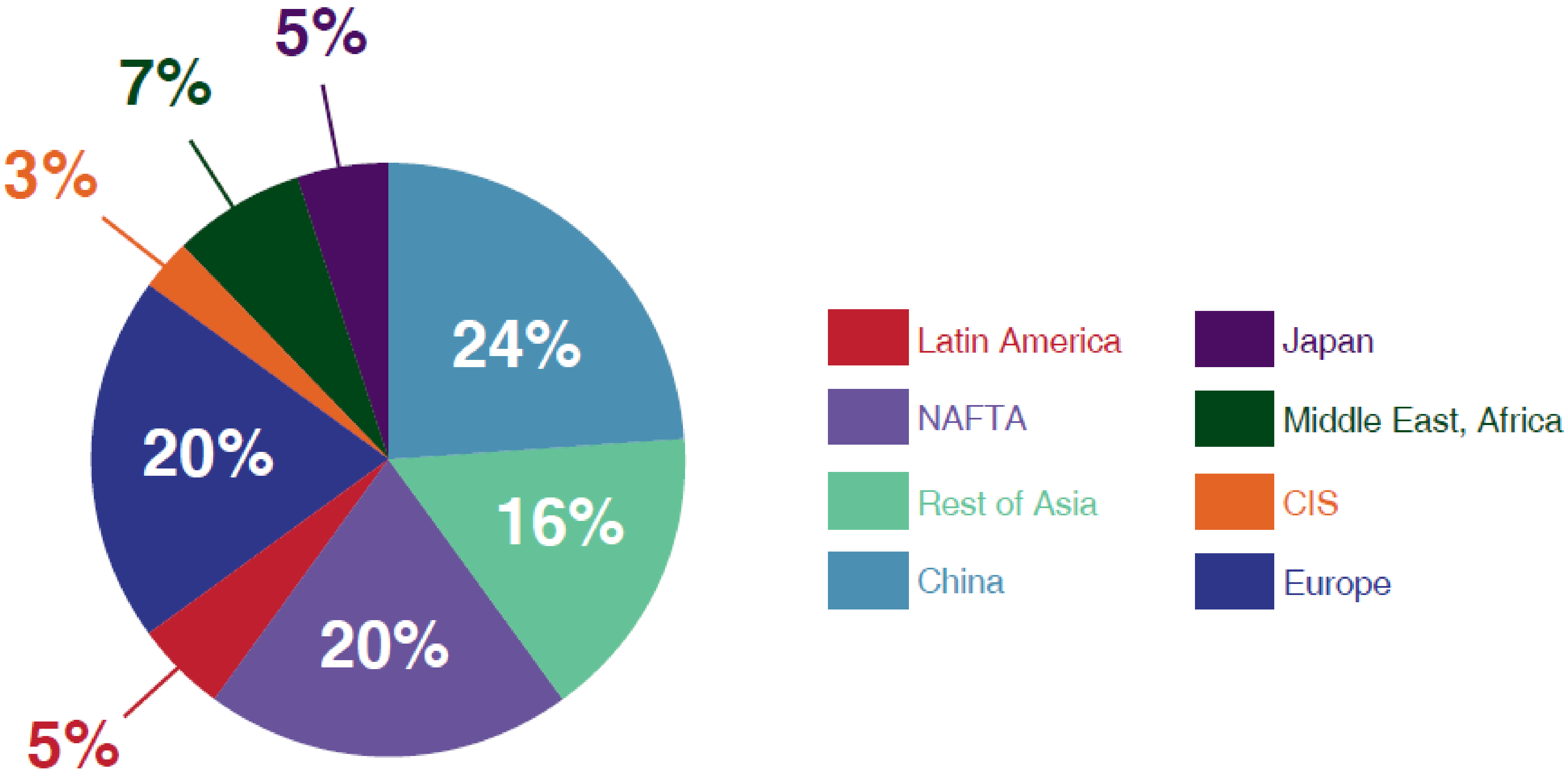
Plastiche:
alcune cifre per capire meglio l’impatto

https://www.plasticseurope.org/it/resources/publications/1804-plastics-facts-2019

Plastics – the Facts 2019

An analysis of European plastics
production, demand and waste data

FIGURE 4: PLASTIC PRODUCTION PER REGION, 2012

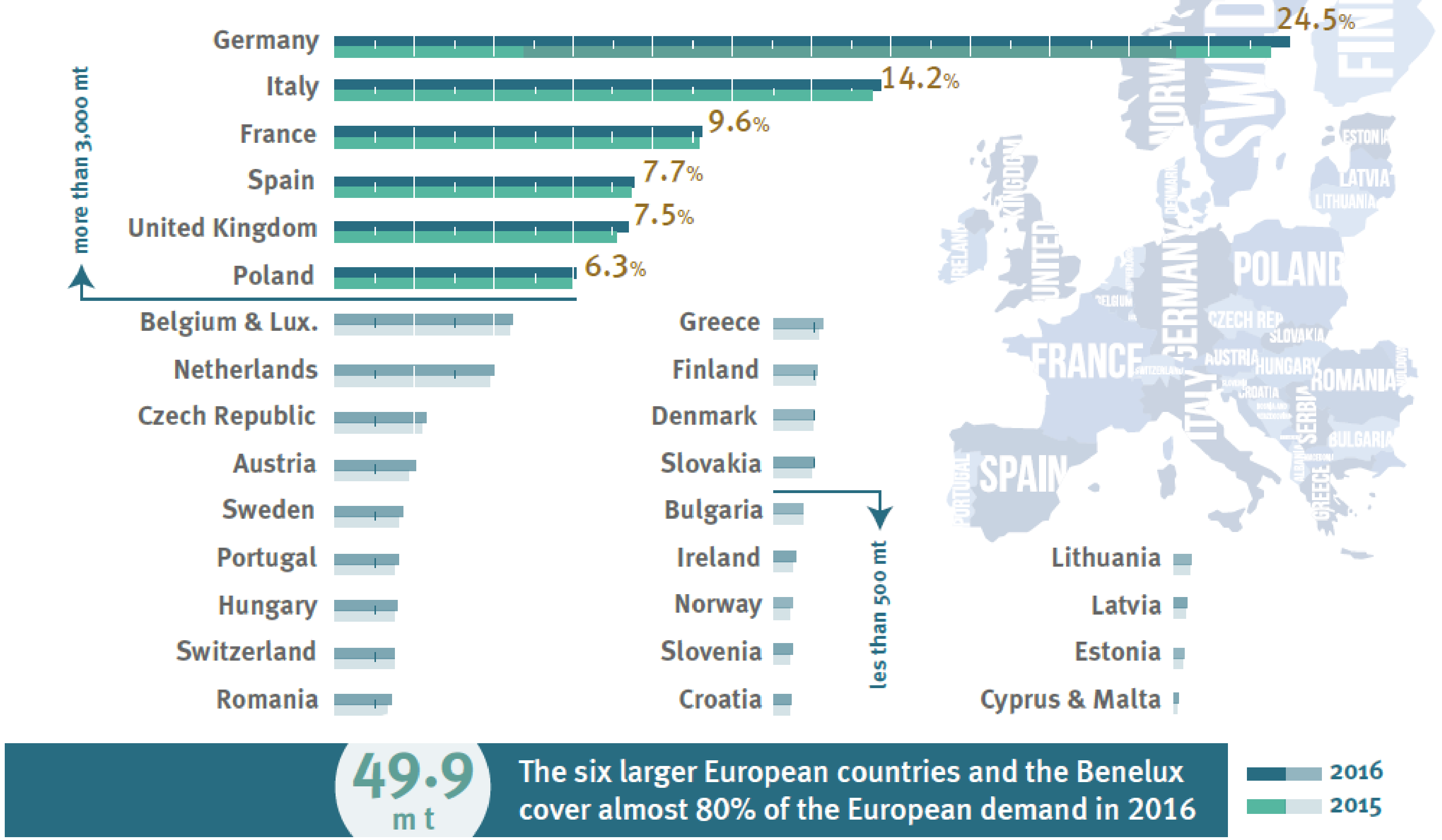


Based on PlasticsEurope data [1]

Plastics EU converter demand per country

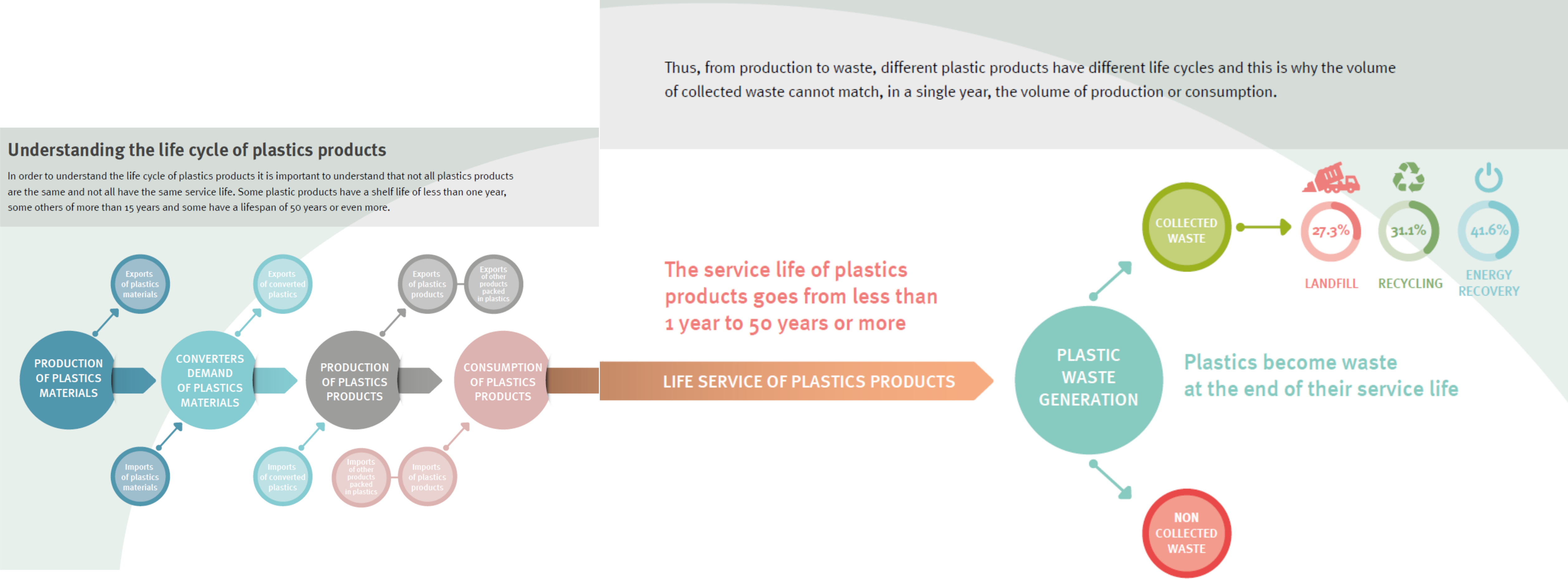
European plastic converter demand includes plastic materials (thermoplastics and polyurethanes) and other plastics (thermosets, adhesives, coatings and sealants). Does not include: PET fibers, PA fibers, PP fibers and polyacryls-fibers.

Source: PlasticsEurope Market Research Group (PEMRG) and Conversio Market & Strategy GmbH (Consultic GmbH for 2015 data)



The six larger European countries and the Benelux cover almost 80% of the European demand in 2016

Life cycle of plastics



Thus, from production to waste, different plastic products have different life cycles and this is why the volume of collected waste cannot match, in a single year, the volume of production or consumption.

Understanding the life cycle of plastics products

In order to understand the life cycle of plastics products it is important to understand that not all plastics products are the same and not all have the same service life. Some plastic products have a shelf life of less than one year, some others of more than 15 years and some have a lifespan of 50 years or even more.

