. Such drop-in plastics are mainly of interest because emissions of greenhouse gases and consumption of non-renewable resources are reduced during their production. They have the same chemical structure as their mineral oil-based counterparts, and therefore the same properties, performance and application versatility. This facilitates their immediate use in the plastic production chain. For the same reason, they also can be recycled within the same recycling facilities as traditional plastics.

Patenting activities in other bio-based polymers, such as natural polymers produced in industrial settings and bio-based rubber, are modest but rising. Likewise, the number of IPFs related to biodegradable feedstocks that are not bio-based remains small, despite a strong increase from 2015 to 2019. Industrial natural polymers, which are made by mimicking nature in industrial settings, show interesting potential.[19] For instance, recent start-up technologies make it possible to upcycle third-generation feedstocks, such as food waste, into polyhydroxyalkanoates (PHAs) using natural or engineered bacteria. PHAs are a series of biocompatible thermoplastic polyesters with low water permeability and high thermal resistance. These offer potential for designing sustainable materials in a wide range of applications: medicine, packaging, 3D printing filaments, textiles, agriculture. They are reusable, recyclable and can be readily broken down by microorganisms present in most soils and marine and fresh water environments to access stored carbon for use in their cellular metabolism. The use of fungi to create bio-composites (see case study "Eco-friendly packaging") is another promising approach.

Figure 3.2.2: Number of IPFs by categories of bioplastics, 1980–2019

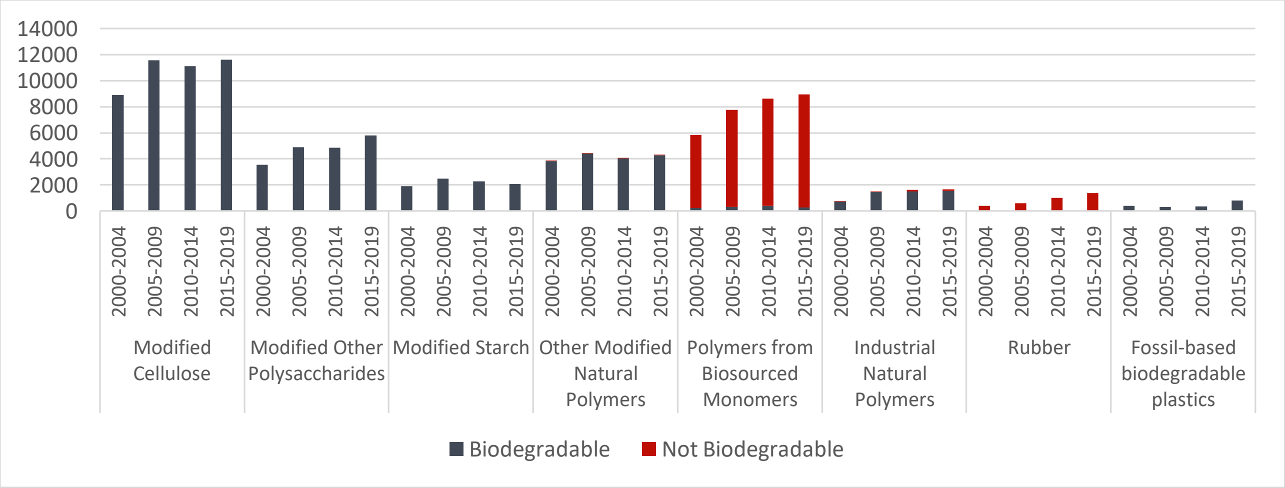
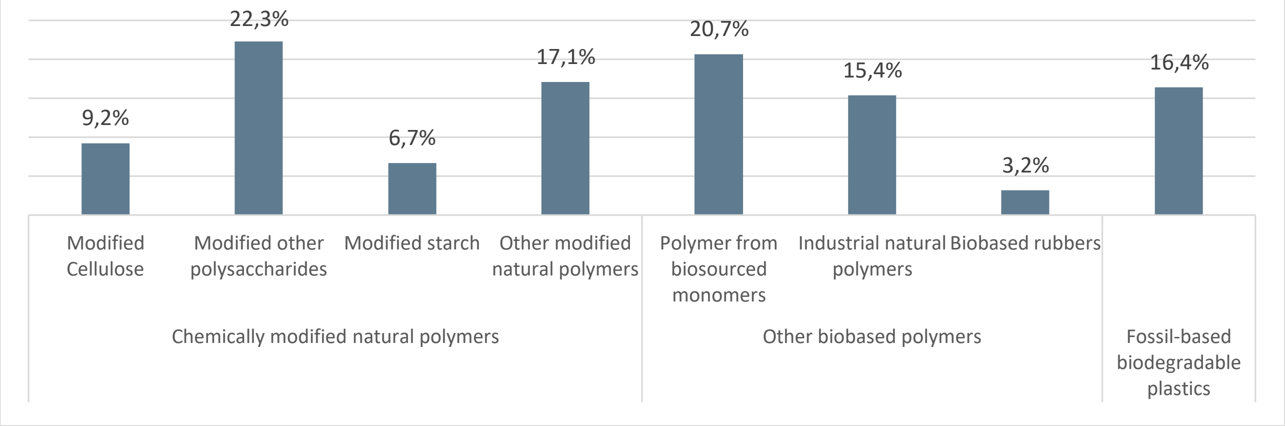


