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REVIEW ARTICLE

A review of the cost and effectiveness of solutions to address plastic pollution

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Abstract

Plastic usage increases year by year, and the growing trend is projected to continue. However as of 2017, only 9% of the 9 billion tons of plastic ever produced had been recycled leaving large amounts of plastics to contaminate the environment, resulting in important negative health and economic impacts. Curbing this trend is a major challenge that requires urgent and multifaceted action. Based on scientific and gray literature mainly published during the last 10 years, this review summarizes key solutions currently in use globally that have the potential to address at scale the plastic and microplastic contaminations from source to sea. They include technologies to control plastics in solid wastes (i.e. mechanical and chemical plastic recycling or incineration), in-stream (i.e. booms and clean-up boats, trash racks, and sea bins), and microplastics (i.e. stormwater, municipal wastewater and drinking water treatment), as well as general policy measures (i.e. measures to support the informal sector, bans, enforcement of levies, voluntary measures, extended producer responsibility, measures to enhance recycling and guidelines, standards and protocols to guide activities and interventions) to reduce use, reuse, and recycle plastics and microplastics in support of the technological options. The review discusses the effectiveness, capital expenditure, and operation and maintenance costs of the different technologies, the cost of implementation of policy measures, and the suitability of each solution under various conditions. This guidance is expected to help policymakers and practitioners address, in a sustainable and cost-efficient way, the plastic and microplastic management problem using technologies and policy instruments suitable in their local context.

Keywords Plastic · Microplastic · Policy measures · Solutions · Pollution control · Waste management · Water · Wastewater

Background

Plastics are light, easy to handle, and economical materials commonly used in sectors such as packaging, building, and construction, the automotive industry, electrical and electronic parts, leisure products, and so forth (Hahladakis et al. 2018). In 2017, 348 million tons of plastic products (excluding derivatives such as synthetic textiles) were manufactured (Plastics Europe 2020). Plastic usage increases year by year and the growing trend is projected to continue at least over the next decade. However, only 9% of the 9 billion tons of plastic ever produced has been recycled (Geyer et al. 2017). Much of the rest has ended up in landfills, dumps, and the environment or in rivers, lakes, and oceans. In 2015, mismanaged plastic waste was estimated to be 52 million tons for Asia, 17 million tons for Africa, and 8 million tons for Latin America (Lebreton and Andrady 2019). Plastic pollution results in an estimated 1–5% decline in the benefit humans derive from oceans and USD2,500 billion in social and economic impacts annually (Beaumont et al. 2019).

Recently, awareness was raised about the importance of microplastics, defined as plastic particles smaller than 5 mm. Microplastics are classified as primary and secondary. Primary microplastics are specifically manufactured in the microplastic size range or directly released into the environment in the form of small particulates. They can be, for example, industrial abrasives used in sandblasting and microbeads used in cosmetics and other personal care

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and cosmetic products. They can also originate from the abrasion of large plastic objects during manufacturing, use, or maintenance, such as the erosion of tires when driving, or the abrasion of synthetic textiles during washing. According to Boucher and Friot (2017), more than 1.5 million tons of primary plastics find their way to the oceans.

Secondary microplastics originate from the fragmentation (or degradation of larger plastic items) while they are exposed to environmental factors (Boucher and Friot 2017). Different plastic types and shapes will fragment at different rates in the environment, with thinner plastic pieces expected to degrade relatively faster (Eubeler et al. 2009; Rhodes 2018). In general, the defragmentation rate for plastics is below 1–3% weight per year in sediment or water, and photodegradation and mechanical degradation are the main drivers (Sundt et al. 2014). Photodegradation is due to solar UV radiation in outdoor exposure. This is generally the initial event, which primes the plastic material for subsequent thermo-oxidative degradation mechanisms (Rhodes 2018). Mechanical degradation occurs through action of abrasive forces, heating/cooling, freezing/thawing and wetting/drying (Duwez and Nysten 2001). It is not as dominant as photodegradation, but it can activate or speed it up (Briassoulis 2005). Other less dominant fragmentation mechanisms for plastics are chemical degradation, through oxidation and hydrolysis, when atmospheric pollutants and agrochemicals interact with polymers, changing the macromolecular properties; and biodegradation, occurring through the action of living micro-organisms (Lucas et al. 2008).

Plastics and microplastics constitute a critical source of pollution to the environment, with important health and economic impacts. Plastics effects include the blocking of canals and sewers, the creation of breeding grounds for mosquitoes, the obstruction of the airways and stomachs of animals, and reduced landscape and touristic value due to polluted beaches, lakes, and rivers. In addition, the possible risks of microplastics to the health of humans, animals, and ecosystems are an increasing concern because they have been detected in human food, the air, and drinking water (Nikiema et al. 2020). Plastic materials can also carry toxic chemicals, including persistent organic pollutants, and pathogenic micro-organisms that may attach and colonize on them (Wright et al. 2013; SAPEA 2019; WHO 2019).

Objectives of the literature review and methodology

Water pollution by plastics is complex and multidimensional, and managing it effectively requires a range of approaches to:

1. Reduce plastic and microplastic pollution at source. This could be accomplished by prevention of plastic littering and through plastic recycling;

Several solutions can be explored to reduce littering of plastics and microplastics at source and prevent the contamination of water, wastewater, or the environment. This will also have a positive impact on secondary microplastics release (McKinsey and Company and Ocean Conservancy 2015; Rhodes 2018; Magni et al. 2019).

2. Treat the pollution when prevention measures cannot be implemented and water contamination has occurred.

As affordable substitutes to undesirable products can be difficult to find, pollution of water, air, and soil may be inevitable at times. In these instances, treatment should be undertaken to reduce or eliminate contamination of water with plastics and microplastics.

This report aims to review solutions that can be adopted to mitigate contamination of waterbodies with plastics and microplastics. It can inform decision-making because it introduces key available technologies and presents cases of application. It also discusses the effectiveness and costs (capital expenditure, and operation and maintenance [O&M]) involved with the adoption of each technology. Ultimately, optimal solutions will combine technologies and policy instruments available to address pollution in cities and river basins.

This study has a global focus. Our literature review mainly covers the last 10 years. Key sources include professional reports, project briefs, news posts, and peer-reviewed articles.

The costs data reported here correspond to published investment or O&M costs over the last few years. These costs have not been actualized, but the year for which they have been reported is provided. In general, O&M costs are given per year and include labor needs, chemicals, maintenance, energy, insurance, and potentially other expenditures such as taxes. Investment costs include engineering design and construction of physical assets as well as the demolition cost of pre-existing systems, when this is required, and land acquisition. It is important to note that costs are country- and location-specific; therefore cost values proposed in this study are indicative. Data compiled in this report are expected to be useful for global-scale comparisons but could require fine-tuning in a local context.

The technologies analyzed in this report are presented in Table 1. They were shortlisted based on their capacity to address the issues they are meant to tackle and their level of adoption.

This study has four key sections:

Table 1 The technologies presented in this report

A. Technologies to control plastics in solid wastes			
Mechanical plastic recycling	Chemical plastic recycling	Incineration of plastics	
B. Technologies to control plastics in-stream			
Booms and clean-up boats	Trash racks	Sea bins	
C. Technologies to control microplastics in wastewater			
Stormwater ponds	Wastewater treatment plants	Sewage sludge treatment	Drinking water treatment
D. Policy measures to reduce plastics and microplastics			
Ban and enforcement of levies to reduce use	Voluntary measures to reduce use, reuse, and recycle	Extended producer responsibility to reuse or recycle	

Light green (minimal) to dark green (significant) = solutions adopted already

Light pink (minimal) to dark pink (significant) = not commonly adopted solutions

This paper

- Policy measures to reduce volumes of plastics or to promote recycling
- Technologies to control plastics in solid wastes
- Technologies to control plastics in-stream
- Technologies to control microplastics in wastewater

For each section, we describe the technical or policy solutions available and review their effectiveness. We also present case studies in the supplemental file and discuss synergies and trade-offs that exist. We compare costs to choose the most suitable option for each scenario.

Policy measures to reduce plastics leakage

Plastic leakage management is the first step towards control of plastic pollution and this requires strong policy support (McKinsey and Company and Ocean Conservancy 2015; Eriksen et al. 2018; Lau et al. 2020). Most countries have enacted policies to address solid and liquid waste management. But they might be incomplete, leaving gaps that do not support sustainable practices, and not properly enforced, which seriously undermines the ability of cities and countries to address plastic waste-related issues. However, policy measures are essential to ensure that a durable solution is found to manage plastic waste and mitigate its generation. They are required to ensure that collection, storage, transportation, and final disposal or recycling are enforced, financially sustainable, technically feasible, socially and legally acceptable, and environmentally friendly. In general, a combination of solutions and strategies is required at different levels of the plastic management service chain for a sustainable intervention, for example:

- Prevention, to enhance resource productivity, reduce volumes of waste generated, and better control of types of wastes and materials, through bans and restrictions;
- Control strategies, by better defining guidelines, standards and protocols to guide practices on the ground. These measures are also necessary to better define the roles and responsibilities of each party among stakeholders, and for better accountability (EU 2015; Nikiema et al. 2020; Shin et al. 2020).

Enforcement of the policies is therefore vital for positive change. Good and well-enforced policies not only help to address increasing public demand for sustainable plastic waste management approaches but are also essential elements of the transition towards a low-carbon and circular economy (EU 2015). In addition, there is a global demand for such approaches as illustrated by the ratification of global conventions and the adoption of Sustainable Development Goal 14—"conserve and sustainably use the oceans, seas and marine resources for sustainable development", thus calling for improved plastic waste management.