The service life of plastics products goes from less than 1 year to 50 years or more

Plastics become waste at the end of their service life

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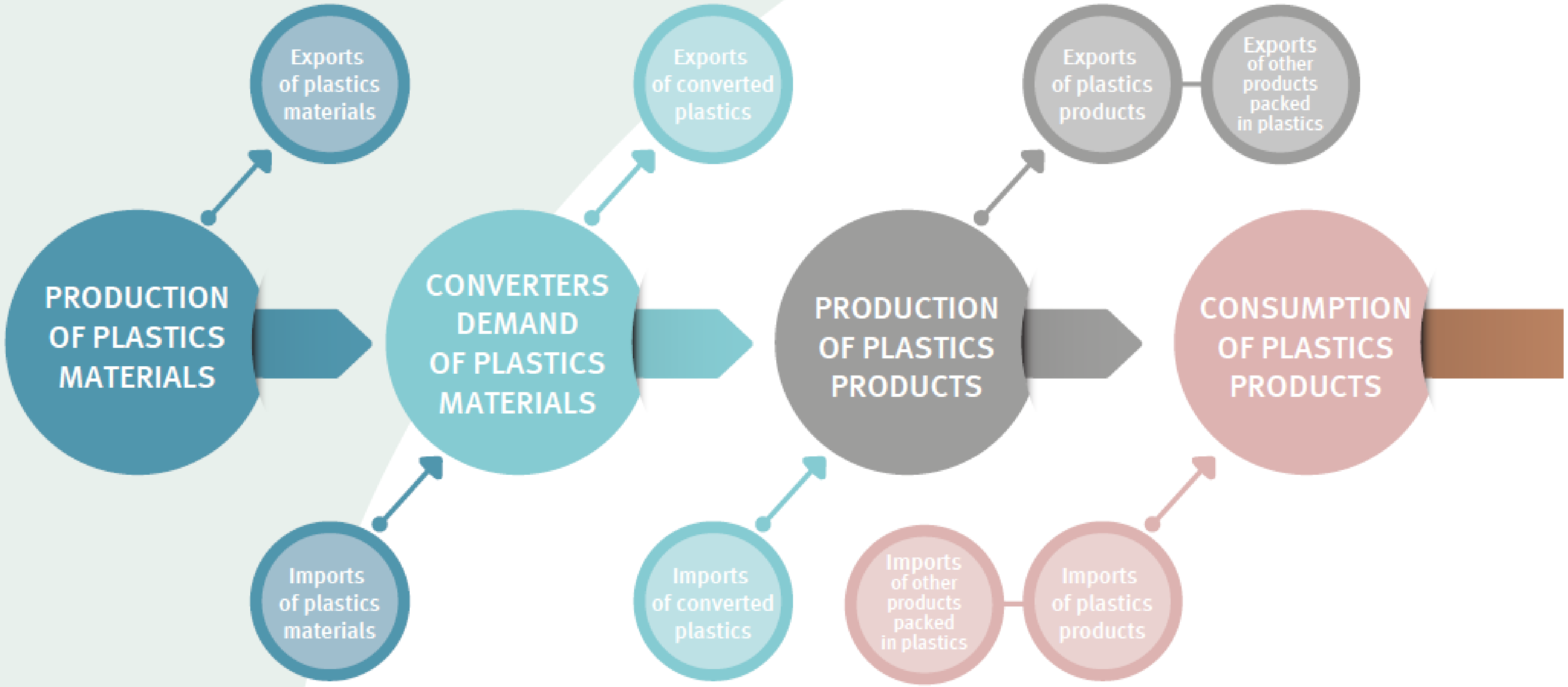
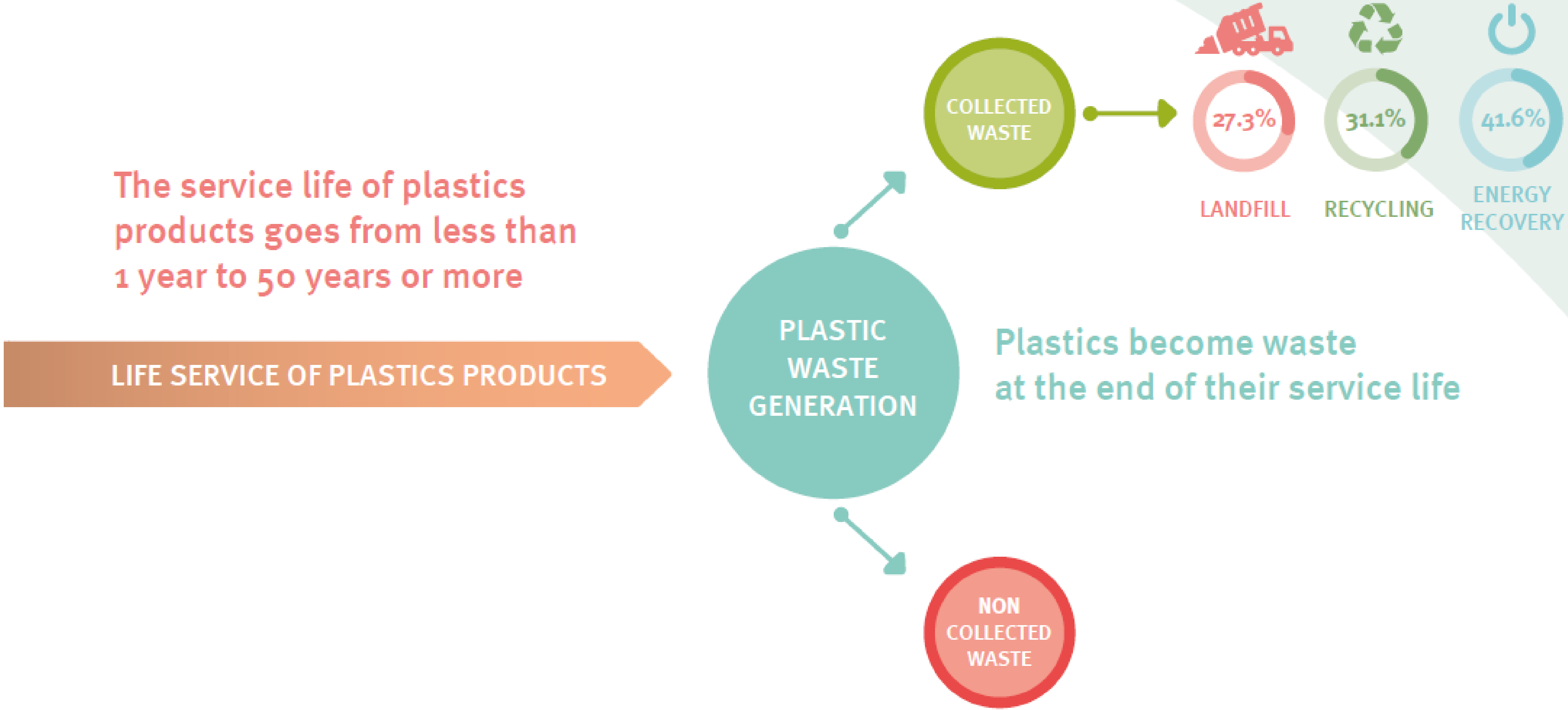


Thus, from production to waste, different plastic products have different life cycles and this is why the volume of collected waste cannot match, in a single year, the volume of production or consumption.

The service life of plastics products goes from less than 1 year to 50 years or more