Figure 3.2.3: Share of IPFs produced by universities and public research organisations, 2010–2019



In terms of geography, Europe and the US strongly dominate innovation in bioplastics, together generating 60% of the related IPFs from 2010 to 2019 (Table 3.2.1). The US shows a stronger

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[19] The artificial spider silk derived from a patented industrial process involving genetically modified bacteria is an example of industrial natural polymer. Developed by founder AMSilk, a spin-off company from the Technical University of Munich (TUM), this patented process allows AMSilk to sell purified silk protein ingredients in three product lines: first, cosmetic products including breathable silk gels and controlled-release silk bead capsules for gels and creams, etc.; second, medical applications such as coatings for medical implants; and finally, a biodegradable performance fibre called Biosteel, which is about 15% lighter than conventional synthetic fibres.

specialisation in terms of both IPFs per capita and RTA. Japan follows in the ranking with only 17.7% of IPFs. With about 5% of IPFs each, the Republic of Korea and China are significantly behind, at levels comparable to large European countries, such as Germany and France. Although Japan and the Republic of Korea show a high number of IPFs per capita as is usual in these innovation-intensive countries, all three Asian countries show a lack of specialisation in bioplastics technologies, according to the RTA indicator.

Within Europe, Germany leads in terms of the number of IPFs but lacks specialisation. In contrast, France, the UK, Italy, Switzerland, the Netherlands, Spain, Denmark and Belgium all show a specialisation in bioplastics. Apart from Germany, Sweden is the only country in the European top ten not to show a specialisation in bioplastics.

Table 3.2.1: Origins of IPFs related to bioplastics, 2010–2019

	Number ofIPFs 2010–2019*	Share of IPFs 2010–2019*	IPFs per mio capita*	RTA 2010-2019**
EPC	15 255	30.8%	22.99	1.12
US	14 905	29.8%	44.81	1.43
EU27	12 072	25.4%	27.11	1.06
JP	8 056	17.7%	64.38	0.70
DE	4 090	8.2%	48.82	0.82
KR	3 644	5.3%	70.65	0.84
CN	3 272	5.0%	2.35	0.56
FR	2 664	4.3%	40.81	1.45
UK	1 654	2.9%	24.36	1.24
IT	1 100	2.9%	18.20	1.18
CH	834	2.3%	96.35	1.33
NL	755	1.5%	44.08	1.14
BE	596	1.0%	51.39	2.07
ES	577	0.9%	12.34	1.43
SE	453	0.7%	44.85	0.72
DK	346	0.6%	59.74	1.29

* The number of IPFs per country is calculated based on the location of the inventors, using fractional counting in case of multiple inventors for the same IPF.

** The revealed technological advantage (RTA) index indicates a country's specialisation in terms of bioplastics technology innovation relative to its overall innovation capacity. It is defined as a country's share of IPFs in a particular field of technology divided by the country's share of IPFs in all fields of technology. An RTA above one reflects a country's specialisation in a given technology.

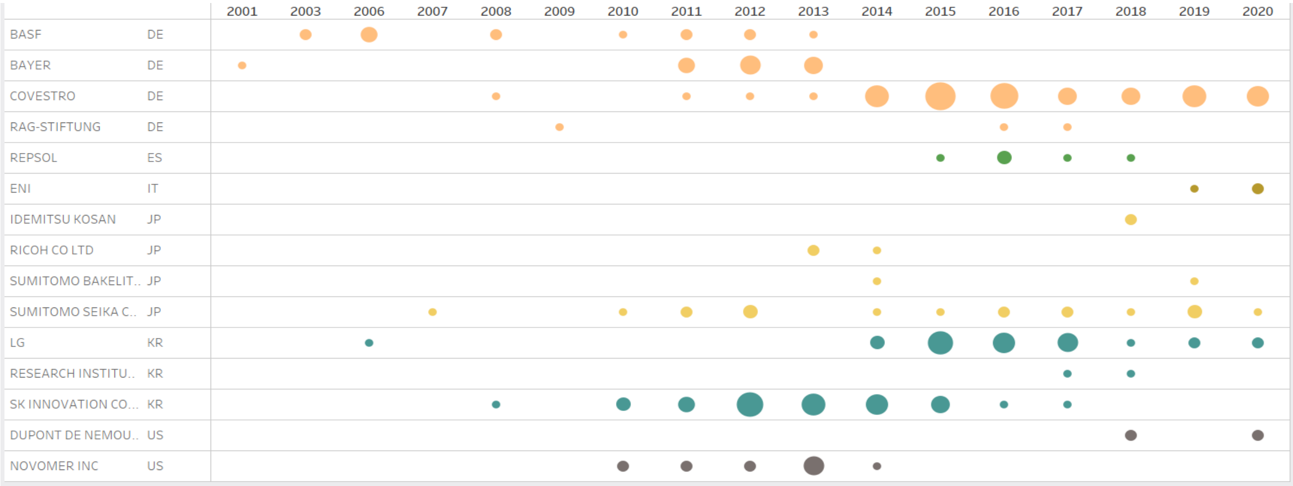
Box 4: Plastics derived from carbon dioxide

