The Fate of Synthetic Polymers - An Analysis On the Future of Plastic Waste

Volker Jansen.Ph.D

Keywords: plastic waste Management, live-cycle of synthetic polymers, recycling, primary plastics, secondary plastics, micro plastics

Abstract

Synthetic polymers have been indispensable since the 1950s and have long been under scrutiny from an environmental perspective. However, there is a lack of reliable global information, especially on the fate of plastics at the end of their life. By identifying and aggregating scattered data on the production, use and disposal of polymer resins, synthetic fibres and additives, the first global analysis of all plastics ever produced was conducted in 2017 by Roland Geyer, Jenna Jambeck and Kara Lavender Law. It is estimated that between 7.3 and 8 billion tons of plastics have been produced to date. Disposal, however, remains problematic. Different studies speak of a global recycling rate of mere 9%. This paper examines the amounts of waste, the amounts of plastic added to the different recycling methods. After a short review of polymer history this paper analysis global waste management systems, waste treatment in compliance with production data, life cycles of synthetic polymers and raises pressing questions for the future.

1. Introduction and background

1933 Polyethylene was created in England by *Imperial Chemical Industries* or ICI for short. At that time, the chemical structure was a well-kept secret, as it was used to insulate radar cables (Britannica 2022). World War II demanded a fast development of the plastics industry and made new products a requirement. The invention of polyethylene was followed by polymers like polystyrene (PS) and nylon, which DuPont released in 1939. It was readily used for military products such as parachutes and ropes. Polymers were increasingly used during the war for the production of weapons and numerous auxiliaries to support the war machine. In a Time magazine article, it was noted that because of the war, ‘plastics have been

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turned to new uses and the adaptability of plastics demonstrated all over again' (Nicholson and Leighton 1942: 306).

During the 1950s then plastic manufactures turned to making consumer and packaging products. High Density Polyethylene or HDPE for short was already developed during the 1940s, however with inconstant results (Science History Institute 2022). The production methods improved during the early 1950s, which led to the Hula Hoop craze when HDPE was introduced to a greater amount1 (Holmes 2022).

In 1965 polysulfones, a family of thermoplastics were introduced for technical applications. The wide working temperature range of -100°C to 200°C, that allows polysulfone to go from a deep freezer directly to a steam table or microwave oven. This was the time when plastic debris in the oceans was first observed, a decade in which Americans and Europeans became increasingly aware of environmental problems.

The reputation of polymers fell in the 1970s and 1980s as anxiety about waste increased. The United States used to be dangerously polluted. Before 1970 the environment and its well-being were not a federal priority and in 1970 President Richard Nixon inaugurated the Environmental Protection Agency to promote environmental protection and waste management.

Eventually, during the 1980s and 1990s the first 'bioplastics' were developed to respond to the growing concerns of environmental conversation. Research continued and bioplastics as a class have resurged in production, however to a small degree, which is due to the specific properties, which limit their use.

Supermarket plastic bags quickly developed into a target for activists looking to ban one-use, disposable plastic sacks, and many cities in the US passed bag bans (Science History Institute 2022). At the turn of the century the ultimate symbol of the problem of plastic waste was the Great Pacific Garbage Patch, which has often been described as a swirl of plastic garbage the size of Texas floating in the Pacific Ocean.

Today, major concerns focus on additives such as bisphenol or BPA for short. This is a class of chemicals which belongs to the group of phthalates. These compounds make the polymer products more flexible, durable and transparent (2022). Phthalates pose a risk especially to the health of children. Despite rising concerns plastics and their components have long become an indispensable material in our lives.

Despite growing mistrust, plastics are critical to modern life, and today plastics have outgrown most man-made materials. They are regularly used to a great amount in packaging, construction, for computers and smart phones, in machines and for consumer products, just to name the most important applications.