LIFE SERVICE OF PLASTICS PRODUCTS

PLASTIC WASTE GENERATION

COLLECTED WASTE

NON COLLECTED WASTE

27.3% LANDFILL

31.1% RECYCLING

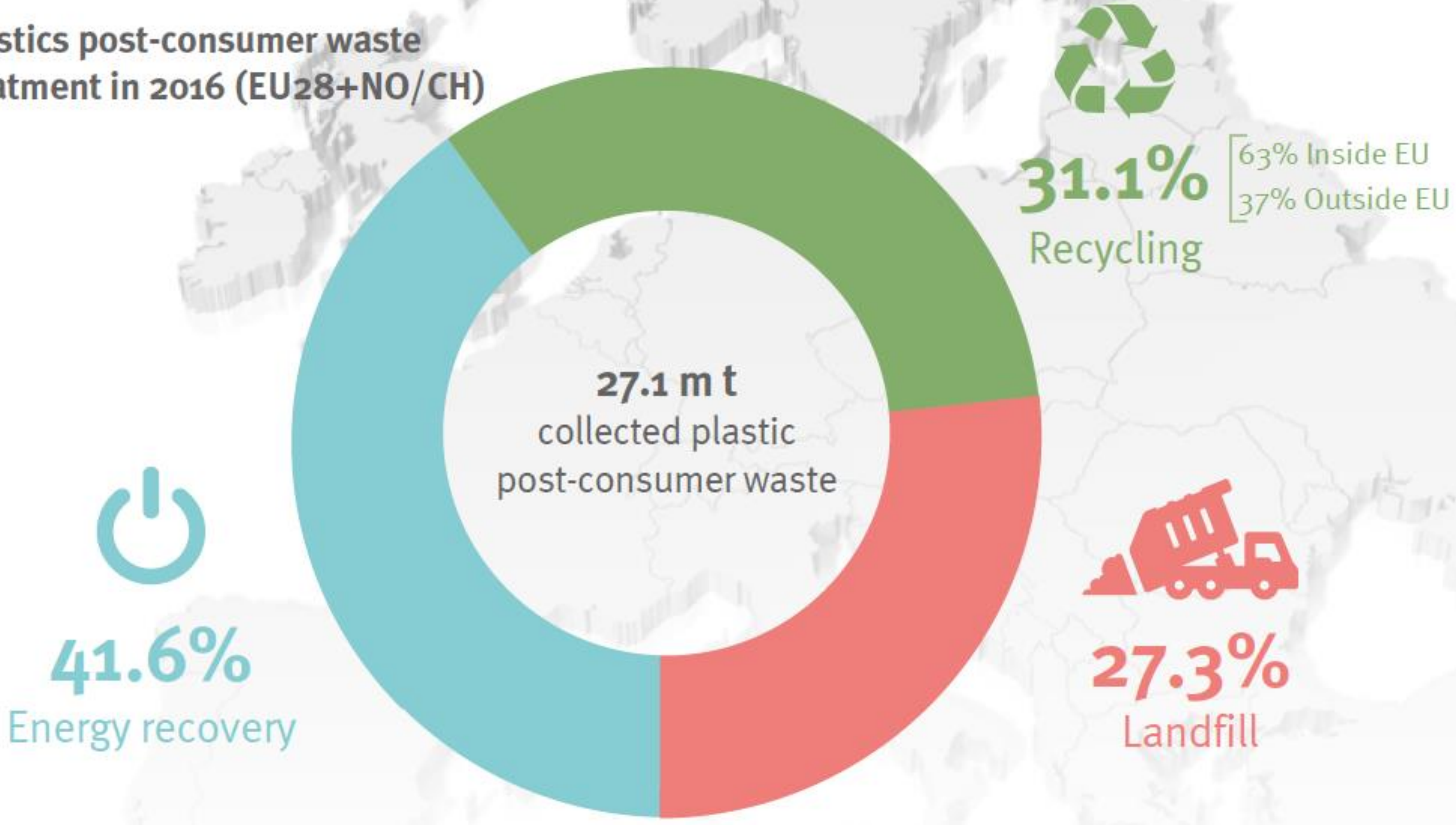
41.6% ENERGY RECOVERY

Plastics become waste at the end of their service life

In 2016, for the first time, recycling overcame landfill

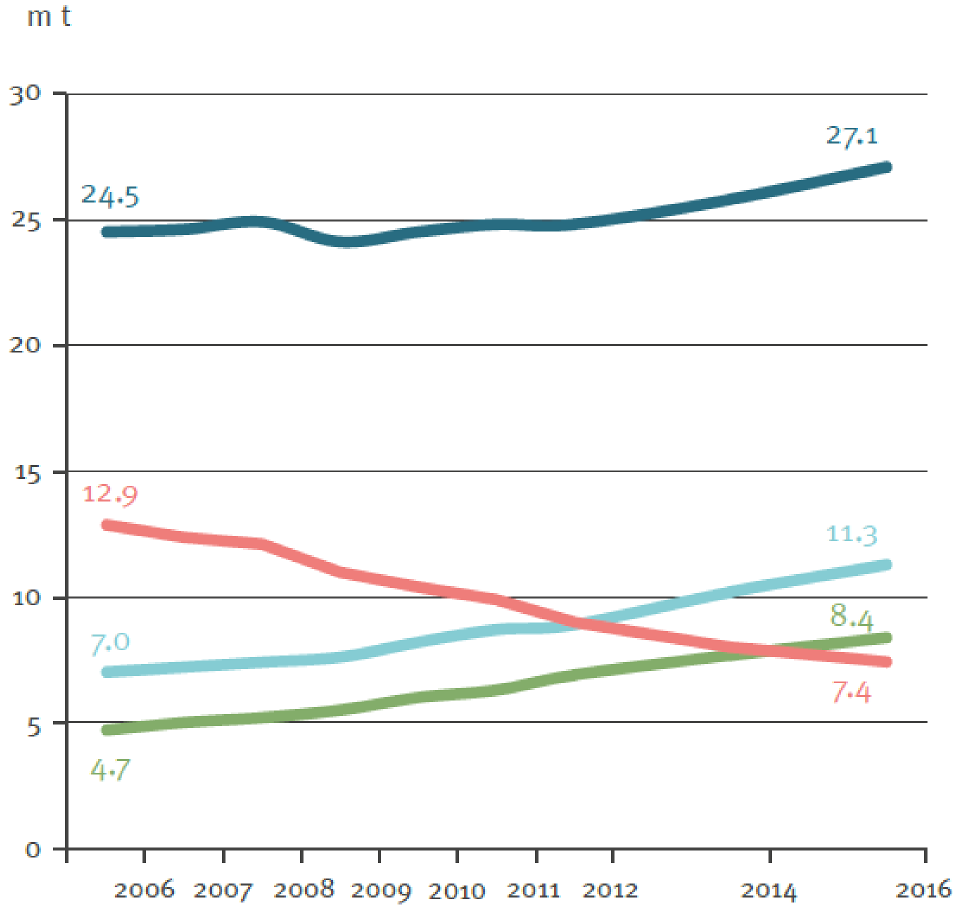
In 2016, 27.1 million tonnes of plastic waste were collected through official schemes in the EU28+NO/CH in order to be treated. And for the first time, more plastic waste was recycled than landfilled.

Plastics post-consumer waste treatment in 2016 (EU28+NO/CH)

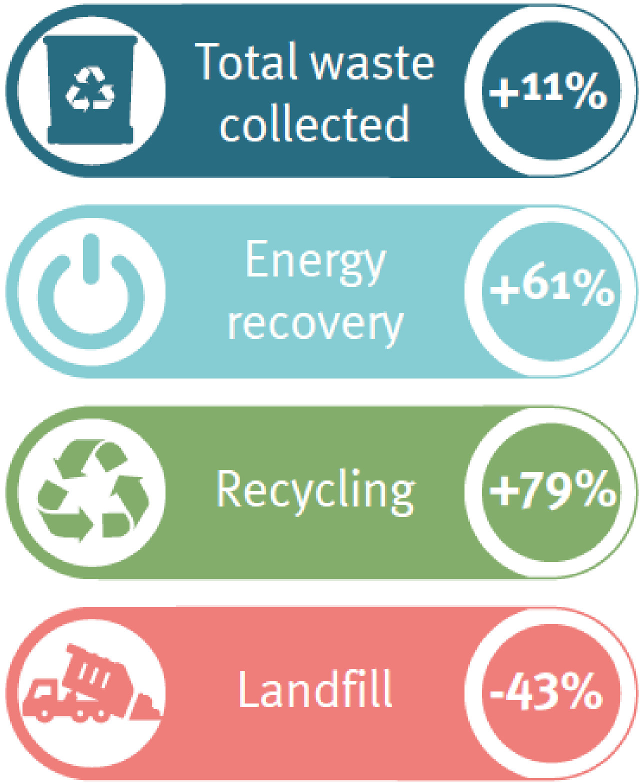


In ten years, plastic waste recycling has increased by almost 80%

From 2006 to 2016 the volumes of plastic waste collected for recycling increased by 79%, energy recovery increased by 61% and landfill decreased by 43%.



2006-2016 evolution of plastics waste treatment (EU28+NO/CH)



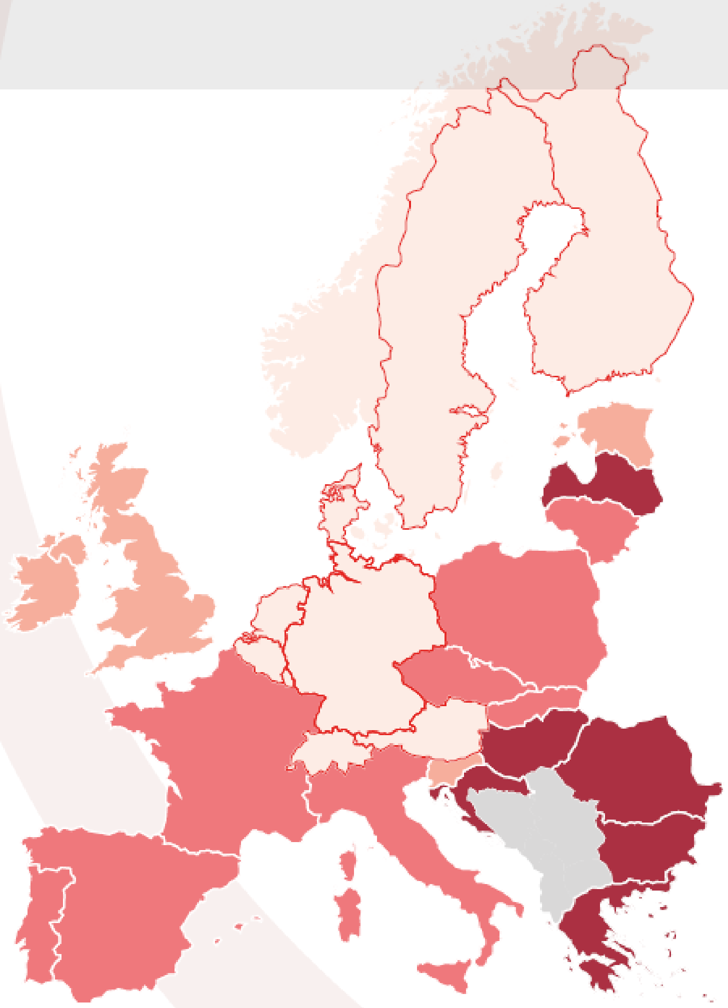
Plastic waste recovery is still very uneven in Europe

Although the total EU situation is improving, in many countries, landfill is still the first or second option of treatment for plastic post-consumer waste.

Source: Conversio Market & Strategy GmbH

Plastics post-consumer waste landfill rate across Europe

- ■ 10% or less
- ■ up to 30%
- ■ up to 50%
- ■ more than 50%
- □ Countries with landfill restrictions implemented



Plastics waste going to landfill in 2016

https://www.plasticseurope.org/it/resources/videos/403-full-life-cycle-thinking-italian

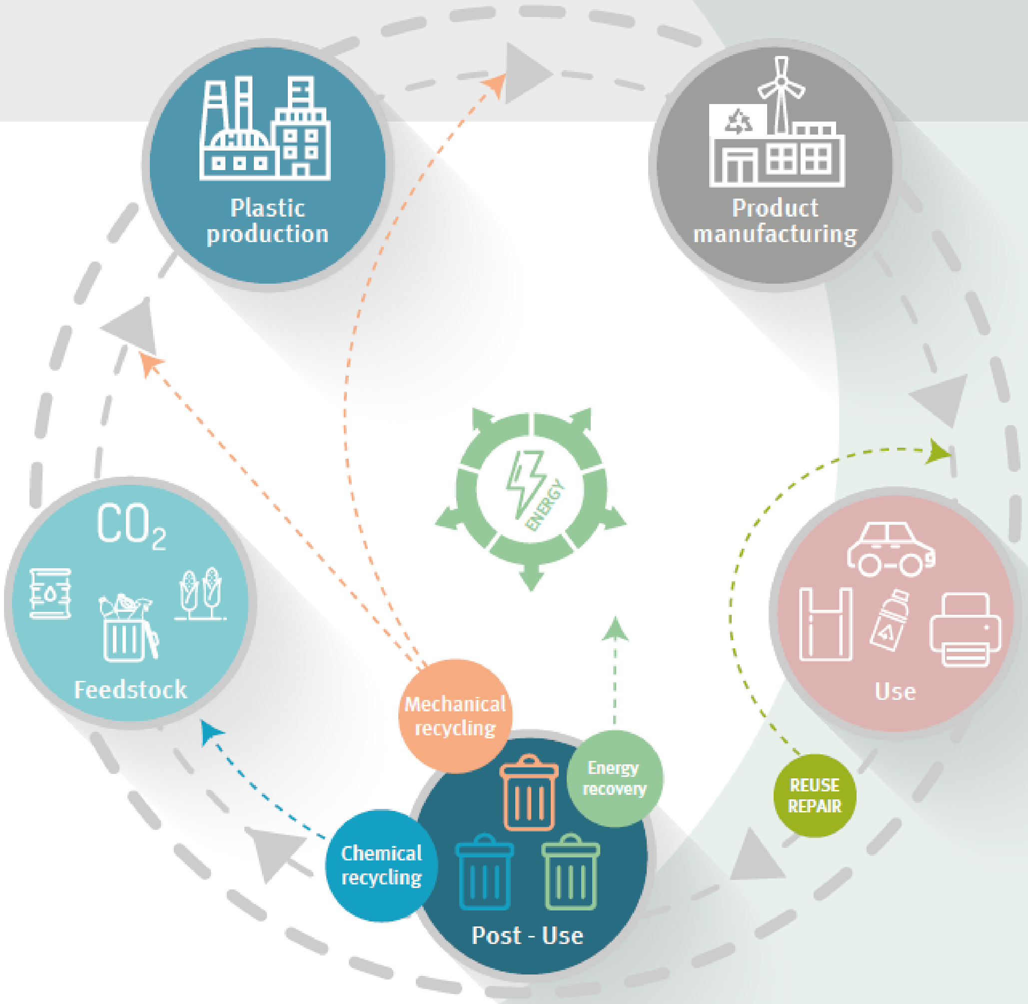
THE CIRCULAR ECONOMY FOR PLASTICS

A European Overview

PlasticsEurope
Association of Plastics Manufacturers

Full life cycle thinking is smart thinking

At the end of their life, plastics are still very valuable resources that can be transformed into new feedstock or into energy.



https://www.plasticseurope.org/it/resources/publications/1899-circular-economy-plastics-european-overview

Collecting and recycling plastics represents an answer to the problem and analysis by the Ellen MacArthur Foundation has shown that “**replacing just 20% of single-use plastic packaging’s with reusable alternatives offers opportunities for economic development worth at least 10 billion USD**” [11].

Notably, in Europe, collection increased from 27.1 million tonnes in 2016 to 29.1 million tonnes in 2018. About 9.4 million tonnes (32.5%) of them were recycled inside or outside Europe while 24.9% ended up in landfills and the rest was incinerated [7].

Why recycling is not sufficient 1.

It must be underlined that **plastics made from fossil fuels account for 20% of the total fossil oil consumption** [11] and their manufacture, recycling and incineration are energy intensive and **cause considerable greenhouse gases (GHG) emissions.**

Analyses indicate that if plastic continues to be produced from fossil carbon sources, it will be responsible for a 15% of the maximum annual global carbon budget, needed to limit global warming to 2°C in 2050 [12].

Therefore, the use of **recycled materials**, when technically and legally feasible, is essential to **enable the dissociation of plastic production** from the exploitation of finite carbon sources. However, in a long-term perspective, it is necessary to boost a **transition to plastics obtained from renewable feedstoc**k, whenever robust evidences support their environmental and social benefits.

Why recycling is not sufficient 2.

