Environmentally sound management of plastic waste

Prepared for : IETC, UNEP
Prepared by : Yumiko Abe, PhD., Consultant
28th March 2024

Executive Summary

Introduction

Plastics have made a significant contribution to facilitate the modern society in almost every human need from food and beverage, healthcare and medicine, transportation, construction, to various household and electronic goods, and other products necessary or useful to support our daily activities. Although plastics are a versatile and widely used material that has revolutionised many aspects of our lives, this material has caused a serious problem of environmental pollution (UNEP, 2023a and 2023b). The plastic pollution situation is particularly severe in the developing countries where public waste management infrastructure is inexistent or inefficient. WWF's report (2023) argues that the true lifetime cost of plastic is 10 times higher in low-income countries and 8 times higher in low- and middle-income countries than in high-income countries due to the lack of proper infrastructure to manage plastic waste.

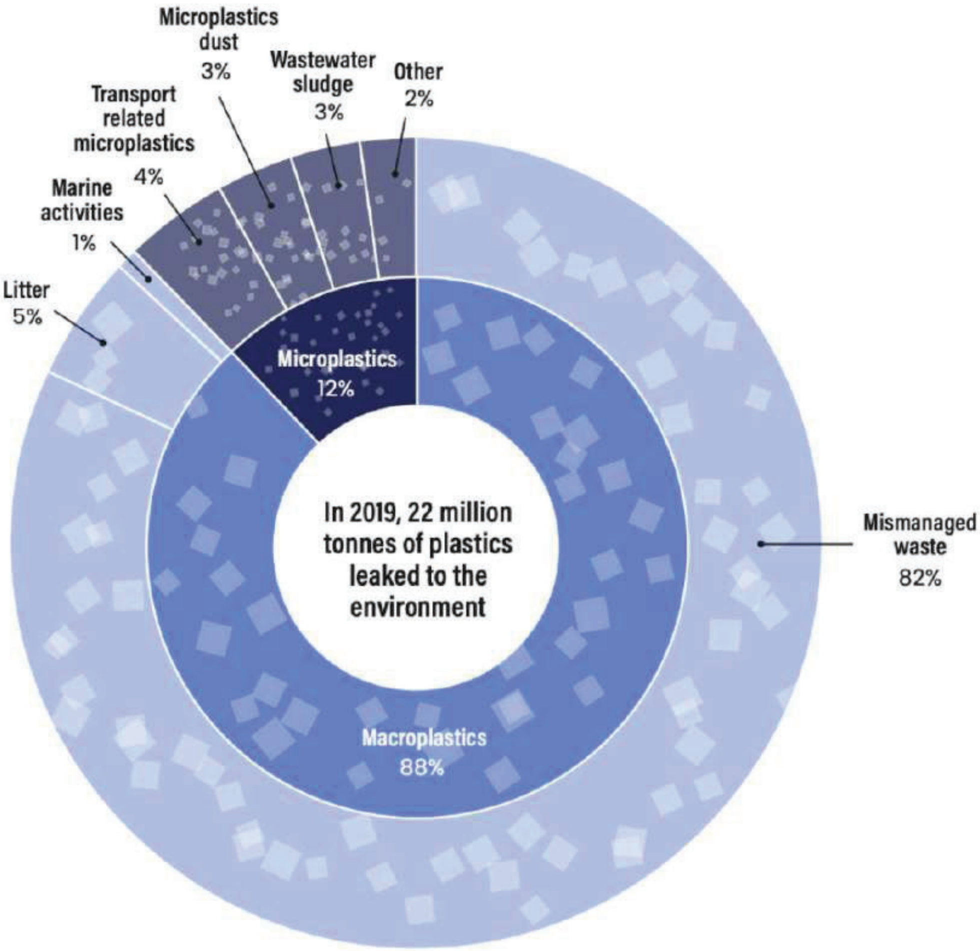
This report highlights the environmentally sound management of plastic waste by integrating the concept of waste hierarchy (reduce, reuse, recycle) and UNEP's policy on environmentally sound management (ESM) (UNEP, 2002). The report presents the findings on the sources of plastic leakage to the environment to identify the regions to focalise the global effort to fight against the plastic pollution. It also presents different municipal solid waste (MSW) management strategies utilised globally, plastic waste management strategies and technologies, economic value of plastic waste, as well as a systematic evaluation mechanism to select appropriate technologies to manage plastic waste in an environmentally sound manner.

1. Sources of plastic waste leakage

The global production of plastics reached 460 million metric tons (Mt) in 2021 with the global market size of 712 billion USD (Plastic Europe 2022), and the packaging industry consumes by far the largest quantity of plastics comprising up to 35% of the total plastic production (OECD, 2022). In addition the global generation of plastic waste was approximately 360 million tonnes in 2019, and a significant portion of this waste, over two-thirds, originated from short-lived applications such as packaging, consumer products, and textiles (OECD, 2022).

