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Agenda item 5 (b) of the provisional agenda
Consideration of the baseline report on plastic waste and the stocktaking of initiatives on plastic waste

Baseline report on plastic waste

Note by the Secretariat

As is mentioned in the scenario note for the first meeting of the Plastic Waste Partnership working group (UNEP/CHW/PWPWG.1/INF/1), the annex to the present note sets out a baseline report on plastic waste. The present note, including its annex, has not been formally edited.

Plastic Waste

Background Report

Draft

Report requested by the Secretariat of the Basel Convention for the first meeting of the Basel Convention Plastic Waste Partnership. Report produced by GRID-Arendal

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The word plastic derives from the Greek πλαστικός (plastikos) meaning "capable of being shaped or molded" and, in turn, from πλαστός (plastos) meaning "molded".

CONTENTS

ABBREVIATIONS

ABS	Acrylonitrile butadiene styrene
ACC	American Chemistry Council
ASTM	American Society for Testing and Materials
BC	Basel Convention
BPA	Bisphenol A
CEN	European Committee for Standardization
CH4	Methane
CO	Carbon monoxide
CO2	Carbon dioxide
ECCC	Environment and Climate Change Canada
EN/ISO	English - International Organization for Standardization
EPA	Environmental Protection Agency
EPI	Environmental Packaging International
EPS	Expanded Polystyrene
EPS	Extended Producer Responsibility
EU	European Union
GB/T	Chinese Standard
H2O	Water
HDPE	High-density Polyethylene
IGO	Intergovernmental Organization
ISWA	International Solid Waste Association
LDPE	Low-density Polyethylene
LLDPE	Linear low-density polyethylene
MRF	Materials recovery facility
MSW	Municipal solid waste
NFTA	North American Free Trade Agreement
NIR	Near-infrared
PA	Polyamide
PBAT	Polybutylene adipate terephthalate
PBS(A)	Polybutylene succinate
PC	Polycarbonates
PCL	Polycaprolactone
PE	Polyethylene
PEF	Polyethylene furanoate
PET	Polyethylene tetrapthalate
PEX or XLPE	Cross-linked polyethylene
PFAS	Polyfluoroalkyl substances
PHA	Polyhydroxyalkanoate
PLA	Poly-lactic acid
PP	Polypropylene
PP&A	Polyphthalamide
PS	Polystyrene
PTT	Polytrimethylene terephthalate
PUR	Polyurethane
PVA	Polyvinyl alcohol
PVC	Polyvinyl chloride
SS-ISO	Swedish Standard – International Organization for Standardization
UAE	United Arab Emirates
UHMWPE	Ultra-high-molecular-weight polyethylene
UK	United Kingdom
US	United States
USA	United States of America
WRAP	Waste and Resources Action Programme

UNITS OF MEASUREMENT

kg	Kilogram
kt	Kilotonnes
Mha	Million hectares
mm	Millimeter
Mt	Million tonnes
µm	Micrometre
MPa	Megapascal pressure unit
tonnes	1000 kg

I. Introduction

a. Purpose of the report

Plastic offers extraordinary properties and its use dominates the modern life. However, these benefits carry challenges with mismanaged plastic waste that turns into important plastic pollution. As a consequence, plastic is found everywhere in nearby surrounding areas to the most remote places in the Arctic. With plastic production steadily rising and predicted to double within the next 20 years, action to stop plastic pollution is needed now more than ever.

In response to this a Partnership on Plastic Waste was established by the Conference of Parties to the Basel Convention. The main aim of the Partnership is "*to improve and promote the environmentally sound management of plastic waste at the global, regional and national levels and prevent and minimize their generation so as to, among other things, reduce significantly and in the long-term eliminate the discharge of plastic waste and microplastics into the environment, in particular the marine environment*".

This report is developed to support the Partnership and its working groups at their first face-to-face meeting by providing a brief baseline study on plastic value chain and the fate of plastics.

This report specifically intends to provide with the latest data on plastic waste related issues and point out to the gaps to establish a baseline level.

This assessment is built on the latest literature review. In addition, the report took into account information provided by members of the Plastic Waste Partnership working group in response to a call for information by the Secretariat in preparation for its first meeting. The data were used in cases where it was compatible with the reporting items.

b. Scope and limitations

The report follows the plastic value chain starting from the production of plastics until it enters into the recovery or recycling phase or is disposed of into the environment in organized or unorganized manner. The report points out to the amounts of plastics ending up in the terrestrial and marine environment each year.

Today, there are about 30 different plastic polymers which are mixed with thousands of additives to achieve desirable quality performance to be used in various applications by different sectors such as packaging, building and construction, textile, and electrical/electronic. This report is an informative summary of the main types of plastic among which are polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polyvinyl chloride (PVC) and Polystyrene (PS) accounting for more than half of the global plastic use.

The report covers plastics originated from fossil fuel and as well non-fossil fuel feedstock plastics or so-called bio-plastics made out of renewable biological resources.

The report briefly discusses the global plastic waste management which is shared between recycling, recovery and final disposal.

Plastic recycling refers to the process of recovering scrap plastic and reprocessing it into useful products. It also includes waste management steps such as collection, sorting, grading, classification, cleaning, baling, trading, storing and eventually transporting to final recycling. The report analyses different plastic recycling methods and their application in different countries. It discusses main challenges with the present plastic recycling.

This report also addresses the issues linked to the fate of mismanaged plastic. Plastic leakage into the environment concerns macro-plastics and micro-plastics both covered in the analysis.

Plastic waste management on land falls under responsibilities of national and local authorities, however plastic recycling is increasingly a global issue. The plastic waste trade is excluded from this report due limited time to uptake additional data collection.

The main limitations of the analysis lay is limited data availability across the regions. A follow up studies should benefit from more focused analysis if requested by the PWP Working Group.

c. Sources of information

Information provided by members and published by governments and IGOs, as well as the scientific community were collated and presented in an informative manner. Detailed data gathering, and modeling of waste flows were not foreseen under this assignment.

II. OVERVIEW OF THE PLASTICS VALUE CHAIN

The plastics value chain includes the full range of activities, which are required to bring a plastic product through the different phases of extracting raw materials, production, distribution to consumers, and final disposal after use (Figure 1). While plastic moves from one stage of the chain to the next, it is expected to gain value. Yet the value chain of plastic remains archetypically linear with less than 20%[1] of plastics re-entering the value chain and huge amounts of plastics ending up in terrestrial and marine environments each year, exposing both the environment and marine life to existential problems. In addition, the diverse nature of the different plastic products, different uses and treatment routes at the end of its lifecycle increases the complexity of the value chain as well as the number of diverse stakeholders including chemical and plastic manufacturers, consumer goods companies, retailers, waste management companies, and recycling technology companies.

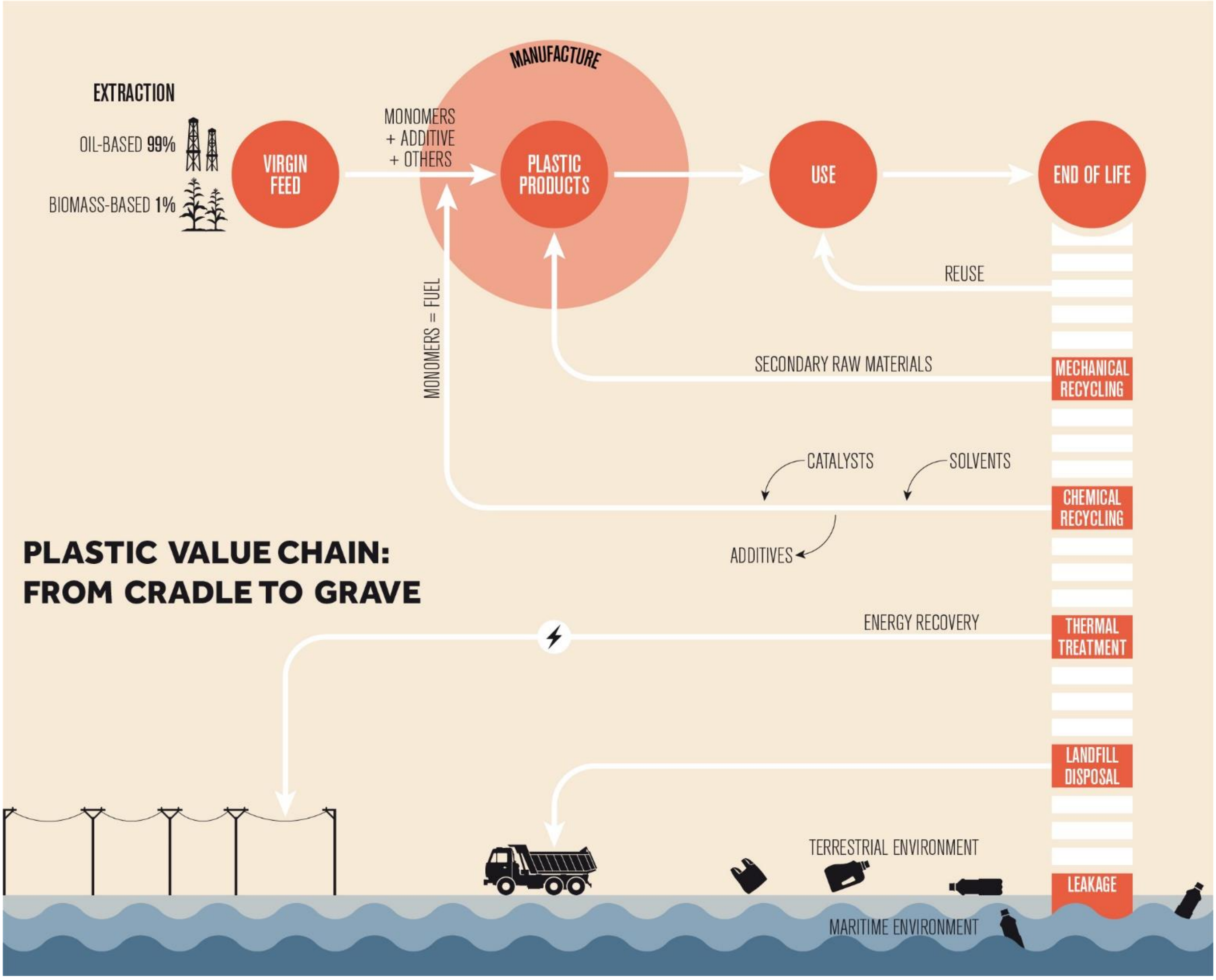


Figure 1: Plastic Value Chain: from cradle to grave

III. WHAT IS PLASTIC?

Derived from the Greek words, πλαστικός, plastikos (meaning fit for moulding) and πλαστός, plastos (moulded), the term plastic refers to a material's ductility during manufacture[2]. This property allows the material to be cast or shaped into numerous forms for a variety of uses. According to the American Chemistry Council, plastic is, "a type of synthetic or man-made polymer; similar in many ways to natural resins found in trees and other plants"[3].

Today, there are more than 30 types of primary plastics, which combined with a number of different additives gives thousands of plastic materials[4]. 97-99%[5] of these plastics derives from fossil fuel feedstock while the remaining 1-3% comes from bio(plant) based plastics[6].

a. Fossil fuel-based plastics

There are two main categories of fossil fuel-based plastics, also known as conventional plastics: thermoplasts and thermosets:

- *Thermoplasts,* are polymers which soften when heated and solidifies upon cooling, allowing them to be remolded and recycled without affecting the material's physical properties in a negative way. Such polymers are polyethylene (PE), polypropylene (PP), polystyrene (PS) and polyvinyl chloride (PVC). Most of everyday consumer plastics are thermoplasts.
- *Thermosets* are plastics that are set into a mold once and cannot be re-softened or molded again. Examples of thermosetting plastics include phenolic resins, amino resins, polyester resins, and polyurethanes. Thermosets are ideal for high-heat applications such as electronics and appliances[2].

The most commonly used plastics around the globe representing 69 %[1][i] of the global plastic are polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polyethylene terephthalate (PET) and Polystyrene (PS) (Table1).

- Polyethylene (PE) is a thermoplastic, and elastic polymer. It is used in plastic containers, bottles, bags and plastic toys. In addition, it can be used for the production of plastic cement. The types of PE, depending on its density and branching, are: ranched Versions (Low-density polyethylene (LDPE) and Linear low-density polyethylene (LLDPE)), Linear Versions (High-density polyethylene (HDPE) and Ultra-high-molecular-weight polyethylene (UHMWPE) and Cross-linked polyethylene (PEX or XLPE). The most common of them are LDPE and HDPE[7].
- Polypropylene (PP) is a thermoplastic polymer used in products such as food containers, packaging, toys, furniture and textiles. It is characterized by being durable, transparent and resistant to chemical stress and it can sometimes contain dyes, antioxidants and, in some cases, flame retardants.
- Polyvinyl chloride (PVC) is one of the most commonly used thermoplastic polymers in the world. It is used in construction, packaging for food, textile and medical material. Some of its common uses are cosmetic containers, electrical conduit, plumbing pipes and fittings, blister packs, wall cladding, roof sheeting, bottles, garden hose, shoe soles, cable sheathing, blood bags and tubing, watch straps, and commercial cling wrap.
- Polyethylene terephthalate (PET) is a clear, strong, and lightweight plastic, commonly found in products such as beverage bottles, perishable food containers, mouthwash, jars

[i] In 2015

and plastic bottles. It hardly weighs anything, and it is impact resistant. PET is used in textiles and packaging and its materials may contain dyes and color pigments.

- Polystyrene (PS) is used for lining refrigerators, packaging, construction, and in medical industry as trays.

Table 1: Main types of plastics, common uses, properties

Symbol	Resin ID Code[8].	Common uses	Properties[9]
Polyethylene terephthalate (PETE)	#01	plastic bottles (water, soft drinks etc.)	Clear, strong and lightweight
Polyethylene (PE)	#02 for HDPE & #04 for LDPE	packaging (plastic bags, plastic films, geomembranes, containers including bottles, etc.).	High ductility and impact strength as well as low friction
Most common types of PE: High-density polyethylene (HDPE)	#02	milk containers, shampoo bottles, cleaning agents, etc.	Stiff and hardwearing; hard to breakdown in sunlight
Most common types of PE: Low-density polyethylene (LDPE)	#04	plastic bags, plastic food wrapping (e.g. fruits, vegetables)	Lightweight, low-cost, versatile; fails under mechanical and thermal stress
Polyvinyl chloride (PVC)	#03	plastic piping, vinyl flooring, cabling insulation, roof sheeting	Can be rigid or soft via plasticizers; used in construction, healthcare, electronics
Polypropylene (PP)	#05	Bottle lids, food tubs, furniture, automobile parts etc.	Tough and resistant; effective barrier against water and chemicals
Polystyrene (PS)	#06	plastic cutlery, food take away containers	Lightweight; structurally weak; easily dispersed
Acrylonitrile butadiene styrene (ABS)	#07	Computers, televisions, kitchen appliances, and toys such as Lego, Keyboard keycaps, musical instruments, automobile components [10],[11][12], 3d printing	Lightweight; resistance and toughness, chemical resistance performance
Polycarbonates (PC)	#07	Electronic applications, Products in construction industry (e.g. for domelights, flat or curved glazing, and sound walls) Compact Discs, DVDs, and Blu-ray Discs, automotive, aircraft, railway, and security components	Strong, tough materials, and some grades are optically transparent
Other plastics (e.g. acrylic, polyactic fibres etc.)	#07	Fiberglass, water cooler bottles	Diverse in nature with various properties

b. Bio-based plastics

Bio-plastics or bio-based plastics are plastics made from renewable biological resources - most often vegetable – which are either biodegradable or not. Bio-plastics encompass a large number of materials that are either bio-sourced or biodegradable or both. Bioplastics could be either biodegradable or non-biodegradable and often, there is a confusion in the differences among the terms, bioplastics, biodegradable plastics, compostable plastics and oxo-degradable plastics.

- *Bio-plastics or bio-based plastics* are plastics made from renewable biological resources - most often vegetable – which are either biodegradable or not. Bioplastics encompass a large number of materials that are either bio-sourced or biodegradable or both[13].
- *A biodegradable material* is one that can be decomposed under the action of microorganisms (bacteria, fungi, algae, earthworms, etc.) and give water (H2O), carbon dioxide (CO_2) and/or methane (CH_4), and by-products (residues, new biomass). This

definition is used in at least five applicable standards (ISO, CEN), including the European and French standard NF EN 13432 as to requirements for "packaging recoverable by composting and biodegradation".

- *Compostable plastics* biodegrade in a composting environment yielding water (H_2O), carbon dioxide (CO_2) and biomass and can be plant-based but they can be petroleum-based as well. BASF® Ecoflex® is a good example of a compostable polymer, which is partly petroleum- based but is compostable at industrial compost facilities[14].
- 'Oxo-degradable', 'oxydegradable' or 'oxo-biodegradable' plastics are conventional plastics such as polyethylene (PE) which include an additive to help them break down fragments and should not be confused with the biodegradable plastics[13]. Oxo-degradable plastic bags is one example, which break down in smaller pieces that could lead to microplastics leakage in the environment.

Bio-based and biodegradable plastics can be divided into three categories[13]:

(a) biodegradable bio-based plastics: poly-lactic acid (PLA), polyhydroxyalkanoate (PHAs), starch blends, bio polymers-polybutylene succinate (PBS(A))

(b) biodegradable fossil-based plastics: Polybutylene adipate terephthalate (PBAT), Polybutylene succinate (PBS(A)), Polycaprolactone (PCL), Polyvinyl alcohol (PVA)

(c) non-biodegradable bio-based plastics: bio-PET, bio-PE, Polyethylene furanoate (PEF), bio-PP, bio-PAs, Polytrimethylene terephthalate (PTT)

c. Additives

The polymers used in plastics are rarely used in pure form. In almost all commercial plastics, they are "compounded" with monomeric ingredients to improve their processing and end-use performance[15].

Typical plastic additives include:

(a) Stabilizers: Polymer stabilizers prolong the lifetime of the polymer by suppressing degradation that results from UV-light, oxidation, and other phenomena. Typical stabilizers thus absorb UV light or function as antioxidants.

(b) Fillers: Many plastics contain fillers, to improve performance or reduce production costs. Typically, fillers are mica, talc, kaolin, clay, calcium carbonate, barium sulphate etc. Most fillers are relatively inert and inexpensive materials make the product cheaper by weight. Some fillers are more chemically active and are called reinforcing agents.

(c) Plasticizers: Plasticizers are, by mass, often the most abundant additives. These oily but nonvolatile compounds are blended into plastics to improve rheology, as many organic polymers are otherwise too rigid for particular applications. Short, medium and long chain-chlorinated paraffins are typical plasticizers.

(d) Colorants: Colorants (pigments, soluble azocolorants, etc.) are another common additive, though their weight contribution is small.

(e) Other functional additives: antistatic agents, flame-retardants, antioxidants, lubricants, slip agents, curing agents, foaming agents, etc.

Some information is already available, and much more is needed, on toxicity and safe handling of these additives during processing and manufacture of plastics products.

d. Plastic recyclability

Nearly all types of plastic can be recycled. However, the extent to which they are recycled depends upon technical, economic and logistic factors.

The structure of the polymers not only defines the type of applications but also is very crucial for plastics' recyclability at the end of their use phase. Some polymers fail and break down under mechanical or thermal stress; this affects their ability to be recycled. In addition, many plastic products may consist of more than one polymer type (known as laminated plastics), which makes them more difficult to recycle. For example, bottle (PET) and a food tray (PP) cannot be recycled together as they have different melting temperatures. Problematic plastics also include black plastic food trays, which are not detected easily from sorting machines because the black carbon makes them invisible.