In this section, we present and discuss some policy measures that could be implemented to reduce loads of plastics in waterbodies. Such measures include the adoption of

policies to strengthen plastic waste management service chains within the informal sector; promulgation of bans and enforcement of levies to reduce plastic use; support for voluntary measures to reduce, use, reuse and recycle, building on extended producer responsibility to secure funds necessary to treat solid wastes and contaminated wastewater; enactment of policies to support recycling; and, finally, dissemination of guidelines, standards and protocols to inform sustainable practices.

Description of policy measures

Measures to support the informal sector

There are some licensed waste collection and recycling firms in developing countries. But often, waste management and recycling actors largely belong to the informal sector. Even where the public service is nearly non-existent, typically, such parallel systems for solid waste collection spontaneously develop, and high-quality and high-value plastic materials are segregated and sold to middlemen—waste aggregators—who link these informal sector actors with main national or international recyclers. The transactions in the informal sector are either completely uncontrolled or at best minimally controlled by policy measures. The informal plastic waste management sector involves individuals working independently or as members of cooperatives (Ugorji and van der Ven 2021; Bjerkli 2005). Often, they are poor and marginalized urban dwellers, including children, who resort to scavenging and waste picking for survival. Their work is often unrecognized, they are subject to low pay and unsafe work conditions although they play an essential role which supports the livelihoods of millions of people (Schlitz 2020). In the informal plastic waste sector, women are further marginalized and can only occupy lower-income tasks, such as waste picking, sweeping and waste separation, whereas men are able to assume positions of higher authority, dealing with the buying and reselling of recyclables for example (Wang et al. 2019).

The long-term viability of informal plastic collection is uncertain in many countries, given the unofficial, and sometimes illegal, nature of this activity. The workers usually suffer from policy changes when they are enacted as they are seldom associated with the decision-making process (Bjerkli 2005). However, there is increasing hope that it might be possible to build on these existing value chains to drive the plastic collection sector into a formalized system, with practices and protocols which are comparatively easier to monitor, helping to safeguard the health and livelihoods of the waste-collecting individuals (Nikiema et al. 2020). Hence, efforts are increasingly being made in developing countries to adopt innovative approaches that will help to address the three main issues that the informal sector faces: (1) improve the collection system's performance, (2) increase its capacity and enhance workers' knowledge, and (3) give better visibility to its workers (Ugorji and van der Ven 2021).

Bans and enforcement of levies to reduce use

To date, more than 67 countries have adopted various bans on single-use plastics (i.e. foamed plastic products like styrofoam or other plastics for packaging) and plastic bags (UNEP 2018). The world's most severe ban on plastic bags was imposed in Kenya in 2017, where anyone producing, selling—or even just carrying—a plastic bag could theoretically receive a jail sentence of up to four years, or a fine of USD40,000 (Lam et al. 2018; Biswas and Hartley 2017). Since the ban, 80% of the population has stopped using plastic carrier bags, according to the government. Some plastic manufacturers relocated to other countries, but others have diversified their operations to produce fabric-based bags, non-woven bags, among others. Overall, around 300 people have been fined between USD500 and USD1,500 or sentenced to eight months in jail for using plastic bags, while a manufacturer has been sent to jail for one year. But some of the alternatives adopted (e.g. use of polypropylene bags) have also been identified as environmentally damaging due to poor waste management and no solution has been found yet (BBC News 2019).

According to recent studies, enforcement of plastic bans was successful (i.e. up to 50–90% reduction in plastic use) during the first year of implementation in 60% of the cases (UNEP 2018; Xanthos and Walker 2017). In the other cases (e.g. in India, South Africa, or other developing countries), enforcement of bans has not been successful due to challenges which include lack of awareness on the policy, weak institutional capacity, and poor governance that resulted in low enforcement of the policy, lack of suitable and affordable alternatives to substitute for banned plastic-based products, or non-prohibitive levies (Gupta 2011; McKinsey and Company and Ocean Conservancy 2015; Borrelle et al. 2020).

Similarly, to prevent wastewater contamination by microbeads, the Netherlands and the USA were first to introduce bans of microbeads in rinse-off personal care and cosmetic products. They were soon followed by many other countries such as Canada, France, Italy, the UK, Thailand, and New Zealand (Xanthos and Walker 2017; Guerranti et al. 2019). As a result of their bans, large manufacturing companies have embarked in efforts to phase out the use of microbeads (Prata 2018; Guerranti et al. 2019); they are now being replaced by different abrasives such as perlite, silica, and microcrystalline cellulose (OECD 2021).

Alternatively, levies are usually enforced to achieve a reduction in the demand for plastics and/or to raise sufficient funds to enable adequate plastic waste management. This

solution is often effective when the collected amount is high enough to dissuade poor practices. There is also a need to explore enforcing segregation at waste source as this could facilitate linkage to plastic value chains more easily, since the sorting and cleaning steps might be simplified (Ugorji and van der Ven 2021). In this context, some countries are considering adoption of citizen science through mobile app use to strengthen monitoring capacities.

Voluntary measures to reduce use, reuse, and recycle

Voluntary campaigns can be successful in reducing plastic consumption (UNEP 2018). These voluntary measures allow people to change their consumption patterns in a progressive manner. Although they are usually successful, some failures have been reported, often linked to the availability of free plastic. Therefore, voluntary initiatives are more efficient if they are facilitated by policy tools to regulate the production and use of disposable plastics or to promote the adoption of sustainable alternatives. They have to be incorporated in financially viable business models, which simultaneously promote sustainable and environmentally-friendly products and services. Voluntary measures require adequate information to be provided to each decision-maker for the change to occur. For example, consumer decisions will affect their consumption choices and ultimately, the extent of the plastic wastes and microplastics waste generation. The costs of implementing voluntary solutions are unclear as they are often borne by entities with a social mandate or as part of a cost-saving strategy.

Table 2 presents examples of voluntary actions taken by retailers to help reduce plastic bag consumption within the European Union. For instance, many supermarkets have voluntarily abolished provision of (free) plastic bags, which has led to notable drops in plastic bags usage (Luís and Spínola 2010). At the same time, alternative bags made of more durable and natural materials, such as cotton, hessian, or linen are made available to consumers. Deposit return strategies have shown high efficiency in reducing the amount of waste with return rates of up to 90% in Sweden and Germany. Other interventions such as 'Operation Clean Sweep' organized by non-governmental organizations (NGOs) to clean beaches and drains can help reduce plastic pollution of the environment (Lam et al. 2018).

The behavioral change towards plastics occurring in society impacts many private companies. For example, globally, the Coca Cola company is now committed to making 100% of its packaging recyclable by 2025, using at least 50% recycled material in its packaging by 2030, and collecting and recycling a bottle or can for each one sold by 2030 (Ugorji and van der Ven 2021). Other multinational companies such as Nestlé, PepsiCo, LEGO, etc. have similar targets.

In addition to voluntary solutions towards reduction of plastic waste, the market for ethically produced goods (including recycled products) is growing worldwide, as consumers are becoming more aware of the negative impacts associated with plastic pollution. Examples of consumer awareness-driven interventions to combat plastic litter include the production of clothes, shoes, skateboards, sunglasses, and swimming gear from derelict fishing gear. Finally, other initiatives are considered to reduce the need

Table 2 Voluntarily actions taken to reduce plastic bags consumption within the European Union

Type of voluntary action (strategy)	Countries having tested the strategy
Substitution with recycled plastic bags	Austria
Enforcement of a voluntary levy to discourage plastic use or to support sustainable plastic waste management and recycling. Mostly around EUR0.05–0.10 per single use plastic bag.	Belgium, Estonia, France, Germany, Hungary, Latvia, Netherlands, Portugal, Sweden, Slovakia, UK
Substitution with biodegradable plastic bags	Austria, France, Sweden
No provision of plastic shopping bags	Austria, Lithuania
Provision of plastic bags on demand only	UK
Promotion/provision of reusable plastic and non-plastic bags. E.g. • Public institutions and private companies offer free multiple-use cloth bags • Shops propose 'bag bins' where used bags can be deposited and reused again by other customers • Reusable bags are produced by NGOs who sell them to finance their activities in part (50% of the sales costs are recovered)	Estonia, Greece, Finland, Luxembourg, Netherlands, Sweden, UK
Paying customers a small amount of money if they do not take any plastic bags (around EUR0.10)	Spain
Awareness raising through media campaigns or billboards reminding customers to reuse their bags	UK

Lam et al. (2018); Luís and Spínola (2010)

for plastics. For instance, public drinking fountains were provided pre-COVID in cities to reduce the need for bottled water. At the same time, buying goods from local farmers' fresh markets is encouraged as a way for customers to lower packaging volume associated with purchases made elsewhere.

Extended producer responsibility to reuse or recycle

Extended producer responsibility (EPR) is a policy mechanism that aims at mitigating risks associated with waste management. With EPR, producers are held legally and financially responsible for mitigating the environmental impacts of their products throughout their lifecycle stages. EPR can help to limit the health, safety, environmental, and social impacts of plastic products (Eriksen et al. 2018). This can help in plastic pollution prevention and mitigation. Enforcing EPR could encourage manufacturers to design and produce plastics that are environmentally friendly. For example, in 2013, the Natural Resources Defense Council in California developed policy concepts to make the producers of selected products responsible not just for recycling, but also for litter prevention and mitigation. Through the new policy, they were required to reduce their products' total volume in the environment by 75% in 6 years and 95% in 11 years (Eriksen et al. 2018).