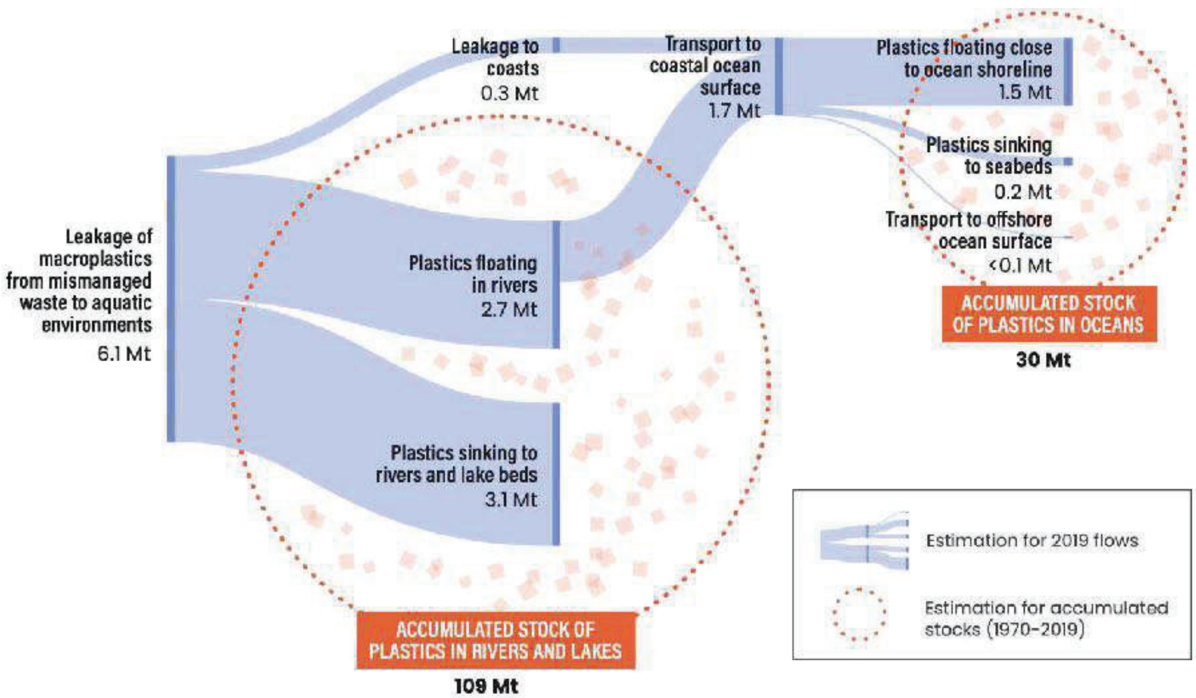
The majority of leaked plastics are macroplastics, plastics greater than 5mm in size, of which most (82% of the total plastics leaked to the environment) arise from mismanaged plastic waste, followed by the littered plastic waste, and from marine activities mainly resulting form lost fish gears as shown below (OECE, 2022 & UNEP, 2023b). Microplastics, plastics smaller than 5mm in size, represent 12% (or 2,64 Mt) of the total leaked plastic waste of which 4% are from transport related microplastics (mainly tire abrasion: 0.7 Mt, break wear: 0.1 Mt, and eroded road markings: 0.2 Mt), 3% are from microplastics dust (0.8 Mt from shoe sole abrasion, paint chips and textile dust), 3% are from wastewater sludge (mainly from loss of synthetic fibres during washing, microbeads in personal care products), and 2% from other origins including accidental losses of pellets (0.28 Mt), and abrasion of artificial turf (0.05 Mt), according to OECD report (OECD, 2022).

Global leakage of macro- and microplastics to the environment (OECD, 2022)



Much has been studies in the last ten years to better understand the fate of mismanaged macroplastic waste especially with respect to the marine plastic pollution. In recent years, many studies demonstrate that the rate of plastic waste leakage to the marine environment is probably lower than previously estimated (Meijer et al., 2021; OECD, 2022; and van Emmerik et al, 2022). According to the OECD report (2022), approximately 9% of total leaked macroplastic waste reaches the ocean as shown below, and the river system serves as plastic waste reservoir with flood events serving as a plastic release mechanism (van Emmerik et al, 2022). Extreme meteorologic events can empty the plastic reservoir, flashing land-based plastic waste from the floodplain, excavating buried plastics from riverbed sediments, mobilising and transporting the retained plastic waste into the ocean.

Aquatic leakage of macroplastic waste (OECD, 2022)

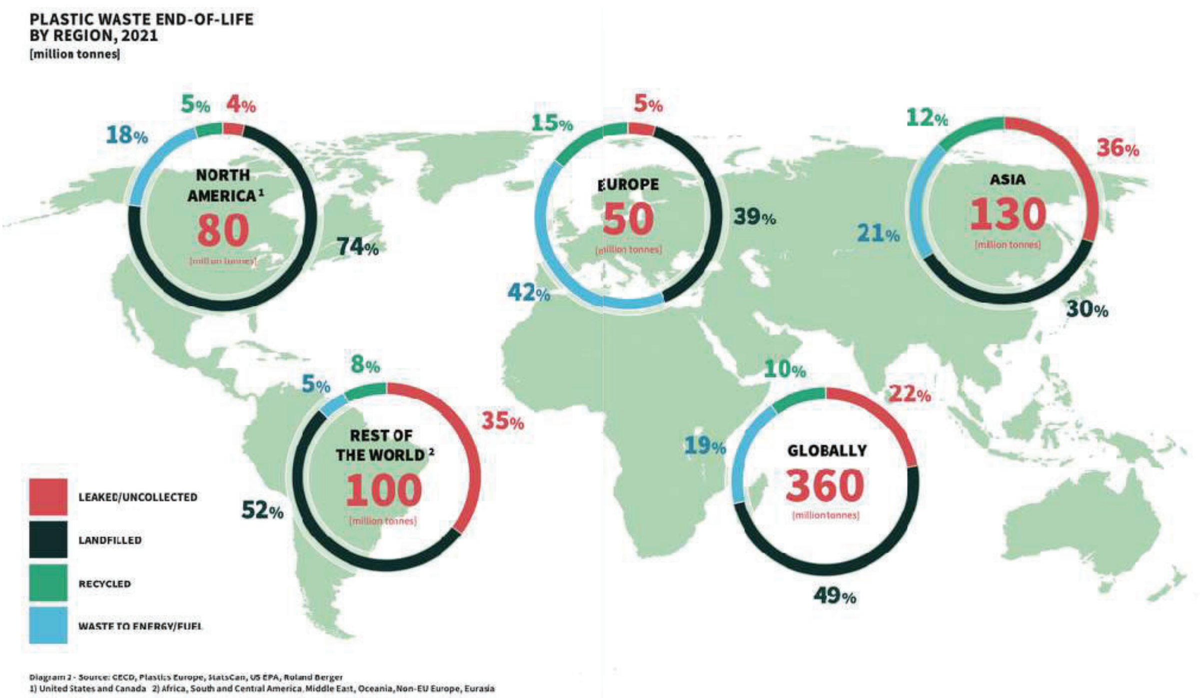


As for microplastic leakage from industrial sources, pellets spills during transportation, pellet loss through mismanagement from plastic manufacturing value chain (virgin and recycled pellets), and the use of abrasive microplastic scrubbers are the main sources of leakage (NEA, 2014). The pellet spills are, by far, the most important factor of industrial microplastic leakage with the estimated value of 280 000 tons/year (OECD, 2022). Plastic pellet leakage poses an additional risk as they can carry a number of different chemicals intentionally added from the production level. A study carried out by IPEN (Karlsson et al., 2021) found that all washed-off pellets from their 23 study locations had target PCBs (polychlorinated biphenyls, banned by the Stockholm convention) and BUVs (benzotriazole, UV stabilisers) with varying concentrations (Karlsson et al., 2021). Hence, plastic pellet leakage is of a particular pollution due to the marine exposure of hazardous chemicals absorbed by the oleophilic characteristics of plastic resins.