In reality, the technology exists to recycle most kinds of plastic if carefully sorted out by type. Even thermosets can be chemically processed. However, owners of recycling units may choose not to recycle all types of plastic waste largely because the economics of doing so make it impractical. The recycled products of plastic waste must compete in price and quality with alternative materials. The end market of a recycled plastic product must be stable and viable in order to cover the cost of collection and sorting of the plastic waste. The type of plastic materials recycled in each country depends on the waste collection schemes and waste management infrastructure in place, the existence of stable and viable end market for recycled plastic products, as well as competitiveness of recycled plastics over virgin material.

How many times can plastic be recycled?

According to Ritchie (2018)[16], the majority of recyclable plastics are only recycled once or twice prior to their final disposal, while Geyer et al. (2017)[17] estimated that of the plastic recycled to date, only 10 percent has been recycled more than once.

IV. PLASTIC PRODUCTION

a. Production of conventional plastics

The post–World War II economic expansion, also known as the golden age of capitalism and the postwar economic boom, was a broad period of worldwide economic expansion[18]. The United States, Soviet Union, Western European and East Asian countries experienced unusually high and sustained growth. At the same time technological advances in the petrochemical industry lead to an increase of plastic products that were cheap and flexible.

The sectors that were favored the most during the year of economic expansion were the packaging sector and the building and construction sector. At the end of the war great cities such as Warsaw, Kiev, Tokyo and Berlin were piles of rubble and ash. In Germany, it was estimated, that 70% of housing had gone and, in the Soviet Union, 1,700 towns and 70,000 villages lost. Reconstruction was massive the years following[19].

Moreover, plastics revolutionized medicine with life-saving devices, made space travel possible, lightened cars and jets saving fuel and pollution as well as saved lives with helmets, incubators, and equipment for clean drinking water[20].

Under this framework the global production of fossil fuel-based plastic has experienced a dramatic increase, from 2 million tonnes in 1950 to more than 454[ii] million tonnes in 2018[21]. Between 1950 and 1980 9.7 billion tonnes of plastics have been produced, 50% of them after 2005 (Figure 2). Projections based on present growth rates indicate that plastic production should double by 2025 and more than triple by 2050[22].

From the total plastics that have been introduced in the market since1950 polypropylene (PP) and Low-density polyethylene (LDPE) account for 17% and 16% respectively of the global plastic production followed by High density polyethylene (HDPE) (13%) and polyphthalamide (PP&A) (13%). In addition, additives used in plastic products manufacturing have also a significant share in global plastic production (6%) (Figure 3).

China is the top plastic producer followed by Europe and NFTA[iii] (Figure 7). In fact, throughout Asia's evolution to global economic prominence, China found itself, manufacturing and exporting a vast amount of plastic products to eventually become the world's largest plastic producer. Today, Asia accounts for about 50% of the global plastics production, followed by EU (19%)[23]. China accounts for 30%[24].

Polypropylene (PP) is the most produced polymer since the 50s

[ii] 382 million tonnes plastic resins and fibers, and 25 million tonnes of additives

[iii] North American Free Trade Agreement countries: Canada, Mexico, and the United States

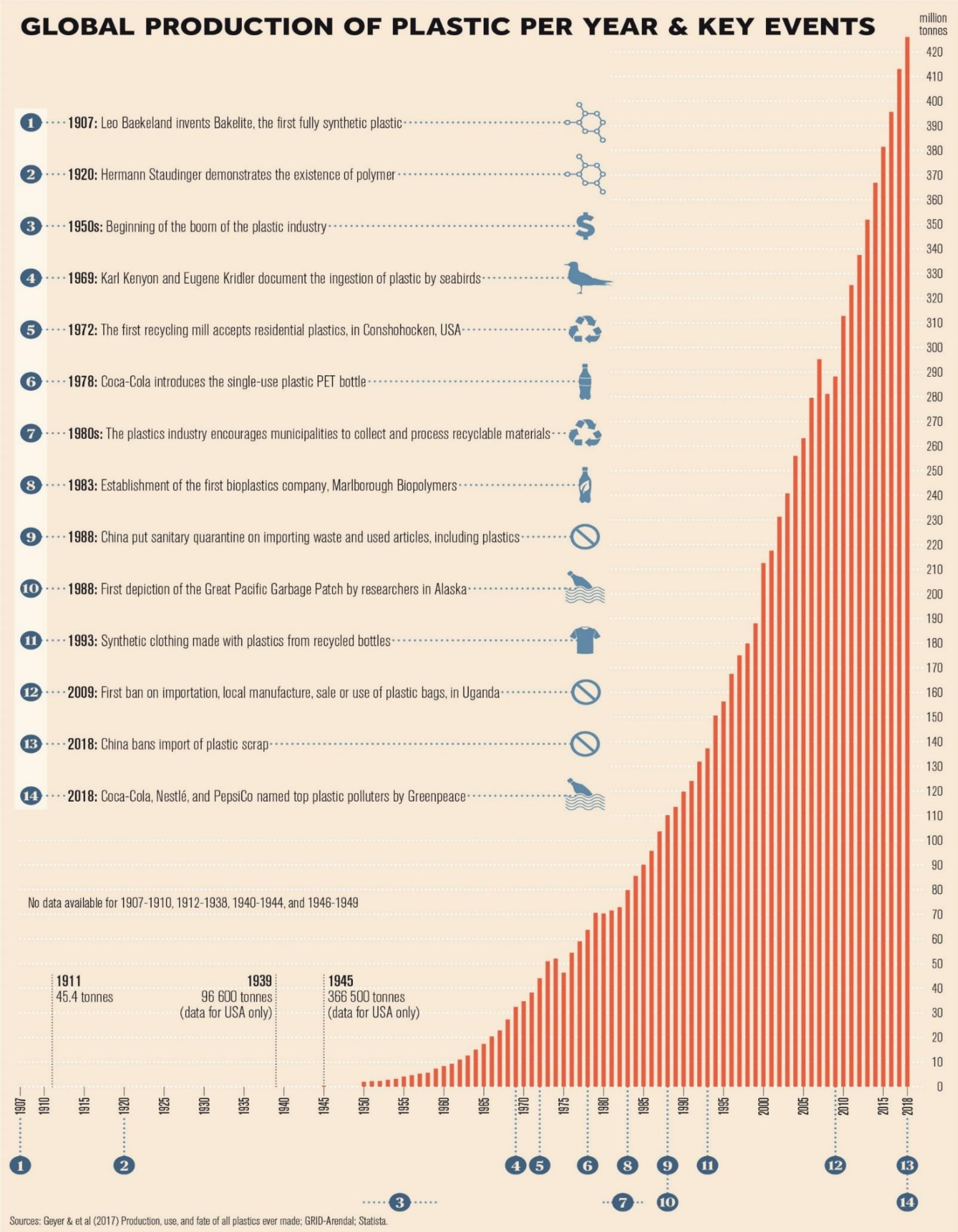


Figure 2: Global production of plastic per year & key events[1,2117]

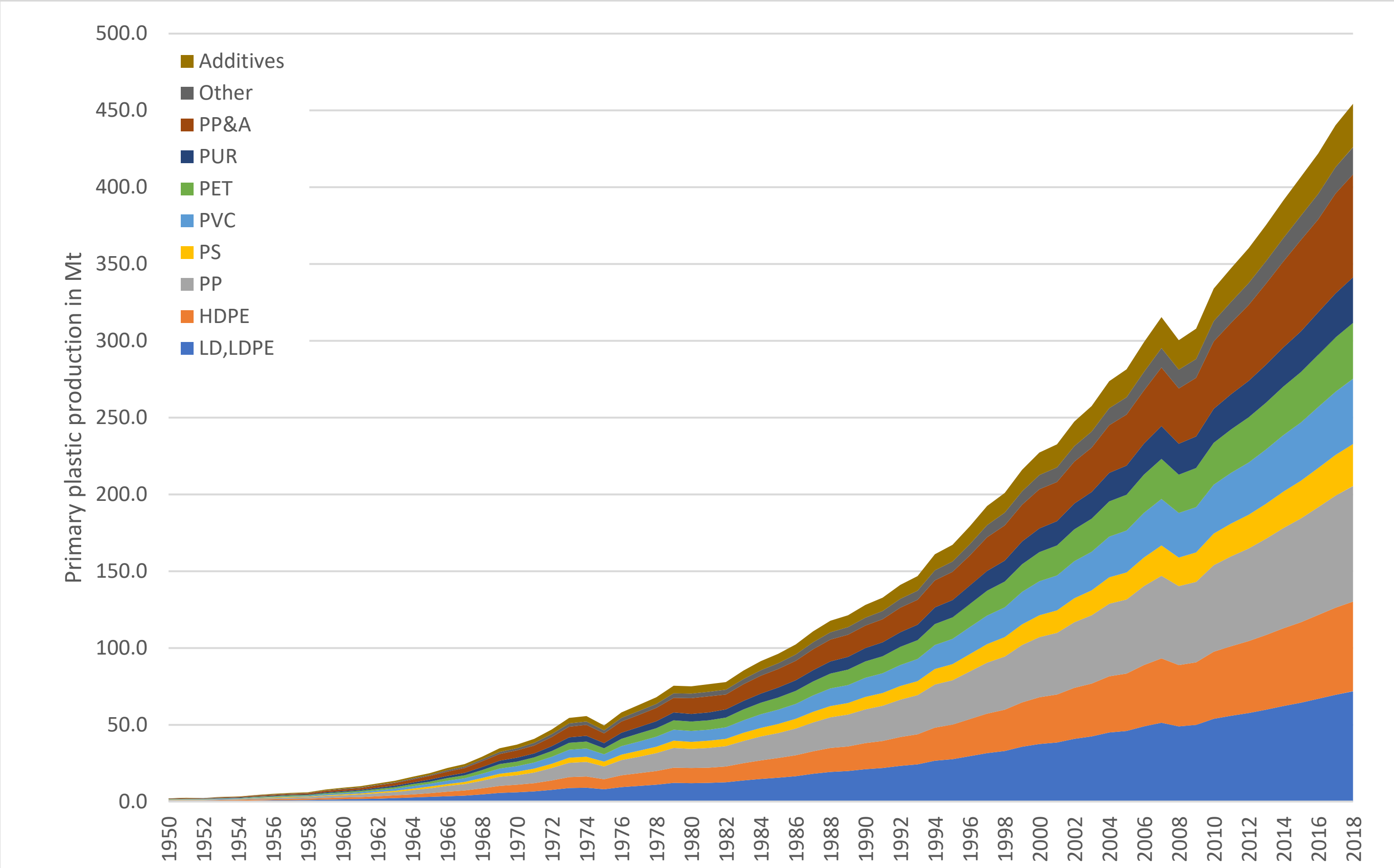


Figure 3: Global primary global plastics production (in million metric tonnes) according to polymer type between 1950-2018 (Geyer, 2020)[21]

b. Production of bio based plastics

In the late 1980s, several U.S. plastics companies began to market products that were "degradable"[25]. They were intended to last in the environment for less than the life span of normal plastics. Non-biodegradable biobased plastics have also been introduced in the market.

Global production of bioplastics (both biodegradable and non-biodegradable) has increased from 0.7 million tonnes in 2010 to 2.11 million tonnes in 2018[26] with Asia being the hub of bioplastics (Figure 4). In 2018 bioplastics accounted for only 0.6% of total plastic production, 57% of which are non-biodegradable.

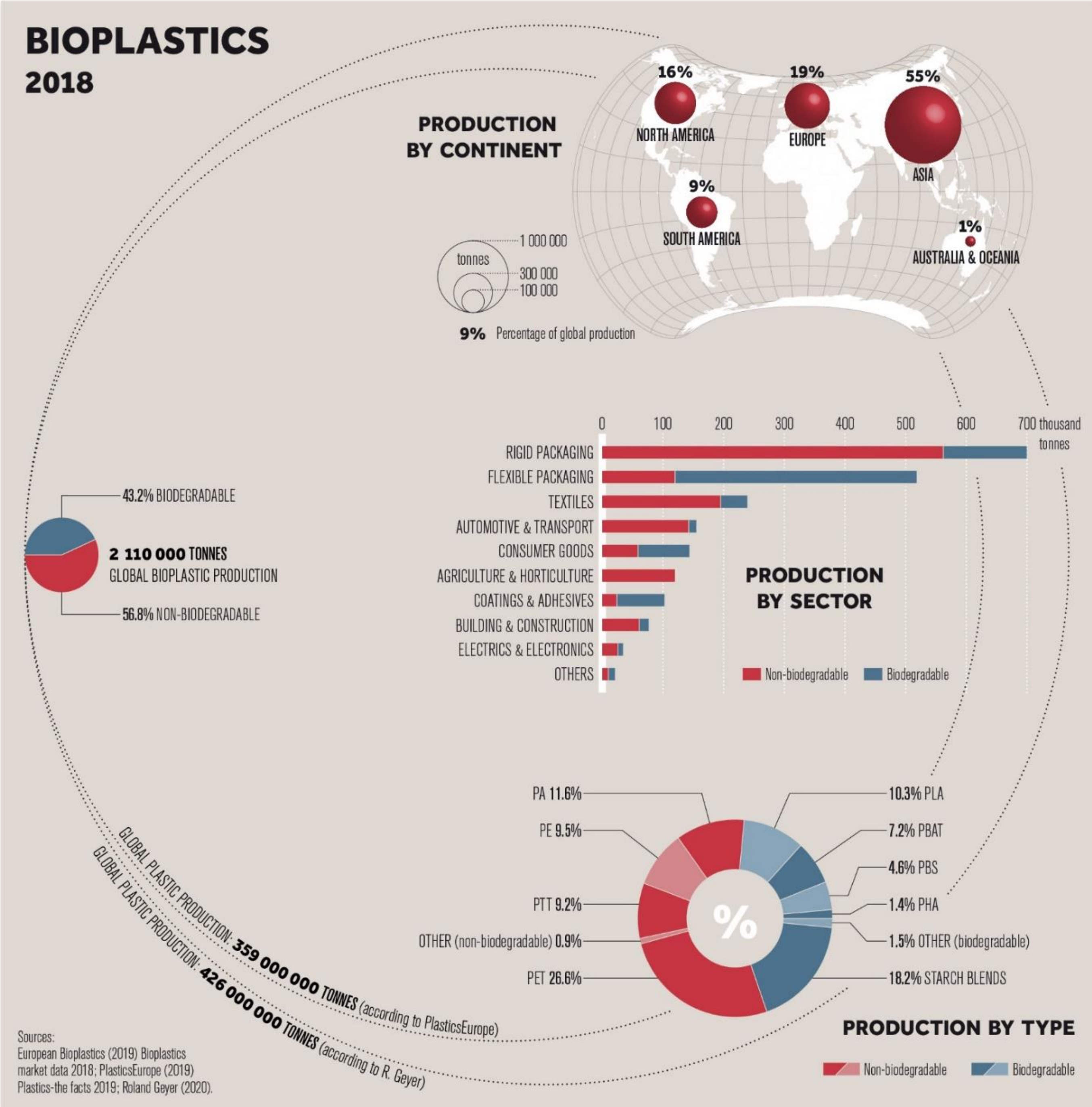


Figure 4 : Bioplastics production[21,24,26]

V. PLASTIC USE

a. Plastics in different sectors

Two sectors account for more than 50% of plastic manufacturing and use since the 50s: packaging and infrastructure (building & construction) (Figure 5). More specific, the total primary production of plastics consumed by each sector is: packaging (163 Mt), building and construction (73 Mt), textiles (67 Mt), consumer and institutional products (47 Mt), transportation (30 Mt), electrical/electronic (20 Mt) and industrial machinery (3Mt)[21].

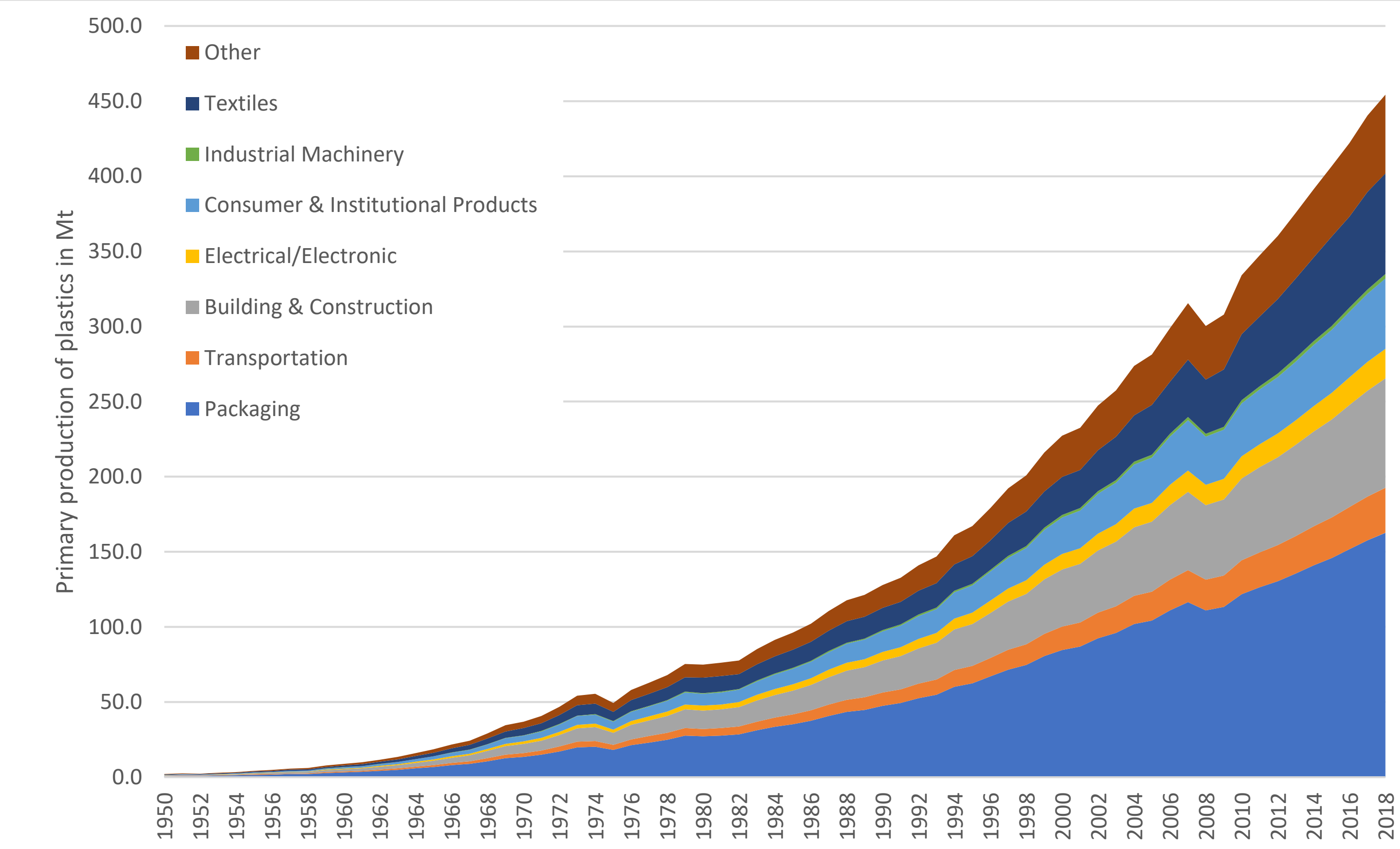


Figure 5: Global primary and global plastic production (in million metric tonnes) according to polymer type between 1950-2018 (Geyer, 2020)[21]

Packaging accounts for 36% of the global annual resin production

Although all sectors use a combination of various polymers, LDPE/LLDPE and PP accounted almost equally to 41% of the worldwide plastic applications between 2002-2014. 22% of LDPE/LLDPE and PP resins were applied in the packaging sector (Figure 6).