The majority of synthetic monomers used to make polyethylene, propylene, polystyrene, and other plastics are derived from fossil hydrocarbons. None of the commonly used plastics are biodegradable. As a result, they accumulate, rather than decompose, in landfills or the natural environment. There is now an estimated 30 million tons of plastic waste in seas and oceans, and a further 109 million tons has accumulated in rivers. 'The build-up of plastics in rivers implies that leakage into the ocean will continue for decades to come, even if mismanaged plastic waste could be significantly reduced' (Bremer 2022). According to the OECD (2022) the world is producing twice as much plastic waste as two decades ago, with the bulk of it ending up in landfill and incinerated, which mean converted into CO_2, or leaking into the environment. On a global scale only 9% are reported to be recycled for reuse. Contamination of freshwater systems and terrestrial habitats is also increasingly reported. Consequently, contamination of the natural environment with near permanent plastic waste is a growing concern, which include synthetic polymers, additives such as plasticizers and synthetic fibres. According to Roland Geyer, Jenna Jambeck and Kara Lavender Law (2017) '[p]lasticizers, fillers, and flame retardants account for about three quarters of all additives. The largest groups in total non-fib[re] plastics production are PE (36%), PP (21%), and PVC (12%), followed by PET, PUR, PS and PA (<10% each)'. It is assumed that these seven polymer groups account for 92% of all plastics ever made, whereas polyester, most of which is PET, accounts for 70% of all synthetic fibre production. Approximately42% of all non-fibre plastics have been used for packaging, which is predominantly composed of PE, PP, and PET. The building and construction sector, which has used 69% of all PVC, is the next largest consuming sector, using 19% of all non-fibre plastics (2017).

When synthetic polymers and fibres are not biodegradable, the question of the fate of discarded plastic products arises, which includes the consideration of appropriate recycling or downcycling methods and energy recovery. The following paper examines the current fate of polymer waste and its treatment based on an analysis of available data.

2. Materials and Methods (Methodology)

Most information on the global fate of plastics at the end of their life cycle is unreliable. The search for reliable data and the analysis of such data is the core element of the methodological approach introduced for this research project. Many of the sources found on the internet or in the literature are ambivalent and do not provide the required information about the origin of the data used. The results presented in this paper are based on data-driven information from various official sources and research projects that can present and identify the source situation. Hence, only data that indicate a reliable source situation are used. Incomplete or ambivalent sources are excluded from this paper.

Major data for the end of use management in Europe and the United States has been obtained by the OECD and from several research related environmental projects. Some of the data on waste management for the rest of the world is based on data from the World Bank, as this source is a reliable data basis. Detailed and comprehensive solid waste management data for the United States were obtained from the U.S. Environmental Protection Agency. European data were retrieved from several reports by PlasticsEurope, which collectively cover 1996 to 2014. Chinese data were synthesized and reconciled from the English version of the China Statistical Yearbook, translations of Chinese publications and government reports, and additional waste management literature. As recommended by Daniel Hoornweg and Perinaz Bhada-Tata (2012) statistics on waste management for the rest of the world is based on figures released by the World Bank.

Concerning independent projects on the topic, the work of Roland Geyer, Jenna Jambeck and Kara Lavender Law provide a well-researched foundation for further analysis of the subject. They have examined the fate of plastics and presented a paper in Science Advance to shed light on the data of production, use and end-of-life management. In 2017 Roland Geyer, Jenna Jambeck and Kara Lavender Law developed the first global analysis of all mass-produce plastics ever manufactured. According to them, when including additives, which are used for the production of polymers, the amount of non-fibre plastics manufactured since 1950 increased to 7.3 billion tons. Synthetic fibres add another billion tons.

3. Results and discussion

Here we may raise the question of the lifetime of plastic products. According to Geyer, Jambeck & Law (2017) most of the plastics used for packaging and flexible films leave use the same year they are produced (Fig. 1). However, construction plastics are employed for decades, and were manufactured when production quantities were much lower. It is estimated that 30% of all plastics ever produced are still in use.