2. Plastic waste management as an integrated part of MSW management strategies

MSW (municipal solid waste) management has a universal work flow starting from waste generation, waste collection and sorting, and waste disposal and valorisation. For recyclable materials such as plastic waste, the material flow can involve reprocessing steps depending on the local capacities. World Bank report (Kaza et al., 2018) reports that waste management costs are disproportionally high for low-income countries compared to high-income countries, and waste management indeed is one of the most costly public services, and many countries can simply not afford such costs as their priorities are placed in public health and education. The figure below shows the fate of plastic waste by global regions. Waste is often not collected at all or landfilled (mostly not in sanitary landfills but in open dumps as reported by Kaza et al., 2018) in the Global South (referred to as « rest of the world » and in Asia due to the lack of financial means. Since mismanaged plastic waste consists of 82% of the total plastic pollution, it is of a global interest to financially support the developing countries in these regions to develop a sustainable and environmentally-sound MSW management infrastructure to avoid future plastic leakage arising from mismanaged MSW.

Plastic waste fate by region, 2021 (Alliance to End Plastic Waste, 2023)



There are two approaches to manage MSW: centralised and decentralised approaches.

Centralised waste management involves collecting waste from homes, businesses, and other sources and transporting it to a large-scale treatment facility. These facilities are often located in industrial areas or on the outskirts of cities.

Decentralised waste management involves collecting, sorting, and processing waste within a smaller geographic area, such as a neighbourhood or district. This approach, sometimes referred to as « community-based approach » is often more suitable for smaller communities or areas with lower waste generation rates.

In general, the centralised approach requires heavy and intensive infrastructure with more space and finance for transfer and management of a large quantity of MSW, and the decentralised approach requires considerably less infrastructures depending on the scale and the method of final disposal (Jayakumar Menon & Palackal, 2022). Most studies and reports recommend the decentralised approachl for the developing countries due to the lower costs associated with implementation and operation, its flexibility and scalability as well as its facility to integrate the existing informal sector (Poerbo, 1991, UN Habitat 2010, Kaza et al., 2018, US EPA 2020, Jayakumar Menon & Palackal, 2022).

The report describes how centralised and decentralised approaches can be applied for waste collection and sorting with some financial information on the capital costs (capital costs and costs of plastic waste separation equipment) to provide a broad understanding of the financial implications.

3. Plastic waste management strategies and technologies

The classification of plastic waste management approaches and technologies was developed from the frameworks proposed by UNEP (2002, 2023), Zhang et al. (2021), and Kassab et al. (2023), and presented in the report. The first classification level involves the disposal method and the fate of plastic waste: reuse, recycling, biodegradation and landfilling. The second level applies to recycling as plastics are one of the simplest and the most cost-effective materials to recycle (Werner et al., 2022).

Recycling classification consists of mechanical, chemical and energy Recovery as defined by ISO 15270:2008, each level with a range of various technology groups as follows:

- Mechanical recycling: closed-loop recycling and open-loop recycling (downdrading and composite recycling).
- Chemical recycling: closed-loop recycling (dissolution) and open-loop recycling (thermolysis and chemolysis).
- Energy recovery: Waste-to-Energy and Alternative fuel production.

The report presents each technology with basic technical and financial information. The advantages and disadvantages of each technology is discussed in Chapter 5.

According the the concept of waste hierarchy, the reuse applications must be considered in priority to recycling. Ellen MacArthur Foundation (2019) identified that reusing plastic packaging materials creates various benefits such as cutting costs, adapting to individual needs, optimising operations. The underlying concept of reuse is the refillability of plastic packaging materials (or containers) so that they can be used repeatedly. Four reuse models proposed include: Refilling at home, Returning from home (pick-up service), Refilling on the go (refilling at an in-store dispensing system) , Returning on the go (return at a store or drop-off point). All models involve business-to-consumer relationships differing in terms of packaging « ownership », and the economic benefit of shifting to reuse models is estimated at USD 10 billion (Ellen MacArther Foundation, 2019 and UNEP 2023b). Increasing the reusability of packagings used for consumer goods is of a great interest to reduce the global plastic waste quantity as the packaging plastics is by far the major source of plastic waste (refer to Chapter 1).

There are over 7000 different types of plastics with over 13 000 additives (UNEP, 2023b), and each type has its own chemical makeup and properties. This chemical heterogeneity makes it difficult to recycle all plastics, as they need to be sorted into the correct categories before they can be processed. In addition, plastics are often used in combination with other materials, such as metal or paper. This makes it even more difficult to recycle plastic, as the other materials need to be separated from the plastic before it can be processed.

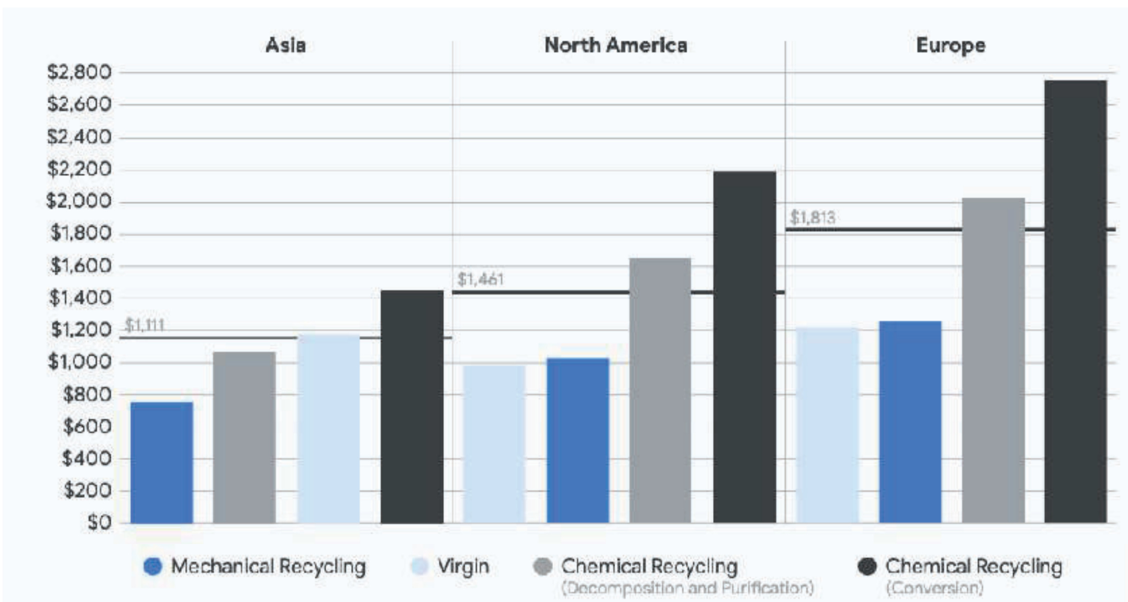
Depending on the recyclability of plastic waste determined by the chemical type and the form of the plastics, plastic waste can be categorised into high-value plastic waste and low-value plastic waste. High-value plastic waste implies hard plastics used in bottles and containers (PET, HDPE and PP) whereas low-value plastic waste implies soft and flexible plastics used for wrapping and packaging as films and bags which generally has no market value. In general, low-value (or no-value) plastic waste is not collected by the informal sector since it does not generate any economic interest; indeed, most mismanaged plastic waste is the low-value plastic waste such as packaging bags and films (Pucino et al., 2020).