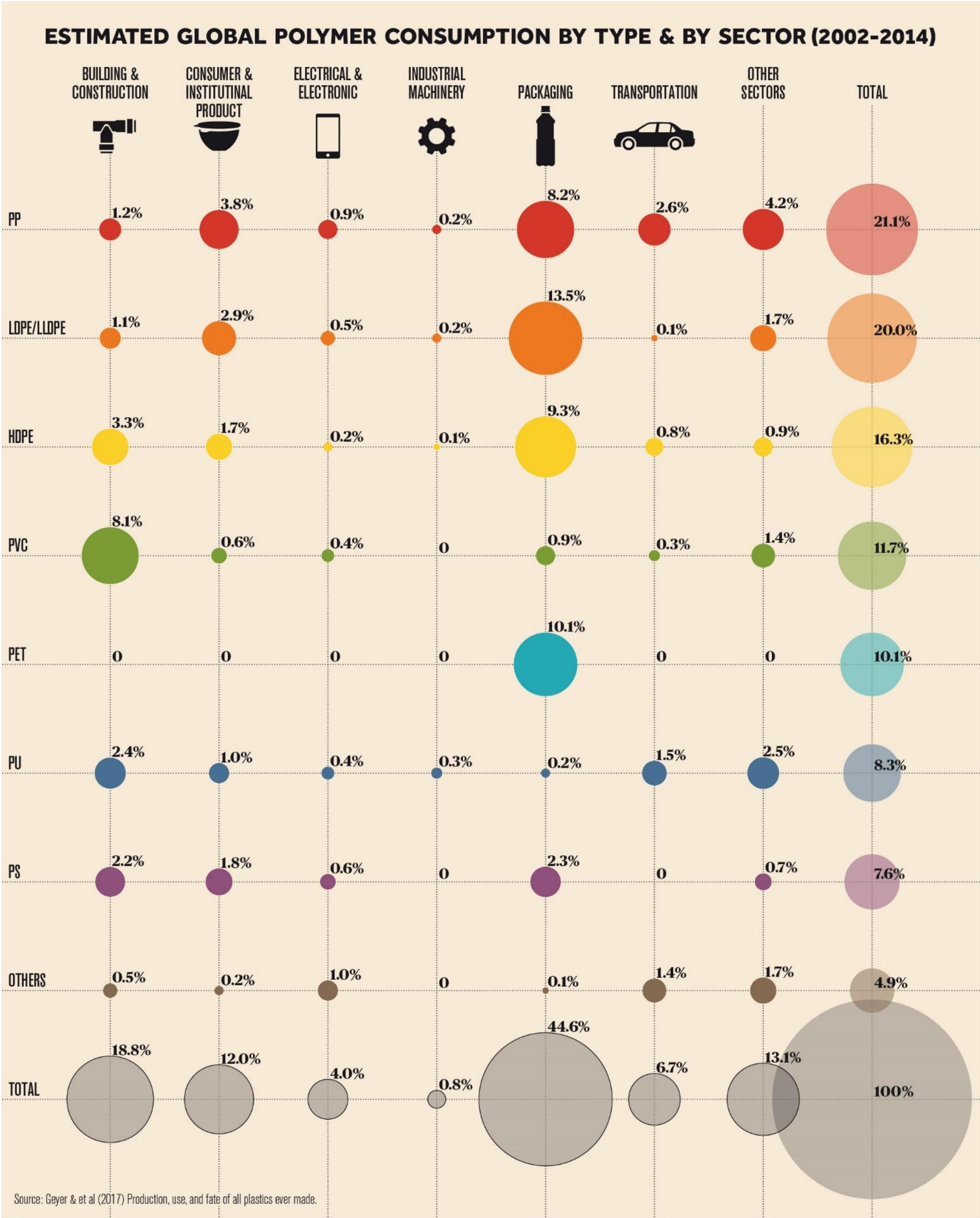


Figure 6: Global polymer consumption by type and sector between 2002 and 2014 [1,17]

Concerning bioplastics have been used mainly in applications in the packaging sector (Figure 4).

b. Plastics lifetime

Some plastic products have long life spans such as building and construction materials (35 years), industrial machinery (20 years), plastic products in the transportation sector (13 years) electrical/electronic plastic products (8 years) and textiles (5 years). However, the majority have a short life cycle lasting between one day (e.g. disposable plastic cups, plates, takeaway containers, plastic bags etc.) to three years (e.g. food and drink containers, cosmetics, agricultural film, etc.).

c. Plastic consumption by country

China is among the largest plastic products consumers accounting for 20% of the global plastic consumption and followed by Western Europe that accounts for 18% of the global plastic consumption and USA (Figure 7)[27]. However, in terms of plastic consumption per capita China is ranks much lower from other countries. On the contrary, Israel is one of the largest per capita consumers of plastic, however it has significant low plastic production rates comparing to other countries.

It seems that developing countries have become the world's production hub of plastic products that are consumed overseas. For instance, India has experienced a steadily increase in PET production in 2015-16, (1,458 kt of PET) comparing to the previous year (982 kt). Much of the PET plastic production (650kt) was exported in 2015-2016 from India to Bangladesh, the USA, Italy, Israel, Romania, Ukraine, the UAE etc. The export volumes have grown in the recent years, closely tracking the overall production levels in India. To a smaller extent, PET is imported to India (107 kt), mainly from Taiwan, China, Iran and Malaysia[28].

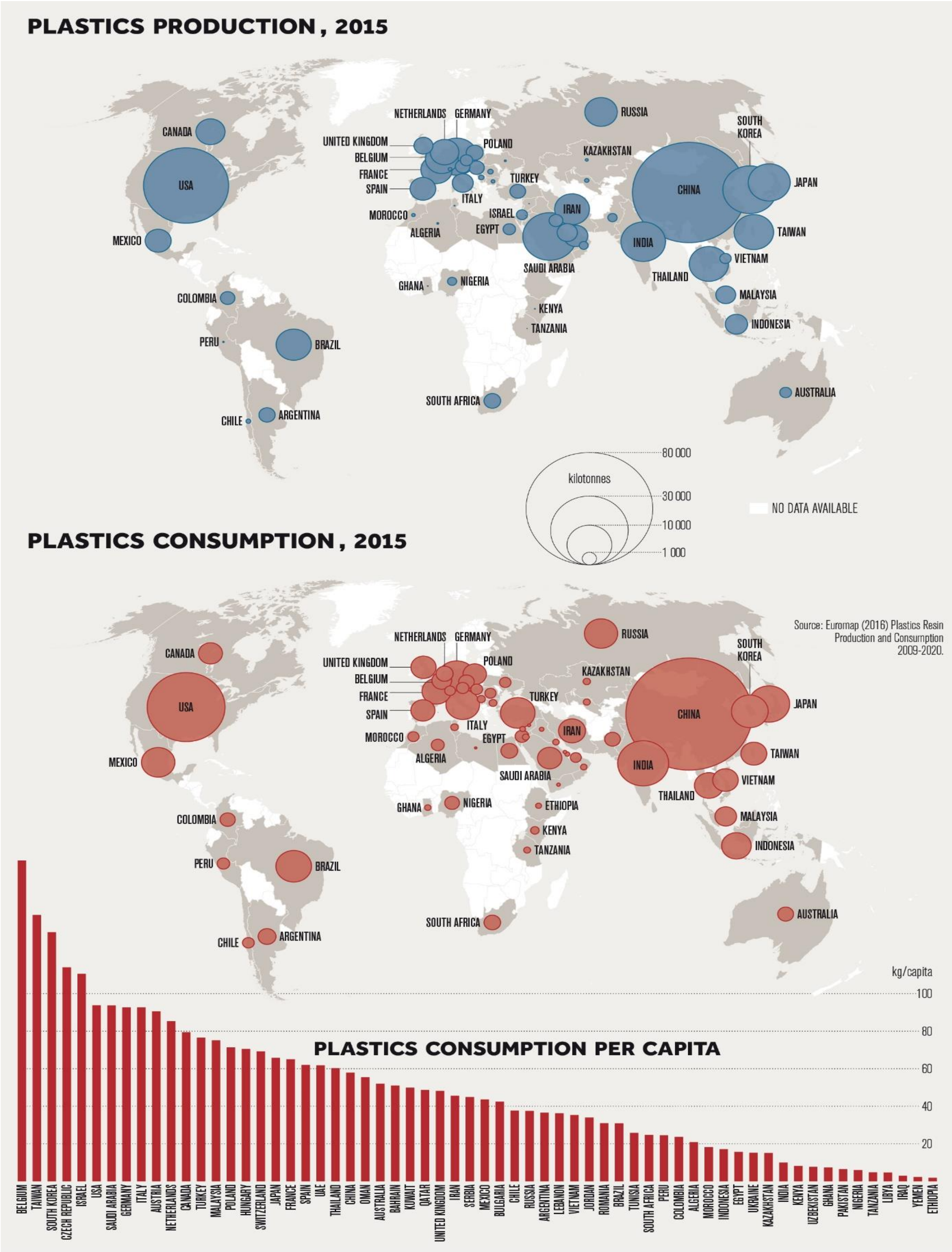


Figure 7: Plastic production and consumption by country [27]

VI. PLASTIC WASTE GENERATION

a. Global plastic waste in numbers

Modern life is flourished with plastic products and would be impossible without plastics. However, challenges lie ahead. The ever-increasing growth in the amount of plastics produced has led to a significant plastic waste generation that has outpaced society's ability to manage it effectively.

In general waste generation rates are influenced by economic development, the degree of industrialization, public habits, etc[29]. Such parameters are also taken into account in order to estimate plastic waste generation in different countries around the world. In this sense there have been different attempts on estimating plastic waste generation, providing different numbers:

Geyer, 2020 has estimated that around 343 million tonnes of plastic waste every is produced every year [21].

Work Bank[58] has estimated that in 2016, the world generated 242 million tonnes of plastic waste—12 percent of all municipal solid waste. This waste primarily originated from three regions—57 million tonnes from East Asia and the Pacific, 45 million tonnes from Europe and Central Asia, and 35 million tonnes from North America.

Lebreton et al[30], has reported that Asia is the largest contributor to global domestic plastic waste, representing 50% of global plastics production, with China alone generating around 29% of the worlds plastic. In 2015 Asia was the largest contributor to global domestic plastic waste, generating 82 million tonnes followed by Europe (31million tonnes) and Northern America (29 million tonnes), Latin America (including the Caribbean) and Africa each produced 19 million tonnes of plastic waste while Oceania generated about 0.9 million tonnes[30].

Jambeck et al.[44], have estimated plastic waste production but only for coastal areas in 2014 (Figure 8). The data are of the most referred around the world and are providing a baseline to make comparisons between countries. Based on these data US and China is of the top producer of plastic waste in the world, however in terms of annual plastic waste generation per capita China ranks much lower than US and many other countries around the world.

On country level based on existing literature and country responses to BC the following latest plastic waste generation data are available (Table 2).

Table 2: Plastic waste in different countries after 2015

Countries	Plastic waste (Mt)	Reference Year
China	61[16]	2016
US	34.5[31]	2015
Indonesia	9.6[32]	2018
Japan	8.9[iv][33]	2018
Canada	3.2[34]	2016
Australia	2.5[35]	2016
Sweden	1.6[36]	2016
UK	1.5[37]	2016
Israel	0.9[38]	2018
Switzerland	0.78[39]	2019*
Denmark	0.35[40]	2017
Zimbabwe	0.3[41]	2019

*2010 data. However, is reported that the numbers are still valid

[iv] 4.2 million tonnes domestic plastic waste and 4.6 million tonnes of industrial waste

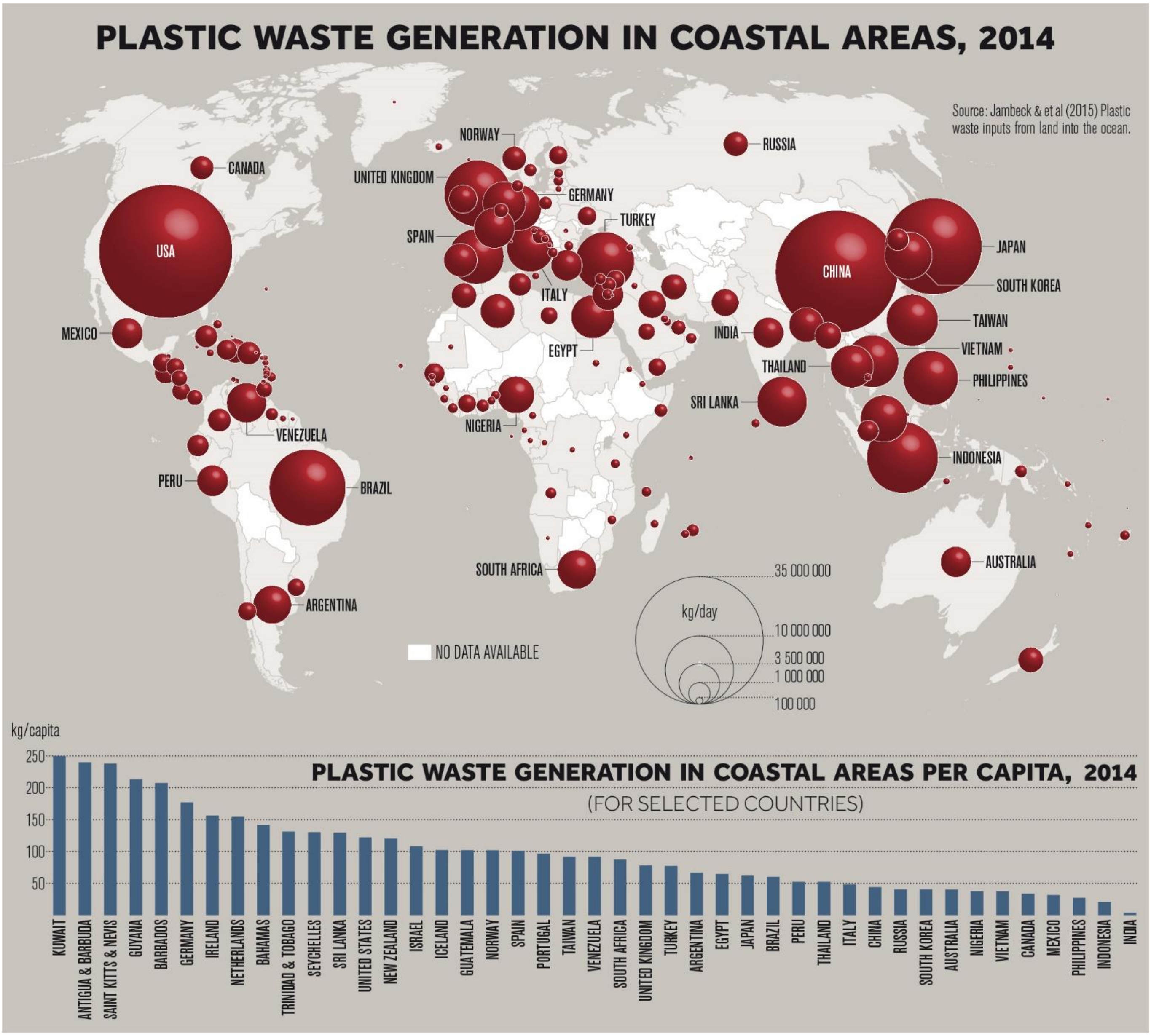


Figure 8: Plastic waste generation in coastal areas, 2014[44]

Asia is the largest contributor to global plastic waste generation

b. Sources and types of plastic waste

The generation of plastic waste can be mainly classified into two categories (Figure 9): (1) preconsumer or industrial plastic waste; and (2) postconsumer plastic waste.

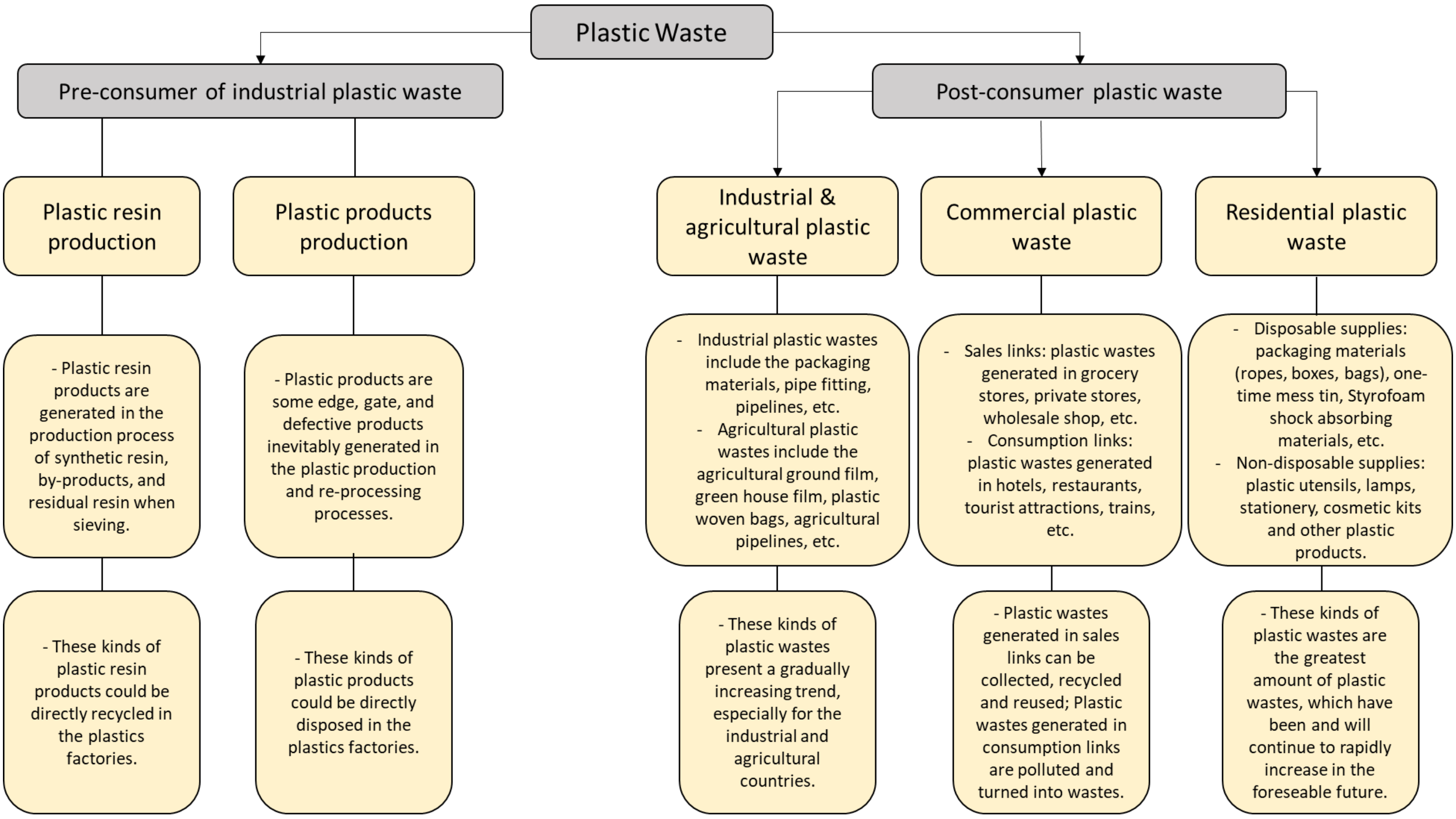


Figure 9: Classification of plastic waste[42]

The majority of plastic waste come from the post-consumer market. Post-consumer waste are found mainly in municipal solid waste (MSW), as well as in the following economic sectors: distribution and large industry, agriculture, construction and demolition, automotive, electronics and electric. Plastic packaging has the largest share (35.8%) in the market of plastic products and a short lifetime. It is also one of the main plastic waste generation sector accounting for 46% of plastic waste generation (Figure 10)[21].