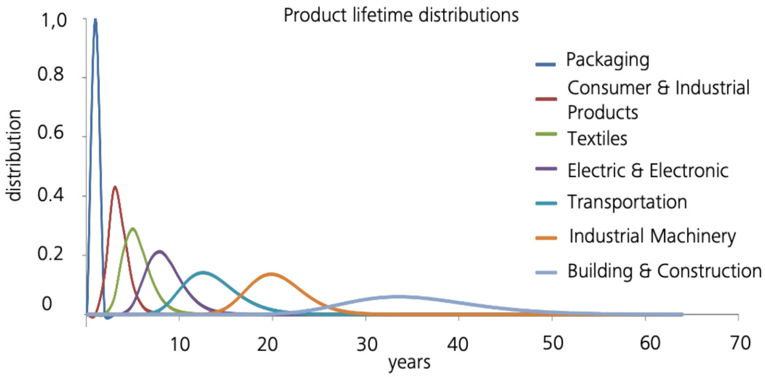

Fig. 1: *The lifetime of plastics in years (2017)*

Research suggests that for example, in 2015, 42% of primary non-fibre plastics produced (1.46 billion tons) entered use as packaging and 19% (65 million tons) as construction, whereas non- fibre plastic waste leaving use was 54% packaging (1.41 billion tons) and only 5% construction (12 million tons). Similarly, in 2015, PVC accounted for 11% of non-fibre plastics production (38 million tons) and only 6% of non-fibre plastic waste generation (16 Mt) (Geyer, Jambeck & Law 2017).

In 2015, 407 million tons of primary plastics entered the use phase, whereas 302 million tons left it (2017). Geyer, Lambert & Law (2017) concluded 'that plastic waste generation in 2010 was 274 million tons, which was 10% less than in 2017'. If we conservatively assume a linear rather than a (probably more realistic) dynamic growth, we determine for the year 2020 a plastic waste generation of 330 million tons, this is 10% higher than in 2015 and about 20% higher than in 2007.

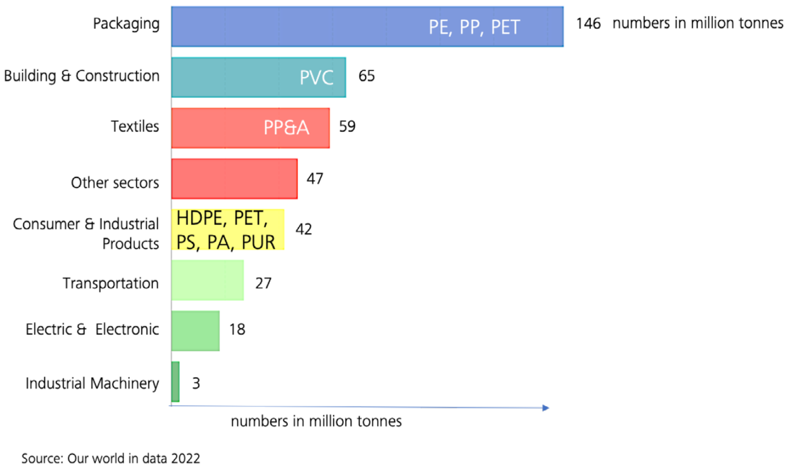

Fig. 2: *Primary plastic production by industrial sector (Our World in Data 2022)*

By the end of 2015 all plastic waste generated reached 5.8 billion tons of which 700 million tons were polyester, polyamide, and acrylic fibres, PP&A for short (OECD 2022).

Annual production of approximately 400 million tonnes of non-fibre plastics, of which 55% is discarded, according to Hannah Ritchie and Max Rosner (2022), has amounted to 7.3 billion tonnes of discarded plastics by end of December 2022 since the 1950s. If we include PP&A fibres the total amount of plastic waste will reach approx. 8.3 billion tons since 1950 of which 4,6 billion tonnes were discarded. Discarded means that the waste is not recycled, reused or incinerated; non-recycled discard includes waste that goes to closed or open landfill, littered, or lost to the environment.