4. Economic value of plastics and plastic waste

Recyclable plastics are traded as a market-driven commodity. Plastic waste and scrap can be traded under the control of the Basel convention. Brown et al. (2023) reports the trading rate evolution of the plastic waste from OECD countries which export their plastic waste when in-country capacity of plastic recycling is not sufficient to recycle all of its collected plastic waste. Sorted plastic waste and scrap for recycling are traded between 0.5 to 0.6 USD/kg in recent years in the OECD member countries (Brown et al., 2023), and the plastic waste exports are subject to strict regulations.

Recycled plastics are also traded globally and the trade value depends significantly on the region as shown in the figure below (Werner et al., 2022). In Asia, mechanically and chemically (chemolysis) recycled plastics are cheaper than virgin plastics where as virgin plastics remain cheaper in North America and Europe.

Trade values of virgin and recycled plastics by region (Werner et al., 2022)



Despite the economic disadvantage, plastic recycling is a growing industry with high economic potential, and the industry is expected to grow up to 400% by 2040[1]. In addition, plastic recycling creates employment opportunities. US EPA reported that the country recycled 1.2 Mt (million tonnes) of plastic waste in 2012 which generated 28,521 employment opportunities with 1 273 million USD wage and 170 M USD tax payment (USEPA 2020). Plastics are the 3rd most profitable recycling material in the US after e-waste and nonferrous metals. In Indonesia, Prevented Ocean Plastic ™ Southeast Asia opened a plastic collection centre with annual collection capacity of 1320 tonnes and created 30 jobs[2], and an aggregation centre (collection and recycling) with annual process capacity of 6000 tonnes created 40 jobs[3]. A PET bottle-to-bottle facility in the

[1] https://www.spglobal.com/commodityinsights/en/market-insights/blogs/chemicals/031121-recycled-plastics-global-market-commoditization-standards-pricing

[2] https://www.preventedoceanplastic.com/25-by-2025-2-north-jakarta/

[3] https://www.preventedoceanplastic.com/25-by-2025-1-plastic-recycling-in-semarang/

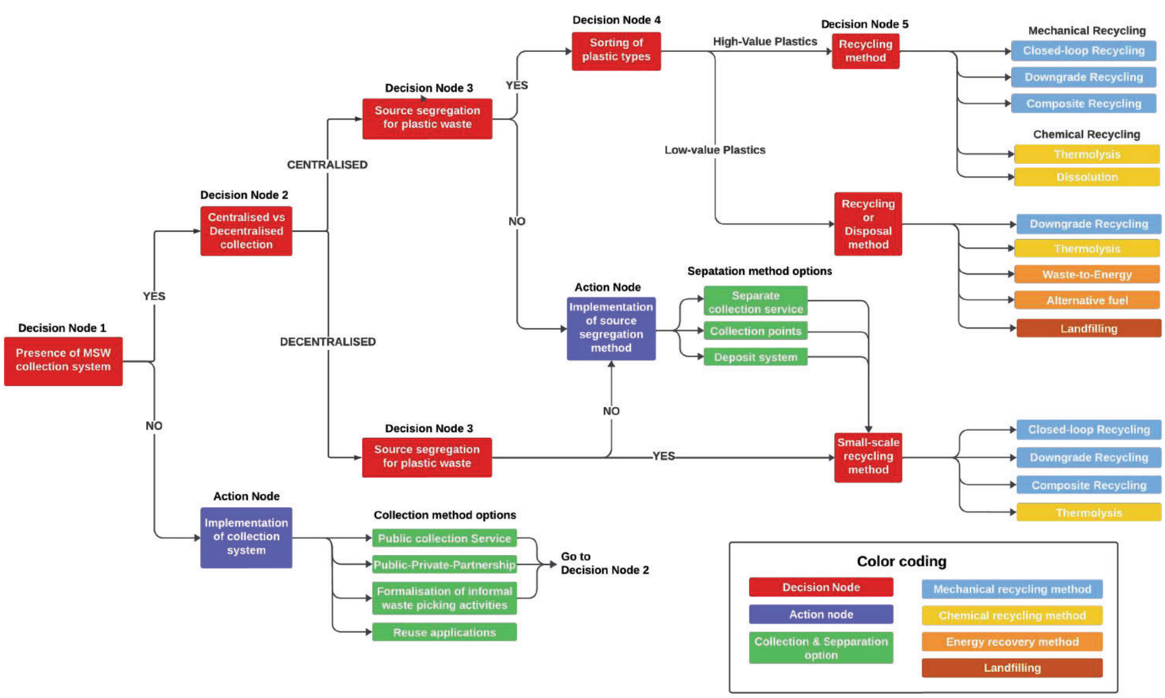
Philippines recycle 750 000 tonnes of PET bottles annually and created 200 local jobs[4]. These business cases clearly demonstrate how plastic recycling can be economically and socially profitable by reducing the environmental footprint related to the plastic waste.

5. Comparison and evaluation of different plastic waste management technologies

Suitable plastic waste management approaches, solutions and technologies are highly context-specific and depend on the level of available waste management infrastructure which, in turn, reflects the country's income level and socio-economical situations. In terms of plastic pollution reduction, countries that make a step to move away from open dumping and implement a basic but effective plastic waste management strategy will contribute significantly to mitigate the global plastic pollution, and it is of a global interest to support these countries.

Environmentally-sound plastic waste management involves waste collection, sorting and the final disposal or reprocessing technology. However, it is important to keep in mind that technology is not a mighty solution to the problem of mismanaged plastic waste. Plastic management technology is not a panacea, but a vehicle to convert the problem into an opportunity to create a better environment and to transform the waste into a valuable resource.