46% of plastic waste is packaging

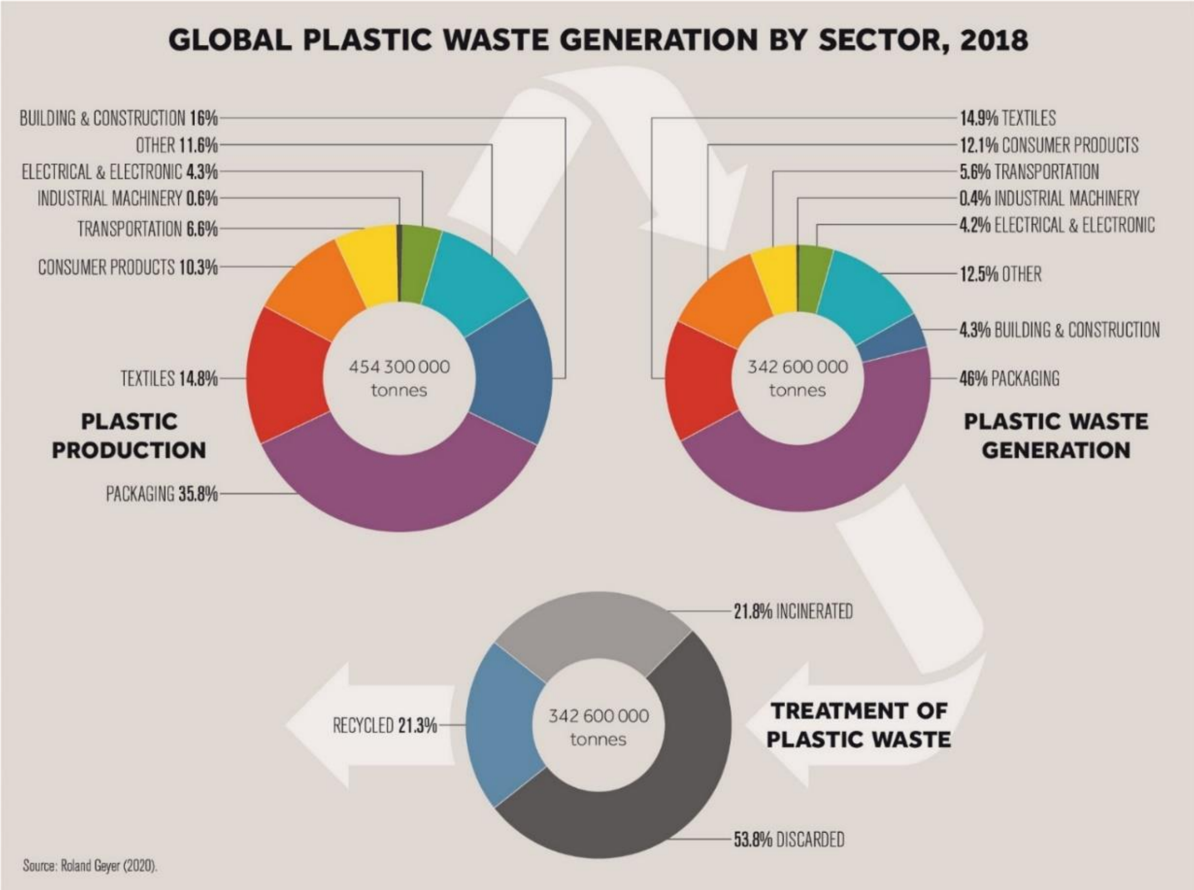


Figure 10: Plastic waste generation by sector (Geyer, 2020)[21]

Post-consumer plastic waste may fall into one of the following categories:

- Plastic bottles, pots, tubs and trays, which are mainly found in the household waste stream.
- Plastic film such as plastic shopping bags, rubbish bags, bubble wrap, and plastic or stretch wrap. Plastic films compose a broad category of materials that can be relatively simple or complex, depending on the demand of a particular product or package. It can be clear or colored, printed or plain, single or multi-layered, thus the only thing that all plastic film really has in common is that it is flexible in nature.
- Rigid plastics, such as crates, pipes, and mouldings. These products are made from a variety of different polymer types and can come from almost any source, from hospitals and caterers to agriculture and large industry.
- Plastic foams, such as expanded polystyrene (EPS) packaging.
- Flexible plastics, such as strapping and cable sheathing. These products are made from a variety of different polymer types and can come from a variety of sources.

Pre-consumer plastic waste, which generally account for less than 10%, are generated during the manufacture of virgin plastic from raw materials (oil, natural gas, salt, etc.) and from the conversion of plastics into plastic products[43]. Examples of off-specification material might include material that has the wrong colour, wrong hardness, or wrong processing characteristics.

VII. PLASTIC WASTE MANAGEMENT

a. Global plastic waste management

Of the 8.3 billion tonnes of plastic that have been introduced in the market between 1950 and 2015, a total of 5.8 billion tonnes of plastic waste have been generated[1]. Of that, 12% has been incinerated, 9% recycled, and around 60% discharged in landfills or in the environment[1,44].

Between 1950-1980, the main practice to treat plastics was the disposal in landfills or the environment and open burning. In the 80s, recycling and incineration of waste (with or without energy recovery) were introduced as treatment methods to deal with the environmental impacts and health hazards related to unregulated waste. Since then recycling and incineration of plastic waste kept increasing and today, recycling and incineration of plastic waste has reached respectively 19%, and 25%. Yet a significant amount of plastic waste (56%) is disposed in landfills and dumpsites or escapes into the environment[1] (Figure 11).

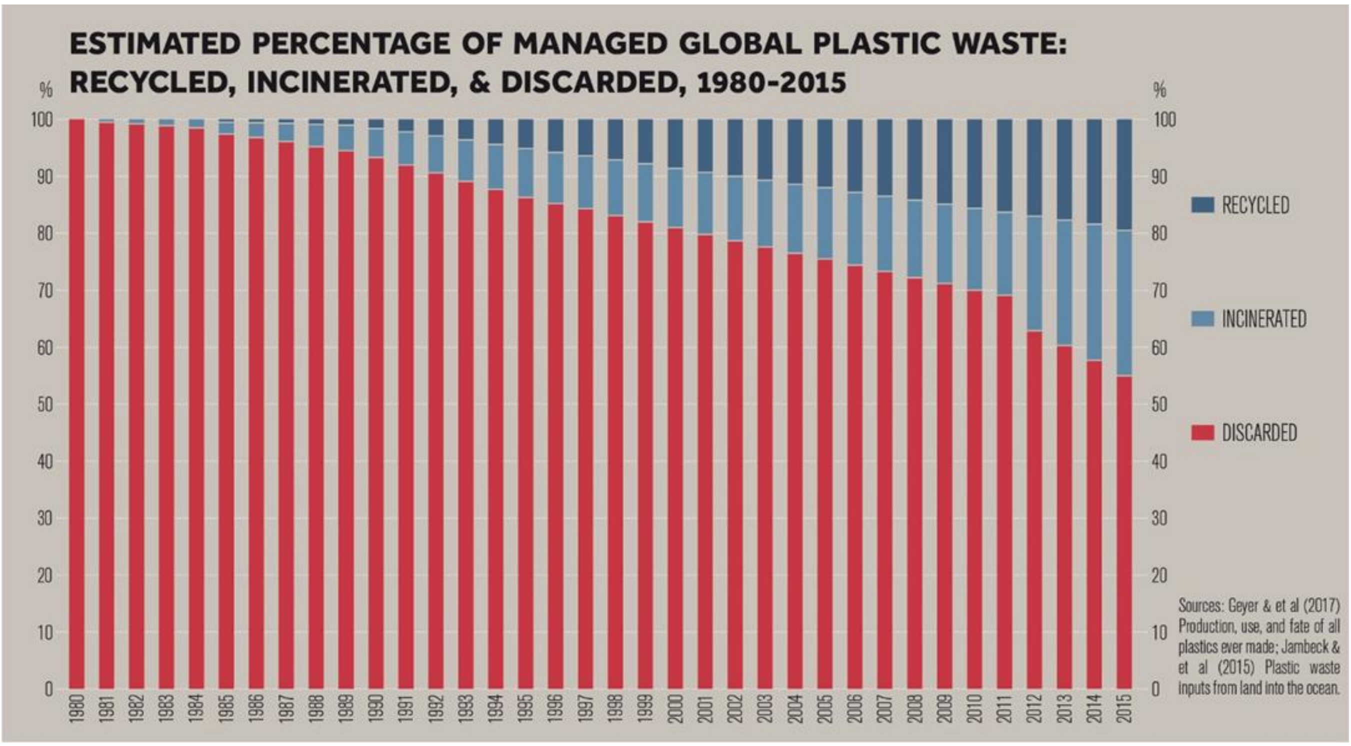


Figure 11: Percentage of managed global plastic waste[1 44]

Less than 20% of plastic waste is recycled annually

Today, recovery of plastics, in the form of material or thermal recovery, across countries and regions as well as among polymers present large variations. Plastic recycling rates vary from as high as 60% in India to as little as 9.1% in the U.S. (See Table 3). In addition, thermal treatment of plastic waste in some countries represents a higher percentage than material recycling. For instance, in Japan and Sweden and Denmark energy recovery of plastic waste is performed at significant higher rates than material recycling representing 56%, 81,7% and 57.1% respectively of the total plastic waste generated(Table 3).

Table 3: Material and energy recovery (or fuel) of plastic waste in different countries

Country	Material Recovery	Energy Recovery or fuel	Reference Year
India	60.0%[45]*	n/a	2017
South Africa	46.3%[46]	n/a	2018
South Korea	45.0%[1]	n/a	2014
UK	45.0%[37]	0.2%[37]	2016
EU	32.5%[47]**	42.6%[47]	2018
Brazil	25.8%	n/a	2017
China	27.0%[48]***	n/a	2017
Japan	27.0%[33]****	56%[33]	2018
Denmark	13.4%[40]	57.1%[40]	2017
Australia	11.8%[35]	1%[35]	2016
Argentina	11.0%[49]	n/a	2014
Indonesia	11.0%[32]	n/a	2018
Switzerland	10.3%[39]	15.5%[39]	2019
Canada	9.4%[34]*****	4.2%[34]	2016
Sweden	8.1%[36]	81.7%[36]	2017
Israel	5.2%[38]	10%[38]	2018

* This is as per the CPCB- CIPET survey conducted for 60 Indian cities. Most of the plastic waste is collected for recyling from the informal sector.
** Recovery other than energy recovery
***It refers to both municipal and manufacturing waste. In 2017 22% of municipal plastic waste was recycled and 31%of manufacturing plastic waste was recycled
**** Thermal treatment of plastics in Japan is 56% 23% material recycling and 4% chemical recycling
***** 7,8% mechanical recycling, 1,6% chemical recycling

While the above table gives an overview of the reported recycling rates of plastic waste in different countries, yet it is not safe to compare plastic recycling rates of different countries. That is because different sources of plastic waste might be taken into consideration in calculating plastic waste recycling rates (e.g. household only or household and commercial waste).

Moreover, comprehensive quantitative data on the levels of plastic recycling for different sectors are limited. In Canada for instance the packaging sector has the highest plastic waste recovery rates compared to the rest of the sectors (Table 4). The same is observed in Sweden (Table 5).

Table 4: Diversion rate, recycling rate and value recovery rate, per sector, 2016 in Canada[34]

Sector	Plastics discarded (kt)	Diversion rate (%)	Recycling rate (%)	Plastics recovered (kt)
Packaging	1542	23	15	327
EEE	214	16	13	33
Agriculture	45	9	5	5
Automotive	309	100	0	0
White goods	130	64	0	7
Construction	175	11	1	11
Textile	235	5	0	17
Other plastics	617	0	0	43
Total	**3268**	**25**	**8**	**442**

Table 5: Material recycling rate and energy recovery or fuel per sector in Sweden, 2016[36]

Plastic Waste	**Amount (tonnes) 2016**	**Materials recycling, Sweden/abroad (tonnes)**	**Materials recycling rate (percent)**	Energy recovery or **fuel, Sweden/abroad (tonnes)**
Mixed waste from businesses to energy recovery (excl. construction)	791 000	0	0	ca 791 000/0
-whereof import	*280 000-560 000**			
Residual waste	278 000	-	0	278 000/0
- whereof plastic packaging	*249 000*			
Construction-and demolition waste	152 000	1 000/-	0.8	ca 151 000/0
- whereof separated plastics	*63 000*	*1000/-*		
Waste from businesses (industry), separated plastic	143 000	-	-	-
Separately collected plastic packaging	96 000	96 000	44	-
Bulky waste - *whereof waste from recycling centers*	77 000	0/2 000	2,6	75 000/0
- whereof plastic packaging	*12 000* *22 000*	*0/2 000* *0*	*17*	*10 000/0*
End-of Life vehicles	41 000	0	0	37 000/0
Electrical waste	31 000	0/14 000	45	15 000/0
Refund bottles -*whereof separately collected*	25 000 *21 000*	21 000/0	84	4 000/0
Plastic from farming operations	18 000	16 000	-	2 000/0
Healthcare sector (number of products)	813 000 000	-	-	-
SUM	**1 652 000**	**134 000**	**-**	**1 350 000**

In terms of plastic recycling by resin type there are also few data available. Figure 12 presents the most recent reported data for key polymers in Japan, Canada and the U.S. illustrating that PET is the most widely recycled type of polymer.

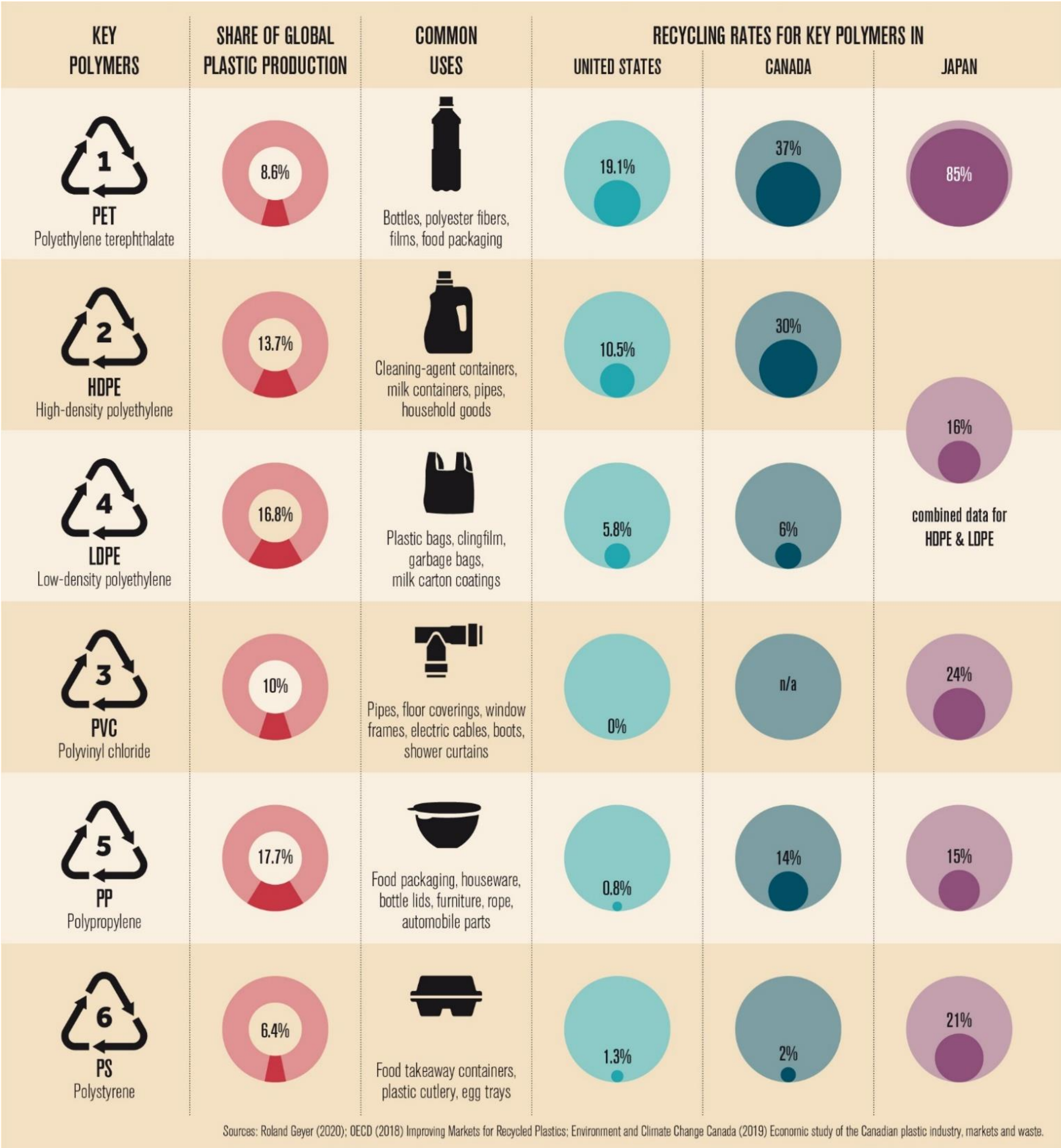


Figure 12: Summary of recycling rates for key polymers in USA, Canada and Japan

PET is the most commonly recycled polymer

Recycled PET has a relatively high value on international markets, driven significantly by demand in China over the last decade. Thus, many countries focus on recovery of PET bottles (Table 4) with recycling rates vary across the world. Norway holds one of the highest PET bottles recycling rates in the world that is 97% (in fiscal 2018)[50]. This is the result of Norway's model that is based on a loan scheme. Consumers are charged a small additional fee when buying a PET bottle that could then be redeemed in several ways. On the other hand, in Japan consumers and corporations cooperate to collect 92.2% of the PET bottles used in Japan (in fiscal 2017) without a deposit system and recycle 84.8% of the recovered material. Many of the recovered PET bottles and flakes are sent to China and other countries for recycling and reprocessing[51]. The success of Japan is based on a rigid Extended Producer Responsibility (EPR) system for the recycling of PET bottle. The system is operated under the Containers and Packaging Recycling Law setting strict obligations to all defined participants[52]. Collecting post-consumer PET bottles is a way of surviving for many informal collectors and recyclers in India, and thus most of the PET recycled in India comes through the informal sector[53]. In the U.S, there are no incentives for sorting and collecting PET bottles and the activities for source separate collection of PET bottles are mainly based on the individuals' initiative behavior [52] .

In addition, PET recycling is not uniformly high, even if one considers only the developed countries (Table 6). For instance, in the US, only a little over 29% of the PET bottles in circulation is collected for recycling, while, a quarter of that is exported to other countries like China to get recycled. The situation is almost the same in Europe. Although Europe has high collection rate of 59%, a very large portion of it is once again exported to China, Hong Kong and other countries[56].

Table 6: PET bottles recycling rated in 2017,2018

Regions/Countries	PET Bottles recycling rates	Year
USA	28.9[54]%	2018
EU	58,2%[55]	2017
India	80%[56,*]	2018
Japan	84,8%[33]	2017
Sweden	84%[36]	
Norway	97%[50]	2018

*India annually, 65% is recycled at registered facilities, 15% in the unorganised sector

b. Plastic waste management in different economies

The characteristics and then subsequently the treatments of pre and post-consumer waste are different. Plastic components often come to the end of their first- life application with the character of the plastic material substantially unchanged.

Pre-consumer plastic waste are typically clean, segregated from other resins, physically close to the point where they can be recycled and well characterized in terms of origin and physical properties. Pre-consumer plastic waste is likely to be the main source of plastics suitable for reprocessing from manufacturers of plastic products; in many instances, off-cuts can be reprocessed in-house. It is typically more valuable than post-consumer plastic waste, as it generally requires little processing to use in a new product.

On the other hand, post-consumer waste are often in the form of composite materials, in particular mixtures of different plastic and/or plastic and non-plastic waste. To be recycled, the plastic(s) must first be cleaned and separated into homogeneous materials. These factors contribute to the increased difficulties and costs of recycling post-user waste when compared to pre-user waste.