According to the OECD (2022) 'global plastic waste set to almost triple by 2060'. Consequently, in 2060 humans would produce 660 million tons of plastic waste per annum compared to the roughly 400 million tons produced in 2022. If we consider this increase and assume that in 2022 220 million tons of plastic were discarded (55%) that would lead to 330 million tons of global discarded non-fibre plastic in 2060 if waste management does not change and no drastic measures are taken to implement new methods of recycling, reuse or avoidance.

Justine Barret (2020) asserts that it is quite difficult to estimate and measure the amounts of microplastics entering the environment. Assumptions of the amounts of microplastics released and formed are uncertain due to the undefined sources and a lack of standards for sampling and measurement. All the same Julien Boucher and Damien Friot (2020) suggest in a paper titled *Primary Microplastics in the Ocean*, published by IUCN in Switzerland in 2020, that at any rate 14 million tons of microplastics have accumulated on the world's ocean floor so far and that an additional (approximately) 1.5 million tons enter the oceans annually. The release of microplastics occurs throughout the whole plastics value chain, during production, transport and use, and most importantly at the end of product life.

Microplastics can be divided into two major types, depending on the formation processes involved: primary and secondary microplastics. Primary microplastics are directly released into the environment as plastic particles, whereby secondary microplastics are formed from the breakdown of larger plastic items in the environment (Eionet 2022). Once a plastic item has a size of less than 5mm, it is defined as microplastic (GESAMP 2015). Due to their small but also microscopic size, microplastics are readily ingested by a wide range of marine organisms (Wright, Thompson and Galloway 2013) and can have negative impacts on the health of marine life (Teuten et al. 2009). 'Given the long residence time of such sequestered particles relative to the lifetime of the organism, even slow chemical release may cause low but chronic delivery within the animal' (GESAMP 2015).

A number of national and international regulations (such as REACH) seek to identify and limit even small amounts of plastics that contribute to the problem of microplastic accumulation in the world's oceans. A good example is the focus on synthetic binders in printing inks, coatings and tie layers. The meaningfulness of these regulations is often questioned, as there is no globally binding enactment for the prevention of plastic waste entering the oceans. The European Chemicals Industry (2023) or ECHA for short recently launched their latest proposal concerning the formation of microplastics. They state that microplastics created by synthetic binders in printing ink, coatings and barrier layers cause considerable administrative burden, as for end of life purposes information must be provided concerning the identity of possible polymers used in inks, paints and coatings to give an estimate of the environmental impact. According to Verband der deutschen Lack- und Druckfarbenindustrie e.V. (2023) or Verband for short there is 'the possibility for enforcement authorities to request further information' regarding the nature of polymers used in inks and coatings. The Verband (2023) informs in their press release 4/2023 'Microplastics: Paints, coating and printing ink under pressure': 'In addition, the [enactment] provides for labelling obligation to prevent releases of microplastics into the environment. Entry into force of the restriction under REACH is planned for 2023'. Issued under the European chemical legislation REACH, the EU Commission's proposal follows the ECHA's findings 'that microplastics pose a risk to the environment that is not adequately controlled' (European Commission 2023). The aim of the new restriction is to reduce the microplastics released into the environment by printing inks and coatings by 0.2 to 0.6 per cent (Verband der deutschen Lack- und Druckfarbenindustrie e.V. 2023). According to the Verband '[t]his is neither effective nor proportionate'. The definition of microplastics in REACH on which the proposed restriction is based is 'too broad' (2023). In its definition it refers to most polymer-containing substances and mixtures (e.g. binding agents in paints, varnishes and printing inks). However, it is claimed by the Verband (2023) that many of the polymeric binders used in paints, inks and coatings do not enter the environment as microplastics. It is assumed that the proportion entering the oceans will be negligible compared to the amount of microplastics formed annually. The layer thicknesses of printing inks and coatings (1 to 10 micrometers) are many times smaller than those of plastic containers (20 to 500 micrometers and even thicker materials). It should be noted that the additives used in plastics have more relevance when it comes to microplastics than the synthetic binders used in printing inks. In order to fulfil the new reporting obligations, the German paints, coatings and printing ink industry claims to have extra costs of 6 million euros per annum (Verband der deutschen Lack- und Druckfarbenindustrie e.V. 2023).