Effective plastic waste management depends strongly on the waste collection capacity, and successful plastic recycling requires efficient sorting of plastics. Hence, it is not possible to implement a plastic waste management strategy without these downstream operations. Recognising these close linkage of downstream operations, the figure below proposes a decision tree to identify applicable plastic waste management technologies for different contexts.



[4] https://www.circularonline.co.uk/news/philippines-pet-recycling-plant-opens-in-partnership-with-coca-cola/

The technology boxes on the right end of the figure above are the potential plastic waste management technologies for each specific context defined by five decision nodes. It is widely recognised that the most environmentally-sound and sustainable disposal plastic waste management method is recycling (UNEP, 2022a). It is important to note that multiple solutions are proposed as the implementation of multiple solutions would increase the effectiveness of plastic waste management strategy and accelerate the future plastic pollution prevention.

Environmentally sound plastic waste management must prioritise the waste hierarchy principal of reduce, reuse, and recycle. Notwithstanding, there are numerous types of plastics with different physical and chemical properties, and it is practically impossible to treat all plastic waste by a single solution; hence, last resort solutions such as landfilling and incineration via waste to energy may be needed to treat dirty low-value plastics in an environmentally sound manner while utilising the high-value plastics for recycling operations.

In this context, developed countries with solid and efficient waste management infrastructure, for example, should lead the global plastic waste management practices by phasing out the incineration via energy recover and landfilling to accelerate the development of plastic circular economy, as in the EU taxonomy for sustainable activities (2020).

When it comes to developing countries, the following technologies are particularly suitable for developing countries as they are scalable with relatively low technical, economic and environmental obligations:

- Closed-loop mechanical recycling (plastic bales, flakes and/or pellet production)
- Downgrading recycling
- Composite recycling
- Thermolysis

Environmentally sound plastic waste management must privilege the waste hierarchy principal of reduce, reuse, and recycle. The options of incineration and landfilling should be considered as resort alternative methods when local context and situation do not allow the implementation of the reduce-reuse-recycle strategy. Developed countries with solid and efficient waste management infrastructure, for example, should lead the global plastic waste management practices by phasing out the incineration via energy recover and landfilling to accelerate the development of plastic circular economy.

The report also proposes the use of holistic evaluation criteria for the decision-making of selecting an environmentally-sound plastic waste management technology. The criteria are classified into eight key categories with a set of criteria as presented in the table below.

Based on these criteria, each recycling technology was evaluated based on the author's professional expertise and discussion with industry insiders in the report. According to the evaluation, the mechanical recycling of plastics is the most technically established and economically viable solution at the moment in agreement with the findings from Uekert et al. (2023), and this recycling technology is present globally and developing rapidly. The plastic recycling industry is expected to grow up to 400% by 2040, and the mechanical recycling will continue to dominate the plastic recycling industry according to the industrial forecast[1].

Comparison and evaluation criteria

Category	Criteria
Waste characteristics and compatibility	Plastic type and composition, Contamination level, Quantity, Presence of hazardous substances, Physical form
Land use	Land surface requirement, Land accessibility, Land availability
Cost effectiveness	Capital costs, Operation and Maintenance costs, Cost effectiveness in the long term, Life cycle cost analysis
Economic benefit	Job creation potential, Revenue generation potential, Product quality and marketability
Technical feasibility	Processing capacity, Scalability and adaptability, Technology compatibility and integrability, Operation and Maintenance requirements, Technology obsolescence
Positive environmental impact	GHG emission, Energy consumption, Water consumption, Water pollution potential, Air pollution potential, Soil pollution potential, Impact on ecosystem, End-waste generation and disposal
Social acceptability	Transparency, Consensual decision-making, Local community acceptance, Public health and safety considerations, Community impacts, Gender inclusiveness
Regulatory compliance	Local waste management regulations, Safety regulations

References

- Brown, A., F. Laubinger et P. Börkey (2023), "Monitoring trade in plastic waste and scrap", OECD Environment Working Papers, n° 210, Éditions OCDE, Paris, https://doi.org/10.1787/39058031-en.
- Ellen MacArthur Foundation (2019), Reuse – rethinking packaging.
- Jayakumar Menon, V., & Palackal, A. (2022). Centralized and decentralized approaches to solid waste management–a case study. The holistic approach to environment, 12(4), 155-164.
- Karlsson, T., Brosché, S., Alidoust, M. and Takada, H. (2021) Plastic pellets found on beaches all over the world contain toxic chemicals. International Pollutants Elimination Network (IPEN).
- Kassab, A., Al Nabhani, D., Mohanty, P., Pannier, C., & Ayoub, G. Y. (2023). Advancing Plastic Recycling: Challenges and Opportunities in the Integration of 3D Printing and Distributed Recycling for a Circular Economy. Polymers, 15(19), 3881.
- Kaza, S., Yao, L., Bhada-Tata, P., & Van Woerden, F. (2018). What a waste 2.0: a global snapshot of solid waste management to 2050. World Bank Publications.
- Norwegian Environmental Agency (NEA) (2014). Sources of microplastic-pullution to the marinne environment
- OECD (2022): Global Plastic Outlook
- Plastics Europe (2022): Plastics – the Facts 2022
- Poerbo, H. (1991). Urban solid waste management in Bandung: towards an integrated resource recovery system. Environment and Urbanization, 3(1), 60-69.
- Pucino, M., Boucher, J., Bouchet, A., Paruta, P., Zgola, M., (2020). Plastic Pollution Hotspotting and Shaping Action: Regional Results from Eastern and Southern Africa, the Mediterranean, and Southeast Asia. Switzerland: IUCN.
- Uekert, T., Singh, A., DesVeaux, J. S., Ghosh, T., Bhatt, A., Yadav, G., ... & Carpenter, A. C. (2023). Technical, economic, and environmental comparison of closed-loop recycling technologies for common plastics. ACS Sustainable chemistry & engineering, 11(3), 965-978.
- UNEP (2002) Technical guidelines for the identification and environmentally sound management (ESM) of plastic wastes and for their disposal
- UNEP (2015) Biodegradable Plastics and Marine Litter. Misconceptions, concerns and impacts on marine environments. United Nations Environment Programme (UNEP), Nairobi.
- UNEP, (2023a). Technical guidelines on the environmentally sound management of plastic wastes : UNEP/CHW.16/6/Add.3/Rev.1