Not all plastics/polymers can be recycled

12.6.2019 IT Gazzetta ufficiale dell'Unione europea L 155/1

La direttiva Europea SUP: single use plastics

(*Atti legislativi*)

DIRETTIVE

DIRETTIVA (UE) 2019/904 DEL PARLAMENTO EUROPEO E DEL CONSIGLIO

del 5 giugno 2019

sulla riduzione dell'incidenza di determinati prodotti di plastica sull'ambiente

(Testo rilevante ai fini del SEE)

Articolo 1

Obiettivi

Gli obiettivi della presente direttiva sono prevenire e ridurre l'incidenza di determinati prodotti di plastica sull'ambiente, in particolare l'ambiente acquatico, e sulla salute umana, nonché promuovere la transizione verso un'economia circolare con modelli imprenditoriali, prodotti e materiali innovativi e sostenibili, contribuendo in tal modo al corretto funzionamento del mercato interno.

TOP 10 SINGLE-USE PLASTIC ITEMS FOUND ON SEA SHORES

1. Drink bottles, caps and lids
2. Cigarette butts
3. **Cotton buds sticks**
4. Crisp packets/sweet wrappers
5. Sanitary applications (sanitary towels, tampons etc.)
6. Plastic bags
7. **Cutlery, straws and stirrers**
8. Drinks cups and cup lids
9. Balloons and **balloon sticks**
10. Food containers, including fast food packaging

Items in **yellow** could soon be banned as non-plastic alternatives are now available.

Source: European Commission

europarl.europa.eu

8 WAYS TO REDUCE YOUR SINGLE-USE PLASTICS

There are an estimated **5 TRILLION** pieces of plastic in the ocean worldwide, with **8 MILLION** metric tons added to the ocean each year*. **Wildlife are dying at a rapid pace due to the ingestion of or entanglement in plastics.**

1. PLASTIC WATER BOTTLE → REUSABLE BEVERAGE CONTAINER
2. TO-GO COFFEE LIDS → TRAVEL COFFEE MUG
3. PLASTIC AND PRODUCE BAGS → REUSABLE CLOTH BAGS
4. SINGLE-SERVE COFFEE PODS → A POT OF COFFEE
5. COFFEE PLUGS AND STIR STICKS → TRAVEL COFFEE MUG
6. BALLOONS → ECO-FRIENDLY DECORATIONS
7. STRAWS → STRAW FREE
8. DISPOSABLE LIGHTER → MATCHES

YOU can help reduce waste by removing single-use plastics from your everyday activities.

CANADIAN WILDLIFE FEDERATION

#StopSingleUse

* (ERIKSEN ET AL. 2014; JAMBECK ET AL. 2015)

Plastic is responsible for around **10% of the generated total waste and composes 60-90% of the marine litter,** mostly with food and beverage packaging, cigarette butts and bags. According to the United Nations Environment Programme (UNEP), 8 million tonnes of plastic are poured into the seas each year, an equivalent to a full garbage truck every minute [6][7].

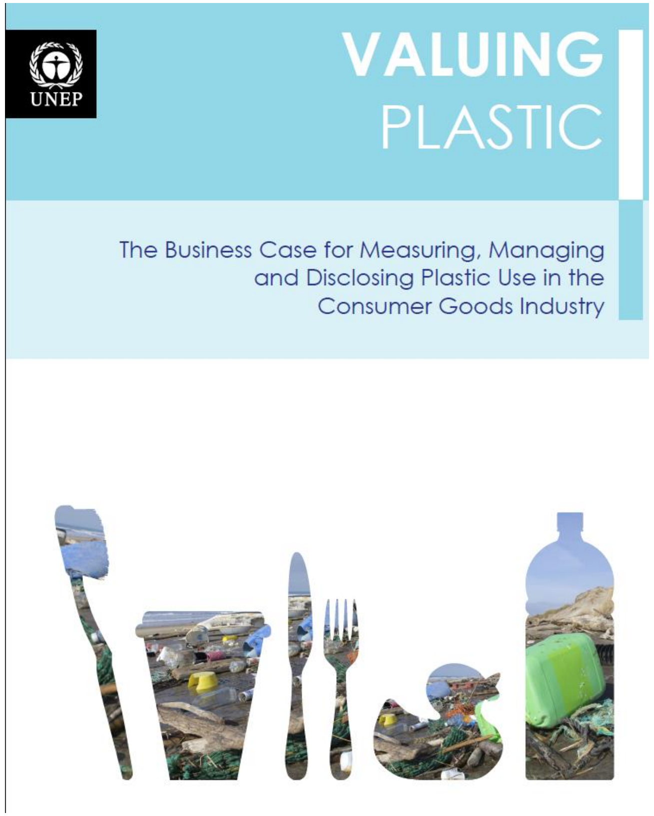
Marine species and humans are being harmed since the plastic waste enters the human food chain through fish consumption, [8] while the rapid spread of microplastics has made this problem even more alarming [9]. Because **it is not effective to remove plastic waste and microplastics once they have entered the sea**, plastic pollution needs to be tackled at its source [10].

The hidden natural capital cost of fossil-based plastics in numbers

A clear understanding of the environmental degradation and resource depletion connected to plastics must rely on a quantitative and transparent accounting of their impact on natural capital.

The term **Natural Capital** [13] describes “Earth’s natural assets, including soil, air, water, and living things, existing as complex ecosystems, as well as the related ecosystem services that human societies need in order to survive and thrive”.

Economic activities depend on these resources and services; however, the latter are often not factored into corporate accounting, and national accounts currently do not fully take their contribution into consideration.



UNEP

VALUING
PLASTIC

The Business Case for Measuring, Managing
and Disclosing Plastic Use in the
Consumer Goods Industry

In 2014, UNEP published a study focused on the evaluation of the natural capital costs of plastics, namely the **environmental and social impacts caused by the use of plastic expressed in monetary terms to reflect the scale of the caused damage** [6].

The study converted physical quantities of plastic into monetary values, using environmental or natural capital valuation techniques [14]. These techniques estimate the value of environmental goods or services in the absence of a market price and aggregate them into a single figure.

As an example, by calculating the amount of GHG caused by plastic production it is possible to ascribe a monetary value on each tonne of GHG in relation to its impact on climate change. Similarly, plastic waste incineration is associated to air pollution, which can be expressed in monetary terms, thus reflecting the scale of damage caused.

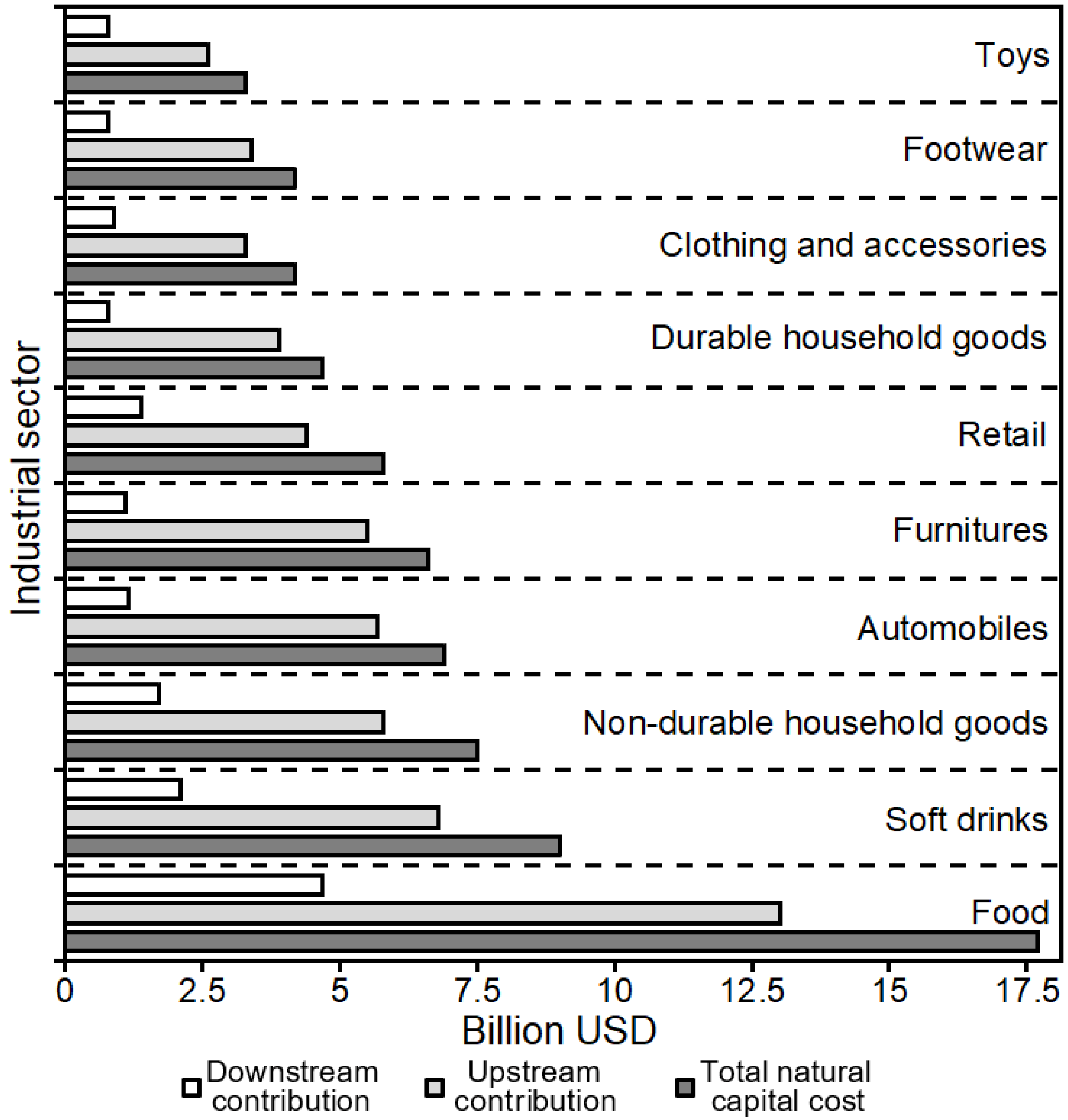
On this basis, the UNEP study estimated that the total natural capital cost of the plastic used in the consumer goods industry is above US$75 billion per year.

Such approach translates physical impacts into a monetary figure, which expresses the potential value that companies would have to internalise if they were held accountable for their impacts.

Upstream and downstream impacts

When considering that most types of plastic are petroleum-based products, one significant outcome of the UNEP analysis is that, across all sectors, **over 75% of the known and quantifiable impacts associated with plastic usage are located in the upstream portion of the supply chain**.

'**Upstream**' refers to "impacts generated from the extraction of raw materials to the manufacturing of plastic feedstock",
'**downstream**' refers to "impacts generated once the consumer has discarded the product".
For example, the downstream impact of consumer electronics is only 17% of its total impact due to established recycling initiatives, whereas the tobacco sector has the largest downstream impact (29%) of its total impact due to the littering of cigarette butts.



Total capital cost for some of the most relevant industrial sectors contributing to the plastic problem. The calculated costs arise from the accounting of the tonnage of plastic used in the selected key consumer goods sector (based on its expenditure), which gave the plastic intensity.

The natural capital cost for a certain sector is the **natural capital intensity** multiplied by the aggregate revenues and it expresses “the dependency of a certain sector on the natural capital”.

The plastic intensity in each sector reflects different contributions of the three main categories of plastic usage:

i) plastic used in products;
ii) ii) plastic used as packaging;
iii) iii) plastic used by suppliers (such as bags containing fertilizer used by farmers supplying the food sector).

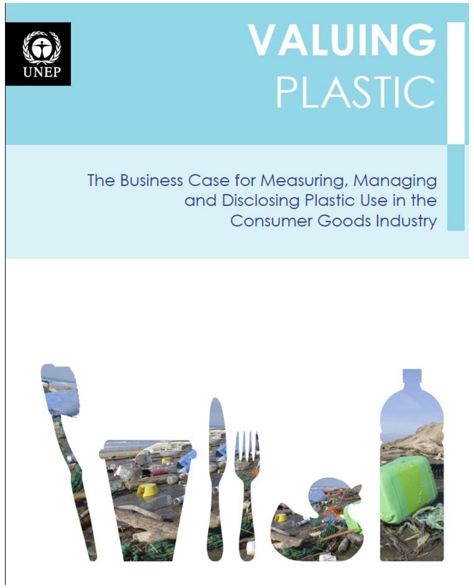
This methodological approach made evident that, for the food, soft drink, retail and personal products sectors, the whole contribution comes from the packaging.