Turning to another aspect. Geyer, Jambeck & Law (2017) compiled statistics from resin, fibres, and synthetic polymer additives from a number of industry sources and combined them according to type and sector. On average they found that non-fibre plastic contains 93% polymer resin and 7% additives by mass. If additives are included in the calculation, the amount of non-fibre plastics produced since 1950 increases from 7.3 to 7.8 billion tonnes in 2022. The scientists claim that '[p]lasticizers, fillers, and flame retardants account for [roughly] three quarters of all additives.' (2017).

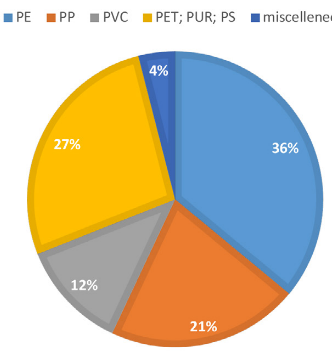

Fig. 3: *Major polymer types according to occurrence*

They assert that 'before 1980 plastic recycling and incineration were negligible. On the basis of limited available data, the highest recycling rates in 2014 were in Europe (30%) and China (25%),

whereas in the United States, plastic recycling has remained steady at 9% since 2012'. According to a study by the OECD (2022) globally only 9% of plastics waste is recycled, while 22% mismanaged, 49% ends up in landfills, and 19% is incinerated.

The mismanaged plastic waste is highest in the Middle East and Africa. The OECD (2022) suggests that 64% of plastic waste in Africa is mismanaged, which means littered or lost in the environment, whereas 30% ends up in landfills. Recycling and incineration are negligible in Africa. In the Middle East 40% of the plastic waste is mismanaged and 54% ends up in landfills. The lowest figures of mismanaged waste is true for the EU and OECD Asia.

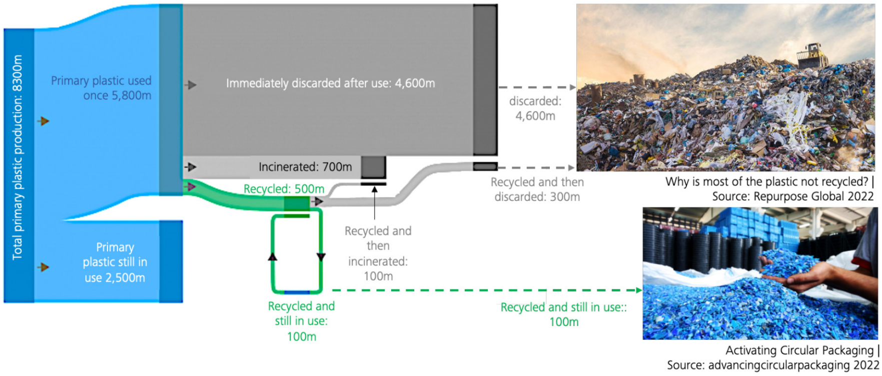

Fig. 4: *Production, use, and fate of all plastics ever made (Geyer et al. 2022)*

Most plastics in use today are primary plastics, made from crude oil or gas. Global production of plastics from recycled – or secondary – plastics has more than quadrupled, however, compared to discarded waste the recycling rate is still on a low level. According to the OECD (2022) the 'world community needs to create a separate and well-functioning market for recycled plastics, which are still viewed as substitutes for primary plastic'. They suggest that 'setting recycled content targets and investing in improved recycling technologies could help to make secondary markets more competitive and profitable' (2022). However, the low costs for crude oil and the high investment and operations costs for sustainable recycling methods, which require an expensive system of curb side collection and waste management stand against each other, which brings us to the question of which methods underlie the recycling of plastics.

The industry distinguishes between primary recycling, which describes a closed-loop circle of pre- consumer plastic scrap, which is recovered via mechanical recycling or physical processing, and secondary recycling, which comprises a downgrading of post-consumer, post-commercial plastic waste. Secondary recycling comprises mechanical recycling processes and physical reprocessing. However, the quality of the resulting product is lower than with primary recycling due to the contamination of packaging.