- UNEP (2023b). Turning off the Tap. How the world can end plastic pollution and create a circular economy. Nairobi.
- UNEP (2023c). Topic Sheet: Reuse Schemes. https://wedocs.unep.org/ 20.500.11822/42237.
- UN habitat (2010). Collection of Municipal Solid Waste in Developing Countries
- United States Environmental Protection Agency and Office of Resource Conservation and Recovery. (2020). Best practices for solid waste management: A guide for decision-makers in developing countries.
- Werner, M., Narayannan, A., Rabenschlag, O., Nagarajan, P., Saboo, R., Banatao, R., Moedritzer, S., Zilnik, D., Wong, T., and Mez, M. (2022) Closing the Plastics Circularity Gap - full report. Google
- Zhang, Fan, Yuting Zhao, Dandan Wang, Mengqin Yan, Jing Zhang, Pengyan Zhang, Tonggui Ding, Lei Chen, and Chao Chen. "Current technologies for plastic waste treatment: A review." Journal of Cleaner Production 282 (2021): 124523.

Table of contents

Executive Summary

Introduction 1

1. Sources of plastic waste leakage 3
    1.1. Plastic production and waste generation by industrial sector 3
    1.2. Overview of plastic waste leakage to the environment 3
    1.3. Microplastic leakage to the environment 5
    1.3.1. Global plastic waste exportation and China’s importation ban in 2018 6
    1.4 .Microplastic leakage to the environment 7
    1.4.1. Plastic pellet leakage to the environment 7

2. Plastic waste management as integrated part of MSW management strategies 8
    2.1. MSW generation pattern by income levels 8
    2.2. MSW management and the fate of plastic waste 9
    2.3. Centralised vs. decentralised waste management approaches 10
    2.4. MSW collection methods 11
    2.5. Waste transfer stations as MSW waste sorting facility 12
    2.5.1. MBT facilities 12
    2.5.2. MRFs 12
    2.5.3. Cost of the construction and operation of MTB facilities and MRFs 13
    2.6. Plastic waste separation methods and sorting technologies 13
    2.6.1. Plastic waste separation methods 14
    2.6.2. Plastic waste sorting technologies 14

3. Plastic waste management strategies & technologies 16
    3.1. Classification of plastic waste management methods 16
    3.2. Reuse 17
    3.2.1. Refilling at home 18
    3.2.2. Return from home 18
    3.2.3. Refilling on the go 18
    3.2.4. Return on the go 19
    3.3. Recycling 20
    3.3.1. Mechanical recycling 20
    3.3.1.1. Closed-loop mechanical recycling 20
    3.3.1.2. Open-loop mechanical recycling 21

3.2.1.2.1. Downgrading mechanical recycling · · · · · 22
3.3.1.2.2. Composite recycling · · · · · 23
3.3.1.3. Costs of mechanical recycling equipment · · · · · 23
3.3.2. Chemical recycling · · · · · 24
3.3.2.1. Closed-loop chemical recycling by dissolution · · · · · 25
3.3.2.2. Open-loop chemical recycling · · · · · 25
3.3.2.2.1. Thermolysis · · · · · 25
3.3.2.2.2. Chemolysis · · · · · 26
3.3.3. Energy recovery · · · · · 27
3.3.3.1. Waste-to-energy · · · · · 27
3.3.3.2. Refuse-derived fuel production · · · · · 28
3.3.4. Global plastic waste recycling effort · · · · · 29
3.4. Biodegradation · · · · · 29
3.5. Landfilling · · · · · 31

4. Economic value of plastics and plastic waste · · · · · 33
4.1. Global plastic waste by polymer types · · · · · 33
4.2. Economic values of primary plastics · · · · · 35
4.3. Economic values of plastic waste and scrap · · · · · 35
4.4. Economic values of recycled plastics · · · · · 36
4.5. Economic impact of recycling plastics · · · · · 37
4.6. Energetic values of plastic waste · · · · · 38
4.7. Financial instruments for implementing plastic waste management solutions · · · 39

5. Comparison and evaluation of different plastic waste management technologies · · · · · 40
5.1. Selection of environmentally-sound plastic waste management · · · · · 40
5.2. Comparison and evaluation criteria for plastic waste management technologies · · 42
5.2.1. Waste characteristics and compatibility · · · · · 43
5.2.2. Land use · · · · · 44
5.2.3. Cost effectiveness · · · · · 44
5.2.4. Economic benefit · · · · · 44
5.2.5. Technical feasibility · · · · · 45
5.2.6. Positive environmental impact · · · · · 45
5.2.7. Social acceptability · · · · · 45
5.2.8. Regulatory considerations · · · · · 45
5.3. Evaluation of different plastic waste management technologies · · · · · 46

6. Conclusions and recommendations · · · · · 50

Annex 1 Waste Separation Equipment List

Annex 2 Case studies & available mobile technologies

Annex 3 Comparison and Evaluation Criteria for plastic waste management technologies

Introduction

Plastics have made a significant contribution to facilitate the modern society in almost every human need from food and beverage, healthcare and medicine, transportation, construction, to various household and electronic goods, and other products necessary or useful to support our daily activities. Although plastics are a versatile and widely used material that has revolutionised many aspects of our lives, this material has caused a serious problem of environmental pollution (UNEP, 2020 and 2023b).

Geyer *et al*. (2017) estimated that 8300 million metric tons (Mt) of virgin plastic had been produced by 2015, and approximately 6300 Mt of plastic waste had been generated of which 9% was recycled, 12% was incinerated, and 79% was accumulated in landfills or the natural environment. At least 14 Mt of plastic waste reach the marine environment each year and more than 80% marine plastic debris are land-based (Boucher *et al*., 2020). Plastic pollution is recognised as one of the most threatening global challenges, and the public awareness has increased significantly in recent years due to the shocking images of marine lives affected by the marine plastic debris.

The plastic pollution situation is particularly severe in the developing countries where there is no public waste management infrastructure to collect and treat such the plastic waste which does not degrade in the natural environment. WWF's report (2023) argues that the true lifetime cost of plastic is 10 times higher in low-income countries and 8 times higher in low- and middle-income countries than in high-income countries due to the lack of proper infrastructure to manage plastic waste.

Given the challenges of the plastic pollution which evolved into a complex global problem, 175 nations agree to develop a legally binding agreement to end plastic pollution. The treaty integrate the environmentally sound management of plastic waste with life cycle approach, covering all stages and actors of the plastic value chain from primary plastic products' design to end-of-life management.