The organic chemistry and plastic sectors cannot be decarbonised as carbon is the main atom in their material structures. However, the use of renewable carbon or CO_2 for the synthesis of plastics can contribute significantly to the circular economy. Unlike plant-based plastics, CO_2-based plastics feedstock production does not have undesired side effects, such as impact on land use or biodiversity. In addition, it decouples plastic production from fossil feedstocks. Carbon emissions released during the production process can be captured and returned into the cycle.

Chemicals and polymers are already being produced using renewable carbon from biomass and recycling – and also directly from CO_2. Due to CO_2's inert nature, its conversion routes are typically energy-intense and inefficient. However, as more effective conversion processes emerge, there is growing interest in using CO_2 for the production of chemicals and polymers.[20] The breakthrough innovations for CO_2 use have all been achieved using specifically designed catalysts. CO_2 is a thermodynamically stable molecule so it requires a significant amount of energy to be activated. Therefore, a catalyst must be used to reduce that energy barrier.

As illustrated in Figure B4, new technologies are starting to emerge among a small number of companies, mainly in Europe and the Republic of Korea. A process developed by German company Covestro deploys new chemical catalysts to drive reactions between CO_2 and petroleum-based propylene oxide to create polymers in a more sustainable and economically viable way.

Figure B4: Main applicants in CO_2-based plastics



Note: Only applicants with at least three identified IPFs in the field are presented in this figure.

The resulting polyol was introduced to the market by Covestro, under the product name cardyon It is already being used to produce soft foam for mattresses, for adhesives in sports floors, padding in shoes and in car interiors. Currently, plastic textile fibres are on the threshold of market maturity. In recognition of their role in developing this new technology, Dr Christoph Gürtler (Covestro AG) and Prof Walter Leitner (Max Planck Institute for Chemical Energy Conversion and RWTH Aachen University) were selected as finalists in the 2021 European Inventor Award's Industry category.

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[20] Direct combination of CO_2 with oxygen-containing, ring-like molecules called cyclic ethers yields linear chain polycarbonates (L-PCs), a polymer family distinguished by some outstanding properties. Although mechanically inferior to and less thermally stable than conventional polycarbonates, L-PCs are biodegradable and exhibit excellent gas-barrier properties, thus becoming attractive for packing applications. As of now, however, L-PCs are mainly used for the production of polyols, chemical compounds for poly(urethane) manufacturing. CO_2 can also be used to yield chemical compounds for polymer production. This opens up the possibility of obtaining a range of thermosetting polymers, such as urea-formaldehyde (UF) and melamine-formaldehyde (MF) resins, as well as engineering plastics, such as poly(oxymethylene) or poly (methyl methacrylate). In the former case, the UF resin can be obtained from urea, which is directly produced from reacting CO_2 with ammonia, and formaldehyde, which is obtained from CO_2-derived methanol. Similarly, the ingredients for MF resins are melamine, obtained from urea, and formaldehyde. In the latter, POM may be produced from CO_2 via formic acid, and PMMA, from methyl acrylate obtained from CO_2-derived methanol.