Many countries are counting on this approach to better address plastic waste. This might work well for in-country plastic production, such as for water bottles, and some successes can be highlighted. Nevertheless, there are issues associated with the adoption of such policies. One is difficulty with enforcement, which requires capacity to monitor disposable products generated per company, and might be challenging in developing countries which, traditionally, are data-scarce (Ugorji and van der Ven 2021).

Measures to enhance recycling

There is increasing agreement about the need to rethink the plastics economy to consider key foundations. It must adopt a circular approach to plastics, meaning that design and production of plastic products should fully respect reuse, repair and recycling needs and plastics that are difficult to recycle should be phased out. This has to be done collaboratively, to ensure buy-in and sustainable adoption. In addition, the plastic economy must support national economies and livelihoods through job creation, economic growth, investment and social fairness. Finally, it must foster collaboration, by bringing private sector, national and regional authorities, cities and consumers towards a set of common goals (EU 2015; Shin et al. 2020). To achieve these targets, there is pressure on industries and retailers to strive to reduce plastic packaging and to design products containing plastics in a way that simplifies recycling. Policy tools for effectively incentivizing adoption of recycling options include:

- Policies targeting the increased adoption of recycled products, e.g. preferential rates for reuse products or policies supporting the creation of a domestic market for recovery and recycling. This has proven successful in the past in other fields, e.g. to drive the adoption of incineration technologies in Europe.
- Zero landfilling policies or policies targeting the reduction of the amounts of plastic wastes discarded or abandoned.
- Policies promoting sustainable practices through tax abatement and fee reductions or application of levies (Ugorji and van der Ven 2021).

Experience in many countries has shown that financial incentives can be very effective in driving change on the ground. However, these policy measures must be accompanied by suitable investments to strengthen the plastic recycling sector as well as research to identify new innovations with great recycling potential. The shift towards a circular economy approach is an essential element of the transition towards a carbon-neutral economy, and they both constitute key global commitments (EU 2015; Ugorji and van der Ven 2021). In this context, strong policies will not only help to address the increasing public demand for sustainable approaches towards plastic waste management, but will also help countries to meet their global commitments.

Guidelines, standards, and protocols

The plastic waste management sector requires clear policies to guide the interventions and protocols for the practices it promotes. Quality standards for recycled products need to be defined. Additionally, in some countries, there is a need to better control plastic waste trade, facilitate imports of relevant goods and better control the markets (Ugorji and van der Ven 2021). It has been argued that trade policies could help to mitigate environmental risks, while also creating new economic opportunities, e.g. for investment, job creation and so forth.

Regarding wastewater, of the many contaminants found in it, microplastics have not been a concern until recently. However, the real impacts of this contaminant remain unclear (WHO 2019) and no country has so far set quality standards for microplastics in treated wastewater. The same applies to drinking water treatment (Novotna et al. 2019). Another challenge is related to the lack of harmonized analytical techniques to quantify microplastics in water which makes it even more difficult to understand the real impacts and extent of the microplastics problem (Elkhatib and Oyanedel-Craver 2020; OECD 2021).

In addition, given the ability of waste to travel across borders, international policies are also needed to manage transboundary waterbodies and they would require specific policies for transboundary plastic waste monitoring (Xanthos and Walker 2017; Alpizar et al. 2020).

Costs, trade-offs, and effectiveness of policy measures

Costs

In 2016, a consulting firm conducted a study for the city of Victoria, Australia (Marsden Jacob Associates 2016). Their findings confirmed that the costs of enforcing policy restrictions measures are non-negligible and impact various stakeholders, such as the government, the retail industry, wholesalers and importers, consumers in the community, and finally the environment in different ways.

By comparing three scenarios (i.e. partial ban, partial ban + voluntary ban and total ban of plastics) to a baseline (no ban), they established that the cost over a 10-year period was about USD27/inhabitant for a total ban scenario versus USD23–26/inhabitant for enforcement of levies and partial bans. The benefit–cost ratio was 1.28 for total bans versus 1.01–1.07 for the other two scenarios. Enforcing bans to mitigate pollution is therefore the most advantageous solution among the three options tested, although expensive. This has different impacts on various stakeholders, such as the government, the retail industry, wholesalers and importers, consumers in the community and finally the environment. However, if the polluter-pays principle, which demands that waste producers should bear the costs of managing it to prevent damage to human health or the environment, is in place, most of this financial responsibility is re-assigned to the industry and to consumers (Prata 2018; He et al. 2018) while the long-term impacts are mostly positive for both consumers and the environment (Table 3).

Synergies and trade-offs

In 2015, the European Union (EU) pledged to address the plastic waste challenge and "to have all plastic packaging reusable or recyclable in a cost effective manner by 2030". Among key targets, the EU-wide strategy on plastics aims at achieving 55% recycling of plastic packaging waste by 2030, reducing annual consumption of plastic bags per person from 90 by 2019 to 40 by 2026, improving plastic-based product design to address durability, repairability and recyclability, while mandating Member States to monitor and reduce their marine litter. Ultimately, the ambition is to improve the economics and quality of plastics recycling, curb plastic waste and littering, drive investments and innovations towards circular solutions, and harness global action (EU 2015). Thus a combination of solutions discussed in this section will be necessary to successfully address the plastic- and microplastic-related challenges, and their implementation requires important investments.

For the EU, financing this transition will be ensured through various funding opportunities, such as Horizon 2020 (over EUR350 million), the European Fund for Strategic Investments, and Structural Funds. In the latter case, over EUR5.5 billion has been allocated to support improved waste management capacity, with the aim of an additional 5.8 million tonnes/year of additional waste being recycled (EU 2015)

In policy implementation, awareness and communication are key. These campaigns involve social awareness and public education programs and usually include a wide range of

Table 3 Typical costs (-) and benefits (+) incurred with the enforcement of bans or policy restrictions

Scenarios Activity	Partial ban	Partial ban + voluntary actions	Total ban	Stakeholders financially affected
Introduce legislation	-	-	-	Government and retail industry
Consumer education campaign	-	-	-	
Monitoring and compliance	-	-	-	
Introduce code of practice		-		
Industry set-up	-	-	-	
Acquiring approved bags	-	-	-	Consumers
Replacing bin liners	-	-	-	
Avoiding plastic bags	+	+	+	
Loss of producer/retailer surplus	-	-	-	Importers of shopping bags
Avoided litter	+	+	+	Community/environment
Improved environment	+	+	+	
Avoided landfill operating costs	+	+	+	

Modified from Marsden Jacob Associates 2016

activities. Some organizations advocate for adequate labelling of goods, to help generate additional pressure on manufacturers to phase out the use of manufacturing of products with high contamination potential (Xanthos and Walker 2017). To succeed in plastic waste management, an integrated effort is needed, and Table 4 summarizes some specific actions that could be explored by key parties to improve overall plastic waste management. Such a concerted effort requires time but also strong commitment by all concerned parties.

To support policy, Alpizar et al. (2020) have released a new toolbox, which helps to identify policy measures that might be suitable for different countries.

Technologies to control plastics in solid wastes

Proper plastic leakage management is the first step towards control of plastic pollution in water and this requires increased waste recycling and ensuring the availability of suitable waste handling facilities (McKinsey and Company and Ocean Conservancy 2015; Eriksen et al. 2018). However, in most developing country cities, a large share of the generated solid waste is inadequately managed. Typically, up to 50% of the waste generated in urban areas of such cities may not be collected because of, *inter alia*, poor road networks, equipment failure, and insufficient budgets (Nikiema 2018). Considering that there is no or limited segregation of solid waste done at source by households in developing countries, it becomes difficult to manage plastic wastes (5–15% of the solid waste generated) in isolation from the other solid waste streams (Ritchie and Roser 2018).

In this section, we present and discuss three technologies that could be implemented to prevent or reduce contamination of water with plastic in municipal wastes. They are:

- Mechanical recycling, which generates similar or slightly downgraded recycled material.
- Chemical recycling, also known as feedstock recycling, which yields liquid fuel, or syngas, or plastic monomers.
- Incineration for energy recovery.

Description of technologies

Mechanical plastic recycling

In Europe, 99% of plastics is recycled through mechanical means. The process is particularly suited for recycling clean and well-sorted plastic waste. The latter is reprocessed mechanically into a raw material or product, without notably changing its chemical structure. The technology is effective for all types of thermoplastics (as opposed

Table 4 Key actions needed from different stakeholders

Industry should	Government should	The public should
• Measure, monitor, manage and report plastic use	• Enforce policies aimed at reducing per capita plastic waste generation, and waste mismanagement and landfilling, and policies that promote recycling	• Make sound consumption decisions, e.g. to reduce or avoid plastic waste generation
• Mitigate ecological risks	• Promote tools that allow all consumers to enhance their awareness of the management of plastic and plastic waste	• Change habits and lifestyles that require plastic usage, e.g. through reducing reliance on single-use plastics or through source separation
• Increase recycling of plastic products	• Openly support alternatives to plastic and encourage industries to move to environmentally friendly packaging	
	• Create/upgrade solid waste collection and treatment	

Governments/private sector should be encouraged to include households/communities and specifically take affirmative action to ensure that women are invited to such discussions as key stakeholders. It is crucial that governments and the private sector promote gender equal employment in the waste sector more actively.

Nikiema et al. (2020)

to thermoset plastics), i.e. those with linear molecular chains that soften when heated and harden when cooled. Examples of the most commonly processed waste materials include crystalline thermoplastics, such as polypropylene (PP), low-density polyethylene (LDPE), high-density polyethylene (HDPE), and polyethylene terephthalate (PET). Alternatives include amorphous thermoplastics, such as polyvinyl chloride (PVC), polystyrene (PS), and semi-crystalline polymers, which combine the properties of the first two types and include polyester polybutylene terephthalate.