This paper aims to support the treaty preparation work undertaken by UNEP by providing information on the following themes:

- Sources of global plastic pollution: facilitating the identification of locations in which applicable and feasible measures shall be implemented.
- Environmentally sound management of plastic waste: supporting the decision-making process of choosing the combination of plastic waste management technologies to be implemented by taking into account the socio-economic situations of different communities and nations.

This report highlights the environmentally sound management of plastic waste by integrating the concept of waste hierarchy which provides a universal priority on how the waste should be treated under the framework of the sustainable development (SDG 12). Waste hierarchy consists of the 3R concept: Reduce, Reuse, Recycle. SD 12 promotes responsible consumption and production which calls for cutting back on the usage of materials and energy from natural resources, reducing the overall waste generation, and managing waste responsibly and sustainably. Therefore, plastic waste management strategies must keep the priorities to reduce, reuse and recycle in the order of importance.

Furthermore, UNEP's policy on environmentally sound management (ESM) is applied to the plastic waste management discussed in this report. More precisely, ESM promotes a holistic approach that combines product design, policy, producer responsibility, investment, and collaboration to achieve a significant reduction in plastic pollution and its environmental impact, and a systemic approach to tackle plastic pollution at its roots. Therefore, the report is organised in the following manner:

Chapter 1: Sources and causes of plastic pollution to delineate the target regions to concentrate the global effort.

Chapter 2: Plastic waste management as an integrated part of Municipal Solid Waste (MSW) management to tackle the root cause of the plastic pollution. Different MSW management strategies are presented and explored to provide an overview of the options for context-specific plastic waste management.

Chapter 3: Plastic waste management strategies and technologies to delve into existing strategies and technologies from which to develop a combination of technologies to frame a context-specific strategy.

Chapter 4: Economic value of plastics and plastic waste as information to sculpt an environmentally sound plastic waste management strategy with potential economic benefits to integrate the circularity in the strategy.

Chapter 5: Comparison and evaluation of different plastic waste management technologies to provide a guidance to develop a roadmap on how to achieve a context-specific and environmentally sound plastic waste management strategy.

Chapter 6: Conclusions

1. Sources of plastic waste leakage

In recent years, much has been studied regarding the sources of plastic waste leakage into the environment from upstream sources (manufacturing waste) and downstream sources (post-consumer plastic waste) in a number of regions and countries because understanding the sources of plastic waste pollution is primordial for developing effective solutions to mitigate such undesirable and long-lasting pollution. This chapter aims to provide a global view on the sources plastic waste and types of plastics that contribute to the global plastic pollution.

1.1. Plastic production and waste generation by industrial sector

The global production of plastics reached 460 million metric tons (Mt) in 2021 with the global market size of 712 billion USD (Plastic Europe 2022). Plastics are produced and used in large quantities in almost all industries and commercial activities. Among various applications of plastics, the packaging industry consumes by far the largest plastics comprising up to 35% of the total plastic production (OECD, 2022)

In addition to the sector-specific plastic production data, the sector-specific plastic waste generation data are available. In 2019, the global generation of plastic waste was approximately 360 million tonnes, and a significant portion of this waste, over two-thirds, originated from short-lived applications such as packaging, consumer products, and textiles. Despite the vast amount of plastic waste produced, only 17% was collected for recycling, highlighting a substantial gap in effective waste management practices (OECD, 2022).

1.2. Overview of plastic waste leakage to the environment

Plastic waste can be categorised as macroplastics and microplastics (plastic debris and waste of less than 5 mm in size). Microplastics can be classified as primary or secondary microplastics where primary microplastics are manufactured intentionally as small plastic particles (ex: microbeads in personal care products and pellets used to make larger plastic products) and secondary microplastics are formed from the breakdown of larger plastic items into smaller pieces (ex: tire abrasion and photodegraded plastic debris). Figure 1 presents the breakdown of the plastic leakage.

The majority of leaked plastics are macroplastics (88%) of which most arise from mismanaged plastic waste, followed by the littered plastic waste, and 1% from marine activities mainly resulting form lost fish gears (OECE, 2022 & UNEP, 2023). Microplastics represent 12% (or 2,64 Mt) of the total leaked plastic waste of which 4% are from transport related microplastics (mainly tire abrasion: 0.7 Mt, break wear: 0.1 Mt, and eroded road markings: 0.2 Mt), 3% are from microplastics dust (0.8 Mt from shoe sole abrasion, paint chips and textile dust), 3% are from wastewater sludge (mainly from loss of synthetic fibres during washing, microbeads in personal care products), and 2% from other origins including accidental losses of pellets (0.28 Mt), and abrasion of artificial turf (0.05 Mt), according to OECD report (OECD, 2022).

Figure 1: Global leakage of macro- and microplastics to the environment (OECD, 2022)