3.3. Innovation in bioplastics in selected industry sectors

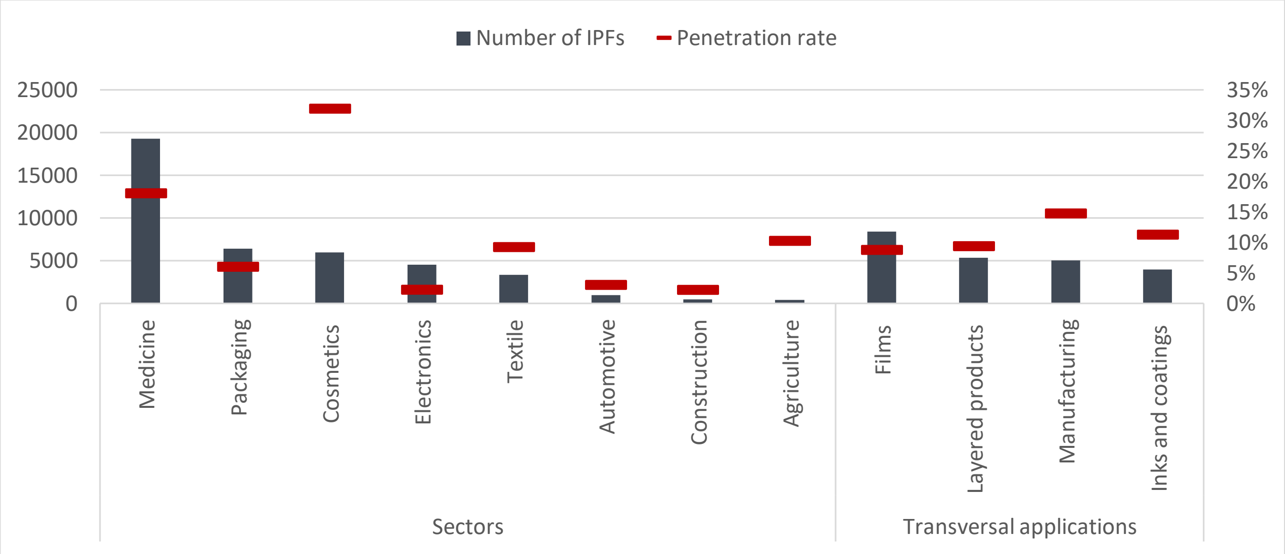
Figure 3.3.1 shows the distribution of IPFs related to bioplastics by industrial sectors and cross-industry industrial applications from 2010 to 2019, as well as the penetration rate of those IPFs with respect to IPFs in conventional plastic technologies.

Healthcare[21] is by far the most important industry in terms of number of IPFs related to bioplastics, with more than 19 000 IPFs recorded, despite accounting for only a modest share of the total demand for plastics (Figure 1.2). However, bioplastic technologies have the highest penetration rate in cosmetics and detergents. In that sector, IPFs related to bioplastics are at 32% of the level of IPFs for conventional plastics, compared with 18% in healthcare.

The packaging, electronics and textiles sectors are also significant innovators in bioplastics, with 6 400,[22] 4 500 and 3 300 IPFs, respectively, from 2010 to 2019. The penetration rate is among the highest in textiles (9%), as compared with 6% in packaging and only 2% in electronics. Interestingly, agriculture shows a high penetration rate (10%), despite a low number of IPFs in bioplastics. In that sector, 2.5 times more IPFs were recorded in 2019 than in 2010, in contrast with the slow growth shown by other industries.

Figure 3.3.1 also provides a similar benchmarking for cross-industry applications of plastic technologies. Plastic films generated the largest number of IPFs from 2010 to 2019, followed by layered products. However, manufacturing[23] (15%) and inks and coatings (11%) show the largest penetration rates.

Figure 3.3.1: Innovation in bioplastics for selected sectors and applications, 2010–2019



Note: The penetration rate is defined as the ratio of the number of IPFs in bioplastics to the number of IPFs related to conventional plastics in the same sector.

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[21] Healthcare is defined here as medical devices and medicinal and dental preparations (e.g. prostheses, catheters, syringes, preparations for dentistry, medicinal preparations, absorbent pads); it does not include personal protective equipment.