The mechanical recycling process includes the following steps: collection and sorting, grinding, washing, and drying. Granulating and compounding may follow eventually (Ragaert et al. 2017). Several research findings confirm that mechanical recycling optimizes the utilization of plastic resources and prolongs their lifespans (Hopewell et al. 2009; Lam et al. 2018). As shown in Table 5 the process is therefore beneficial, from an environmental point of view and, compared to landfilling as well as other recycling methods, it has the least negative environmental impacts. For example, by avoiding production of virgin materials, mechanical recycling saves 1.5 to 2.3 tons of CO_2 per ton of plastic recycled (Tullo 2019; Jeswani et al. 2021).

Poor separation of plastic fractions will reduce output quality and the end-use options (Davidson et al. 2021). Other issues also need to be controlled, such as the risk of thermo-mechanical degradation of plastic polymers during the process. Other types of degradation of output quality may also be observed, e.g. as a result of exposure to natural light (photodegradation), oxygen, or moisture (biological degradation). Another issue is related to the presence, in the original plastics, of additives, fillers, or even other polymers that are hard to recycle, resulting in contamination of the mixture, downgrading the recycled output quality (Ragaert et al. 2017; Singh et al. 2017).

Chemical plastic recycling

During this recycling process, the chemical structure of plastic wastes is transformed through thermo-induced chemical or biochemical reactions into shorter molecules, readily usable in other applications or to manufacture new products. The common three variants are pyrolysis, catalytic pyrolysis, and conventional gasification (Lam et al. 2018; Davidson et al. 2021), as presented in Table 6. These recycling options were developed more recently than the other alternatives and remain the least implemented (Davidson et al. 2021). A detailed comparison of technologies for chemical or tertiary recycling of plastics is provided in the supplemental file.

Pyrolysis cracks long plastic polymer chains under oxygen-deficient conditions into short-chain hydrocarbons, which yield valuable liquids with properties similar to diesel or naphtha. The latter can then be fed into petrochemical plants to be processed into virgin plastic (e.g. polyethylene, polypropylene) (Tullo 2019; Devasahayam et al. 2019; Davidson et al. 2021). However, during gasification, plastic waste is reacted with gasifying agents (e.g. steam, oxygen, and air) at high temperatures, which can produce syngas, a mixture of mainly hydrogen (typically up to 65–70%) and carbon monoxide (e.g. 25%). Based on the process, light hydrocarbons are also found in the syngas such as methane (typically up to 3–4%). It may also include impurities such as carbon dioxide (6–7% typically) and nitrogen. Once purified, syngas can be used to synthesize other products, e.g. new plastics, new chemicals, or be used as industrial fuel or to generate electricity (Hirn 2016; Saebea et al. 2020; Plastics Europe 2020; Davidson et al. 2021). The process also enables metal recovery from the solid residue. Hydrocracking yields similar products to pyrolysis by using heat and pressure in an inert, hydrogen-rich atmosphere to break the carbon-carbon bonds in plastic waste. Finally, depolymerization converts selectively a plastic polymer into its monomer(s) (e.g. polystyrene will yield styrene). It can be achieved using enzymes or thermo-chemical processes (Davidson et al. 2021; Zhu et al. 2021).

Table 5 Water, energy requirements, and global warming potential of selected plastics

Plastic type	Energy requirement (GJ/ton)	Water requirement (m^3/ton)	Global warming potential (CO_2 eq.)	2015 global production (million tons)
Virgin PET	82.7	66	- 3.4	33
Virgin HDPE	76.7	32	- 1.9	53
Virgin LDPE	78.1	47	- 2.1	64
Virgin PVC	56.7	46	- 1.9	38
Virgin PP	73.4	43	- 2.0	68
Virgin PS	87.4	140	- 3.4	25
Recycled plastics	8-55	3.5	- 1.4	60

Luijsterburg (2015); Geyer et al. (2017); Singh et al. (2017); Devasahayam et al. (2019))

Table 6 Costs of technologies used to prevent municipal wastewater contamination

Technology	Investment cost to process 1 ton/day capacity	Annual O&M to process 1 ton/day capacity	Typical annual output per ton waste input (plastic only, except for incineration which is done for a mix of wastes, including plastics) and remarks	Typical net CO_2 emissions (ton per ton of plastic)	References
Mechanical recycling	USD 2,000–10,000 Lifecycle cost of recycling (capital and O&M) is typically EUR204/ton	Typically USD500–1,500[a]	Up to 100% since simple remolding is only done. Recycled plastics are seen as inferior substitutes for virgin plastics.	-2.3 to -0.27	MakeInBusiness (2018); Gradus et al. (2016); Devasahayam et al. (2019); Civancik-Uslu et al. (2021)
Chemical recycling (pyrolysis)	USD857,000	USD500–1,000 (in Europe and North America)	The distribution of the gas, liquid, or solid fraction depends on process operating conditions applied and catalysts used. Case 1 in the USA: • 0.68 m^3 of diesel and naphtha • 0.22 m^3 of industrial wax.	-1.5 to -0.1 Case 2 in Japan: • 0.59 m^3 of liquid fuel • 0.20 tons of solid fuel (used to produce 0.27 kW of electricity and 0.27 kW of heat)	Devasahayam et al. (2019); Homolka (2018); Porcu et al. (2019); Tullo (2019); Klean Industries Inc (2015); Devasahayam et al. (2019); Jeswani et al. (2021)
Chemical recycling (gasification)	USD385,000	Labor: USD4,250 Maintenance: USD18,100	Typically, syngas generation is about 2,500 normal m^3 per ton of plastic waste. The energy content of the syngas is usually between 2–2.4 kWh per normal m^3. Hence, energy obtained from 1 ton of plastic is 5.3 MWh in the form of syngas. This could produce 3.6 MWh of electricity per ton of plastics. Consequently, 2.5 tons of plastic waste will give energy equivalent to 1 ton of natural gas	0.4–1.1	Hirn (2016)

Table 6 (continued)

Technology	Investment cost to process 1 ton/day capacity	Annual O&M to process 1 ton/day capacity	Typical annual output per ton waste input (plastic only, except for incineration which is done for a mix of wastes, including plastics) and remarks	Typical net CO_2 emissions (ton per ton of plastic)	References
Incineration	• USD100,000–330,000 in Myanmar • EUR455,000-480,000[b] in France	• USD10,800–14,000[c] in Myanmar • EUR40,000 in France (EUR120 to 130 per ton of waste)	Case 1: in the USA (1/3 of the carbon in the solid waste comes from plastics): 0.72 MWh of electricity and 10% ash. Case 2: in Myanmar up to 0.40 MWh of electricity (some used internally) Case 3: in France 20–25% solid residues, recycled in road construction; 3% of residues recovered from gas exhausts which must be landfilled. Energy generated: • 1.5 MWh if hot water only • 0.3–0.4 MWh if electricity only • About 0.3–0.5 MWh each of hot water and electricity, in a co-generation mode	1.8–2.8	JFE Engineering Corporation (2018); Tullo (2018); Maxime (2018); Huisman et al. (2017); Turchet (2015); Gradus et al. (2016); Planete Energy (2014); Devasahayam et al. (2019)

[a]Estimated in India. Includes cost of acquiring raw plastics.

[b]Typically, 14% for engineering, 4% for the site preparation and the remaining for the construction of the plant.

[c]56% for maintenance and management, 11% for personnel, and 25% for utilities.

Plastic wastes that are difficult to recycle mechanically, such as grocery bags, bubble wraps, trash bags, retail packaging, food wraps, carpet fibers, and others, constitute a valuable input resource for this recycling mode. The purity level required for the waste feedstock depends on the process. Depolymerization requires pure feedstock, which may be unclean. However, pyrolysis is more omnivorous and can easily intake a mix of plastics (usually polypropylene, polystyrene, and polyethylene). Finally, gasification can be applied to mixed waste but it is sensitive to corrosion, given the high operating temperatures (Tullo 2019; Weiland et al. 2021).

Incineration of plastics

In 2015, about 26% of the plastic waste produced worldwide was incinerated (Geyer et al. 2017), usually along with other municipal and industrial solid wastes. Plastic wastes have a notable potential for energy generation because the calorific value of plastic is similar to that of hydrocarbon-based fuel (Sun et al. 2018). Other innovative technical options for recycling of plastic waste include co-processing of plastic waste in cement kilns or foundries (McKinsey and Company and Ocean Conservancy (2015). Typically, for the iron and steel industry, use of plastics instead of conventional energy sources (e.g. coal) reduced the carbon footprint by 30% and led to energy savings (given the higher hydrogen content of plastics) (Devasahayam et al. 2019).

Waste incineration may release a flue gas effluent contaminated by toxic compounds such as sulfur dioxide (typically 0.23 kg per MWh of energy generated), nitrogen oxides (typically 1.5 kg per MWh of energy generated), dioxins (e.g. when processing chlorine containing plastics like polyvinyl chloride), especially when incinerators are old or inefficient (Tullo 2018; Devasahayam et al. 2019). Microplastics from unburnt plastic wastes can be found in the cinders produced. A recent study established that, in several Chinese incinerators, 1 ton of municipal solid waste (containing 12% in mass of plastic wastes) incinerated will yield 1.9–565 microplastic particles (e.g. 43% granules, 34% fragments) per kilogram of ash formed (Yang et al. 2021).

Typically, 70–80% of the energy from waste incineration can be recovered to produce hot water only. If the interest is in electricity only, the energy recovery is 20–25%. In the case of co-generation, both electricity (same amount as earlier) and hot water are produced, for a total energy recovery of 50–60% for both outputs (Planete Energy 2014; Gradus et al. 2016).