On average, the total natural capital cost of plastic use is 52% of the total economic cost. When only considering the upstream natural capital cost as a percentage of plastic prices, the potential cost increase is 44% on average. This means that, if the upstream impacts of plastic were taken into account and fully paid by businesses, the price of plastic would be 44% higher on average.

With current knowledge, the analysis indicates that, across consumer goods sectors, over 30% of the natural capital costs originates from GHG released in the upstream supply chain. The most significant downstream impact is marine pollution, which has a natural capital cost of at least $13bn, and includes economic losses incurred by fisheries and tourism as well as time spent cleaning up beaches.

The environmental impacts associated with plastic use was calculated using lifecycle analysis techniques, using official databases as the US Toxic Release Inventory [15] and Plastics Europe eco-profiles [16]. The **impact of additives leachate from plastics** was also accounted, since there is a growing concerns on their impacts on human health and the environment [17,18]. **Additives** are added to plastic during their manufacturing to improve their mechanical and thermal properties and the study calculated the amount of additives per type of plastic based on a report of the Organisation for Economic Co-operation and Development [19]. According to the same report, the annual leaching rate of additives is 0.16% per year, which means that it would take 625 years for 100% of the additives to be released from the plastics. These data were used to quantify and, ultimately, valuate the toxic impact of plastics additives.

Overall, the disclosing of the natural capital costs of plastics highlighted “the urgent need for businesses to measure, manage and disclose information on their annual use and disposal of plastic, as many companies already do with carbon emissions” [6].



UNEP

VALUING PLASTIC

The Business Case for Measuring, Managing and Disclosing Plastic Use in the Consumer Goods Industry

Companies need a single tool that measures environmental impacts in an integrated way together with other business issues. This is where **natural capital valuation** comes in. The technique enables companies to put a financial value on a range of impacts, including plastic, so environmental management can be fully embedded within the business.

This research then analyses the exposure of companies to these risks and opportunities by expressing quantities of plastic used as a natural capital cost. The results show that the total natural capital cost of plastic used in the consumer goods industry is over $75bn per year. Broken down by sector, food companies are by far the largest contributor to this cost, responsible for 23% of the total natural capital cost (see figure 1).The results also show each sector's natural capital intensity – or its natural capital cost per $1m of annual revenue. The toy sector has by far the highest intensity, at 3.9% of revenue.

FIGURE 1: TOTAL NATURAL CAPITAL COST AND INTENSITY OF SELECTED SECTORS

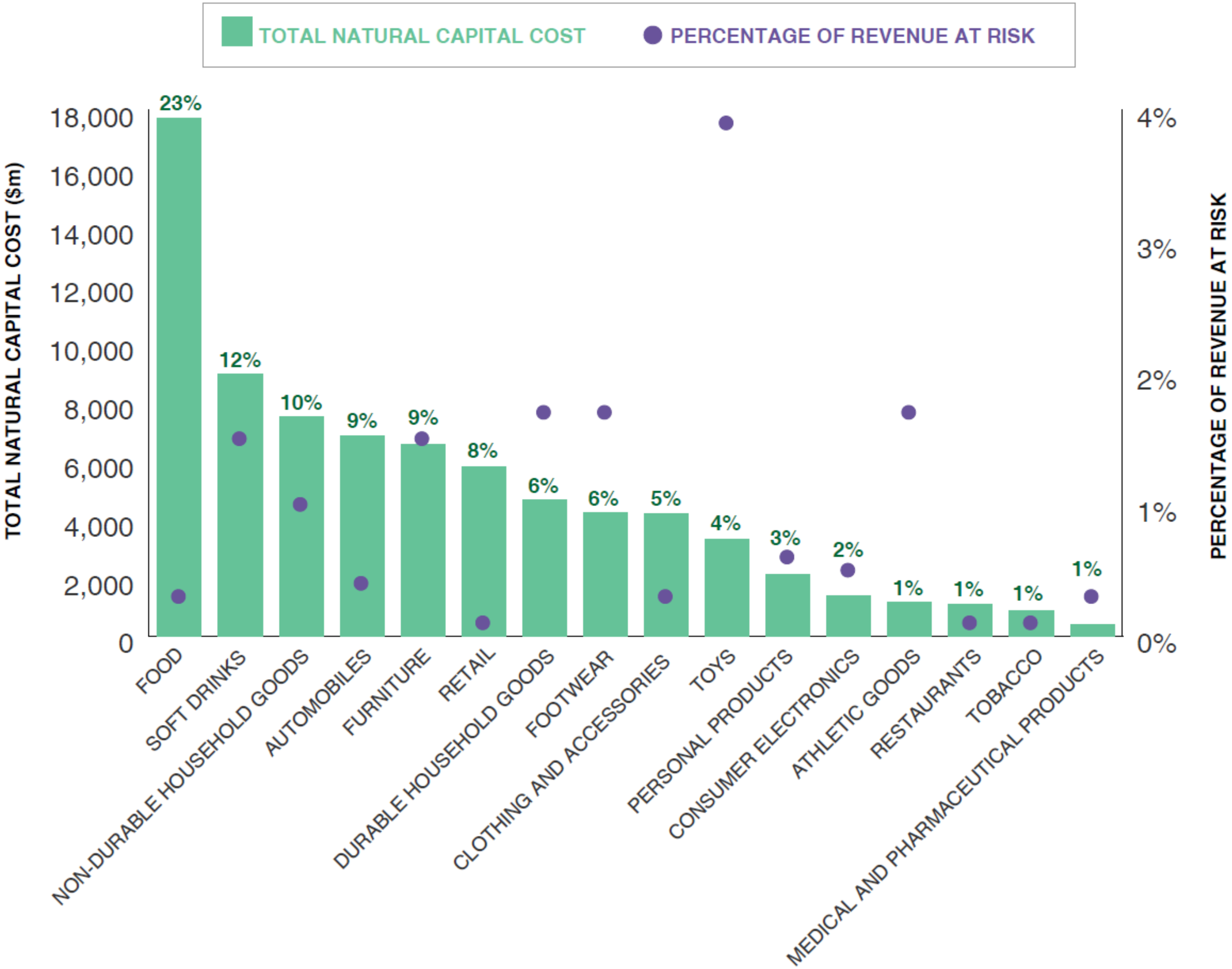


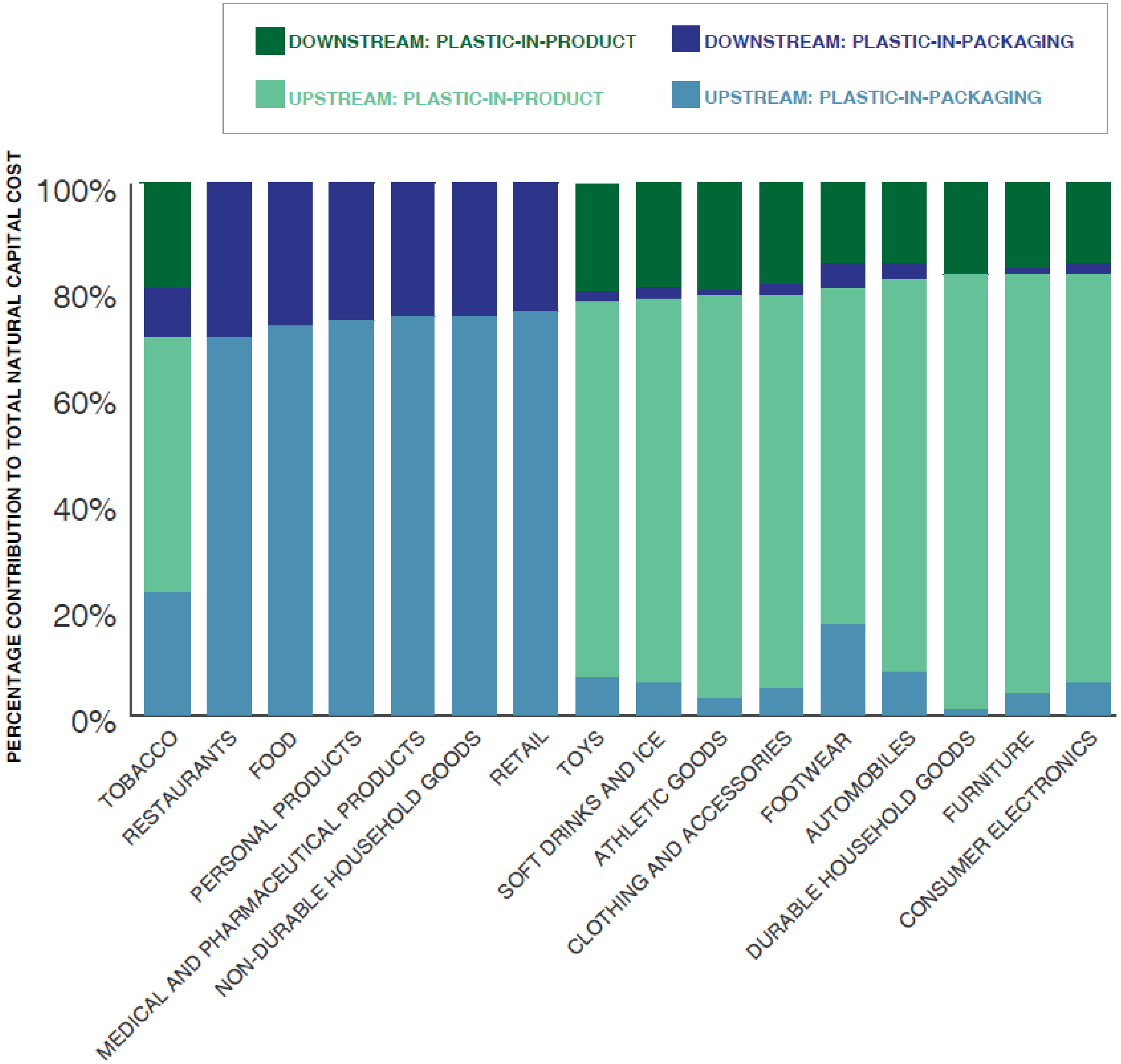
TABLE 3: TOTAL NATURAL CAPITAL COST ($) AND NATURAL CAPITAL INTENSITY

SECTOR	TOTAL NATURAL CAPITAL COST ($M)	TOTAL NATURAL CAPITAL COST ($M) PER SERVICE YEAR
Food	17,700	8,900
Non-durable household goods	7,500	7,100
Soft drinks	9,000	4,500
Retail	5,800	2,900
Footwear	4,200	2,700
Tobacco	900	2,200
Personal products	2,100	1,000
Clothing and accessories	4,200	1,500
Furniture	6,600	1000
Durable household goods	4,700	800
Toys	3,300	700
Consumer electronics	1,400	600
Restaurants	1,100	500
Automobiles	6,900	500
Athletic goods	1,100	200
Medical and pharmaceutical products	400	200

TABLE 2: PLASTIC INTENSITY PER SECTOR (TONNES PER $1m REVENUE)