Then the waste management routes of post-consumer plastic waste differ between the different economies. There are four different approaches of post-consumer plastic waste management and recycling economies[57]:

- developed economies where recycling is enhanced through strategies and regulations
- developed economies that miss incentives for enhancing recovery of plastic for recycling
- developing economies with significant industrial activities, and
- developing economies with little industrial activity

The main characteristic in the plastic recycling industry and the plastic recycling approach for each of these groups of countries are provided in brief in Table 7.

Table 7: Plastic waste management and recycling in different groups of countries around the globe[57]

Type of economies	Countries	Plastic waste management practices & infrastructure	Main drivers for recycling	Plastic recycling rates*
Developed economies where recycling is enhanced through strategies and regulations	Western Europe Japan	- 82%-96% waste collection coverage[58] - Source separation schemes for mixed dry recyclables and/or plastics is highly encouraged - Sorting and processing plastic waste units in place. Sorting is performed either manually, or by selectively dissolving mixtures, or with techniques such as near- infrared spectroscopy and electrostatic separation that increase efficiency of Material Recycling Facilities (MRFs). - Advanced waste management technologies for treating plastic scrap (mechanical recycling, chemical recycling etc.) - Plastic scrap of low financial value is sent overseas.	- Plastic recycling strategies that enhance recovery of plastic at source. - Bans, or restrictions on landfilling - Taxes on landfilling and/or incineration - Extended Producer Responsibility schemes that finance part of the costs for collection and sorting of plastic waste. - Plastic (bottles) deposit return schemes	~25-30%
Developed economies that lack incentives for enhancing recovery of plastic for recycling	USA Australia Balkan region in transition phase	- More than 82% waste collection coverage[58] - Few effective plastic source separation schemes in place. - Focus on traditional waste management options such as landfilling and/or incineration due to low costs of treatment. - Plastic scrap of low financial value is sent overseas.	- Recycling is enhanced by some source separation and deposit systems in place - Bans of plastics	~10-15%
Economies on transition phase with significant industrial activities	China, Brazil, India	- Waste collection coverage is around 51% and/or frequency of collection is not adequately covering the needs of many municipalities of the Global South[58]. - Old fleet and equipment for waste collection and transportation. - Sorting of plastics is performed mainly manually. - Improper handling of plastics at sorting/ recycling facilities and transfer stations leads to direct and indirect run-off of plastic that ends up in the environment. - Recycling processes is at a primary level and thus value addition for recycled materials is far less than market expectations. - Large percentage of plastic waste is disposed in unregulated landfills and/or dumpsites. - Receive low value plastic scrap from developed economies (Imported plastic is not considered in domestic plastic recycling rates).	Recovery and recycling of plastic waste is enhanced by local industrial demand and opportunity for locals to increase levels of livelihood. The presence of **informal structures** is very well established.	20%-60%
Transition economies with little industrial activity	Low-income economies and remote areas such as Small Pacific Islands	- Collection coverage is very low <39% or absent[58]. - Plastic waste is dumped directly in the environment and/or waterways.	A very limited market for recyclables and it is also a fact that in a number of areas the general recycling market is just not aware of the potential value in reclaimed materials.	no sufficient recycling could be developed

*based on the recycling rates that have been reported in Table 2 for countries of different economies

c. Management of plastic packaging, textile and agricultural waste

Below there is a brief analysis on the management of post-consumer plastic waste of the packaging and textile sector which are the top plastic waste producers. In addition, management of agricultural plastic waste is presented due to the debate that is only just beginning over microplastics leakage from mismanaged agricultural plastic waste in the in the soil, in livestock and in our food[59].

Plastic packaging waste

Management of post-consumer plastic packaging waste include capture through either the formal or informal collection or recycling systems in place.

Collection methods of packaging plastic waste includes:

i) mono-material collection systems where plastic is segregated at the source as one material fraction including more than one type of plastic, together (as mixed plastics) or targeting specific plastic types (e.g. PET bottles, or rigid plastic such as pots, tubs and trays),
Mono-materials can also be recovered from deposit systems and are typically used for the collection of beverage bottles. Such deposit systems are very common in a number of European countries.

ii) co-mingled collection systems where several types of source separated dry recyclables (e.g. metals, glass and plastics) are collected together, and

iii) mixed waste collection systems where plastics are collected together with the rest of household waste.

To enhance the capture of plastic packaging and encourage recycled content of plastic packaging there have been introduced different polices and/or incentives in different countries around the world. Such policies/incentives are:

- Plastic packaging waste recycling targets
- Packaging Extended Producer Responsibility (EPR) fees
- Reduce the use of or ban single-use plastic
- Plastic bag taxes or bans
- Targets for reusable, recyclable or recoverable plastics

Europe and Canada are examples of countries that have introduced such policies/incentives. More specific, EU waste legislation and the EU strategy for plastics in the circular economy adopted in January 2018[60] has enshrined a number of elements to drive reuse and recycling of plastic and plastic packaging waste. It sets out the goal that by 2030, all plastics packaging placed on the EU market is reusable or easily recycled and target for recycling 55% of plastic packaging waste in 2030[61]. In addition, in 2019 the European parliament voted to ban single-use plastic cutlery, cotton buds, straws and stirrers to come inforce in all member states by 2021. By 2025, plastic bottles should be made of 25% recycled content, and by 2029 90% of them should be recycled.

Environment and Climate Change Canada (ECCC) is working to ban harmful single-use plastic product and take steps towards eliminating plastic pollution in Canada. ECCC is also collaborating with industry and other partners to achieve Canada'goals of 100% reusable, recyclable or recoverable plastics by 2030, and increasing recycled content in plastic products were applicable by at least 50% by 2030.[62]

Countries of the Global South have also starting implementing EPR schemes for packaging and ban or taxes to plastic bags (See Figure i and Table i, Annex I).

Performance in plastic packaging recycling

The EPA estimated that 14.5 million tonnes of plastic containers and packaging were generated in 2017, in the U.S. which are approximately 5.3% of MSW generation. Of that, 13% (1.9 million tonnes) of all plastic packaging waste has been recycled while 17% (2.5 million tonnes) has been treated thermally with energy recovery while the remaining 70% has been disposed of in landfills[63]. The recycling rate of PET bottles and jars was 29.1% in 2017 (860,000 tonnes) and recycling of HDPE natural bottles (e.g., milk and water bottles) was 31.2% (240,000 tonnes)[63].

In 2017, 32% of Australia's plastic packaging was recycled, this out of 0.9 million tonnes in total of plastic packaging waste. All different basic resins (PET, HDPE, LDPE PS, PVC, PP) of plastic packaging had about the same recycling rates varying between 27-30%[64].

In 2017, material recycling of plastic packaging waste in EU was 41.7% (7 million tonnes) out of all plastic packaging waste (16.7 million tonnes) with the highest recycling rates recorded in Lithuania (74%) and the lowest in Malta (24%)[65] .

In Australia, charges for plastic bags have resulted in the reduction of plastic bags used by more than 80% (no of bags)[66].

Textile waste

Plastic waste in textile sector account for almost 15% of the global plastic waste generation and may come from residential or industrial, commercial and institutional sources. Residential textile waste is mainly clothing and home textiles such as towels, curtains, bedding, which consists of synthetic and natural fibres. Textiles are mainly disposed along with other municipal solid waste or reused through charity organizations. In some countries, clothing is also collected separately through organized source separation structures and they are either reused as second-hand materials or recycled.

73 percent of discarded textiles are either incinerated or landfilled together with municipal solid waste and only 13% of total material input is recycled[67]. The textiles which retain high enough quality for reuse are often sent abroad. In EU countries such as UK good quality clothing and textiles are sent to Eastern European or African countries (Figure 13), and the remaining flow is sent to recycling plants. Since only a few different methods for textile recycling exist today, the majority of the flow is downcycled into wipes, rags or is used as insulation in different industries. The remainder of the collected used textiles is either landfilled or incinerated[68].

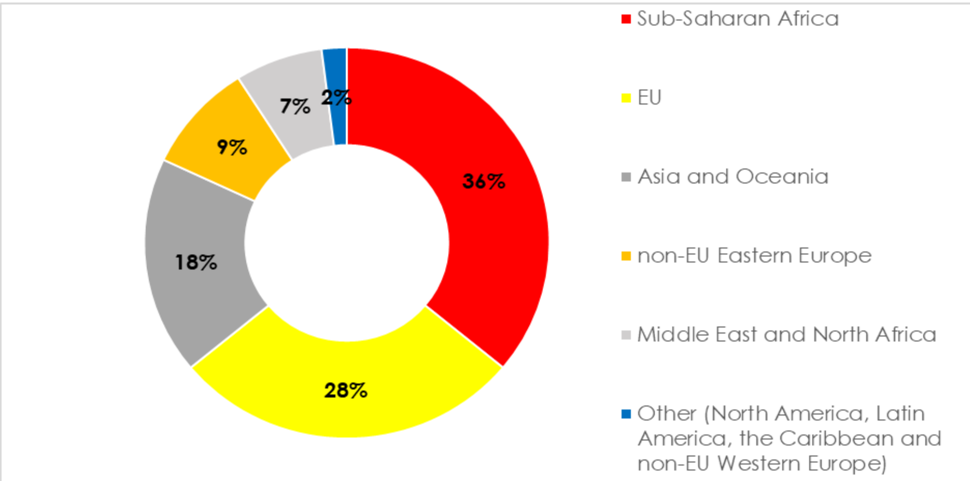


Figure 13: UK exports of used textiles in 2014 (% of total mass)[69]

While the output of the textile industry is continuously increasing, most EU member states managed to reduce their textile waste levels from 2004 to 2014. An overall decrease of 48% from about 4.4 million tonnes to 2.3 million tonnes of waste was reported[70].

Mechanical recycling of textile waste faces many limitations and there are many difficulties in separating dyes, contaminants and blended polyester and cotton. However, there are efforts in EU and US of improve and incorporated new technology in recycling facilities to increase efficiency of textile recycling[71].

Plastic agricultural waste

From the 265 million tonnes of plastic produced in 2010 worldwide, 2% of them were used in agriculture[72].

Plastic products and packaging are also used extensively in agricultural applications. Plastic films, mulch fields, irrigation and maple tubing nursery containers, as well as containers used for pesticides and dairy sanitizers are some of the plastic products used in the agricultural sector[73]. In addition, polyethylene films are greatly used to extend and increase yields, expand growing seasons, reduce the usage of pesticides and herbicides, and help conserve water. These plastics comprise about 80% of the agricultural plastic waste[1].

The collection and treatment of the plastic used in the agricultural sector varies. In developed economies such as Europe the recovery and recycling of agricultural plastic has been developing steadily over the past years. In 2017, the collection rate of agricultural plastic waste is around 60%[74]. More specifically, the Irish Farm Film Producers Group have reported that Ireland has achieved 74% recycling of farm plastic films due to a well-functioning collection scheme and value chain collaboration. Moreover, data from waste management specialist RIGK shows that the volume of collected agricultural films, in 2016 was over 5,412 tonnes in Germany[74]. The collected agricultural plastics are then mechanically recycled. For instance, collected plastic films are usually washed to eliminate sand, herbs and pesticides, and then are grinded and extruded into plastic pellets. When mechanical recycling is not viable, agricultural plastic waste is sent for treatment in co-combustion units[75].

American and/or European Standards for agricultural films and nets have already been developed to satisfy mechanical and physical requirements in order to play an optimum role in agriculture and minimize environmental impacts[73].

However, not all developed countries have established a well-functioning collection and waste management system for agricultural plastics. For instance, in Greece, agricultural waste collection systems are not yet in place and the path of disposal is in many cases illegal and uncontrolled causing soil and water pollution. Subsequently, the situation gets worse when farmers burn the agricultural plastic waste on the field[76].

The problem of adequate collection and waste management of agricultural plastic waste is much greater in developing economies such as in China. According to Wenqing et al. (2017), in China, the amount and area of plastic film have increased steadily to 1.41 million tonnes or more than 18.14 Mha, in 2014. Plastic film mulching has assumed a key role in ensuring the supply of agricultural goods. "White pollution" in China caused from mulching films applied on soils are of the most problematic issues of the Chinese agricultural sector concerning post-treatment of plastic waste. In contrast to developed economies such as Europe and the U.S. where the plastic film applied on the agricultural fields has thickness more than 15 μm, and is easy to reclaim by machine, in China plastic film mulch for agricultural use is very thin (4-8 μm). This makes, mulch films fragile and easily damaged, and thus not easily reclaimed by the machines and are extremely difficult to recycle because of the high labour requirement.[77]. Also, the lack of a mandatory recycling policy until 2015 when, the Ministry of Agriculture of China set the environmental goals of "one control, two reductions, and three basics" by 2020, has worsen the situation leading to very low recovery rates of plastic film in China in the past decades[78]. On the contrary, much of the plastic films have been burned in the field or dumped in out of the way areas on the farm leading to potential soil contamination and microplastic leakage at the nearby aquifers[79].

Currently there is a lot of research around biodegradable mulch films as an alternative to PE plastic film mulches that can be buried directly in the soil, where no removal from the field is required, or could be disposed in a composting plant[80].

d. Plastic recycling methods

Plastic recycling is approached in the global market by mainly two recycling methods which are mechanical recycling, chemical recycling, whilst other recovery and disposal operations include waste to energy and incineration (q.v. Basel Convention, Annex IV, R1 and D10) (Table 8). Each of these plastic waste treatment methods includes different technological approaches on treating plastic waste based on the type of polymers with different advantages and disadvantages[81].

Sorting of plastic waste is an essential stage within the plastic recycling chain influencing the management techniques applied after this stage. Sorting could be either manual or automated/mechanical. The sorting technique that is applied depends upon the type of waste input, and the plastic recycling market in place. In the Global South, manual and/or low-tech solutions for sorting waste are the common practice due to the fact that these countries cannot afford to apply more sophisticated techniques due not only to capital costs, but also to labor costs and maintenance programs. Countries of the Global North, with better market structures apply more sophisticated technology-based sorting solutions[96]. Manual sorting operations are usually part of the mechanical sorting techniques at pre-sorting stage aiming to remove unwanted or contaminated input materials and improve efficiency of the downstream-automated process. In addition, manual sorting applies in quality controls at the end of the sorting process to ensure that sorted plastics meet the technical specifications of the market.

Table 8: Overview of the different plastic recycling methods, process steps, emissions and applications

Definition	Process step	Emissions	Application
Mechanical Recycling is the processing of plastic waste into secondary raw material or products without significantly changing the chemical structure of the material[82]	Mechanical Recycling includes the following steps[83]: ***Sorting*** - *Sorting (prior):* this occurs based on shape, density, size, color or chemical composition. Sorting could be either manual or mechanical -automatic[8485] - *Balling* when recycling is not performed at the sorting unit ***Re-processing*** - *Cutting*: large plastic parts are cut by saw or shears for further processing - *Shredding*: plastics are chopped into small flakes, allowing the separation of materials (e.g. metals, glass, paper) and plastic types (e.g. PET bottles from PP lids). - *Contaminant separation*: contaminants (e.g. paper, ferrous metals) are separated from plastic in cyclone separators and magnets. - *Grinding*: size reduction from products to flakes. - *Flakes separation by floating*: different types of plastic are separated in a floating tank according to their density. The density of the liquid can be modified to enable separation (e.g. adding salt to water). - *Washing & drying*: for removal of contaminants -all kinds of glue particles or chemical washing by using caustic soda is done for glue removal - *Extrusion*: The flakes /pellets/agglomerates are fed into an extruder where they are heated to melting state and forced through,	The environmental impacts from plastic scrap mechanical recycling process are[87]: - air emissions in the form of dust - wastewater emissions from the washing of plastics flakes - direct air emissions associated to heat production (e.g. for flake washing), if the heat is generated on-site by gas, oil, etc. - electricity consumption	Mechanical recycling facilities are found in both the developed and the developing world. The difference between mechanical recycling in the Global South and the Global North is the degree of sophistication of the equipment. In most developing countries it is not possible to find new equipment within the country and shall either be imported, manufactured locally, or use improvised equipment[88]

Definition	Process step	Emissions	Application
	converting into a continuous polymer product. - *Filtering*: The last step of extrusion may be filtering with a metal mesh - *Compounding & pelletizing*: optional reprocessing of the flakes into a granulate ***Processing Stage*** Secondary recycling (processing stage) includes various methods of recycling[86]: - screw extrusion - injection molding - blow molding - drawing - shredding		
Feedstock Recycling or Chemical Recycling is the depolymerization of long polymer chains into monomers through a chemical reaction by means of heat and/or chemical agents to produce monomers, chemical raw materials and/or fuels[89,90].	The chemical reactions used for decomposition of polymers into monomers are[89]: - Hydrogenation - Glycolysis - Gasification - Hydrolysis - Pyrolysis - Methanolysis - Chemical depolymerization - Thermal cracking - Catalytic cracking and reforming - Photodegradation - Ultrasound degradation - Degradation in microwave reactor The most well-known feedstock recycling process includes[92]: Chemical depolymerization - Thermal cracking (pyrolysis) - Gasification - Catalytic conversion - Coke oven chemical feedstock recycling	Direct environmental impact of pyrolysis and gasification are: - Toxic gases - Ash that contains heavy metals	Chemical recycling technologies are sophisticated and require technical expertise in handling and maintenance. Due to high capital costs and technical expertise required it is difficult to be adopted in developing countries. Currently there is no sufficient evidence on their application to countries of the Global South. According to Kumar et al, 2019 feedstock-recycling technologies mostly appear in some developed countries like the U.S. and Europe[91].

Definition	Process step	Emissions	Application
Energy Recovery in the form of heat, steam or electricity generation is the process of utilizing waste (plastics) as substitutes of primary fossil fuel resources for the production of fuel, for energy recovery. (SS-ISO 15270:2009, 2009)[82]	Energy recovery from waste plastics is realized in: - waste incineration plants - cement kilns - co-combustion of waste plastics in power plants (rare) Incineration of waste with energy recovery involves the following four stages[91]: - pretreatment - incineration (combustion) - energy recovery - flue gas cleaning	The most common environmental impacts from incineration processes are[92]: - air emissions of CO2, CO, oxides of nitrogen, water vapor - toxic gases (acetaldehyde, acetone, Benzaldehyde, benzole, formaldehyde, phosgene, dioxins, furans, hydrochloric acid, salicyl-aldehyde, toluene, xylene, etc.) - Ash that contains heavy metals	Incineration of plastic has high investment and operation costs and requires skilled employees to run the facility. There is evidence of waste incineration in both the developed and the developing countries[91].

Mechanical recycling

Mechanical recycling is one of the most popular methods employed around the world to treat plastic waste. The main operations in the mechanical recycling chain includes collection, sorting, reprocessing and the end-use of the recycled material (processing of plastics).[93] Only the thermoplastic polymers can be utilized with mechanical recycling, since based on their structure they can be re-melted and reprocessed into end-products. Recycled plastic is often mixed with virgin plastic in order to increase the mixture values. In addition, the heterogeneity of municipal waste is an obstacle on recovering large homogenous amounts of targeted plastic for efficient mechanical recycling. Equipment for plastic recycling and processing varies in size and level of sophistication.

While the developed countries have easy access to relevant equipment, in most countries of the Global South, except Asian countries, it is not possible to find new equipment, which can be purchased locally. Usually the necessary equipment will either have to be imported, manufactured locally, or improvised[88].

The efficiency of the mechanical recycling varies based on input material characteristic and technology applied.