Costs, trade-offs, and effectiveness of technologies

Costs

Table 6 presents a compilation of typical capital costs required to set up a plant with equivalent 1 ton/day capacity. It is to be noted that the lifespan of the plant depends on the type of plant, with low-cost systems tending to last for a shorter time (i.e. 5–15 years) than expensive systems (i.e. 30 years and more). These costs range from USD2,000 to USD10,000 for mechanical recycling (if no mechanical waste sorting is required) to USD857,000 for pyrolysis, and the lifespan would also be different (higher in the case of highly engineered systems). Accordingly, O&M costs per ton per day of capacity vary notably, depending on the technology considered, from as low as USD500 in the case of mechanical recycling, when processing already sorted plastics, to several thousand US dollars for gasification and incineration. The obvious conclusion is that mechanical recycling of plastics can be more affordable to set up and run where sorting of waste is done effectively at minimal cost, and value chains for quality plastic collection exist. In this case, a mechanical recycling plant can be operated profitably at different scales. In other cases, e.g. when costly sorting processes of collection schemes are required, incineration could become cheaper than mechanical methods (Gradus et al. 2016). Larrain et al. (2021) estimated that mechanical recycling will remain unprofitable in Europe unless oil prices increase notably or supporting policies to increase the demand for recycled products are adopted.

Chemical recycling plants reach profitability only when large volumes of plastics can be processed, usually from 50,000 to 100,000 tons/year (Ragaert et al. 2017; Solis and Silveira 2020). However, pyrolysis, often highlighted as the best chemical recycling method, will not be attractive when oil prices are less than USD100/barrel (Davidson et al. 2021). For European countries such as France, the minimum capacity to ensure the financial viability of incineration is 60,000 tons. Usually, incineration plants are profitable only when tipping fees are high (typically, more than USD70/ton for the USA) or plants benefit from policy measures setting high rates for sales of derived electricity and hot water. In 2017, Covanta, which operates two-thirds of the waste incineration facilities in the USA, generated 70% of its income from tipping fees whereas energy and metals recovery would cover only one-third of the plants' operating expenses. Gradus et al. (2016) reported that in the Netherlands, energy recovery and sales offset 95% of the incineration cost due to supporting policies. Other plants may not be profitable, such as the Myanmar incineration plant, due to low tipping fees of less than USD20/ton and low processing capacity (only 20,000 tons/year approximately) (JFE Engineering Corporation 2018; Huisman et al. 2017).

Synergies and trade-offs The technologies described in this section are generic, but complementary, as each one addresses a specific challenge. While mechanical recycling works well in the presence of well sorted and clean plastic waste (which would lead to high plastic rejection rates),

chemical recycling enables treatment of a wider range of plastics, but incineration only processes highly mixed solid waste.

There are also trade-offs when opting for recycling instead of incineration. Typical benefits, limits, and drivers for each process in the Netherlands are shown in Table 7.

Many authors reported that mechanical recycling results in better net environmental impact compared to other processes. In addition, pyrolysis is often reported to yield the highest positive environmental impacts compared to other chemical recycling processes or to incineration (Civancik-Uslu et al. 2021; Jeswani et al. 2021). Typically, in the UK, net carbon dioxide emissions are +71, +1,858, -160, -133, 431–1,104 kg per ton of mixed plastic waste subjected to landfill, incineration, pyrolysis, catalytic depolymerization, and gasification, respectively (Devasahayam et al. 2019). Proper management of plastic wastes also has additional benefits via reduction of secondary emissions of microplastics (Rhodes 2018; Magni et al. 2019).

Technologies to control plastics in freshwater or the sea

According to Schmaltz et al. (2020), 80% of freshwater/sea plastic pollution is manifested by land-based sources such as leakages from waste management channels. Plastics may enter waterbodies through various sources, including sewage effluents, storm drains, winds, tides and via recreational and commercial activities such as water sports and fishing (Tyler 2011; Benioff Ocean Initiative 2019; Borrelle et al. 2020; Schmaltz et al. 2020). Once items are in a freshwater system they can accumulate over time and get flushed into coastal and sea habitats (Li et al. 2016). According to Helinski et al. (2021), recent research has found that rivers are the leading pathways for the transport of plastics into coastal and sea habitats but there is limited research on plastic pollution in freshwater systems compared to marine environments (van Emmerik and Schwarz 2020). Properties of plastics such as size, shape, and polymer type are other key transporting drivers (Tramoy et al. 2019; Weideman et al. 2019).

In this section, we present and discuss technologies that could be implemented to reduce loads of plastics in surface water either by directly preventing or collecting existing plastic pollution. These technologies include booms and clean-up boats, trash racks, and sea bins.

Description of technologies

Booms and clean-up boats

A boom is a floating layer of logs that intercepts surface wastes (including plastics) along waterbodies. The logs are typically hinged together with stainless steel connectors (Schwarz et al. 2019; Nikiema et al. 2020; Schmaltz et al. 2020). According to Helinski et al. (2021), booms are independently effective technologies, however, they can be used in synchrony with clean-up boats for the collection of trapped wastes. Clean-up boats collect wastes from the surface of the river or sea using a system of nets and baskets (Cordier and Uehara 2019). The different types of water conditions (i.e. drainage volume and weather conditions) will demand different types of floating booms (Tyler 2011;

Table 7 Benefits, limits and drivers for recycling and incineration in the Netherlands

Solutions	Expected benefits	Limits	Drivers
Mechanical recycling	• Avoidance of CO_2 that otherwise would be emitted during incineration • Production of (new) plastic material	Only applicable for selected plastic types collected in large volumes	• Environmental awareness • Affordability • Policy promotes recycling • Carbon credits
Chemical recycling	• Avoidance of CO_2 that otherwise would be emitted during incineration • Processing of materials which cannot otherwise be recycled • Production of new plastics and products which constitute good energy sources	• Complex technology • High implementation costs • High volumes to be processed per plant	• High energy cost •High oil cost • High volumes of waste available • Carbon credits
Incineration	• Heat and electricity production leading to fewer emissions in the regular energy production sector • No sorting required, hence less expensive collection cost for solid wastes	• High capital investments • High volumes to be processed per plant • Environmental impacts of flue gas	• Lack of space for landfilling • High demand and tariffs for electricity and hot water • Policy promotes incineration

Gradus et al. (2016)

Nikiema et al. 2020). However, booms do not offer a solution for plastics travelling below the surface (Tyler 2011; Helinski et al. 2021). Booms are modelled in many shapes and sizes, and they have different levels of effectiveness in different types of water condition, such as calm, slow-flowing, and fast-moving water (Nikiema et al. 2020). Booms can comprise different materials such as styrofoam, polyvinyl chloride, and HDPE. They appear to be a simple, flexible, and practical technology option for river plastic clean-up.

Trash racks

Trash racks are the most common technique to prevent wastes carried by water, including plastics, from entering waterbodies (Zayed et al. 2018; Nikiema et al. 2020). They are structures with bars that block and guide litter into the set trap before it flows downstream (Schmaltz et al. 2020). These bars are spaced according to the minimum waste size that needs to be removed (Zayed et al. 2018). Trash racks are generally made of mild carbon steel, while wrought iron, alloy steel, and stainless steel are likewise used in certain applications. The challenge with trash racks is their frequent structural fatigue, which is a severe design concern (Zayed et al. 2018; Nikiema et al. 2020). Accumulated wastes are usually removed manually or mechanically by raking.

Sea bins

Sea bins are floating trash bins that collect floating waste and plastics as small as 2 mm from the surface of freshwater and marine systems. They are designed to be placed in calm waters near a power source (a dock or a marina, for example) (Nikiema et al. 2020). As the sea bin is placed in position, water is drawn in from the open top and passes through a filter bag inside the sea bin which only traps the waste (Riggs and Naito 2012). Small and large sea bins have been successfully used in California, Oregon, Hawaii, and Texas (Benioff Ocean Initiative 2019).

Costs, trade-offs, and effectiveness of technologies

Costs

Table 8 indicates the cost ranges of technologies used to prevent runoff contamination. According to Helinski et al. (2021), synergistic technologies are in the medium or high cost category while independent technologies are usually low cost. The cost of booms declines when length is higher and it also depends on the type of material used in construction. Cheap inflatable booms may degrade in the sun over time leading to more frequent replacement (Tramoy et al. 2019). Trash racks constructed with onsite burned logs are economically efficient. However, in particular cases, a heavy rail or steel structure may be worth the investment, depending on the type of material that is mobilized and the values at risk (Wildfire Guide 2020). O&M costs for technologies presented in this section are rather high. This is supported by the need for removal/clearing of the accumulated waste, requiring a collection device and labor.

Synergies and trade-offs

Successful intervention strategies to control plastic wastes will eventually consist of a combination of technologies and tools that is logistically and financially feasible in a given location (Table 9). A practical example is sole use of booms that will result in the accumulation of the wastes without a collection mechanism, so a combination of booms and a clean-up boat is appropriate. Also, installing an upstream trash rack will capture wastes travelling in the water, as booms will not offer a solution for wastes travelling below the surface, which can be a problem in areas that experience large dense wastes. Similarly, booms put downstream will capture any wastes that overflow the upstream trash rack.