For primary and secondary recycling every item must be collected, sorted, directed into defined streams or reclaimed. Collection is the first step of a multi-step procedure leading to downcycling, reuse, or disposal of flexible plastic packaging waste.

Residual postconsumer flexible plastic packaging shows the lowest recycling rates due to inefficient sorting technologies. Multilayer packaging is the most problematic material and can hardly be targeted by collection schemes. It is not currently recycled, 97% of all post-consumer

plastic films are incinerated or end up in landfills and oceans. The reason is that multilayer materials sport different barrier, carrier and tie layers of chemically different materials.

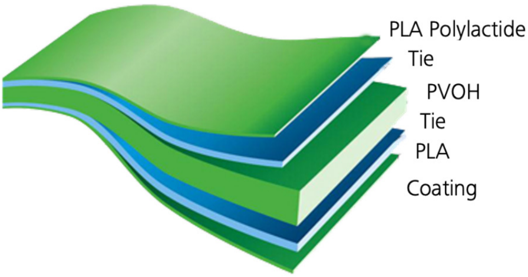

Fig. 5: *Multilayer film for Cheese or fresh pasta packaging (Food and Drink Business News 2021)*

Even if the film material is of single origin, for instance polyethylene, the recycling of film and flexible packaging still presents specific challenges and difficulties. According to Enrico Siewert (2022) 'the first challenge is the low bulk density of these materials […]. [Plastic films and foils] tend to move around on a sorting plant's conveyors and wrap themselves around the bearings of the shafts, affecting the equipment's performance and maintenance. Also, these materials are susceptible to trapping moisture, they tend to crumple locking in the moisture, and it takes a lot of energy to clean them'.

Hence, flexible plastic packaging result in a disappointingly low recycling rate due to inefficient sorting technologies and the high percentage of multi-layer materials. For flexible packaging chemical or tertiary recycling seems a likely option.

Tertiary or chemical recycling encompasses a depolymerization processes, hence referred to 'feedstock recycling'. It seems an attractive option for plastic products that are difficult to recycle mechanically due to low quality, composite nature or low economic value. The monomers can be used as primary material alternatives in manufacturing new polymers. The syncrude generated via depolymerisation, however, is incidentally more costly than natural crude oil, which makes a wide spread introduction of tertiary recycling less attractive. Consequently, tertiary recycling remains a small market. It can be achieved by pyrolysis, gasification and hydrogenation.

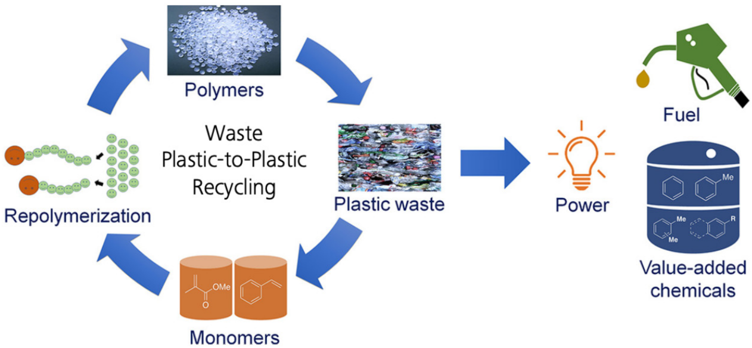

***Fig.6: Thermochemical** Recycling of Waste Plastics by Pyrolysis (ACS Publications – American Chemical Society 2022)*

The recycling methods discussed lead us to the question of renewable feedstocks of biological origin such as biomass, by-products derived from sustainable materials. Biological recycling involves the decomposition, physical fragmentation of an end-of-life product. The combination of moisture, temperature, mechanical action and microbial activity is responsible for the disintegration process.

According to European Bioplastics (2017) the current share of biodegradable plastics in the total plastic waste designed for organic recycling sold in the EU is comparatively small. The detected biodegradable plastic material is the waste stream is not higher than 0.3%, that makes biological recycling less likely to become financially viable on an industrial scale. However, we must not forget that the level of biodegradability is currently discussed and the available options are questionable concerning their biodegradability as they end up as micro plastics polluting the soil.