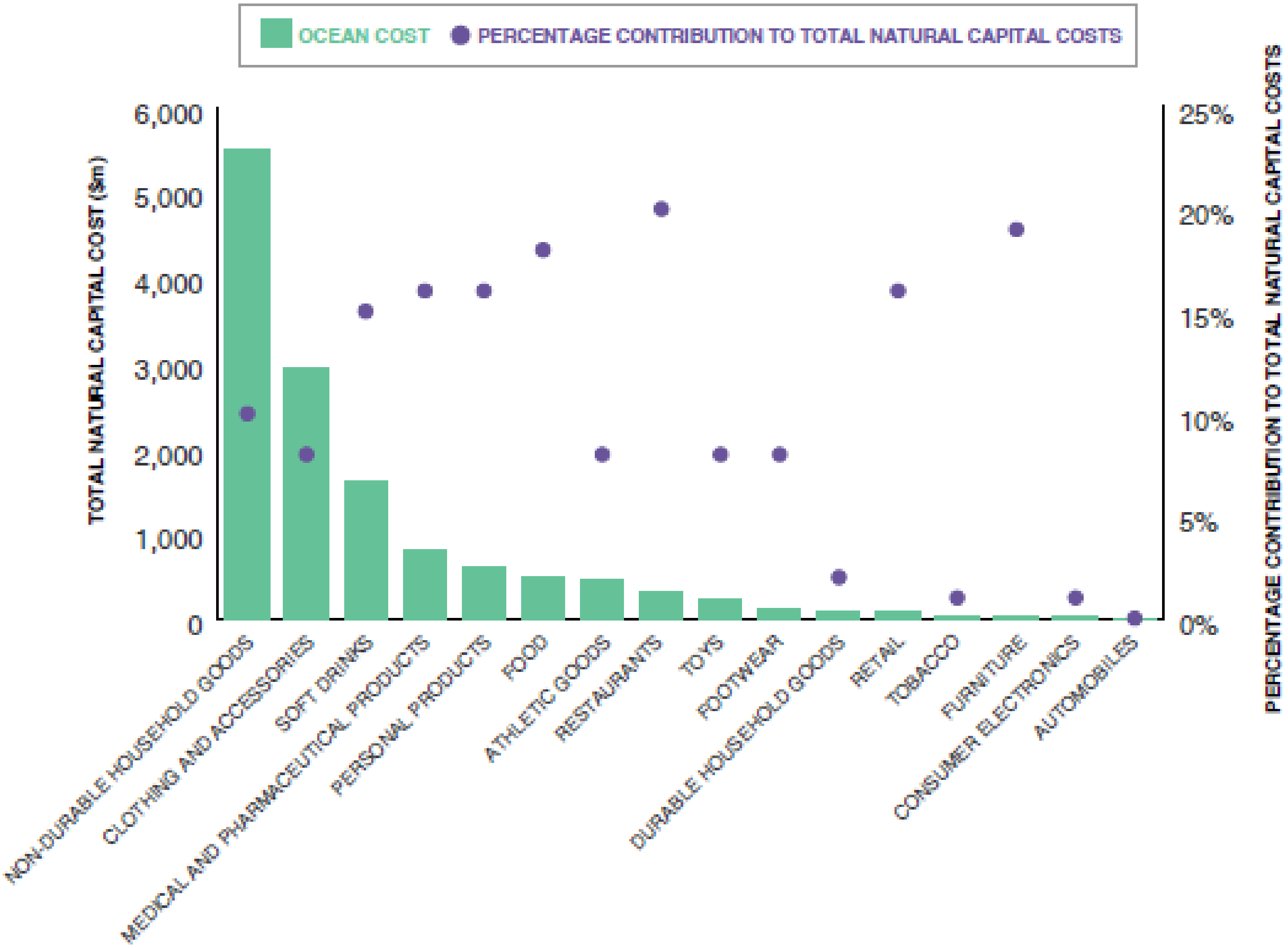
SECTOR	PLASTIC-IN-PACKAGING	PLASTIC-IN-PRODUCT	PLASTIC-IN-SUPPLY-CHAIN	TOTAL
Toys	2.9	37.5	7.6	48.0
Soft drinks	14.9	-	19.7	34.6
Furniture	0.8	15.2	10.9	26.9
Durable household goods	1.6	16.2	7.2	25.0
Footwear	3.6	13.8	6.8	24.2
Athletic goods	0.8	16.7	4.0	21.5
Personal products	5.9	not estimated	10.0	15.9
Non-durable household goods	1.0	9.7	3.8	14.4
Automobiles	0.0	4.5	5.3	9.9
Food	3.2	-	6.3	9.5
Consumer electronics	0.4	4.7	3.6	8.7
Clothing and accessories	0.2	3.3	4.7	8.2
Medical and pharmaceutical products	3.1	-	3.5	6.6
Restaurants	1.2	-	3.2	4.4
Tobacco	0.3	0.7	2.5	3.5
Retail	0.5	-	1.5	2.1

FIGURE 10: UPSTREAM AND DOWNSTREAM IMPACT DISTRIBUTION



Trucost calculations derived from, but not limited to, World Bank [7]; PlasticsEurope [8]; Eurostat [9], and the US EPA [10] datasets (full set of references and methodology available in appendices 3 and 4 of this report)

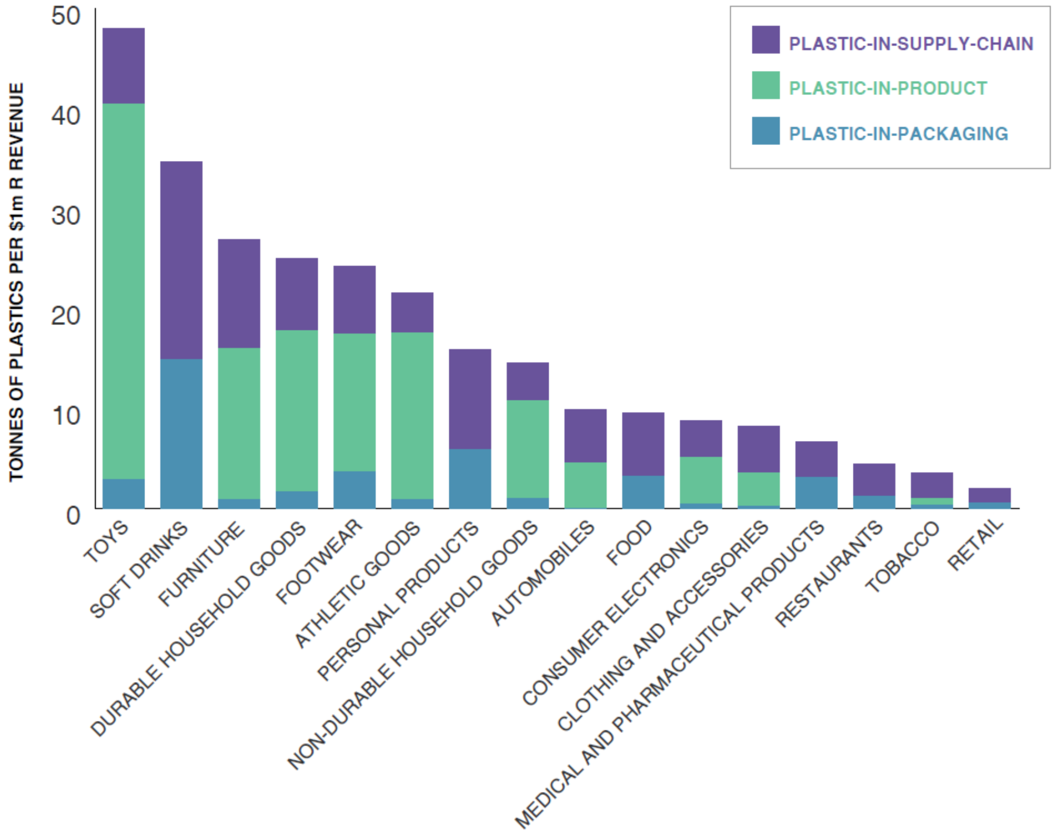
FIGURE 13: TOTAL NATURAL CAPITAL COST OF PLASTIC IN MARINE ECOSYSTEMS ($)



Total natural capital costs correspond approximately to over 80 million tonnes of plastic.Trucost calculations derived from, but not limited to, World Bank [7]; PlasticsEurope [8]; Eurostat [9], and the US EPA [10] datasets (full set of references and methodology available in appendices 3 and 4 of this report)

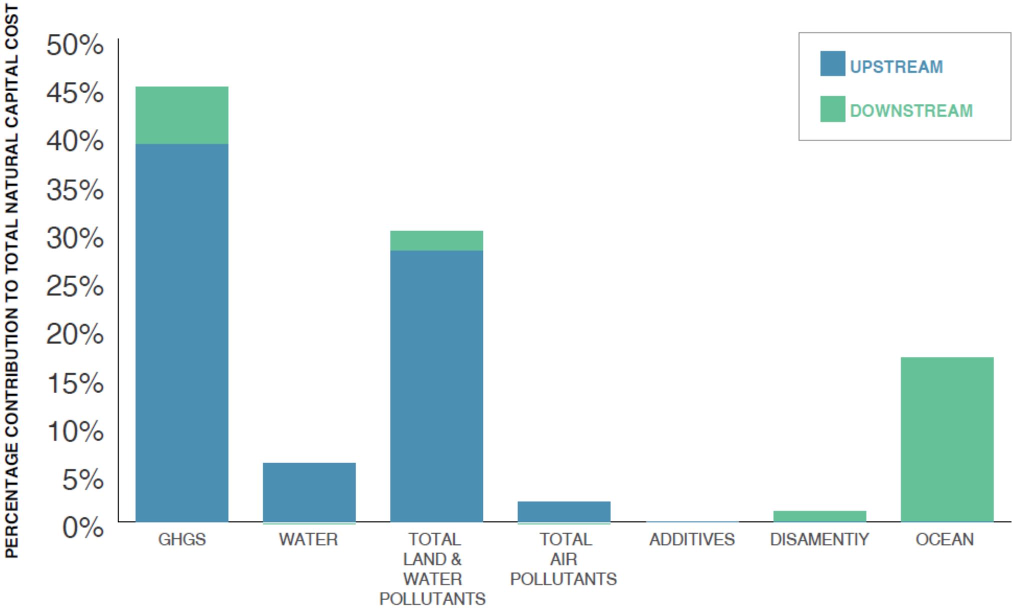
Sectors with the highest supply-chain-plastic intensity in relation to the total plastic intensity are the retail (75%), restaurants (72%), tobacco (70%) and food (66%) sectors – meaning that companies operating in these sectors may need to pay attention to plastic used in their supply chains. The retail and restaurant sectors are located further down the supply chain compared to others. Their low direct intensity is because it only includes packaging added to the product in the shop, such as carrier bags. This explains the low intensity of the sector's direct operations and proportionately larger plastic-in-supply-chain intensity. The retail, restaurants, tobacco and food sectors are also significant users of agricultural commodities in their supply chain, which has been recognized as a plastic intensive sector. As highlighted by Plastics Europe, agriculture contributed 4.2% to the overall plastic demand in Europe in 2012.[1]

FIGURE 7: PLASTIC INTENSITY PER SECTOR (TONNES PER $1M REVENUE)



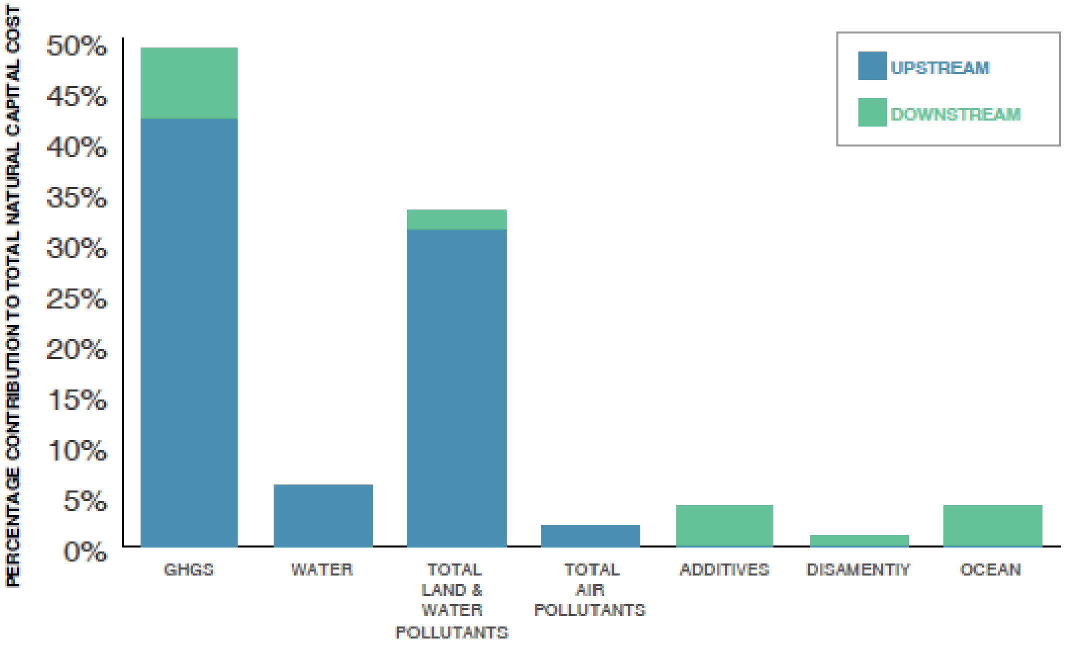
Trucost calculations based on input-output modelling techniques (full methodology available in appendix 3 of this report)