Table 8 Costs of technologies used to prevent runoff contamination

Technology	Investment cost	Annual O&M	Profitability and durability	References
Booms	USD485–1,200 per m-long boom	USD533 per m-long boom	Booms can last 3–5 years in turbulent water, and 10 years and more in calmer situations	Bauer-Civiello et al. (2019); ELASTEC (2020)
Trash racks	USD1,000–4,000 for a simple unit. It could rise to USD30,000 for large ones, and depending on the materials selected	Manual clean-up units: USD1,800–9,000 per unit. Mechanical clean-up units: USD2,100–9,700 per unit	Rack will last 10+ years when properly maintained	Keating et al. (2014)
Sea bins	Typically USD4,000 for a 20-kg trash load or 1 bin	Typically, USD1,200 (if using 1 bin bag per day).	Recyclable components and structure are mobile. Seabin can be used for 5+ years	The Seabin Project (2020)

To clean rivers, a framework for the selection of suitable plastic capture devices has been recently published (Helinski et al. 2021).

Most importantly, for successful plastic waste capture, biophysical characteristics such as flow rate, width, and depth of the freshwater body must be taken into consideration. Furthermore, the social characteristics of the site should be considered thoroughly when choosing the best technology for a plastic wastes control strategy. For example, runoff water that flows through wetlands will likely demand a different combination of treatment solutions compared to flow through sewers, channels, drains, or under urban areas.

Technologies to control microplastics in water

Table 10 presents recent reports on concentrations of microplastics in different water sources, as well as possible mitigation measures. The quantified plastic particles detected varied significantly across studies. In most cases, wastewater and sewage sludge studies targeted particle sizes, larger than in freshwater and drinking-water studies, making direct data comparisons difficult (Nikiema et al. 2020).

In this section, we present and discuss technologies that could be implemented to reduce loads of microplastics in runoff, municipal wastewater, sewage sludge, and freshwater used for drinking. The technologies studied are stormwater retention ponds, wastewater treatment plants and the associated sewage sludge management or treatments units, and the drinking water treatment plants.

Description of technologies

Stormwater ponds and wastewater treatment plants

Many pollutants are often found in stormwater. Traditionally, the focus has been on controlling heavy metals, oils, and other organic pollutants or nutrients (Olesen et al. 2019). Recently, it has been established that stormwater also carries microplastics of various origins, which are deposited on land. End-of-the-pipe stormwater treatment is often done in artificial basins called retention or detention ponds, based on their *modus operandi*.

Municipal wastewater is purified as it passes through steps defined as preliminary, primary, secondary, and tertiary (Fig. 1). The treatment process is therefore complex and integrates chemical, physical, and biological processes taking place simultaneously or interacting, in order to achieve, ultimately, a high final effluent quality (based on case-specific requirements), enabling its reuse or safe return into the environment. Based on the treatment target, individual processes are combined on a case-by-case basis to aid in the removal of the targeted pollutants.

Primary treatment: It is commonly the main step during which the largest amounts of microplastics are removed from wastewater (Raju et al. 2018; Saur 2020), light microplastics during the skimming (Murphy et al. 2016), and heavier microplastics during filtration/gravity settling processes (Talvitie et al. 2017; WHO 2019). Microplastics removal performance during this treatment stage usually attains 42–82% (Nikiema et al. 2020). It could be up to 95% where advanced wastewater treatment and rigorous monitoring are the norm (Talvitie et al. 2017; Sun et al. 2018; Gies et al. 2018; Lv et al. 2019).

Secondary treatment: This is the minimum treatment level that enables treated water quality requirements to be satisfied in most countries. In principle, any secondary wastewater treatment plant system can achieve some removal of microplastics (Saur 2020). However, membrane bioreactors are among the most effective secondary treatment processes because they combine the benefit of biological treatment and membrane filtration. In general, between 86 and 99.8% of microplastic particles in raw wastewater are removed after this stage for treatment plants located in Europe and North America (Nikiema et al. 2020). In other countries, such as China, the removal performance of microplastics by wastewater treatment plants might be lower, typically 64% (Liu et al. 2019b) due to design or suboptimal O&M of the plants.

Tertiary treatment: With more and more stringent regulation adopted in some parts of the world, many wastewater treatment plants are retrofitted to also enable tertiary treatment to take place. Processes such as biological aerated filters and rapid sand filters tend to yield inconsistent, sometimes minimal, removal of microplastics (Bayo et al. 2020; Saur 2020). Nevertheless, processes such as filtering disks, dissolved air flotation, and membrane-based systems (i.e. reverse osmosis; membrane filtration) seem to be able to achieve multiple benefits, treating both microplastics and nutrients or heavy metals.

Sewage sludge treatment

Sewage sludge is a mixture of solids and water generated during wastewater treatment. Specifically, the wastewater treatment process transfers the microplastics from the liquid being treated into the sludge fraction. This means that, typically, 69–99% of the microplastics initially in the influent wastewater are transferred to the sludge fractions produced at different stages of the treatment process. Usually, the average size of microplastics in the sludge is higher than that in the initial wastewater, showing that the sludge mainly concentrates large microplastics. Composition of sludge also depends on the phase of the process

Table 9 Benefits, limits, and suggested position and combination of technologies to control and remove plastic wastes in freshwater

Technology	Opportunities	Barriers/limitations	Position and combination suggestions
Booms	• Booms can address climate-specific or extreme conditions, like storms, which result in large fluxes of water and hence plastic pollution • Booms have the significant advantage of not requiring the installation of permanent structures into the water bed	Booms cannot remove wastes travelling below the freshwater surface	• Downstream/upstream position • Combine booms and clean-up boats
Clean-up boats	Many clean-up boats are small in design and thus are easy to maneuver and simple to operate	• Can only collect surface wastes as they move on the waterbody • Possibility of high cost for a freshwater body with larger surface area due to the high amount of fuel require to power the boat to cover more distance	•Upstream/downstream positions • Combine clean-up boats with downstream trash racks
Trash racks	They have the advantage of being able to remove plastic wastes throughout the freshwater column and are not restricted to floating plastic wastes only	• Severe accumulation of wastes leads to head loss to the racks and causes structural fatigue of the racks • Removal of accumulated wastes on the trash rack by a trash rake, requires a large amount of power and infrastructure to operate	• Upstream position • Combine trash rack with downstream booms or clean-up boats or sea bins
Sea bins	Sea bin construction and materials are usually 100% recyclable	There could be a need for more than one sea bin, placed at different positions, to be able to capture most of the wastes. This is because of the smaller size of filter bags (20 kg/sea bin)	• Upstream/downstream position • Combine sea bins with upstream trash rack

Keating et al. (2014); Bauer-Civiello et al. (2019); Cordier and Uehara (2019); Nikiema et al. (2020); ELASTEC (2020); The Seabin Project (2020); Helinski et al. (2021)

Table 10 Type of contamination with microplastics and measures to contain pollution

Water source contaminated	Microplastic concentration (particle per L or kg) (minimum size quantified)	Effective measures	Source
Domestic wastewater	Up to 10,000/L, with lower particle size of 10–300 µm (in general, between 20–125 µm)	• Policy restrictions • Washing machine filters • Domestic wastewater treatment systems • Municipal wastewater treatment plant	Nikiema (et al. 2020)
Runoff	0.49–22.89/L, with quantified particle sizes between 10–2,000 µm	• Policy restrictions • Runoff filtration and treatment system • Municipal wastewater treatment plant	Liu et al. (2019a)
Industrial wastewater	• 1,200–54,000/L for textile industries (0.47 µm) • 1,000–254,500 for laundromats (0.65 µm)	• Industrial wastewater treatment plant • Municipal wastewater treatment plant	Nikiema et al. (2020); Brodin et al. (2018)
Freshwater /drinking water sources	• 1,400–3,600/L (1 µm) • 7 10^{-4}/L (20 µm)	Drinking water treatment through sedimentation, flotation, sand filtration, granular activated carbon filtration, and membrane-based filtration	Pivokonsky et al. (2018); Mintenig et al. (2019); Nikiema et al. (2020)
Sewage sludge	• 660–14,900/kg (0.7–300 µm) • 1,565–240,000 per dry kg (10–250 µm)	• Sedimentation and filtration devices • Sedimentation ponds • Wetlands	Sun et al. (2018); Olesen et al. (2019); Nikiema et al. (2020); Zhang and Chen, (2020)

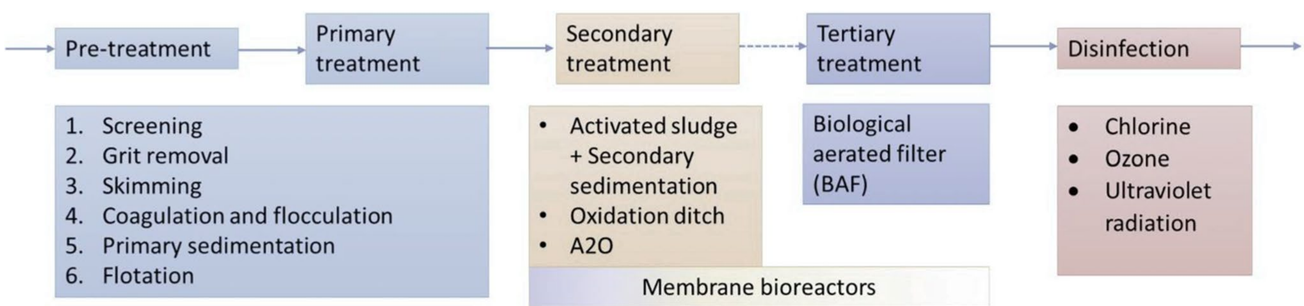

Fig. 1 Wastewater treatment stages

from where it was obtained. It also varies with the type of biological wastewater treatment processes implemented.