As primary and secondary recycling methods involve sorting, separating and classifying waste, which incurs high costs, a very common method is quaternary recycling, which is not recycling in the true sense of the word, as it involves energy recovery or mostly pure incineration with CO2 emissions. According to the OECD (2022) the highest incineration rates are in OECD Asia and accounts for 72% of the plastic waste. Good examples for countries who have widely introduced quaternary recycling are Singapore and Taiwan. In the EU 44% of the entire plastic waste is incinerated whereas in the US only 19% are burnt. In China about 24% of the total plastic waste are incinerated (OECD 2022) in comparison to 27% of the waste, which is still unmanaged and littered. Quaternary recycling is mostly negligible in South America and Africa, the percentage of incinerated plastic waste ranges between 1 and 5% (OECD 2022).

4. Conclusions

Due to the unavailability of reliable data for the period between 1950 to 2010, we can only reliably estimate global recycling rates from the last decade. According to PlasticsEurope (2016) the highest recycling rates in 2014 were in Europe (30%) and as stated by the National Bureau of Statics of China (2021) in China (25%). In the United States, plastic recycling has remained steady at 9% since 2012. The reports suggest that in Europe and China incineration rates have increased over the last years. In the report, Annual Data, China Statistical Yearbook, 1996-2016 by the National Bureau of Statics of China (2021) the incineration was to reach 40% and 30%, respectively, in 2014. It is not clear whether these figures reliably base on the entire production volume of plastics consumed in China. In any case, they differ significantly from the data obtained by the OECD (2022).

The OECD has recorded much smaller recycling rates in China and Europe. Giving their findings in 2022 China has recycled only 13% of its waste whereas 36% of Chinas plastic waste ended up in landfills. For the United States figures for primary and secondary recycling of plastic waste ranges at 4% in 2019 whereas OECD

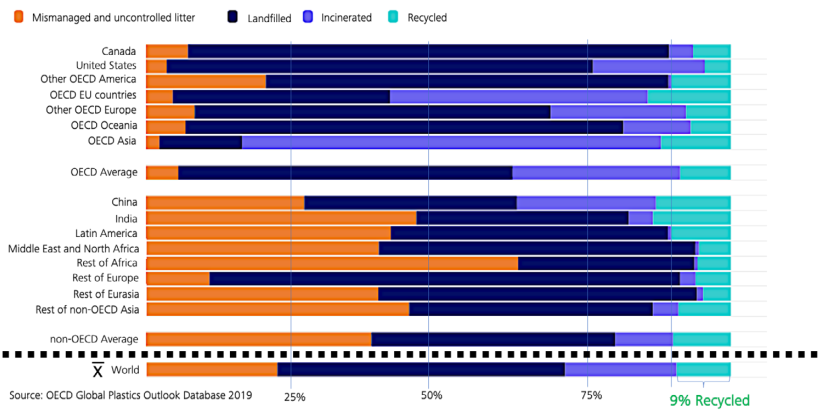

Fig. 7: Wasted or recovered (graphic created in 2019) (OECD 2022)

Europe is reported to recycle 8% of and India 13% of its plastic waste in 2022. Finally, it should not go unmentioned that since the 1990s the global recycling rate for non-fibres has increased 0.7% per annum. Assuming that this (linear) trend continues, the global recycling rate would reach 44% in 2050. With this assumption, the global discard rate would decrease from 58% in 2014 to 6% in 2050 (Geyer, Jambeck & Law 2017).

Nevertheless, measured against global population growth and the steady increase in global prosperity, despite crises and wars, this is a rather sobering result. Also, there is currently no significant recycling of synthetic fibres (2017). We can therefore assume that used textiles will continue to be incinerated and disposed of together with all other municipal solid waste in the future. If current trends in production and waste management continue, about 12 billion tons of plastic waste may end up in landfills or in the natural environment by 2050.

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