FIGURE 11: PLASTIC-IN-PACKAGING NATURAL CAPITAL COSTS COMPARED



Trucost calculations derived from, but not limited to, World Bank [7]; PlasticsEurope [8]; Eurostat [9], and the US EPA [10] datasets (full set of references and methodology available in appendices 3 and 4 of this report)

FIGURE 12: PLASTIC-IN-PRODUCT NATURAL CAPITAL COSTS COMPARED



Trucost calculations derived from, but not limited to, World Bank [7]; PlasticsEurope [8]; Eurostat [9], and the US EPA [10] datasets (full set of references and methodology available in appendices 3 and 4 of this report)

Main players in the bioplastic sector

- Albis Plastic GmbH (D, www.albis.com)
- Agrana (A, www.agrana.at)
- Amynova Polymers GmbH (D, www.amynova.com)
- Arichemie GmbH (D, www.arichemie.com)
- Arkema SA (F, www.arkema.com/en/)
- BASF SE (D, www.basf.com/en.html)
- Bayer MaterialScience AG (D, www.bayermaterialscience.de)
- BioAmber (CA, www.bio-amber.com/)
- Bio-On srl (I, www.bio-on.itwww.minerv.it)
- Biomater Ltda.(BR, www.biomater.com.br)
- Biomer (D, www.biomer.de)
- BIOP Biopolymer Technologies AG (D, www.biop.eu)
- Biotec Biologische Naturverpackungen GmbH & Co. KG (D, www.biotec.de)
- BioTec Environmental (USA, www.bio-tec.com)
- Borregaard (N, www.borregaard.com)
- Braskem (BR, www.braskem.com.br/)
- Cardia Bioplastics (AU, www.cardiabioplastics.com)
- Cereplast (USA, www.cereplast.com)
- Cargill Inc. (USA, www.cargill.com/)
- Clarifoil (UK, www.clarifoil.com)
- DaniMer Scientific, LLC (USA, www.danimer.com)
- Dow Chemical (D, www.plastics.dow.com)
- Dow Wolff Cellulosics (D, www.dowwolff.com)
- DuPont (USA, www.dupont.com/Plastics)
- Eastman Chemical GmbH (D, www.eastman.com)
- Fkur Kunststoff GmbH (D, www.fkur.com)
- Futerro (B, www.futerro.com/)
- Gehr GmbH (D, www.gehr.de)
- Genomatica (USA, www.genomatica.com/)
- Goodfellow Cambridge Ltd. (UK, www.goodfellow.com)
- HallStar (USA, www.hallstar.com)
- Horn & Bauer GmbH & Co. KG (D, www.horn-bauer.de)
- Huhtamaki Deutschland GmbH & Co. KG (D, www.huhtamaki.com)
- Innovia Films Ltd. (UK, www.innoviafilms.com/)
- Ire Chemical Ltd. (K, www.irechem.co.kr)
- Jinhui Zhaolong High Tech (CN, www.ecoworld.jinhuigroup.com)
- Kaneka Corp. (JP, www.kaneka.co.jp/kaneka-e/)
- Kareline Oy Ltd (FIN, www.kareline.fi)
- Kingfa (CN, www.kingfa.net/)
- Koninklijke DSM N.V. (NL, www.dsm.com/corporate/home.html)
- Lanxess AG (D, lanxess.com/en/corporate/home/)
- Limagrain Cereales Ingredients (F, www.lci.limagrain.com/)
- Masterbatch Winter Herstellungs und Vertriebs GmbH (D, www.masterbatch-winter.de/)
- Mazzucchelli 1849 SPA (I, www.mazzucchelli1849.it)
- Meredian Inc. (USA, www.meredianinc.com/)
- Metabolix Inc. (USA, www.metabolix.com/)
- Mitsubishi Chemical USA Inc (USA, www.mitsubishichemical.com)
- Mitsui Chemical Europe GmbH (D, www.mitsuichem.com)
- NAPAC Schweiz AG (CH, www.napac.ch)
- Natureplast (F, www.natureplast.eu)
- NatureWorks LLC (USA, www.natureworksllc.com/)
- Novamont SpA (I, www.novamont.com)
- Novomer (USA, www.novomer.com/)
- Ofotec Folien GmbH (D, www.ofotec-folien.de)
- Perstorp AB (S, www.perstorpcaprolactones.com)
- Peter Holland BV (NL, www.peterholland.nl)
- Plantic Technologies Ltd (AU, www.plantic.com.au)
- Polymer Chemie GmbH (D, www.polymer-chemie.de)
- Polyone Corp. (USA, www.polyone.com/en-us/Pages/default.aspx)
- Procter & Gamble (D, www.pg.com)
- Purac (NL, www.purac.com)
- Radici Plastic GmbH & Co. KG (D, www.radiciplastics.de)
- Rhein Chemie Rheinau GmbH (Lanxess Group, D, www.rheinchemie.com/)
- Rodenburg Biopolymers B.V. (NL, www.biopolymers.nl)
- Shanghai Disoxidation Macromolecule Materials Co., Ltd (CN, www.dmmsh.com)
- Showa Denko (JP, www.shp.co.jp)
- So.F.teR. Spa (I, www.softergroup.com/)
- Solvay SA (B, www.solvay.com/)
- Sukano AG (CH, www.sukano.com)
- SwissGel AG (CH, www.swissgel.ch)
- Tate & Lyle PLC (UK, www.tateandlyle.com/Pages/default.aspx)
- Telles (USA, www.mirelplastics.com)
- Tecnaro GmbH (D, www.tecnaro.de)
- Tianan Enmat (CN, www.tianan-enmat.com)
- Thantawan Industry PLC (BioFoammat Division, T, www.biofoammat.com)
- Toray Industries Inc. (JP, www.toray.com/)
- Toyobo (JP, www.toyobo-global.com/),
- Unitika Ltd. (JP, www.unitika.co.jp/terramac)
- Vegeplast S.A.S. (F, www.vegeplast.com/uk)
- Ventura AG Kunststofftechnik (CH, www.ventura-ag.ch)
- Wentus Kunststoff GmbH (D, www.wentus.de)
- W.W. Textile Co. Ltd. (CN, www.2wtextile.com)

Table 2.

Naturally biosynthesized biopolymers and their chemically modified derivatives.

Chemical classification	**Polymer**	**Properties and applications**	**Ref.**
Polyisoprene (terpenes)	Natural rubber	Waterproof items, engineering applications in antiseismic buildings or offshore installations for oil extraction,	[38]
Polysaccharides	Starch based polymers; thermoplastic starch -TS	Component of biodegradable and biocompostable plastics.	[39]
	Cellulose based polymers: Cellulose acetate Cellulose nitrate Acetylphthalylcellulose	Applications in textiles, cigarette filters, surface coatings, ink additive, photographic negatives, motion picture film, microfilm, microfiche, membranes for water desalinization. Chemical modifications decrease the biodegradation of cellulose although derivatives are attacked by both aerobic and anaerobic microorganisms.	[40, 41]
	Chitosan	Obtained from deacetylation of chitin. Biodegradable, non-toxic, bacteriostatic and fungistatic with wide application in the pharmaceutical field. Industrially applied as carrier for enzyme immobilization.	[42]
Polyphenols	Lignin based polymers	Because of its aromatic and phenolic components, lignin itself is used in polymer blends as compatibilizer, plasticizer, hydrophobizing agent or as a natural antioxidant in active packaging. Employed in flame retardants, optical modifiers, stabilizers. Lignin-based polyols, reacted with diisocyanates, are used as drop-in replacement of fossil polyols in polyurethane foams for their flame-retardant properties.	[43-45]

Table 3. Bio-engineered polymers bio-synthesized by microorganisms and plants.

Chemical classification	Polymer	Properties and applications	Ref.
Polyesters	Polyhydroxy alkanoates - PHAs: poly(3-hydroxybutyrate) and poly(3-hydroxybutyrate -*co*-3-hydroxy-hexanoate)	Biodegradable and compostable. Chain length determines the flexibility of PHA: short chain butyrate provides rigidity, with T_m of 160°C, whereas longer carbon chains confers T_m below 145°C. Sensitivity to thermal degradation makes its processing challenging. Fields of application include agriculture, packaging, biomedical sector.	[46]
	Polymalic acid	Linear anionic polyester composed of L-malic acid monomers, with potential applications as drug carriers, surgical suture, and biodegradable plastics.	[47]
Polyamides	Poly-γ-glutamic acid - PGA	Water-soluble, anionic, biodegradable, edible. Applications in foods, pharmaceuticals, healthcare, cosmetics, water treatment, curable adhesives.	[48, 49]

✹ Not biodegradable

Table 4. Bio-based synthetic polymers obtained from bio-based monomers or a combination of bio- and fossil-based monomers.