By far, land application is the main post-treatment process applied to the stabilized sludge. However, it increases the microplastics content of soils for many years after (Sun et al. 2018). Microplastics in soils may be carried by runoff water or wind back to the aquatic environment (He et al. 2018). Sludge incineration could solve this issue, but it also removes the opportunity to enhance soil health through enrichment with organic matter and nutrients also contained in sludge.

Drinking water treatment

Data on the efficacy of microplastics removal during drinking water treatment remain very limited. Preliminary findings highlight that processes such as coagulation/flocculation, sedimentation/flotation, and filtration using sand or membranes can be quite effective in removing small particles (<100 µm) (typically, 70–83% for microplastic removal) (Pivokonsky et al. 2018; Uhl et al. 2018; Ma et al. 2019; WHO 2019; Mintenig et al. 2019; Elkhatib and Oyanedel-Craver 2020). Treating drinking water may not be the end of the story because it may be re-contaminated with microplastics via the distribution network since pipes and containers

used by households are often made of plastic, which themselves may be a source of microplastics in drinking-water (WHO 2019).

Costs, trade-offs, and effectiveness of technologies

Cost

Table 11 presents the costs of implementation of technologies associated with treating wastewater or drinking water. Retention ponds used for stormwater runoff treatment are usually the most cost-effective way to remove microplastics. They require vast areas of land, and therefore, the opportunity cost is not negligible (Nikiema et al. 2020). From the perspective of microplastic removal in municipal wastewaters, secondary treatment plants seem to be more cost effective than tertiary treatment plants. In fact, the incremental benefit achieved with tertiary treatment compared to secondary treatment does not seem to be financially justified when considering microplastics only, although at this stage, data still have to be harmonized for this finding to be confirmed. However, tertiary treatment aids in removing other pollutants, which are also critical from environmental and health perspectives. Hence, the assessment of the benefits of the secondary and tertiary treatment processes must factor in all these benefits to reach a holistic conclusion. Cost of sludge management is usually accounted for as part of conventional wastewater treatment plant cost. However, the implementation of incineration in lieu of land application may require additional equipment and could therefore be costlier.

The cost of drinking water is highly reliant on the source of the water and the contaminants it may contain (such as suspended and colloidal solids, silica and colloidal silica, bacteria, and hardness) as well as the level of treatment required to attain the water quality needed. Factors such as turbidity could increase treatment cost (Heberling et al. 2017). But available data currently do not allow researchers to determine if treating drinking water to target microplastics is necessary since the concentration levels detected remain low.

Synergies and trade-offs

The water management strategies described in this study offer multiple co-benefits. For example, beyond microplastics removal, all water and wastewater treatment plants remove simultaneously contaminants which have various impacts on human, animal, and environmental health (OECD 2021). Currently, most of these systems are not designed with an intentional microplastic removal target because there are important knowledge gaps concerning the extent of the risks associated with microplastics and their relative importance compared to other risks. Another challenge lies with the management of treatment by-products. Conventional practices linked to sludge management involve land application, which leads to the recontamination of the land and environment.

Discussion

Fig. 2 presents a systems diagram and shows sources, sinks as well as areas for possible interventions to mitigate plastic pollution. Overall, landfills and waterbodies are the main sinks of plastics in the environment. Indeed, in cities, if waste management is viewed as an essential utility service, it is often delivered in partnership with the private sector. Besides, waste management can be depicted as an expensive, labor-intensive and low-margin business. Challenges such as poor governance, inadequate finance, logistical constraints, poor operation and maintenance of equipment and systems, social and financial barriers within communities, just to name a few, drive the collection rates in cities down (Cofie et al. 2016; Alpizar et al. 2020). Yet, the collected waste may not be managed optimally. Most is sent to open dumps or to poorly managed landfills causing notable waste (including plastic) leakage. On the other hand, uncollected waste is burned, recycled informally or illegally dumped on land and drains, and becomes a source of water contamination by plastics.

Commercial fishers are another key pollution source for waterbodies, mostly through lost and derelict fishing gear (Croft et al. 2021). The problem they pose needs to be tackled through a combination of approaches involving adoption and enforcement of bans, restrictions and guidelines to reduce or prevent generation of plastic waste that leads to water contamination. Otherwise, it is also useful to rethink and redesign plastics materials used by this industry to ensure they are compostable or fully recyclable. Ultimately, clear plastic reduction targets throughout entire fishing operations need to be enforced, but given their notable cost implication, strong political will is essential in this context.

With regard to microplastics, the main sinks are soil, mostly as a result of land application of sludge which is the most widespread management technique (Nikiema et al. 2020).

Effective management of plastics and microplastics needs to combine different solutions and measures, as described in previous sections. First, there will be a need to reduce waste generation and to find a solution to the poor management, which globally, is responsible for the contamination of waterbodies with millions of tons of plastics, annually. To that effect, households need to be actively engaged. Another key factor is the need to develop mechanisms to value and proportionally incentivize households and industries engaged in sustainable practices. Currently, services

Table 11 Costs of technologies used to prevent municipal wastewater contamination

Technology	Investment cost (per m^3/d)	Annual O&M (per m^3/d or per m^3)	Profitability and durability	References
Stormwater runoff ponds	20% lower than that of wetlands which are known to be USD379–11,016 with an average of USD3,441 per m^3/d treated	1–6% of investment costs	Costs can vary greatly, depending upon the initial site conditions. Once operated sustainably, these structures can become permanent in the landscape	Hunter et al. (2018); Noack (2018); Coalition Clean Baltic (2017); Tyndall and Bowman (2016); Strassler and Strellec (1999)
Secondary wastewater treatment plant	USD399–9,246 with an average of USD3,308 (2017)	USD29–1,321 with an average of USD437 (2017). This corresponds to between 4 and 25% of investment cost (13% on average)	Highly dependent on how the treatment plans have been designed as well as the type of contaminants that are expected to be removed	Hunter et al. (2018); Guo et al. (2013); SAMCO (2016a); SAMCO (2019); Pajares et al. (2019)
Tertiary wastewater treatment plant	USD984–144,224 with an average of USD57,534 (2017)	USD76–21,804 with an average of USD6,168 (2017). This corresponds to between 1 and 33% of investment cost (10% on average)		
Drinking water treatment	USD600–24,000	Typically, around USD60–100 for groundwater. In many cases, between USD146 and USD550, in Europe, Australia and North America. In Europe and USA, USD0.40–1.5 per m^3. Values as low as USD0.2 per m^3 are reported in the case of groundwater treatment for drinking purposes	Highly dependent on how the treatment plans have been designed as well as the type of contaminants that are expected to be removed. In general, costs are less when treating groundwater for drinking purposes	Heberling et al. (2017); SAMCO (2016a); Plappally and Lienhard (2012); Atta-Asiamah (2010)

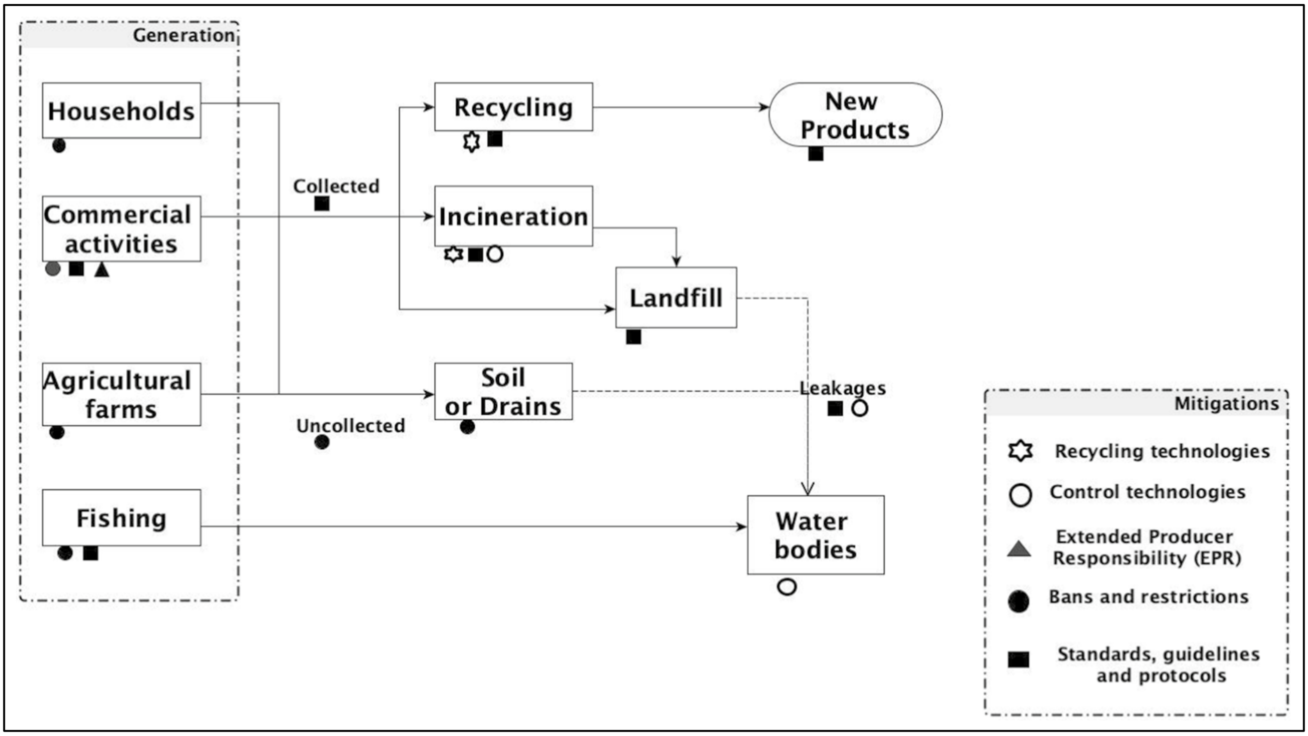

Fig. 2 Systems diagram showing sources and sinks for plastics in the environment, as well as locations for possible interventions

devoted to waste management in houses are mostly delivered by women on an unpaid basis, a value that has never been measured or even officially acknowledged (Wang et al. 2019). Policies must also be enacted at national, regional and global levels to support efforts, leading to reduced generation of waste and adoption of sustainable mitigation and recycling strategies. These policy-based solutions need to be coupled with recycling options and treatment measures.