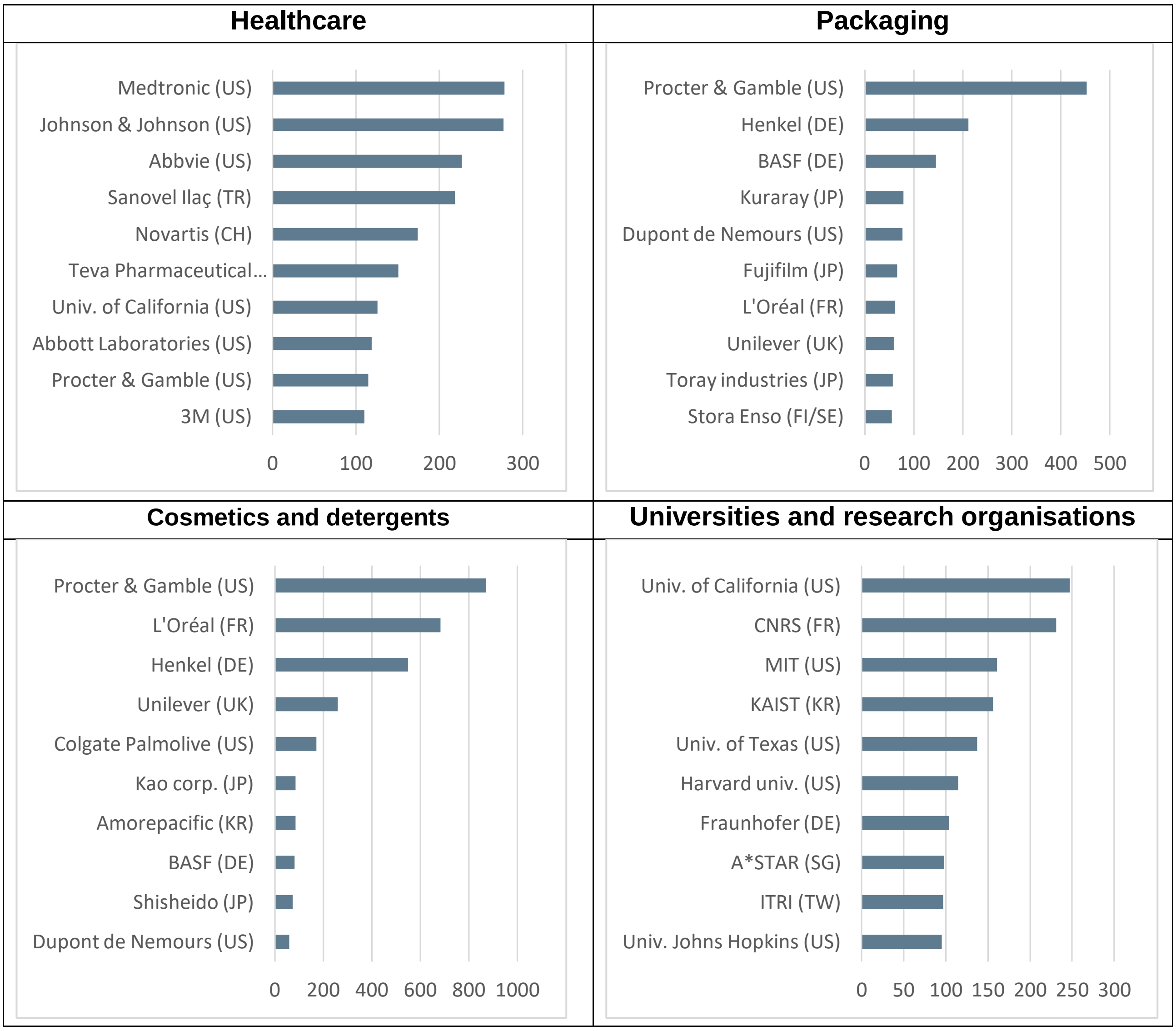
[22] More than half of the 6 400 IPFs are related to bio-sourced monomers.

[23] This category refers to any IPFs claiming a process to manufacture a polymeric article, including dispersions, films, hydrogels, composites, membranes, coated or treated polymeric articles, etc. Part of films is also in manufacturing (i.e. monolayer films).

The top ten applicants in bioplastic technologies are listed in Figure 3.3.2 for healthcare, packaging, cosmetics and detergents. The top ten universities and PROs in bioplastics are also listed. In healthcare, US companies represent seven of the top ten applicants, with IPF portfolios of roughly comparable sizes. The only exceptions are Novartis and Sanovel Ilaç (pharmaceutical companies from Switzerland and Turkey, respectively) and the University of California. This US university also ranks top among academic applicants, followed by four other US institutions, and five non-US public research organisations from France (CNRS), the Republic of Korea (KIST), Germany (Fraunhofer Institutes), Singapore (A*STAR) and Chinese Taipei (ITRI).

Apart from Procter & Gamble, the top ten applicants in packaging and cosmetics differ from those in healthcare. There is, however, a strong overlap between packaging and cosmetics, both of which are dominated by consumer products and cosmetics companies, with US company Procter & Gamble leading both sectors. In addition, five other US or European companies are listed in both rankings (Procter & Gamble, Henkel, BASF, Dupont de Nemours, L'Oréal, Unilever).

Figure 3.3.2: Top applicants in bioplastics by selected categories, 2010–2019



Box 5: Additional circular strategies

The European Green Deal provides an action plan to boost the efficient use of resources, prioritising the reduction and reuse of materials. The SUP directive is an important initiative in this context. Other examples include single-use personal protective equipment (PPE), such as the estimated 129 billion face masks and 65 billion gloves used during COVID-19. Innovation in reusable PPE could be instrumental in reducing waste while preserving the safety of healthcare workers.

Packaging remains the main target sector for the implementation of efficient use strategies, with 39.6% of the total demand for plastics in Europe in 2019 (PlasticsEurope, 2020) and 47% of global plastic waste production (Smith and Vignieri, 2021). The industry is exploring various circular options for plastics. As reported in Figures B5.1 and B5.2, most related inventions focus on zero waste strategies, such as edible packaging for food, alternative distribution methods or cosmetics and detergents in a solid form. Other circular strategies include more sustainable end-of-life designs for plastic products (see Box 3), as well as refill-reuse strategies.