Polymer		Properties and applications	
Poly(trimethylene terephthalate) - PTT*	✹	Polyester. Same properties as fossil-based PTT. Scarcely biodegradable. Semi crystalline thermoplastic, easily molded or thermoformed and spun into fibres. Good tensile and flexural strength, excellent flow and surface finish. Used in textiles and engineering applications (automotive parts, mobile phone housings.	
Poly(ethylene terephthalate)-PET*	✹	Polyester. Same properties as the fossil-based PET. High-performance plastic used for engineering applications, fibres, films, bottles.	
Poly(1,4-butylene succinate) - PBS		Polyester. Biodegradable in soil and biocompostable. Its T_m of 115 °C and tensile strength of 30–35 MPa make PBS suitable for applications in packaging as an alternative to polyolefins.	[
Poly(ethylene succinate) - PES		Moderately biodegradable. Good oxygen barrier and elongation properties. Used for film applications.	
Poly(ethylene furanoate) - PEF	✹	Polyester. Durable, good oxygen barrier. T_m of 211 °C and T_g of 86 °C. Suitable for packaging, in the food and beverage industry.	[
Poly(trimethylene furanoate) - PTF	✹	Polyester. Not biodegradable. T_m of 172 °C, T_g of 57 °C, good oxygen barrier properties. Employed in light weighting packaging.	
Poly(butylene furanoate) - PBF		Polyester. T_m of 172 °C, T_g of 44 °C. Potential replacer of PET and PBT.	[
Poly(1,4-butylene adipate-*co*-1,4-butylene terephthalate) - PBAT		Polyester. Biodegradable. Used in blends with PLA and fibers due to low thermo-mechanical properties. Obtained from fossil feedstock or bio-tereftalic acid	
Unsaturated polyester resins - UPR	✹	Properties varies according the percentage of unsaturated diacid (e.g. itaconic acid) and the curing procedure. Applied in waterborne UV-curable coatings for wood and flooring industry.	
Poly(L-lactide) -PLLA		Polyester. Thermoplastic. Processable by extrusion, injection molding, blow molding. Degradable by hydrolysis rather than microbial attack. Industrially compostable. Crystallinity can be controlled by co-polymerization of selected ratios of L- to D-stereoisomers of lactic acid or lactide. Mechanical, thermal and barrier properties justify applications in food packaging. Used for medical applications and drug delivery because of its biocompatibility.	[
Polyamides containing four carbons - 4C PAs: 4; 4.6 and 4.10	✹	Not biodegradable. 4C PAs match properties of fossil-based PAs 6 and 6.6, such as thermal durability and mechanical strength, with a Tm above 250°C. All 4C PAs have higher dielectric strength and higher retention of tensile properties as compared to PA 6.6. PA 4.10 has low moisture uptake. Applications range from water management to cable coating, food contact products and automotive.	[
Polyamides with longer chains. PAs: 6.10; 10.10; 11 and 12	✹	Long chain carbon monomers confer flexibility to these polymers, which find application in fuel lines in cars, offshore pipelines, gas distribution piping systems, electronics, sports equipment, furniture and automobile components.	
Polyvinyl chloride – PVC*	✹	Not biodegradable and poorly chemically degradable. Same properties as fossil-based PVC. Used in construction profile applications, bottles and non-food packaging. When made more flexible by the addition of plasticizers, it is used in electrical cable insulation, imitation leather, flooring and as rubber replacer.	[
Polyethylene – PE* (from bio-ethanol)	✹	Polyolefin. Same properties of fossil-based PE. Not biodegradable, recyclable through dedicated infrastructures. Thermoplastic. High Density PE (more crystalline) finds applications in construction sector. Low Density Polyethylene is used in packaging. Ultrahigh Molecular Weight Polyethylene has applications in medical devices and bulletproof vests.	
Polypropylene - PP*	✹	Polyolefin. Same properties as the fossil PP. Not biodegradable, non-polar. Partially crystalline thermoplastic with low density. Used in a large variety of applications and in packaging.	
Poly(methyl methacrylate)–PMMA*	✹	Not biodegradable. Lightweight material used as glass replacement in automotive for shatterproof and UV resistant properties.	[
Ethylene propylene diene monomer – EPDM (synthetic rubber)	✹	Not biodegradable. Good resistance to hot water and polar solvents but poorly resistant to aromatic and aliphatic hydrocarbons. Chlorine-free synthetic rubber used for technical clothing, elastomers with shock absorption. Ozone and thermal resistant. Electrical insulation properties. Used also for automotive applications.	
Polyurethanes -PURs		Produced through the reaction of a diisocyanate with a polyol. Microbial degradation depends on the chemical structure. Often blended with polyethers to increase flexibility or extensibility. Used as de-halogenated flame retardant foams, paints, powder coatings, medical devices (blood contacting applications). Biodegradable polyurethane scaffolds have been used in tissue regeneration.	[
Poly(furfuryl alcohol) - PFA	✹	Not biodegradable. Synthesized from bio-based furfuryl alcohol (FA) deriving from sugars. Used in the fabrication of nanoporous carbons structures for molecular sieve adsorbents, membranes and as a component for electrochemical and electronic devices.	
Acrylonitrile butadiene styrene - ABS	✹	Obtained from butadiene rubber dispersed in a matrix of styrene-acrylonitrile copolymer. Not biodegradable. Thermoplastic, used to make light, rigid, moulded products such as pipes, automotive parts. Used also for its flame retardant properties.	[
Polyacrylic superabsorbent polymers - PA-SA		Its high swelling capacity is tuneable by controlling the degree of crosslinking. Its biodegradation in soil can be improved under conditions that maximize solubilisation. Find applications in personal disposable hygiene products, such diapers and sanitary napkins.	[
Poly(itaconic acid) - PIA	✹	Due to the presence of a vinyl moiety, itaconic acid is structurally similar to acrylic and methacrylic acid, providing a suitable bio-based alternative to poly(meth)acrylates via radical polymerization to yield poly(itaconic acid) (PIA). Applications include fibers, coatings, adhesives, thickeners, binders. As co-monomer itaconic acid gives glass-ionomer dental cement.	

Table 5. New bio-based monomers and chemical strategies for expanding the engineering applications of bio-based polymers.

Building blocks and monomers	Structural evolution	Targeted performance	Ref.
Aromatic lignin derivatives	2,4-, 2,5-, and 2,6-pyridinedicarboxylic acid obtained by re-routing the lignin degradation pathways of *Rhodococcus jostii* RHA1	New bio-based aromatic / apliphatic polyesters obtainable via enzymatic polycondensation with Mn around 14000 Da	[101,, 102]
Ricinoleic acid	Confers biocidal activity to poly(hexamethylene succinate) modified at the chain ends. Imidazolium salt was anchored on C=C bond of ricinoleic acid to improve biocidal activity.	Antimicrobial activity.	[103]
Terpenes	Pinene transformed into pinocarvone, which contains a reactive exo-methylene group exploitable for radical polymerization	High molecular weight plytherpenes with excellent thermal properties (Tg > 160 C). Polymerization of pinene would require low temperatures (-70°C) unviable for industrial purposes.	[104]
Amides	Branched chains of polyamide 4.	Moderation of rigidity. Increased MW. Improved mechanical properties without decreasing T_m.	[105]
	{(4,40-diyl-α-truxillic acid dimethyl ester) 4,40-diacetamido-α-truxillamide}, obtained from bio-based 4-aminophenylalanine, UV coupled with cinnamic acid	High-performance biobased polyamide with T_g >250 °C	[106]
Isosorbide	Confers rigidity	Increasing thermos and mechanical properties while preserving the biodegradability.	[107]
Modified lactides for improved PLAs	Phenyl-substituted lactide synthesized by cyclic dimerization of bio-based mandelic acid to obtain mandelide (meso stereoisomer), which is polymerized *via* ring opening polymerization (ROP)	Overcoming low T_g and low transparency of PLA by inserting hydrophobic bulky side chains. Polymandelide has T_g> 100°C and is less biodegradable than PLLA.	[108]
	Norbornene-substituted lactide obtained by brominating the bio-based lactide. Elimination and Diels Alder reactions yield the norbornene lactide used in ring-opening metathesis polymerization.	Polymers have T_g> 190°C and narrow polydispersity.	[109]
Cyclic diols	Bio-based 1,4-cyclohexanedimethanol (CHDM) is obtainable from renewable terephthalic acid.	As co-monomer in polyesters of 2,5-furandicarboxylic acid-increases rigidity, confers mechanical properties comparable to PET and improves barrier properties. Its polycondensation requires temperature around 240-280 °C due to the high boiling point but such temperatures promote its decomposition. Mild enzymatic polycondensation overcomes this drawback.	[110]
Phenols	4-hydroxycinnamic acid (4HCA)	The aromatic ring confers liquid crystalline properties to polyesters. The bio-based liquid crystal polymers exhibits remarkable properties (strength = 63 MPa, Young's modulus = 16 GPa, maximum softening temperature = 169 °C [	[111, 112]
Succinic acid derivatives	Polyesters obtained by co-polymerization of succinic acid with furan dicarboxylic acid (FDCA)	Modifying soft properties of linear poly(succinates)s by introducing aromatic furan moieties. The corresponding polyesters poly(butylene succinate-co-butylene furandicarboxylate)s (PBSF) have Mw from 39 000 to 89 000 g/mol and display excellent thermal stability. Their structure and properties can be tuned ranging from crystalline polymers with good tensile modulus (360-1800 MPa) and strength (20–35 MPa) to nearly amorphous polymer of low Tg and high elongation (~600%), so that they may find applications in thermoplastics as well as elastomers or impact modifiers.	[113]
Furan derivatives	Nucleophilic aromatic substitution polymerization of 2,5- bis(4-fluorobenzoyl)furan (BFBF) derived from FDCA and potassium salts of aromatic bisphenols	Bio-based poly(thioether ketone) (PEEK) with Tm >300 °C, comparable to fossil-based PEEK	[114]
Itaconic acid derivatives	Functionalization of the unsaturated double bond of dimethylitaconate by thia-Michael addition reaction using 1-octanethiol.	Improve the stability of itaconic derivative monomers toward common conditions of polycondensation (high temperatures and metal-based catalysts)	[115]
	Post-polymerization modification of vinyl group of poly(itaconate) *via* Michael addition of primary amines.	Amine-triggered degradable materials; oligoesters displaying amine functionalities for biomolecules anchoring or covalent crosslinking.	[116, 117]]
	Michael additions of proline, cysteine and other S-containing nucleophiles to vinyl moiety of poly(itaconate)s.	Addition of pendants to polyester chain. Modifying polymer properties.	[118–119]
	Michael addition of C-nucleophiles (acetylacetone and dimethyl malonate) to vinyl moiety of poly(itaconate)s.		[120]

[1] Haskell VC, Owens DK. A Structural Comparison of Films Regenerated from Cellulose Acetate and Viscose. Text Res J 1960;30:993–8. https://doi.org/10.1177/004051756003001213.

[2] Martino L, Basilissi L, Farina H, Ortenzi MA, Zini E, Di Silvestro G, et al. Bio-based polyamide 11: Synthesis, rheology and solid-state properties of star structures. Eur Polym J 2014;59:69–77. https://doi.org/10.1016/j.eurpolymj.2014.07.012.

[3] Casein; its preparation and technical utilisation : Scherer, Robert : Free Download, Borrow, and Streaming : Internet Archive n.d. https://archive.org/details/caseinitsprepara00scherich/page/n6/mode/2up (accessed April 28, 2020).

[4] Skoczinski P., Chinthapalli R., Carus M, Baltus W., de Guzman D., Käb H., Raschka A., Ravenstijn J.. Bio-based Building Blocks and Polymers – Global Capacities and Trends 2017-2022.
http://bio-based.eu/download/?did=208823&file=0 (accessed April 28, 2020).

[5] Plastics-the Facts 2019. An analysis of European plastics production, demand and waste data.
https://www.plasticseurope.org/application/files/9715/7129/9584/FINAL_web_version_Plastics_the_facts2019_14102019.pdf (accessed April 28, 2020).

[6] Raynaud J. Valuing Plastics: The Business Case for Measuring, Managing and Disclosing Plastic Use in the Consumer Goods Industry. United Nations Environment Programme (UNEP), 2014.

[7] Jambeck JR, Geyer R, Wilcox C, Siegler TR, Perryman M, Andrady A, et al. Plastic waste inputs from land into the ocean. Science 2015;347:768–71. https://doi.org/10.1126/science.1260352.

[8] Smith M, Love DC, Rochman CM, Neff RA. Microplastics in Seafood and the Implications for Human Health. Curr Environ Heal Reports 2018;5:375–86. https://doi.org/10.1007/s40572-018-0206-z.

[9] https://www.unenvironment.org/news-and-stories/story/plastic-planet-how-tiny-plastic-particles-are-polluting-our-soil (website visited on April 28th 2020)

[10] https://ecostandard.org/news_events/tackling-microplastic-pollution-at-its-source-the-example-of-pellets/ (accessed April 28, 2020)

[11] http://www3.weforum.org/docs/WEF_The_New_Plastics_Economy.pdf (accessed April 28, 2020)

[12] https://www.trucost.com/publication/scaling-sustainable-plastics/ (website visited on April 28th 2020)

[13] Natural Capital Accounting: Overview and Progress in the European Union. Publications Office of the European Union, 2019. doi:10. 2779/819449

[14] Caparrós A, Oviedo JL, Álvarez A, Campos P. Simulated exchange values and ecosystem accounting: Theory and application to free access recreation. Ecol Econ 2017;139:140–9. https://doi.org/10.1016/j.ecolecon.2017.04.011.

[15] Toxics Release Inventory (TRI) Program. US EPA.
https://www.epa.gov/toxics-release-inventory-tri-program (accessed April 28, 2020).

[16] Eco-profiles : PlasticsEurope.
https://www.plasticseurope.org/en/resources/eco-profiles (accessed April 28, 2020).

[17] Wegener Sleeswijk A, Heijungs R. GLOBOX: A spatially differentiated global fate, intake and effect model for toxicity assessment in LCA. Sci Total Environ 2010;408:2817–32. https://doi.org/10.1016/j.scitotenv.2010.02.044.

[18] Van Zelm R, Huijbregts MAJ, Van De Meent D. USES-LCA 2.0-A global nested multi-media fate, exposure, and effects model. Int J Life Cycle Assess 2009;14:282–4. https://doi.org/10.1007/s11367-009-0066-8.

[19] Environment Directorate Joint Meeting Of The Chemicals Committee And The Working Party On Chemicals, Pesticides And Biotechnology. Series on Emission Scenario Documents No. 38 JT03447969, 2019.