There are five main routes for safe plastic waste management and they are presented in Table 12. The selection of the suitable route will depend on local conditions. However, Route 3 maximizes circular economy benefits.

Table 13 presents the costs per technology in USD per kilogram of plastics removed. Data used to obtain these values are taken from earlier (respective) parts of this report. The main takeaway from Table 13 is that prevention seems cheaper than treatment. With treatment, the earlier it occurs along the pollution chain and the larger the plastic size, the cheaper it is.

Typically, policy measures cost in the range of USD 0.04–0.09 per kg of plastic, which is the lowest possible cost experienced in managing plastic waste. The cost in this case is mostly borne by the retail industry, wholesalers and importers, consumers in the community, and only to a minimal extent by the government (mostly to enable awareness creation and enforcement). This means that policy measures should preferably be the first step in preventing or reducing contamination with plastic, particularly in developing countries. For instance, average consumption per person is only about 16 kg per capita in the Middle East and Africa. However, due to underdeveloped waste management systems, the pollution problem has accrued tremendously and current challenges will likely be worsened by growth and industrialization plans that are expected in the future (Ugorji and van der Ven 2021). Hence, developing countries will need to invest in effective regulatory and enforcement capacities to enable institutions that are tasked with implementing policies and action plans to play their roles effectively.

In addition, the cost of mechanical recycling is between USD 0.003 and USD 0.23 per kilogram, which covers the lowest and highest ends of the cost range for plastic waste recycling options. This means that mechanical recycling is the most cost-effective way to recycle plastics when value chains for waste collection and sorting are in place. Low mechanical recycling values are observed in developing countries where informal arrangements enable waste collection to be achieved at minimal cost, although often at the expense of vulnerable community groups which are exposed to poor work condition, health risks and generate insufficient revenues. Recycling options are to be preferred to incineration which does not support circular economy principles. Besides, each technology has specific needs and offers opportunities that may constrain its adoption in a given context, even when it appears to be an affordable option.

Table 12 Multiple barrier approach to address plastic pollution

Route	Enabling environment	Solid wastes		Freshwater streams, drains, or the sea	Stormwater treatment	Municipal wastewater treatment	
1	Suitable policy measures to reduce and recycle plastics and microplastics	Mechanical recycling	Incineration	Trash racks (booms and sea bins could be used in selected cases)	E.g. ponds, wetlands, etc.	Secondary or tertiary level, at minimum	Safe sludge management
2			Landfilling				
3			Chemical recycling				
4		Incineration					
5		Landfilling					

This article

As expected, elimination of plastics once they have entered waterbodies appears to be very expensive. Depending on where the treatment is conducted, the costs of removal are 10 to several hundred times higher than when the treatment is done as part of the solid waste management plan, with trash racks and sea bins being among the most affordable treatment solutions. So far, only wastewater treatment plants can achieve important microplastic removal. Although the cost is much higher compared to the removal of larger plastics, it is important to note that wastewater treatment plants have multiple other functions, which are of great value to society (OECD 2021).

According to Bassetti (2020), the future of plastics remains uncertain. So far, plastics have been some of the most ubiquitous materials used as they are perceived to be inexpensive and easy to manufacture and process into any given shape, depending on requirements. Drawing on current trends, some major players from the oil industry (e.g. the International Energy Agency) anticipate that the demand for plastics will continue to grow at a sustained rate in the next 20 years. Betting their future growth prospects on higher demand for plastics, they are therefore investing heavily (over USD 400 billion) to increase their production capacity over the coming years (S&P GLOBAL 2020).

However, more attention is being drawn towards the externalities associated with plastics, which have been estimated to lie between USD0.8 and USD1.4 per kg (Bassetti 2020), resulting in a growing thrust towards stricter regulation of plastic use, which might impact the current projected trend. An increasing number of large private companies, especially in the agro-food sector, have pledged to reduce the amount of single-use plastics and more generally the demand for plastics, increase the use of biodegradable and/or recycled plastics materials in their products, or resort to alternative substitute materials, in response to consumer preferences and new/stricter legislation (Bond et al. 2020; Bassetti 2020). But these efforts are yet to yield the high impacts expected as no substitute, which complies with sanitary restrictions while remaining affordable, has been identified. Typically, the use of bottled or sachet water remains a necessity in developing countries and is a key part of national strategic plans to preserve public health from sanitation-related diseases associated with microbial contamination. Until these sanitary issues are significantly addressed, hope lies in the development of new plastic products, which are expected to be more environmentally friendly. Using materials such as rice straw, these innovations are proposed as part of a circular economy approach to generate biopolymers, that may, ultimately, partially replace conventional plastics. But their environmental benefits and possible long-term impacts are still undefined.

It is therefore obvious that plastics are here to stay, at least in the short term. Following the surge of the COVID-19

Table 13 Summary of costs

Technology	Typical investment and O&M Cost (USD per kg of plastic)	Target (plastic) wastes	Value generated from plastic waste
Mechanical recycling	0.003–0.23	Thermoplastics such as PP, PET, PVC	New plastic products
Chemical recycling (pyrolysis)	0.083	Grocery bags, bubble wraps, trash bags, retail packaging, food wraps, carpet fibers, and others that cannot be recycled mechanically	New plastic products and/or energy
Chemical recycling (gasification)	0.102		Energy and/or new plastic and non-plastic products
Incineration	0.04–0.15	Various wastes, including all types of plastics	Energy
Booms	22.5–30.1[a]		No value. Additional waste disposal cost is incurred
Trash racks	4.87–8.46[b]		
Sea bins	1.24–1.55[c]		
Secondary wastewater treatment plant	21–821 (average: 276)[d]	Various wastes, including all types of plastics and microplastics	No value. Waste disposal fees, often landfills which could contaminate soils, are included
Tertiary wastewater treatment plant	54–13,150 (Average: 4,000)[d]		
Stormwater treatment	6,000–78,000 (average: 30,000)[d]	Various wastes, including sediments, plastics, and microplastics	No value. Sediment disposal cost is incurred
Drinking water treatment	395,000–5,000,000[d]	Microplastics	No value. Waste disposal cost should be negligible given the low quantities
Policy tools	0.04–0.09[e]	Single use plastics, and plastic bags	Variable. Includes waste minimization measures and substitution of conventional plastics with other materials, such as biodegradable plastics
No treatment[f]	3.3–33	Estimated for plastic waste contaminating marine ecosystems	

[a]Typically, plastics represent 80% of debris removed, estimated at 0.088 kg/d for each meter of boom (ELASTEC 2020). The lifecycle of the boom is taken as 5 to 10 years (see Table 8)

[b]This is obtained considering a typical example of a USD100,000 rack removing 2.55 kg/day of plastics . The lifecycle of such equipment might be between 15 and 30 years

[c]Typically, plastics represent 90% of debris removed (The Seabin Project 2020). The lifecycle of the bin is taken as 5 to 10 years (see Table 8)

[d]Removal efficiencies for treatment plants are: 95% for stormwater, 97% for secondary wastewater treatment, 99% for tertiary treatment, and 90% for drinking water treatment. Inlet concentration of microplastics at a municipal wastewater treatment plant is typically 5.60 g/m^3 (Lv et al. 2019). MP concentration in stormwater ponds was taken as 1.143 mg/m^3 (Liu et al. 2019a). This concentration corresponds therefore to the outflow concentration. The lifecycle of treatment plants was taken as 50 years for stormwater and 30 years for secondary and tertiary wastewater treatment and drinking water treatment

[e]This value is obtained assuming that these policy measures reduce plastics by 30–50%. Plastic waste generation in Australia averaged 107 kg per capita in 2015 (Pickin and Randell 2017). It considers only the cost of policy implementation. Other costs are borne by households, industries, among others

[f]Beaumont et al. (2019)

pandemic in March 2020, many efforts that were ongoing to reduce the use of single-use plastics have been hampered (Bassetti 2020). The response to the pandemic required the urgent mass production of face masks and single-use medical protection to break transmission chains as much as possible. This resulted in a major increase in plastic waste generation and has increased pressure on waste management in many cities.

At the same time, there is higher awareness that climate change mitigation must occur. For many years, Asian and African countries have been importing plastic waste from the western world. But recently, some countries such as China have banned all or some types of these imports, citing the effects these practices have on their national ecosystems. This major disruption forces many countries in the West to re-think their model for consumption of plastics and management of the associated waste. They need to identify new adequate mechanisms to sustainably finance the cost of plastic waste management in-country or to meet plastic waste export quality requirements imposed

by some countries. Indeed, under the Basel Convention and amendments, which came into force in 2021 and has been signed by 53 countries globally, plastic waste trade is only permitted if it is clean, sorted and easy to recycle—unless the importing country has been granted an exemption (Ugorji and van der Ven 2021). Globally, there is a greater quest towards social responsibility, and issues of fairness and equity are becoming essential considerations in the process, as there is a need to ensure that everybody pays for their fair share to address the challenge in a durable manner. The plastic industry, which has grown by 4% annually, will have to invest more funds to make the industry cleaner.

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