Figure B5.1: Number of IPFs related to circular strategies in packaging, 2010–2019

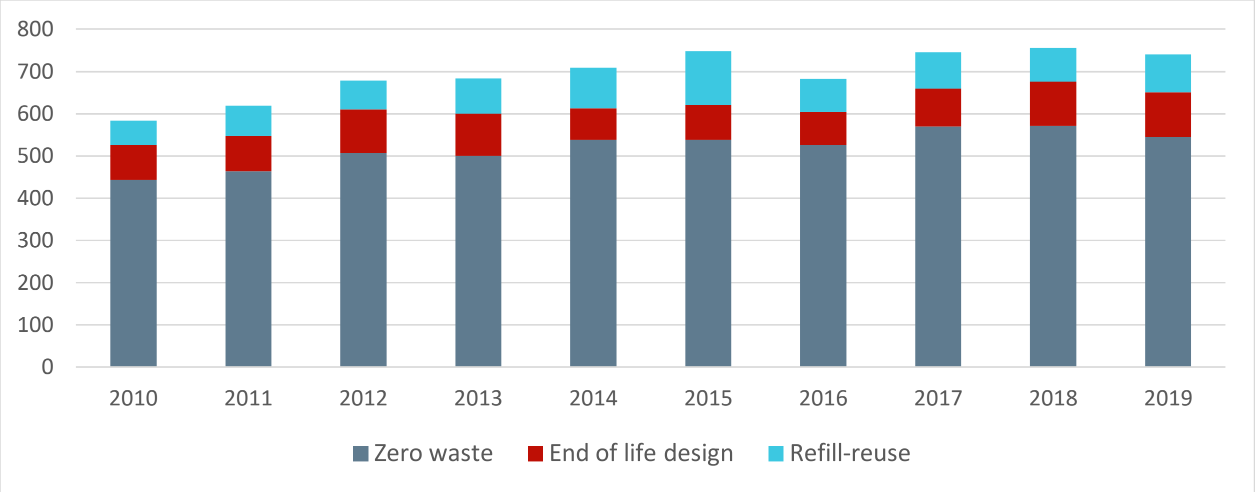
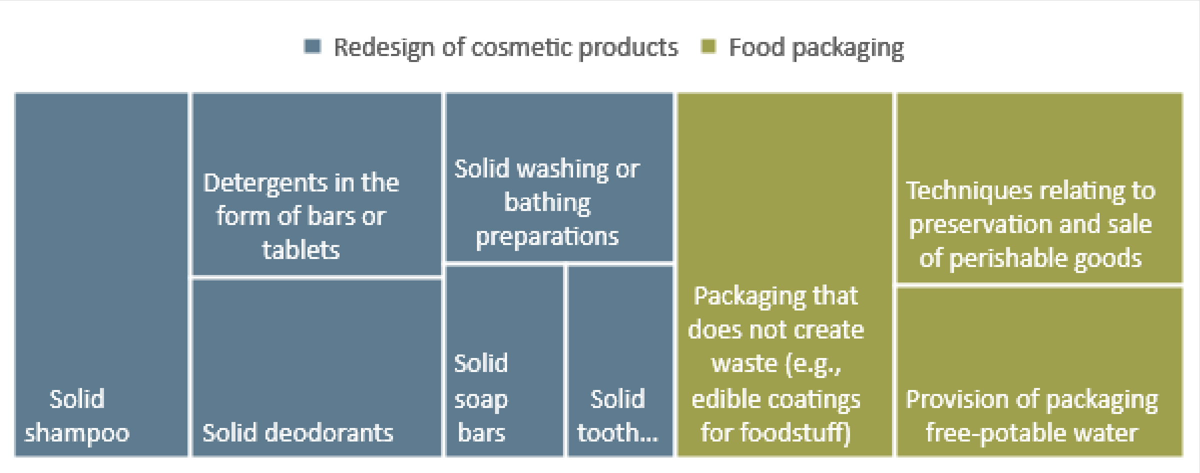


Figure B5.2: Applications of zero waste inventions, 2000–2019



Note: This Figure is based on the number of IPFs in each application field in the period 2000 to 2019 and based on the earliest publication year of the IPFs.

Case study: Eco-friendly packaging

Invention: Packaging grown from mushroom mycelia

Company: Ecovative Design

Sector: Green technology

Country: United States

Approximately 40% of plastics produced is used in SUPs (Geyer et al, 2017). Unfortunately, this results in a double environmental burden. Firstly, the production of plastics requires large quantities of oil or gas. Secondly, some plastics are recycled but an overwhelming majority is either burned, ends up in a landfill or in the ocean.

US entrepreneurs Eben Bayer and Gavin McIntyre (European Inventor Award 2019 finalists in the Non-EPO countries category) invented a biodegradable bioplastic that can be used as an alternative to plastic and polystyrene foams. Grown from mushroom mycelia, the new material can be moulded into multiple shapes and products for a wide variety of industrial and consumer applications. In 2007, Bayer and McIntyre co-founded the company Ecovative Design to commercialise their invention.

Forming a bond

Eben Bayer grew up on a farm, where he noted that fungi acted like glue, binding wood chips together. While at university, he met McIntyre and the two enrolled in an innovation course called Inventor's Studio. They pitched a mushroom-based glue idea to lecturer and mentor Burt Swersey, who encouraged them to take the idea further. As they conducted research, they realised that almost all agricultural waste, such as corn husks, rice, or hemp, can be bound together and the resulting material moulded into various shapes.