Chemical recycling

Chemical recycling is defined as the process in which polymers are chemically converted to monomers or partially depolymerized to oligomers through a chemical reaction (a change occurs to the chemical structure of the polymer). The resulted monomers can be used for new polymerizations to reproduce the original or a related polymeric product. Chemical recycling can be used with mechanical recycling as a complementation to recycle plastic waste that cannot be mechanically recycled and converted to monomers, chemical raw materials and/or fuels. The chemical recycling is not fully developed, since it requires a lot of investment and expert personnel, and for this reason, there is a lot of interest from the petrochemical industry. However, after the Chinese ban in the last years, chemical recycling is seen as a very promising plastic recycling method, and installation capacity around the world is expected to increase. Currently, numerous chemical recycling methods are under investigation; for example, the gasification and pyrolysis method are under extensive research to establish the suitable conditions. The process that have reached commercial maturity at this moment are glycolysis and methanolysis. Depolymerization technologies, such as methanolysis, and glycolysis, are recognized as technically feasible routes to convert condensation polymers like PET, polycarbonate, polyester, polyurethane (PUR), and nylon into basic chemicals such as ethylene glycol and terephthalic acid outputs[94].

Energy recovery

Energy recovery is the process of utilizing waste (plastics) as substitutes of primary fossil fuel resources for the production of fuel, for energy recovery in the form of heat, steam or electricity generation. (SS-ISO 15270:2009)[102]. Energy recovery from waste plastics is realized in:

- waste incineration plants
- cement kilns
- co-combustion of waste plastics in power plants (rare)

Incineration of waste with energy recovery involves the following four stages:

- pretreatment
- incineration (combustion)
- energy recovery
- flue gas cleaning

Incineration of plastic is a good solution for non-recycled plastics and in general combustion of plastic waste generates considerable energy. However, it requires a high capital investment equipped with adequate and modern cleaning systems to prevent increased air emissions that can manage bottom and fly ashes being treated in a sound environmental manner. Under other conditions, incineration cannot be considered as an environmental acceptable solution to treat plastics.

Downcycling in Asian Countries: Adopted from GAIA, 2019[95]

Struggling with an ever-staggering amount of plastic waste, most of which is not being recycled, some countries have explored less conventional forms of plastic recycling. These include "plasticto-road" or "Plasphalt" as well as "plastic-to-brick" and other building materials or furniture made from plastic waste. India has been leading the way, introducing a regulation to make the use of plastic waste in road construction mandatory. As of 2018, almost 10,000 km of roads have been paved in India using plastic waste, such as water bottles, single-use bags, and food wrappers. In Indonesia, the government announced plans to use a similar technique to build roads in Bali, Jakarta and other cities in 2017. Behind these recycling efforts is Dow Chemical, a major producer of plastics and associated chemicals, which launched several plastic-to-road pilot programs in India and Indonesia in 2017. Consumer goods corporations are also investing in various downcycling practices. In the Philippines, Nestle collaborates with the Philippine Plastics Industry Association (PPIA) to produce bricks using multi-layered single-use plastic waste in four cities, and in Mexico, Procter & Gamble is using diapers to produce roof tiles and upholstery filling.

e. Plastic reprocessing capacity

Table 9 shows the plastic reprocessing capacity in different countries. Yet, there is a lack of data on the plastic reprocessing capacity in other countries around the world.

Table 9: Plastic reprocessing capacity

Country		Number of Plastic Waste Recyclers	Amount of plastics processed (tonnes/yr)	Mean Processed per company (tonnes per year)	Reference
China		25,000	24,500,000.00	980.00	PRI, 2019[71]
EU	flexible PE (LDPE, LLDPE, MDPE and HDPE)	n.a	2,300,000.00	n.a	Plastics Recyclers Europe[96]
EU	PET	78	2,100,000.00	n.a	Plastics Recyclers[96] Europe
USA		107	2,210,310.00	16,676.00	PRI, 2019[71] ACC, 2018[97] Etc[98 99]
UK*		40	1,300,000.00	32,500.00	PRI, 2019[71]
Poland		324	1,315,841.00	4,061.00	PRI, 2019[71]
Austria		35	330,000.00	9,429.00	PRI, 2019[71]
Argentina**		n.a	240,000.00	n.a	Argentina, 2020[102]
Canada		n.a	202,135.00	n.a	ECCC, 2019[100]
Australia		135	117,900.00	n.a	Australia, 2018[101]

*Includes dedicated sorters
* The recycling industry is working at 60% idle capacity due to lack of raw material due to the absence of differentiated collection and separation at source[102].

f. Challenges in plastic recycling

Plastic recycling faces many challenges, ranging from mixed plastics to hard-to-remove residues and high contamination levels. Cost-effectiveness and efficient recycling of the mixed plastic stream is perhaps the biggest challenge facing the recycling industry. Experts believe that designing plastic packaging and other plastic products with recycling in mind can play a significant role in facing this challenge[103].

According to Vilaplana et al., 2007[104] the quality of plastic scrap for recycling is mainly influenced by three quality parameters (14), namely:

- the degree of mixing (polymers cross contamination)
- the degree of degradation
- the contamination levels

Product design and source separation could enhance recycling of plastic

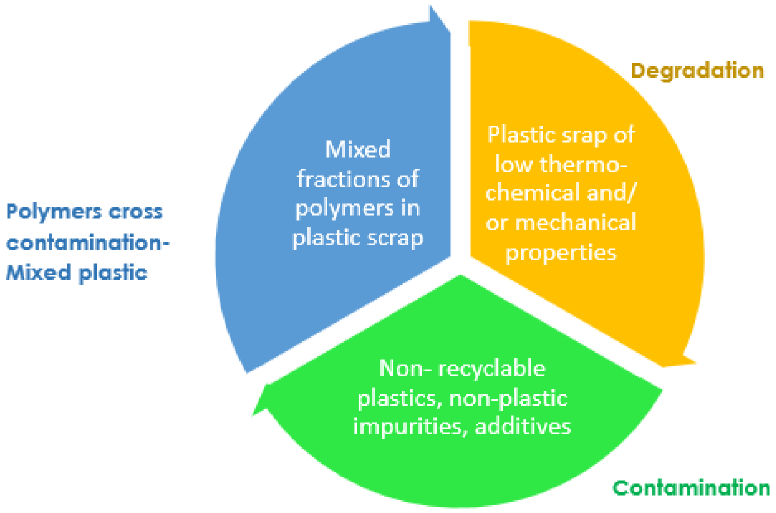


Figure 14: The three quality parameters influencing the quality of plastic scrap for recycling

Mixed plastic waste

Mixed plastic waste streams consist of several different types of polymers. The major plastic polymers predominantly found in household waste and other Municipal Solid Waste (MSW) sources are Polyethylene (PE), Polyethylene Terephthalate (PET), Polypropylene (PP), Polystyrene (PS), and Polyvinyl Chloride (PVC).

Mixed plastic waste streams which are also referred to as cross contamination of plastics may occur during segregation and collection, within a plastic re-processing facility, in a scrap yard or in a sorting unit during the process (e.g. MRF plant).

If the contaminants are from the same family of the main polymer and the proportion does not exceed about 8% there will be no major challenges in the re-processing of plastic waste. For instance, polyethylene fits well with most other thermoplastics because of its simple chemical structure and easy processing.

However, most polymers are not compatible with each other and even simple mixing of different waste polymers leads typically into a blend, which has limited or no commercial use due to its inadequate mechanical properties especially concerning the mechanical recycling process (downcycling).

According to Ellen MacArthur Foundation and UNEP (2019)[105], *innovation activity could improve the quality of output that can be achieved via mechanical recycling, including from mixed plastic waste streams. In 2019 PetStar gained a Cradle to Cradle certification for a recycled PET resin — the first PET recycled resin to achieve this — while APK is now focusing on scaling a technology which generates pure re-granulates, with a quality comparable to virgin.*

Plastic recycling contamination

Plastic recycling contamination is when incorrect items/materials are put into the system (such as used-nappies, food waste, paints, and other problematic materials) or when the right items are prepared the wrong way (e.g., food residue in plastic containers, recyclables in plastic bags, and shrink plastic wrap recycling mixed in with cardboard, paper etc.)[106] .

More specific contamination of plastic scrap concerns:

Non- recyclable plastics**:** e.g.: nappies, rubble

Non-plastic impurities which is any material different from plastic: e.g. metals, paper, glass, natural textiles, earth, sand, ash, dirt, stones, dust, wax, bitumen, ceramics, rubber, organic matter (food waste) and wood, except when these materials are integral constituents of the plastic structure before it is re-melted, such as talc, limestone, glass fiber or wood fibers used as fillers and structural or mechanical reinforcements.

Contamination of plastic with food waste may limit applications of recycled plastics in the food industry for health and safety issues.

In addition, plastic maybe contaminated with oils, solvents, paints, fatty food particles or detergents adsorbed by plastic.

The above type of contamination can occur during the source separation, collection and transportation of plastics as well as at the reprocessing facilities. Such types of contamination are presented in Annex II.

In general, it is difficult to obtain information on the contamination levels of plastic entering the re-processing facilities of plastic waste. According to a Guardian report 20% to 70% of plastic entering recycling facilities around the globe is discarded because it is unusable.

Additives could also be considered as a type of plastic contamination at the recycling industry. Although the role of additives in plastics is to improve the performance (e.g. limit degradation), to enable processing, to give certain desired properties for a specific application they could also pose a challenge due to their potentially hazardous properties, and unpredictable effect on the next product[107]. Recently Denmark has announced that it will be the first country to ban Per- and Polyfluoroalkyl substances (PFAS) in food packaging, due to the fact that they have been linked to cancer, high cholesterol and decreased fertility[108].

In addition, **colorants**, and **fillers** used during plastic production are also a challenge in plastic recycling. For instance, LDPE-film and PP-film that contain colorants and/or fillers are not sorted out by the Near-infrared (NIR) detectors at mechanical sorting units[109].

Bio-based plastic recycling challenges

Concerning the end-of lifecycle options of bio-based plastic waste, there are few considerations from academics. When applications and the market of bio-based plastics will increase then there will also be an increase of their presence in waste streams and as such enter the established recycling processes for fossil-based plastic. As sorting of plastic in most cases is based on appearance (visual discrimination) it would lead such materials to be treated in the same units along with conventional plastic waste or organic waste.

Even in mechanical recycling facilities, there might be a risk that mechanical sorting techniques would not be able to sort out bio-based plastic. For instance, a bottle made from PET and from PLA is not possible to separate by appearance since both materials are transparent and very similar. Also, PLA is denser than water so in the flotation tank any PLA fragments will eventually follow the PET stream towards mechanical recycling. This mixing of PLA with PET materials would cause problems to the reprocessing unit since PLA and PET have different melting points[110].

VIII. FATE OF MISMANAGED PLASTIC WASTE

Based on the definition provided by Jambeck et al., 2015[44] mismanaged waste is the sum of material, which is either littered or inadequately disposed of including disposal in dumps or open, uncontrolled landfills. The amount of mismanaged plastic is therefore linked to the effectiveness of the waste management across the world. Jambeck et al., estimates that total mismanaged plastic waste from coastal population has been 31.9 million tonnes in 2010 [44]. Later Lebreton et. al, 2019[30] estimated that for the 2015 calendar year, between 60 and 99 million metric tons of global municipal plastic waste were improperly disposed of and released into the environment out of 181[v] million tonnes of global generated municipal plastic waste.

Countries in Southeast Asia and the pacific have the highest share of plastic waste that is deemed inadequately mismanaged and leads to escape of plastic in the terrestrial and marine environment. In Asia and Sub-Saharan Africa, between 80-90 percent of plastic waste is inadequately disposed of with China, Indonesia, the Philippines, Thailand, and Vietnam producing half of all plastic waste in the world's oceans[44]. On the other hand, high-income countries such as European countries, North America, Australia and Japan have effective waste management systems in place and almost no plastic waste is considered inadequately managed [16](See Figures 15 & 16).

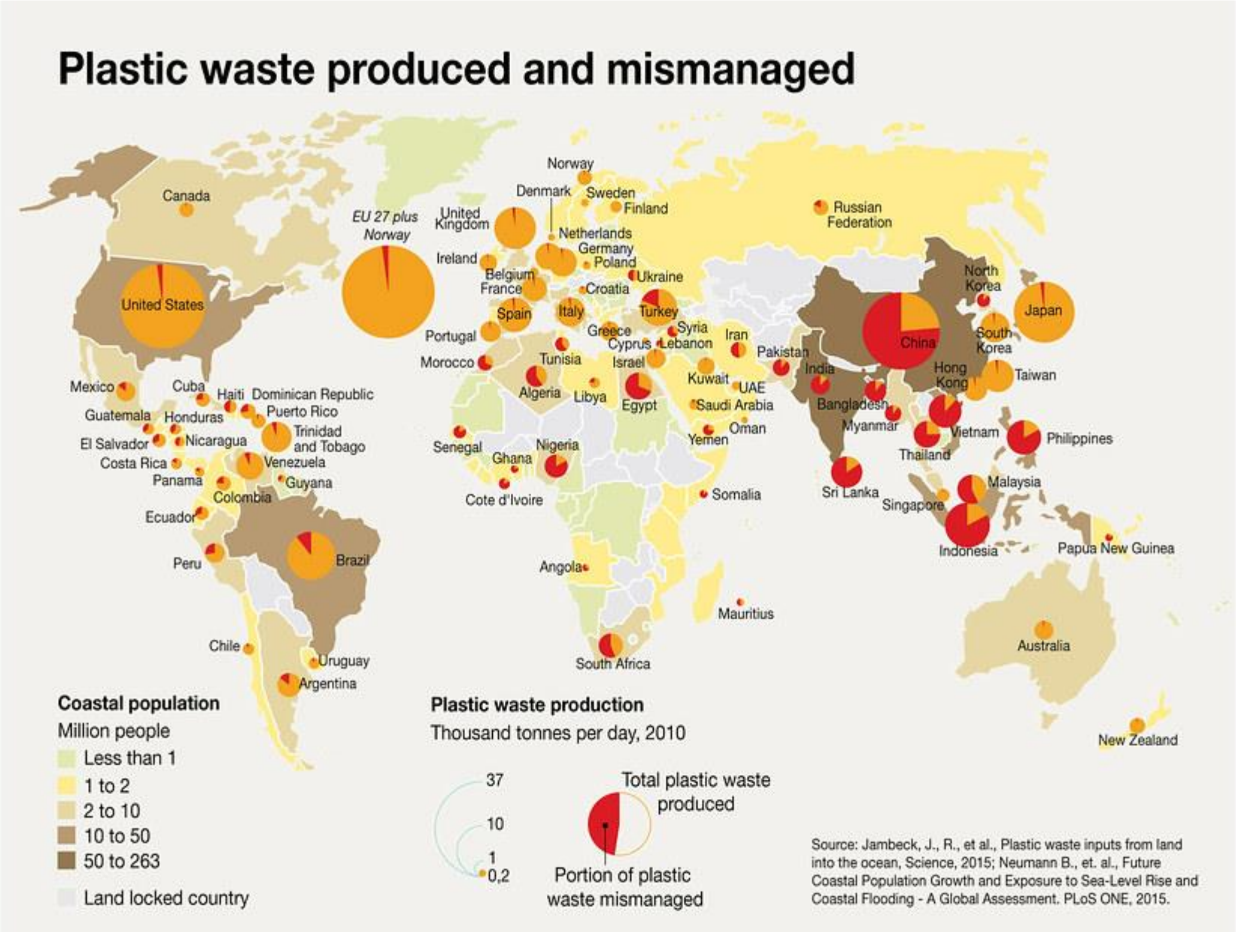


Figure 15: Plastic waste generation and mismanagement in coastal areas, 2010[44]

[v] The number has been estimated by Lebreton et al., 2019

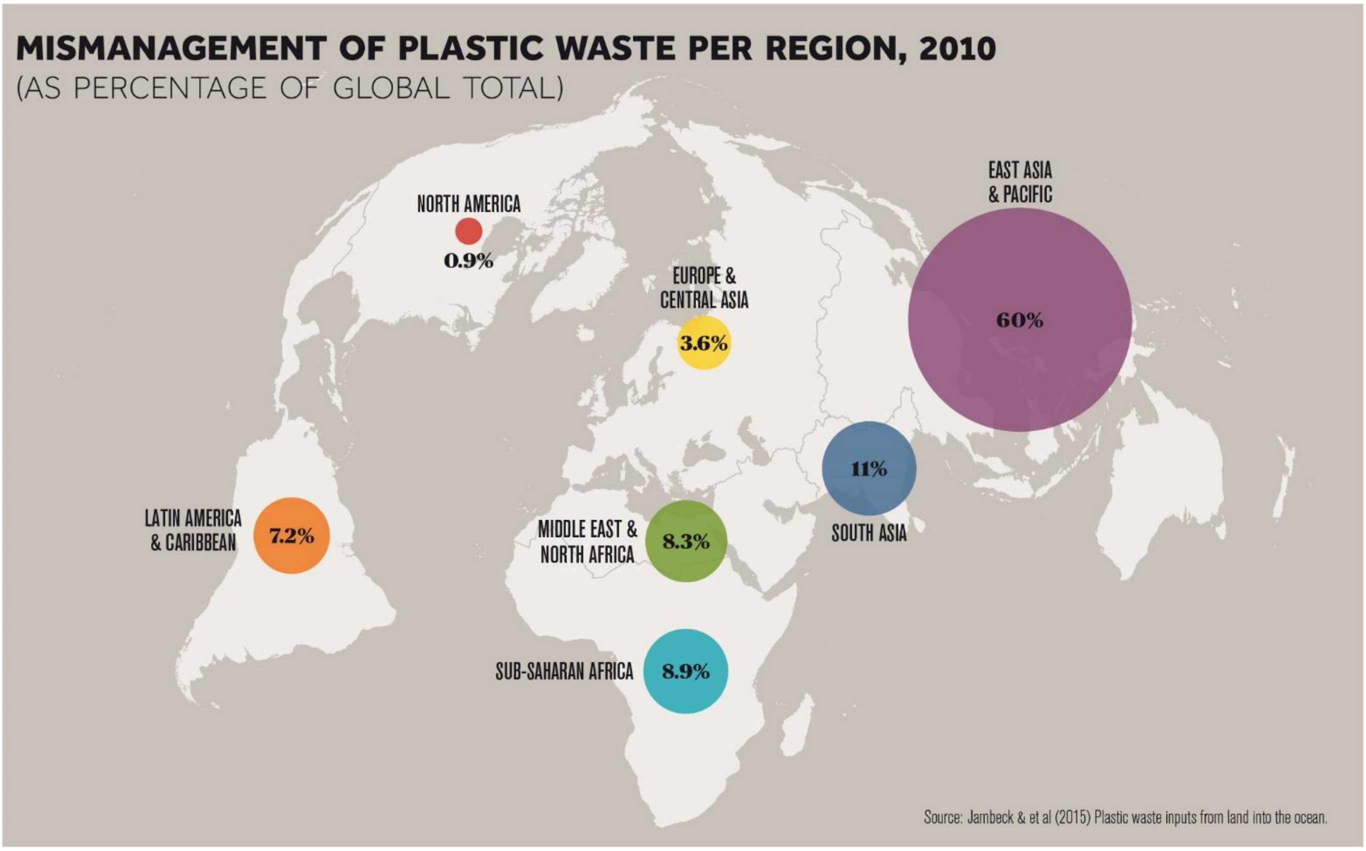


Figure 16: Share of global mismanaged plastic by region, 2010[44]

a. Escapes of plastics

Many efforts have been made over the past decade in defining and quantifying different sources of plastic leakage either at country level or globally; into the terrestrial environment and into waterways[111,112,79](Table 10). It has been defined that plastic may escape and is found in the environment in the form of macroplastics or microplastics.

Macroplastics are large plastic waste that usually enter the marine environment in their manufactured sizes, while small plastic particulates below 5 mm in size called microplastics[113].

Microplastics may be plastic that directly escapes into the environment in the form of small particles (e.g. microplastics in cosmetics, textiles etc.) or may be the result of plastic fragmentation once exposed in the environment due to photodegradation and/or weathering.