Perfecting the new material was a process of trial and error but their perseverance paid off. First, live mycelium is fed agricultural waste at room temperature and harvested every four to six days. Then, the shaped, non-toxic material is dried and baked, rendering it biologically inactive. The result is a material that can be recycled or composted, is biodegradable within 45 to 180 days, and delivers a strength-to-weight ratio similar to many plastic-based products. Its biofabrication process uses between one-fifth and one-eighth of the energy needed to produce plastic foams.

Today, the company has a library of 450 strains of mycelium with varying properties, enabling the inventors to tailor their products according to client requirements. During processing, the material can also be adjusted to achieve a specific density, strength or texture. This versatility has paved the way to product lines that extend far beyond packaging.

Moulding a sustainable future

Ecovative continues to research new applications for their material. After receiving a capital injection in late 2019, they began building an advanced research facility that includes custom-designed incubation devices and data analysis tools. Through a growing network of licensing partners, many mycelium-based products are now available in Europe, Asia, Africa and Australia. These range from eco-friendly furniture to home insulation, and from insulated jackets to foams for footwear. The company has developed a mycelium alternative to leather and a meat substitute that can be infused with flavour and used in vegan food products.

A recent EU Horizon 2020 collaboration between the University of the West of England (UK), Mogu S.r.l. (Italy), Istituto Italiano di Tecnologia (Italy) and the Universitat Oberta de Catalunya (Spain) showed that fungi can be incorporated into smart, sustainable textiles. The building industry has also shown interest in mycelium, exploring its use as a thermal and acoustic insulation product. While these applications are yet to be commercialised or are still at an early phase, reducing plastic packaging waste by using a cost-effective, biodegradable and sustainable alternative is within reach.

Case study: Vitrimers

Invention: A new class of polymers

Company: Arkema France & CNRS

Sector: Material sciences/polymers

Country: France

Every day, we encounter various types of polymers. Each has properties that make it suitable for a given application. For example, thermoplastics such as PET and polystyrene are mouldable via heating and can be recycled or reshaped, making them ideal for packaging. On the other hand, fibre-reinforced plastic composites and vulcanised rubber are strong and durable types of thermoset plastics. However, they cannot be reshaped once hardened and are difficult to recycle.

Ludwik Leibler (European Inventor Award 2015 winner in the Research category) invented a new class of polymer that combines desirable properties of both thermoset and thermoplastics. Dubbed vitrimers by the Polish-born French scientist, the new plastic is robust, self-healing and can be endlessly reshaped and recycled.

Like glass but unbreakable

Leibler and his team at ESPCI Paris Tech (Ecole Supérieure de Physique et de Chimie Industrielles) studied thermosetting plastics, where molecular bonds are not replaced once broken, causing the material to weaken and eventually fracture. The researchers had a breakthrough when they began synthesising a new material using zinc and carboxylic acid as a catalyst. At 150°C they observed that the molecules changed their binding partner without reducing the actual number of bonds among the molecules. Effectively, for every bond broken another new one formed. Using this method, the team created vitrimers: a new plastic that is light yet robust and malleable without liquefying.

When heated, vitrimers can be welded like metals, thereby enabling complex shapes to be produced that ordinarily would require moulding or intricate and expensive procedures. However, even when hardened, the new plastic can be reshaped and is therefore recyclable, taking an essential step towards closed-loop plastic production. The new class of polymers can replace current plastics in many applications, ranging from aircraft components to self-healing surfboards. Currently, Leibler and other researchers are examining methods for converting common thermoplastics into vitrimers using existing processing equipment.

From the lab to the world

Since Leibler's initial breakthrough, scientists from various fields have explored new techniques to produce vitrimers with wide-ranging properties. NASA-funded research found that reversible adhesives could benefit in-space assembly, allowing for the construction of larger and more complex structures. In Europe, the EU-backed AIRPOXY consortium was recently set up to reduce the production and maintenance costs of composite parts in the aeronautics sector. VITRIMAT is another EU-funded project, which aims to combine the expertise and technologies of various academic, technical and industrial partners to bridge the training gap between research and commercial production.

While much of the work in this field still takes place in the lab, some manufacturers are beginning to commercialise products that can be used in sporting goods, automotive parts or wind turbines. With ongoing research and policy steering the future of plastics, vitrimers are set to become part of our daily lives.

Annex 1 Patent metrics

The property rights granted by patents are strictly territorial. To protect a single invention in multiple markets, a number of national, regional or international patent applications may be required. A large number of patent applications, therefore, does not necessarily mean a large number of inventions. A more reliable measure of inventive activity is to count international patent families (IPFs), each of which represents a unique invention and includes patent applications targeting at least two countries. More specifically, an IPF is a set of applications for the same invention that includes a published international patent application, a published patent application at a regional patent office or published patent applications at two or more national patent offices. The regional patent offices are the African Intellectual Property Organization (OAPI), the African Regional Intellectual Property Organization (ARIPO), the Eurasian Patent Organization (EAPO), the European Patent Office (EPO) and the Patent Office of the Cooperation Council for the Arab States of the Gulf (GCCPO).