Table 10: Plastics and microplastics losses to the environment

Study	Million tonnes of plastics losses to the environment	Million tonnes of microplastics losses to the environment
Ryberg et al., 2019[114]	9.2	3.0
UN Environment, 2018[115]	8.28	3.01
Boucher and Friot, 2017[135]	-	3.5

Plastic escapes in the environment occur from a variety of land-based and ocean-based sources. The main on-land based sources of plastic escape are the [116] *uncontrolled dumping* of waste which is more usual the result of the absence of waste management systems in place and *littering by members of the public* from day-to-day and recreational activities.

Other sources of on-land and ocean-based plastic pollution are presented in Table 11.

Table 11: Categories of main sources of plastics & types of plastic input[79]

Main sources of plastics	Comments	Types of plastic input
Uncontrolled dumping	Uncontrolled dumping of waste from municipal sources: this uncontrolled management of waste occurs in low and lower middle-income countries, which is more usual than the result of the absence of waste management systems in place.	Household waste
Littering -and Fly-tipping	The causes of littering and illegal dumping (fly-tipping) in urban areas occur because of inadequate availability of litter bins along walkways, inadequate public awareness of their responsibilities as urban dwellers, and inadequate waste collection service. Littering occurs everywhere and often into drains, while fly-tipping is commonly on vacant plots, public spaces, or along waterways. Accumulated waste may attract disease vectors and contribute to clogging of drainage which is the main cause of severe flooding in cities[117]. According to ISWA (2017), littering hotspots in urban areas depend on a mix of consumer behavior, levels of deprivation, population density, traffic levels, the location of public events, and the number of visitors to different areas. According to the Department of Environment Food & Rural Affairs (2017), for 2015 and 2016, local authorities of England dealt with 936 thousand fly-tipping incidents, an increase of 4% compared to previous years.	Food wrappers, containers, plastic bags, plastic cups, plastic straws, PET bottles, and other plastic litter
Escape of plastic from mismanaged SWM activities	Plastics may escape from formal and informal waste management actives at all stages including, storage, collection, transportation and treatment of plastic waste.	Waste, plastic items and materials of all types, including plastic pellets
Sanitary items & consumer cosmetic products	These types of products can be captured at wastewater treatment plants as they are small[118]. Though there are some cases where due to rain levels exceeding sewage treatment facilities can enter waterways.	Sanitary items & consumer cosmetic products
Synthetic fibres from washing clothes	These microfibres pass through domestic wastewater into sewage treatment plants where some of the tiny plastic fragments are captured as part of sewage sludge. The rest passes through into rivers and eventually, oceans. According to Falco (2019)[119], microfibres released during washing range from 124 to 308 mg for kg of washed fabric depending from the type of washed garment that corresponds to several microfibres ranging from 640,000 to 1,500,000. According to Napper (2016)[120], an estimation of over 700.000 fibres could be released from an average 6 kg wash load of acrylic fabric. This outcome of the study indicates that fibres released by washing of clothing could be an important source of microplastics to aquatic habitats.	Microfibres
Industrial	The plastic generated by industrial activities contains resin pellets, the virgin material used within the plastic manufacturing process. Through disposing and/or transporting them, they can end up to the environment.	Microplastics

Main sources of plastics	Comments	Types of plastic input
	Europe, North America and some fast-growing countries in Asia can observe the industrial plastics in rivers and the marine environment. More specifically, automotive, furniture, clothing and large packaging manufacturing companies are the important sectors which pollute the environment with plastic.	
Agricultural & Horticultural	Not collected and well managed plastic such as mulch films are sources of microplastic pollution in soils and waterways. (see section above)	Irrigation plastic pipes, pots, plastic mulch and other plastic films/sheets from agriculture have been reported as sources of riverine plastics.
Fisheries & shipping in waterways	Fishing industry is one of the most polluting industries in the world, responsible for 1 million tonnes of ocean plastic waste (Siegel, 2018)[121]. Nets, fishing line and bait boxes have been found in rivers coming from items related to the recreational and commercial activities of fishermen. These types of plastic affect the marine environment.	Nets, fishing line, bait boxes from fisheries; industrial plastic packaging, strapping, plastic containers etc. from shipping.
Micro-plastics from road vehicle tires	The type of plastic from road vehicle tires are the largest single use microplastics. Based on the study of Jan et al. (2017)[122], the relative contribution of tire wear and tear to the total global amount of plastic ending up in our oceans is estimated to be 5–10%. However, according to other studies[,123][124], 30 vol% of the microplastic particles that pollute rivers, lakes and oceans consist of tire wear, thus affecting aquatic wildlife.	Particles of rubber dust

Dumping of plastics in the environment may occur in two ways:

1. Direct dumping of the plastic into the terrestrial and/or surface aquafers. This includes high amounts of plastic dumped directly into the rivers.
2. After the plastic is collected, it could end-up to non-engineered landfills or dumpsites.

<u>The case of dumpsites</u>

It is estimated that of the entire world's waste, 33% ends up in uncontrolled dumpsites and up to 25% at unspecified landfills[58]. Many of these dumpsites are so poorly regulated that the waste in them overflows directly into the ocean. This phenomenon is the main source of the problem of plastic pollution in our oceans. In the Waste Atlas Report (2014)[125] it has been stated that 44 out of the 50 largest dumpsites around the world are very close to natural resources (less than a 10 km distance), including several rivers and lakes, which are certainly affected (See Table 12). The annual waste disposed of to those 50 dumpsites is more than 21.5 million tonnes per year and the waste in place has been estimated between 258-368 million tonnes.

44 of largest dumpsites around the world are close to natural resources

Table 12: The world's 50 Biggest Dumpsites [125]

Continent	Country	City	Site Name
Africa	Ghana	Accra	Agbogbloshie
	South Africa	Port Elizabeth	Arlington
	Nigeria	Ibadan	Awotan (Apete)
	Kenya	Dandora	Dandora
	Mali	Bamako	Doumanzana
	Nigeria	Port Harcourt	Eneka
	Nigeria	Lagos	Epe
	Sierra Leone	Freetown	Granville Brook
	Mozambique	Maputo	Hulene
	Kenya	Mombasa	Kibarani
	Republic of South Sudan	JUBA	Lagoon
	Nigeria	Ibadan	Lapite
	South Africa	Kagiso	Luipaardsvlei
	Senegal	Dakar	Mbeubeuss
	South Africa	Pietermaritzburg	New England Road
	Nigeria	Lagos	Olushosun
	Tanzania	Pugu	Pugu Kinyamwezi
	Nigeria	Lagos	Solous2
Asia	Jordan	Zarqa	Al Akaider
	Jordan	Mafraq	Al Husaineyat
	Jakarta	Bekasi	Bantar Gebang
	Kyrgyzstan	Bishkek	Bishkek
	India	Bangalore	Bruhat Bangalore Mahanagara Palike
	Gaza strip	Deir al Balah	Deir al Balah
	India	Mumbai	Deonar
	India	New Delhi	Ghazipur
	Myanmar	Yangon	Htain Bin

Continent	Country	City	Site Name
	Myanmar	Yangon	Htwein Chaung
	Pakistan	Surjani	Jam Chakro
	Gaza strip	Gaza city	John al Deek
	Pakistan	Lahore	Mehmood Booti
	Philippines	Quezon City	Payatas
	Gaza strip	Rafah	Sofa
	Indonesia	Denpasar	Suwung
	Timor Leste	Tibar	Tibar
Europe	Ukraine	Alushta	Alushta
	Serbia	Belgrade	Vinca
Latin America	Argentina	San Carlos de Bariloche	Bariloche
	Peru	Puno	Cancharani
	Peru	Trujillo	El Milagro
	Brazil	Brasilia	Estrutural
	Peru	Cusco	Jaquira
	Bolivia	Cochabamba	K'ara
	Peru	Arequita	Quebrada Honda
	Peru	Reque	Reque
Caribbean	Guatemala	Guatemala City	El Trebol
	Nicaragua	Managua	La Chureca
	Honduras	Tegucigalpa	Tegucigalpa
	Haiti	Port au Prince	Trutier
	Dominican Republic	Santo Domingo	La Duquesa

There are not many studies that report the amount of plastic waste present in dumpsites. However, a recent study has provided some estimates for plastic waste in the 2380 dumpsites spread across Thailand. Taking the average composition of waste analysis from the current study, the total capacity of dumpsites in the country is 231.08 million tonnes and the accumulated plastic waste is 97.48 million tonnes[126].

<u>The case of rivers</u>

It is estimated that between 1.15 and 2.41 million tonnes of plastic waste currently enters the ocean every year from rivers, with over 74% of emissions occurring between May and October. The top 20 polluting rivers, mostly located in Asia, account for 67% of the global total (Table 13)[127].

1.15 -2.41 Mt of plastic waste enters the ocean every year from rivers

Table 13: Top 20 polluting rivers as predicted by the global river plastic inputs model [127].

Catchment	Country	Midpoint mass input estimate (t/yr)
Yangtze	China	3.33×10^5
Ganges	India, Bangladesh	1.15×10^5
Xi	China	7.39×10^4
Huangpu	China	4.08×10^4
Cross	Nigeria, Cameroon	4.03×10^4
Brantas	Indonesia	3.89×10^4
Amazon	Brazil, Peru, Columbia, Ecuador	3.89×10^4
Pasig	Philippines	3.88×10^4
Irrawaddy	Myanmar	3.53×10^4

Catchment	Country	Midpoint mass input estimate (t/yr)
Solo	Indonesia	3.25×10^4
Mekong	Thailand, Cambodia, Laos, China, Myanmar, Vietnam	2.28×10^4
Imo	Nigeria	2.15×10^4
Dong	China	1.91×10^4
Serayu	Indonesia	1.71×10^4
Magdalena	Colombia	1.67×10^4
Tamsui	Taiwan	1.47×10^4
Zhujiang	China	1.36×10^4
Hanjiang	China	1.29×10^4
Progo	Indonesia	1.28×10^4
Kwa Ibo	Nigeria	1.19×10^4

Littering

Although, Jambeck et al. (2015)[44], has provided a uniform estimation of plastic escape from littering activities as 2% for all countries, however plastic littering may vary significant from country to country. Littering estimations are by nature complex to produce and depends of consumption and littering behavioral patterns. In addition, the degree of leakage of plastic litter depends on effectiveness of municipality cleaning operators. This fraction of plastic pollution is by definition not measured, and is very difficult to estimate.

There are limited studies estimating littering in terms of types of litter counted per different site, types within urban environments that could be accounted as potential escape to the terrestrial and marine environment.

Plastic items are second in the rank of litter items detected in field studies following cigarette butts which contain plastic filters. South Australia's litter study conducted in 2019 estimated that 30% of items littered in urban centers are plastic followed by cigarette butts (32%). Most of the littering has occurred in highways (34% of total litter items) and car parks (17% of total litter items)[128] (Figure 17).

Cigarette butts: top litter item

Another study conducted in Ireland showed that plastic items represent around 18% of total litter items and the main causes of littering have been passing pedestrians (42% of causing factors) and passing motorists (22.4% of causing factors)[129] (Figure 18).

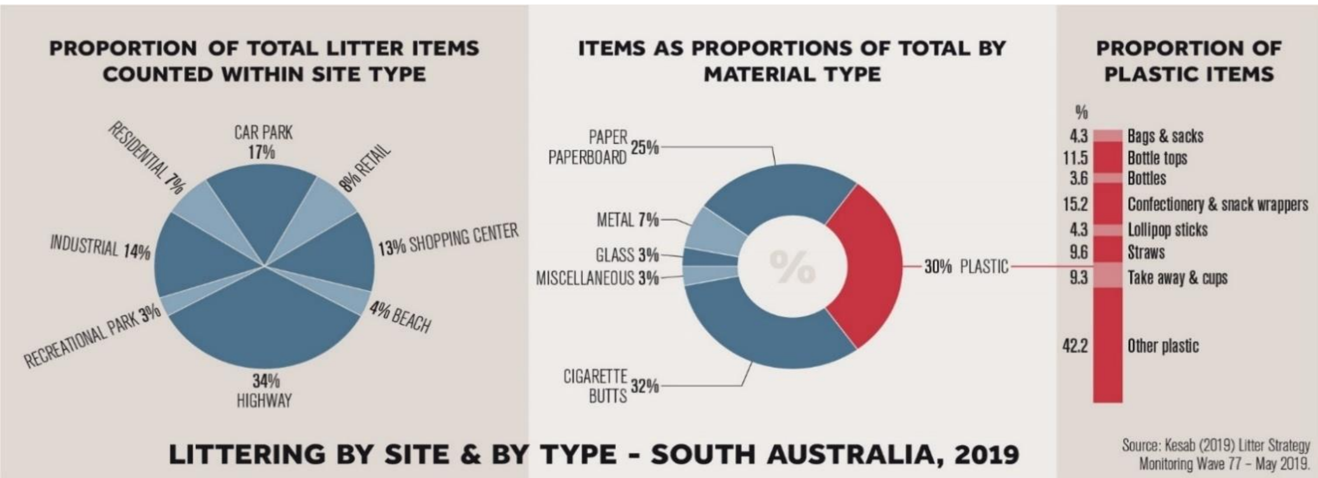


Figure 17: Littering by site & by type in South Australia, 2019

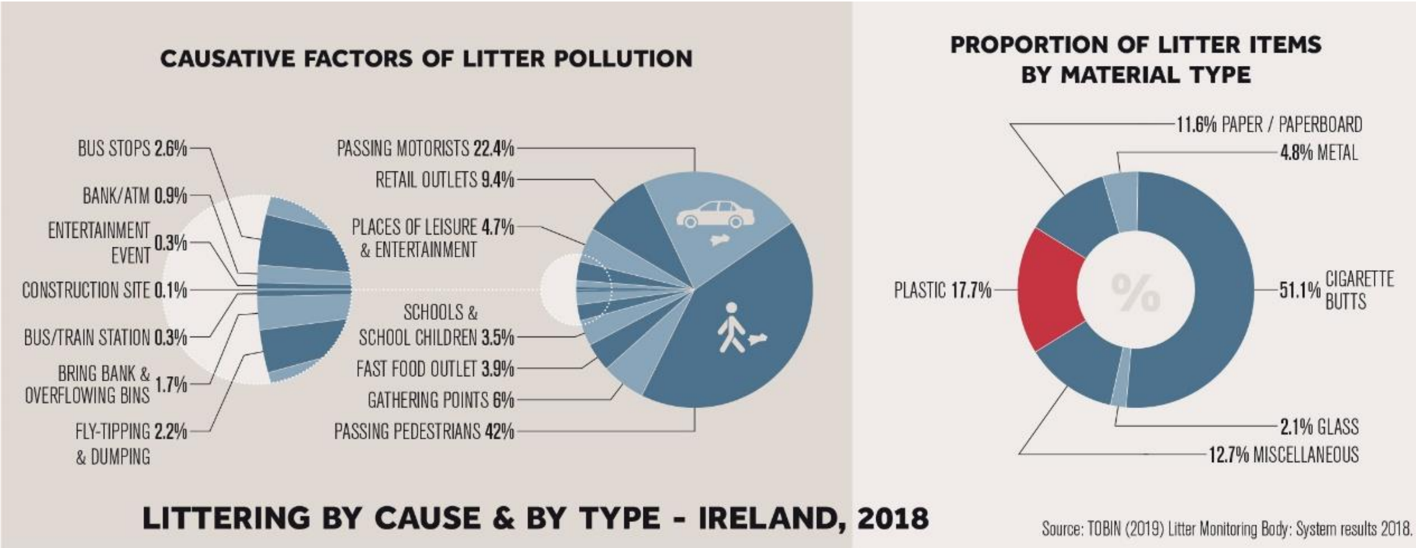


Figure 18: Littering by cause & by type in Ireland, 2018

b. Final destination

Plastic waste is accumulated in the landfills and the natural environment. Compared to the marine environment, there is a lack of data regarding the accumulation of plastic debris in terrestrial and marine environments [130]. Final destination of plastic waste are:

- Landfills and dumpsites
- Vegetation
- Coastline (Beach)
- Ocean/lakes
- Wildlife & the human

Disposed in landfills

Considerable quantities of plastic are disposed of in landfills. However, the number of landfills in some locations are exponentially increasing which means that less space is available. Also, in the future, because of the longevity of plastic, disposal to landfill may be a problem. According to Teuten et al. (2009)[131], landfills can present a significant source of contaminants, such as BPA, to aquatic environments.

Trapped in vegetation

Mismanaged plastic may also be found trapped in the vegetation exposed to weather conditions and photodegradation. There is no sufficient data on the amount of plastic trapped in vegetation.

Polluting coasts

Ocean Conservancy holds a long record of items collected during annual Beach Cleanup activities taking place around the globe since the 80s. The International Coastal Cleanup organized in 2018 with the participation of 1,080,358 volunteers removed 10,584 tonnes of litter totaling 35.890 km of coastline around the world. From the collected items (97,457,984) the top-ten most commonly found items were made of plastic (including cigarette butts, which contain plastic filters) and these are[132]:

1. Cigarette butts 5,716,331
2. Food wrappers: 3,728,712
3. Straws stirrers: 3,668,871
4. Forks, knives, spoons: 1,968,065
5. Plastic beverage bottles: 1,754,908
6. Plastic bottle cups: 1,390,232
7. Plastic grocery bags: 964,541
8. Other plastic bags: 938,929
9. Plastic lids: 728,892
10. Plastic cups, plates: 656,276

The National Waste Agency throughout Algerian coast has reported that nearly 81% of the collected waste are plastics, mainly single-use plastics[133].

Reaching the Ocean

The last sink of plastic garbage is the oceans. Due to the circular ocean currents, plastic can be moved and transported around the world. Floating plastic waste has been shown to accumulate in five subtropical gyres that cover 40 percent of the world's oceans[20].

There have been different attempts from different authors to provide the number of plastics entering the environment and the sea each year (Table 14). It is reported that more than 10 million tonnes of plastic enter the ocean per year with an estimated 40% of that falling into the single use category[134], while hundreds of thousands of tonnes of lost abandoned and discarded fishing gear litter the world's oceans. Microplastics account for around 1.5 million tonnes of plastic entering the ocean[135].

An ocean of single-use plastics

Table 14: Plastics and microplastics entering the marine environment

Study	Million tonnes of plastics entering the marine environment	Million tonnes of microplastics entering the marine environment
Jambeck et. al, 2015[44]	4.8-12.7	n/a
EUNOMIA, 2016[136]	12.2	0.95
Boucher and Friot, 2017[135]	10	1.5

According to Boucher and Friot[113] that most of the global plastic leakage in the ocean comes from China (2.21 million tonnes per year) followed by India and South Asia (1.99 million tonnes year) (Figure 19).