IPFs are a reliable and neutral proxy for inventive activity because they provide a degree of control for patent quality and value by only representing inventions deemed important enough by the applicant to seek protection internationally (Dernis et al., 2001; Harhoff et al., 2003; Van Pottelsberghe and van Zeebroeck, 2008; Frietsch and Schmoch, 2010; Martinez, 2011; Squicciarini et al., 2013; Dechezleprêtre et al., 2017). A relatively small proportion of applications meet this threshold, and this varies widely across country of residence of the inventor and other important vectors. As such, this concept enables a comparison of the innovative activities of countries, fields and companies internationally, since it creates a sufficiently homogeneous population of patent families that can be directly compared with one another, thereby reducing the national biases that often arise when comparing patent applications across different national patent offices.

Each IPF identified as relevant to plastic recycling or alternative plastics technologies is assigned to one or more sectors or fields of the cartography. The analysis covers the period 1980-2019. The date attributed to a given IPF always refers to the year of the earliest publication within the IPF. Unless specified otherwise, the geographic distribution of IPFs is calculated using information about the origin of the inventors disclosed in the patent applications. Where multiple inventors were indicated on the patent documents within a family, each inventor was assigned a fraction of the patent family.

Where necessary, the dataset was further enriched with bibliographic patent data from PATSTAT, the EPO's worldwide patent statistical database, as well as from internal databases, providing additional information, for example, on the names and addresses of applicants and inventors, or whether the applicant is a company or a research organisation. In addition, information was retrieved from the Bureau van Dijk ORBIS (2020 version) database and used to harmonise and consolidate applicant names and their addresses. Each applicant name was consolidated at the level of the global ultimate owner according to the latest company data available in ORBIS. If that information was not available, the data was cleaned manually. The Crunchbase database (2021 version) was also used to analyse the patenting activities of start-ups in the field of chemical and biological recycling.

Annex 2 Cartography of technologies related to plastic recycling and alternative plastics

The patent cartography used in the study was assembled from the intellectual input of patent examiners at the EPO and developed and populated in the following three steps.

Step 1: Linking technology fields to the patent classification scheme

Technology experts were asked to identify the technologies relevant for plastic recycling and alternative plastics from their areas of expertise (Table A1) and, together with patent classification experts, to provide information about the field ranges of the Cooperative Patent Classification (CPC) scheme in which the inventions of the different technologies can be found. The results were used to create a concordance table of relevant technologies and CPC ranges. The table contains around 780 different technologies with assigned CPC field ranges in all technical fields and sectors of the cartography scheme used in the study. The cartography and the assignment of CPC ranges were verified by applying ad hoc queries against the EPO's full-text patent database and analysing the results. Anomalies were re-assessed and corrected/amended where necessary.

Table A1: Overview of the cartography

Level 1	**Level 2**	**Level 3**
Plastic recycling	Waste recovery	Collecting
		Sorting and separating
		Cleaning
	Waste recycling	Pre-consumer plastic to product
		Post-consumer plastic to feedstock
		Plastic to feedstock
		Plastic to compost
		Plastic to monomer
		Plastic to incineration or energy recovery
Alternative plastics	Bioplastics (bio-based and/or biodegradable)	Modified cellulose
		Other modified polysaccharides
		Modified starch
		Other modified natural polymers

		Polymers from bio-sourced monomers
		Natural polymers produced in industrial settings
		Natural rubber and synthetic rubber from bio-sourced monomers
		Biodegradable polymers
	Design for easier recycling	Covalent adaptable networks
		Others
	Others	Synthesis from CO_2
		Self-repairing

Step 2: Identifying patent applications

Upon identification of the relevant technology fields, a distinction has been made between specific classes (i.e. specific to the study) and non-specific ones. The specific ones have been included in their entirety. The non-specific ones have been combined with a set of semantic keywords. On patent documents in these non-specific classes, full-text search queries were applied to all published applications in the respective CPC ranges in order to tag documents relating to the concepts of plastic recycling and alternative plastics. Some of the queries were also only full-text search queries.

Additionally, patent documents relating to the use of conventional plastic technologies have been identified for some industrial sectors and cross-sector industrial applications. These have been used as benchmarks to allow comparison of the number of IPFs in bioplastics with the number of IPFs relating to conventional plastic technologies.

Step 3: Classifying patent applications to the cartography fields

All CPC codes and tags assigned to all identified IPFs were extracted and combined. The unique CPC classes and tags for each IPF were then linked to the respective technology fields and sectors of the cartography using the concordance table from step 1. The details of all preparations can be made available on request.

For the purposes of this study, the statistics on IPFs were based on a simple count method, reflecting the number of inventions assigned to a particular field or sector of the cartography, independently of whether some of these inventions were also classified in other fields or sectors.

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