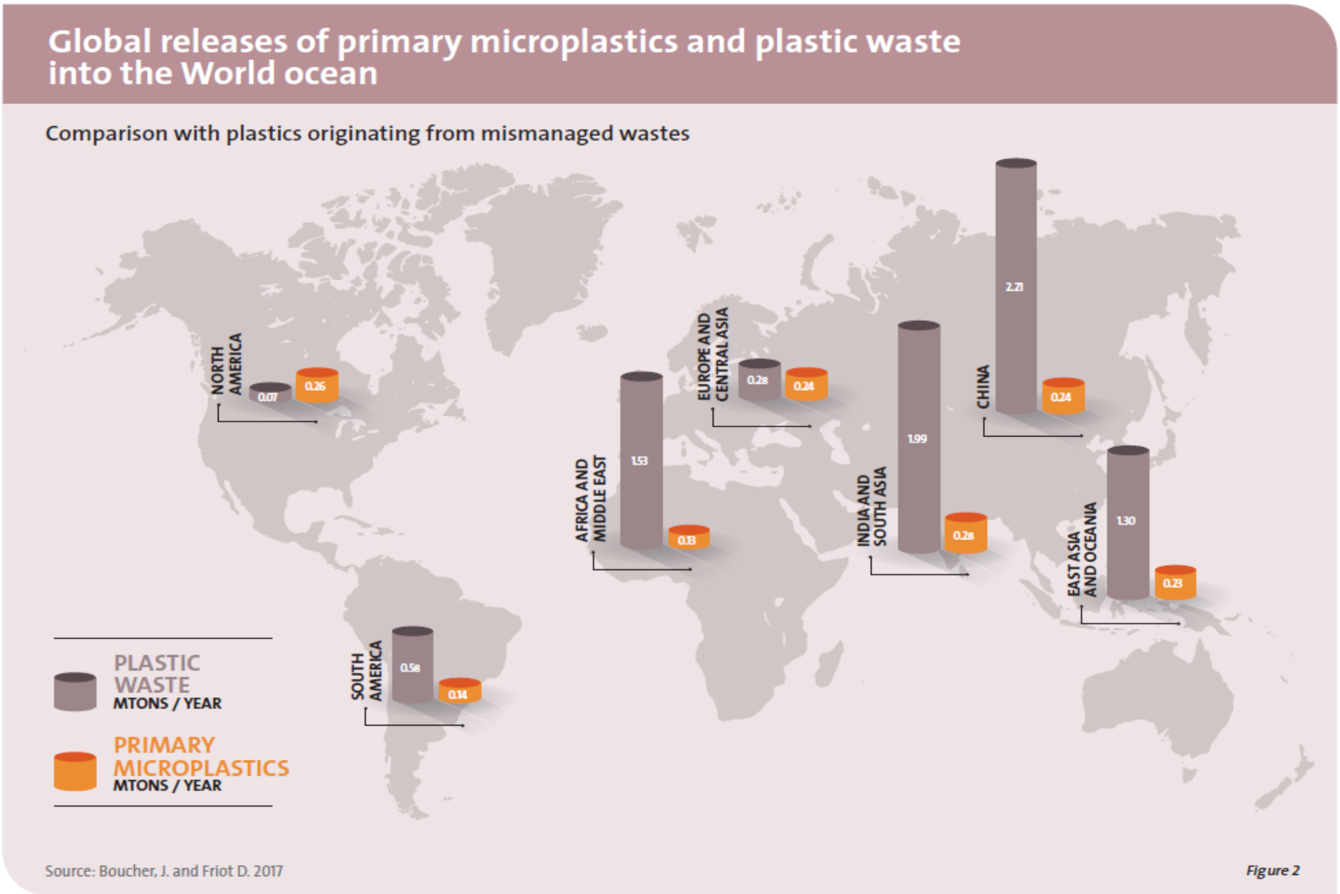
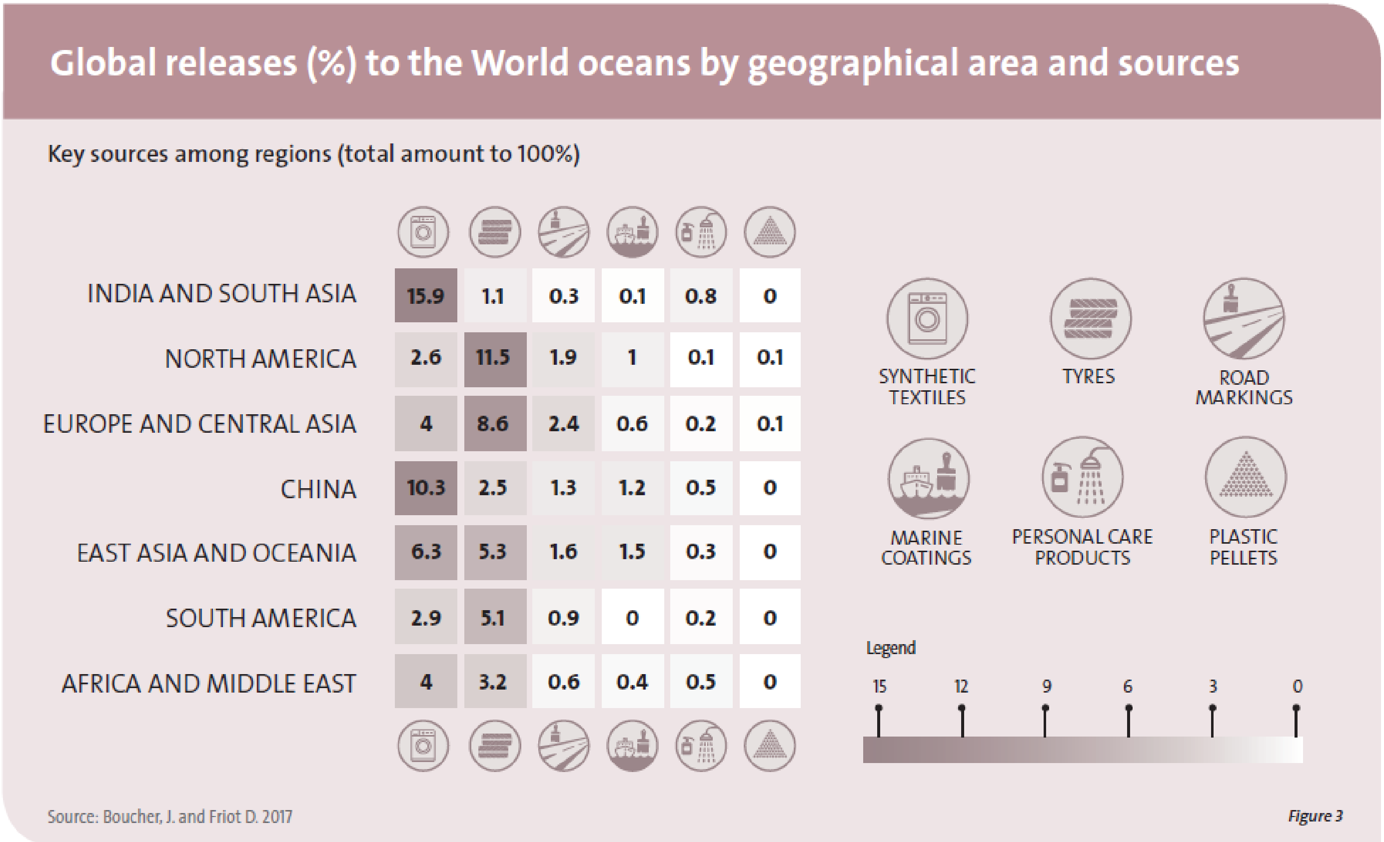


Figure 19: Global releases of primary microplastics and plastic waste into the world Ocean. Adopted from Boucher et. al, 2019[113]

Macroplastics in the marine environment are expected to have the same composition to the macroplastic found on the coastline also including abandoned and discarded fishing gear.

Microplastics in the marine environment mainly derives from washing of synthetic textiles (46%) followed by tiny bits of tyre rubber material (37%) due to car tyres wear down (Figure 20)[113].

Tyres! The plastic polluter we never thought about



INDIA AND SOUTH ASIA	15.9	1.1	0.3	0.1	0.8	0
NORTH AMERICA	2.6	11.5	1.9	1	0.1	0.1
EUROPE AND CENTRAL ASIA	4	8.6	2.4	0.6	0.2	0.1
CHINA	10.3	2.5	1.3	1.2	0.5	0
EAST ASIA AND OCEANIA	6.3	5.3	1.6	1.5	0.3	0
SOUTH AMERICA	2.9	5.1	0.9	0	0.2	0
AFRICA AND MIDDLE EAST	4	3.2	0.6	0.4	0.5	0

Figure 20: Global releases (%) of primary microplastics to the world's oceans by geographical area and sources. Adopted from Boucher et. al, 2019[113]

Frozen microplastics in Arctic sea ice[137]

Wildlife & Human

Plastic affects both wildlife and human well-being.

Large plastic items can be ingested by marine megafauna, which can ultimately lead to death by starvation. Plastic bags, fishing nets and gear as well as beverage bottle caps, were rated as most harmful among the 20 most common marine litter items to (marine) wildlife due to the risk of entanglement[138].

In addition human may ingest plastics through the food chain or in direct contact to plastic products. According to a recent study the average person eats at least 50,000 particles of microplastic a year and breathes in a similar quantity[139].

Microplastics have been detected in bottled water and other beverages[140]. The Public Library of Science's journal found that on average, beer contains 4.05 man-made particles, mostly plastic fibers, per liter[141]. In addition, tests of 250 bottles from 11 bottled water brands revealed microplastics in 93 percent of the samples, with an average of 325 particles per 34 fluid ounces (1 liter) of water[142].

In countries of the Global South mismanaged plastic waste comes also with great cost for human health as it has been reported in recent reports of GAIA, 2019[95] and CIEL et. al. 2019[140].

ANNEX I

EPR schemes for packaging & taxes/bans on plastic bags

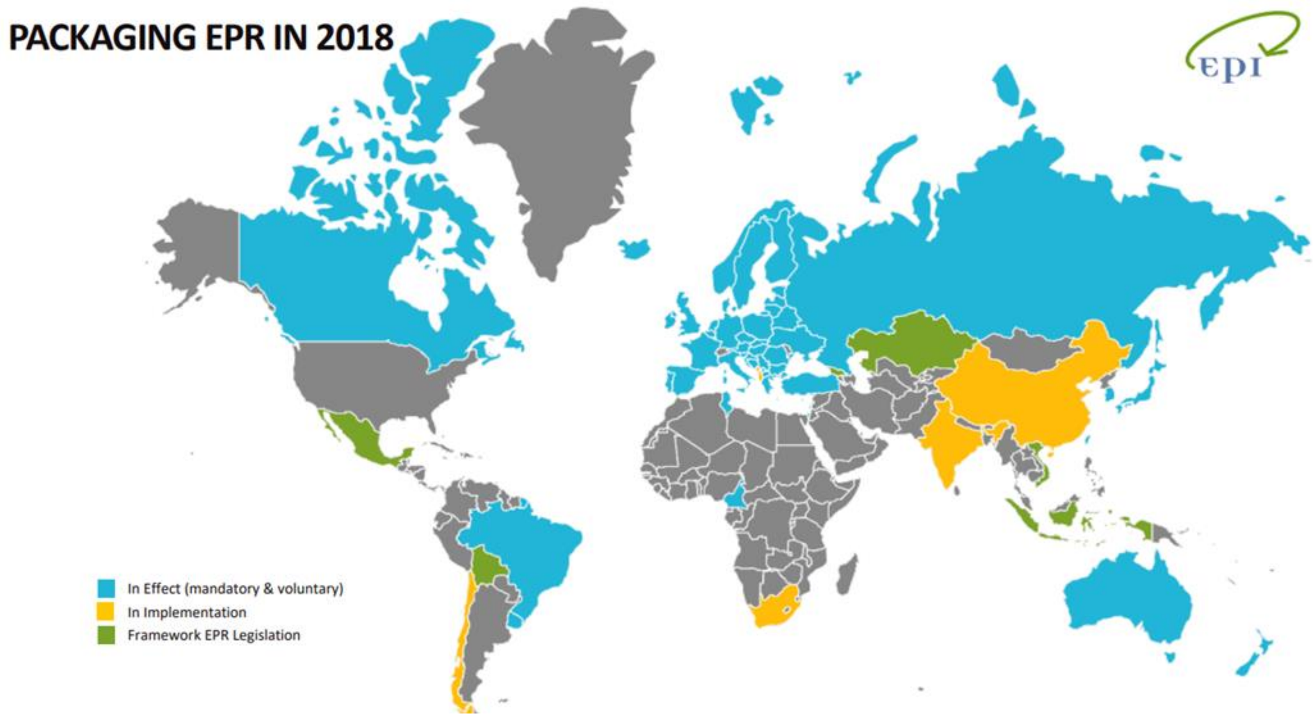


Figure i: Extended Producer Responsibility (EPR) schemes around the world. Adopted from Environmental Packaging International, 2018[143]

Table i: Countries with plastic bag policies. Adopted from Knoblauch et. al, 2018[144]

Year	Country	Type of Policy	Global North(N)/ Global South (S)
1991	Germany	tax	N
1994	Denmark	tax	N
1999	Bhutan	ban	S
2002	Bangladesh	ban	S
2002	Ireland	tax	N
2002	India	ban	S
2003	South Africa	tax	S
2003	Taiwan	ban	N
2004	Rwanda	ban (plastic bags banned from shops)	S
2004	Luxemburg	voluntary agreement	N
2005	Eritrea	ban	S
2005	India	ban (including thicker bags)	S
2005	Somaliland	ban	S
2005	Bhutan	ban (reinforced due to ineffectiveness)	S

Year	Country	Type of Policy	Global North(N)/ Global South (S)
2006	Tanzania	ban	S
2006	Romania	tax	N
2007	Kenya	ban (manufacture and import)	S
2007	Kenya	tax (on other bags)	S
2007	Uganda	ban (plastic bags < 30 μm)	S
2007	Uganda	tax (for bags > 39 μm)	S
2007	Botswana	tax	S
2008	Rwanda	ban (plastic bans banned completely)	S
2008	China	tax	S
2008	China	ban	S
2009	Macedonia	tax	S
2009	Hong Kong	tax (for supermarkets and retail outlets)	N
2009	South Australia	ban	N
2009	Malta	tax	N
2010	Gabon	ban	S
2010	Mexico	ban	S
	Australia Capitol	ban	S
2011	Territory, Norther Territory	ban	N
2011	Republic of Congo	ban	S
2011	Kenya	ban (renewed ban on manufacture and import for thicker bags, due to former ineffectiveness)	S
2011	Kenya	tax (on other bags)	S
2011	Malaysia, state of Penang	tax	S
2011	Wales	tax	N
2011	Ethiopia	Ban (import and manufacture of single use plastic bags)	S
2012	Bulgaria	tax	N
2012	Serbia	tax	S
2013	Tazmania	ban	N
2013	Uganda	ban (extended to manufacturing and use of most plastic bags)	S
2013	Italy	ban	N
2013	Mauritania	ban	S
2013	Macedonia	ban	S
2013	Niger	ban	S
2013	Northern Ireland	tax	N
2013	Haiti	ban	S
2014	Scotland	tax	N
2014	Cameroon	ban	S
2014	Ivory Coast	ban	S

Year	Country	Type of Policy	Global North(N)/ Global South (S)
2015	England	tax	N
2015	Hawaii	ban	N
2015	Hong Kong	tax (levy widened to all retailers)	N
2015	Gambia	ban	S
2015	Madagascar	ban	S
2015	Senegal	ban	S
2015	Malawi	ban	S
2015	Portugal	tax	N
2016	Canada	voluntary agreement	N
2016	California	ban	N
2016	Netherlands	tax	N
2016	Puerto Rico	ban	N
2016	Morocco	ban	S
2016	Papua New Guinea	ban	S
2016	Mozambique	tax	S
2016	India	Ban (including thicker bags)	S
2016	Guinea-Bissau	ban	S
2016	France	ban	N
2016	Nepal	ban	S
2016	Germany	voluntary agreement (due to EU legislation)	N
2016	Finland	voluntary agreement	N
2016	Antigua and Barbuda	ban	S
2017	Israel	tax	N
2017	Kenya	ban (regarding use, manufacture and importation of plastic bags)	S
2017	Benin	ban	S
2017	Sri Lanka	ban	S
2017	Tunisia	ban	S
2017	Estonia	tax	N
2017	Georgia	ban	S
2017	Austria	voluntary agreement	N
2017	Catalonia	tax	N
2017	Norway	tax	N
2017	Switzerland	voluntary agreement	N
2017	Colombia	tax	S
2017	Colombia	ban	S
2017	Moldova	ban	S
2018	Wallonia, Brussels	ban	N
2018	Cyprus	tax	N
2018	Czech Republic	tax	N
2018	Poland	tax	N
2018	Greece	tax	N

Year	Country	Type of Policy	Global North(N)/ Global South (S)
2018	lithuania	tax	N
2018	Luxemburg	tax	N
2018	Slovakia	tax	N
2018	Panama	ban	S
2018	Australia	ban	N
2018	Vanuatu	ban	S
2018	Spain	tax	N
2019	Turkey	ban	S
2019	Croatia	tax	N
2019	Latvia	tax	N
2019	Belize	ban	S
2019	Jamaica[145]	ban	S
2020	Ethiopia	ban (on plastic bags use)	S
2020	Cambodia	tax	S
2020	Bahamas	ban	N
n.d	Sweden	tax	N
n.d.	Hungary	voluntary agreement	N

ANNEX II

Segregation and collection stage

USA

The National Waste & Recycling Association has reported that 25% of the materials source separated and collected for recycling in U.S. are sent to landfills since they are too contaminated (commingled-stream 1.6% contamination and dual-stream 10.8% - single stream 27%)[146].

According to the "Waste Management" firm contamination in single stream recyclables entering MRFs in the U.S. between September 2011 to June 2013 is on average 16% of inbound tonnes including non-recyclable materials and low-value materials. This contamination cost is an average of $140 per tonne[147].

MRF operators in the U.S. report that curbside collection presents a particularly large contamination challenge for their units since materials that come from their facilities are contaminated to a range between 15% to 25%[148].

In Minnesota (U.S.) 9% of local recycling is contaminated, dirty or heavily mixed with non-recyclables (e.g. dippers)[149].

Nearly 1,000 recycling plants in California alone have shut down within the last two years due to the recycling contamination crisis[150].

The Recycling Partnership and the Massachusetts Department of Environmental Protection (MassDEP) recently wrapped up a yearlong project to craft and test a protocol for clamping down on contamination in residential curbside recycling. Based on the findings of this project contamination levels of household recyclables entering the MRF unit in Memphis, Tennessee are too high. Top contaminants from the carts (by weight) are: tanglers (1%), food waste (2%), wood & yard waste (3%), liquids (3%), scrap metal (4%), textiles (4%), film (8%), unacceptable plastics (10%), refuse in bags (14%), all other (21%), recycling in plastic bags (29%)[151].

In the city of Lyn (U.S.) communities around the country typically produce contamination levels between 10 and 20%. Contamination include not only common contaminants such as food waste, but also other wood, propane tanks, and garden hoses even dog chains, ropes, extension cords that cannot be recycled[152].

Canada

Many cities in Canada are facing high rates of contamination in the stream of recyclables (blue bin). In Toronto 26% of the blue bin material (recyclables) heads to the landfill due to contamination[153]. In addition, Edmonton is one of the Canadian cities with the dirtiest recycling at 24% of contamination[154].

Table i: Rate of contamination of residential recycling in main cities of Canada[154]

City	Rate of contamination of residential recycling (blue bin)
Toronto	26%
Edmonton	24%
Halifax	21%
Fredericton	14%
Calgary	13%
Prince Edward Island	13%
Winnipeg	13%
Regina	11%
Montreal	7,5%
Ottawa	5%
Vancouver	4.6%
St John's	3%
Whitehorse	No city data available
Yellowknife	No city data available

England

WRAP has reported that in 2012-13, between 0% and 27% of material input to MRFs in the UK were rejected and sent for waste to energy or landfill. Anecdotal evidence suggests the true figure for contamination could be much higher than that since the reported 'rejected tonnage' contamination in bales dispatched to re-processors or in materials sent for further sorting at MRFs was not included[155].

Findings of the "Recycling Tracking Survey 2018" prepared by WRAP revealed that 76% of households in England put at least one unacceptable item in their recycling collection. The most common items that contaminate the recycling bin include plastic bags and wrapping (29%), toothpaste tubes (24%), dirty pizza boxes (21%), bubble wrap (14%) and plastic carrier bags (14%)[156].

In 2017, over 467,000 tonnes of household recycling in England was reported as rejected from recycling plants that represent less than 5% overall collected recyclables, although in some areas levels of contamination were much higher[157].

Germany & Denmark

Based on the findings of the 2012 Plastic Zero Life funded project the share of contaminants, non-targeted materials and lost material at sorting facilities in examined facilities in Germany and Denmark was as high as 50% in many of the cases.

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