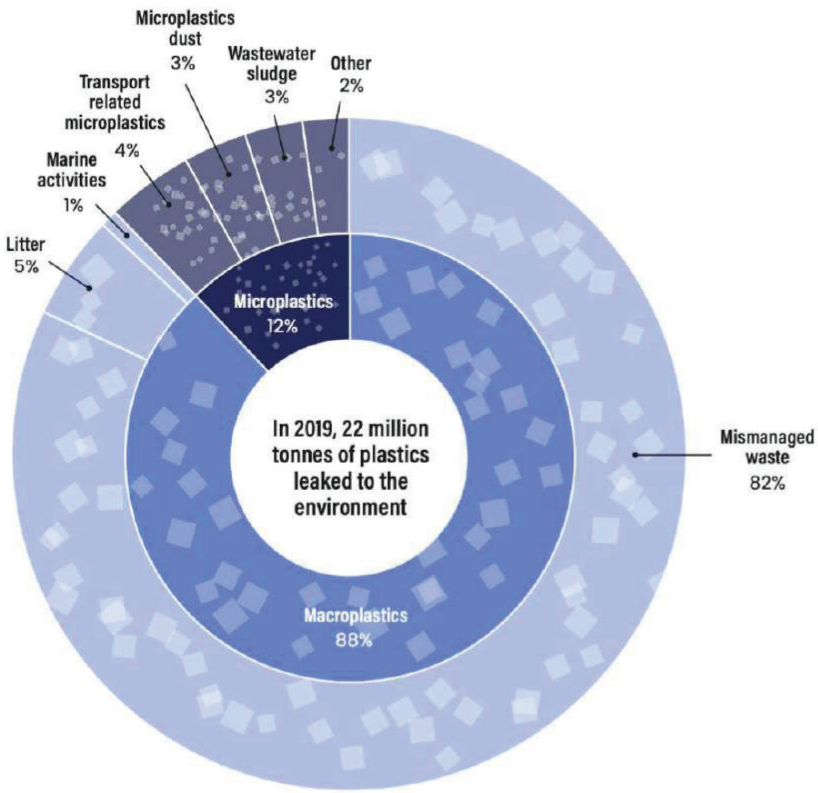
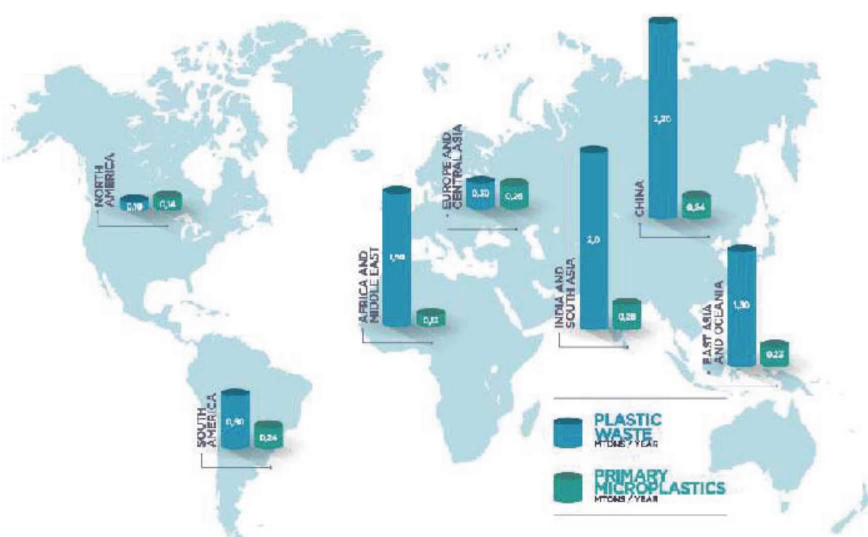


Figure 2 shows the global distribution of the plastic waste leakage (macroplastics and primary microplastics) from the 2017 IUCN report (Boucher and Friot, 2017), depicting the regional characteristics of the plastic leakage problems. It is clear from Figure 2 that most macroplastic waste leak from emerging economies due primarily to the lack of efficient plastic waste management infrastructure whereas the primary microplastic leakage is ubiquitous despite the socioeconomic situations (Boucher and Friot, 2017).

Figure 2: Global plastic leakage to the ocean (Boucher and Friot, 2017)

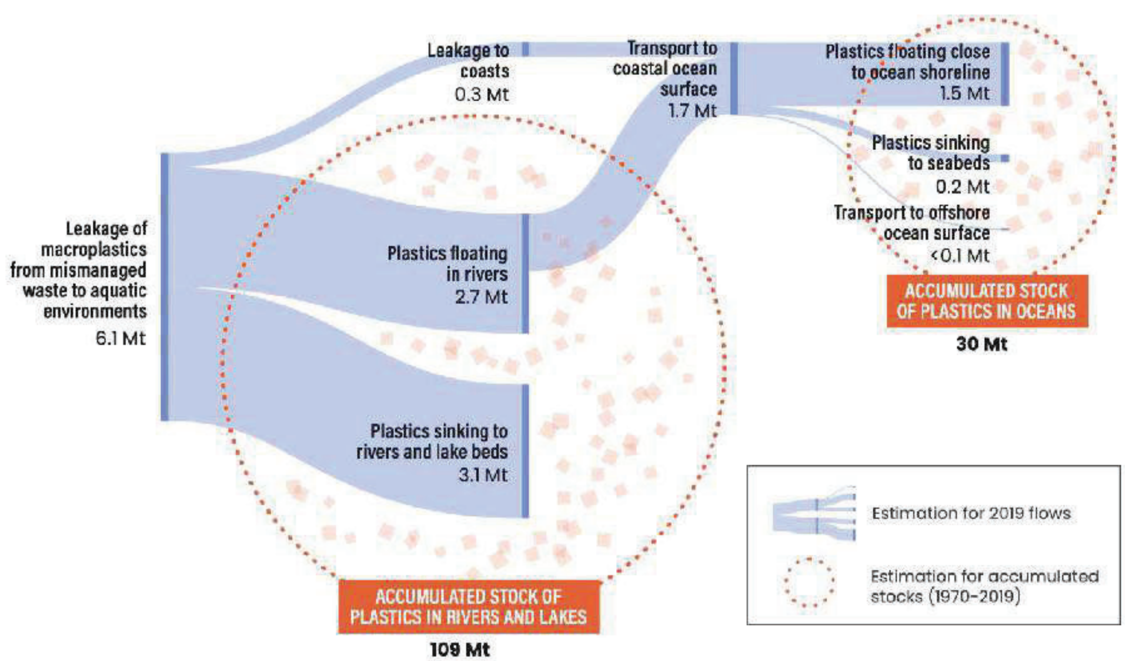


Understanding the sources of plastic waste pollution is important for developing effective solutions to reduce and prevent the future pollution by plastic waste leakage. It also allows to raise awareness for public mobilisation and to target specific interventions as different plastic pollution sources require different strategies and solutions. The following sections explore the plastic pollution caused by macroplastic leakage and microplastic leakage.

1.3. Macroplastic leakage to the environment

Much has been studies in the last ten years to better understand the fate of mismanaged macroplastic waste especially with respect to the marine plastic pollution. In recent years, many studies demonstrate that the rate of plastic waste leakage to the marine environment is lower than previously estimated (Meijer et al., 2021; OECD, 2022; and van Emmerik et al, 2022). OECD (2022) conducted numerical fate analyses and reported that from 22 Mt of plastic waste leaked to the environment in 2019 (see Figure 1), 87% were the macroplastic waste (or 19.1 Mt) of which 6.1 Mt leaked to aquatic environments, and 1.7 Mt ended up in the ocean as shown in Figure 3, leading to a conclusion that approximately 9% (1.7 Mt /19.1 Mt) of total leaked macroplastic waste reaches the ocean. In addition to this 1.7 Mt of plastic waste, 0.22 Mt of plastic is lost in the marine environment from marine activities annually, adding to the total of about 2 Mt of macroplastic pollution in the ocean.

Figure 3: Aquatic leakage of macroplastic waste (OECD, 2022)



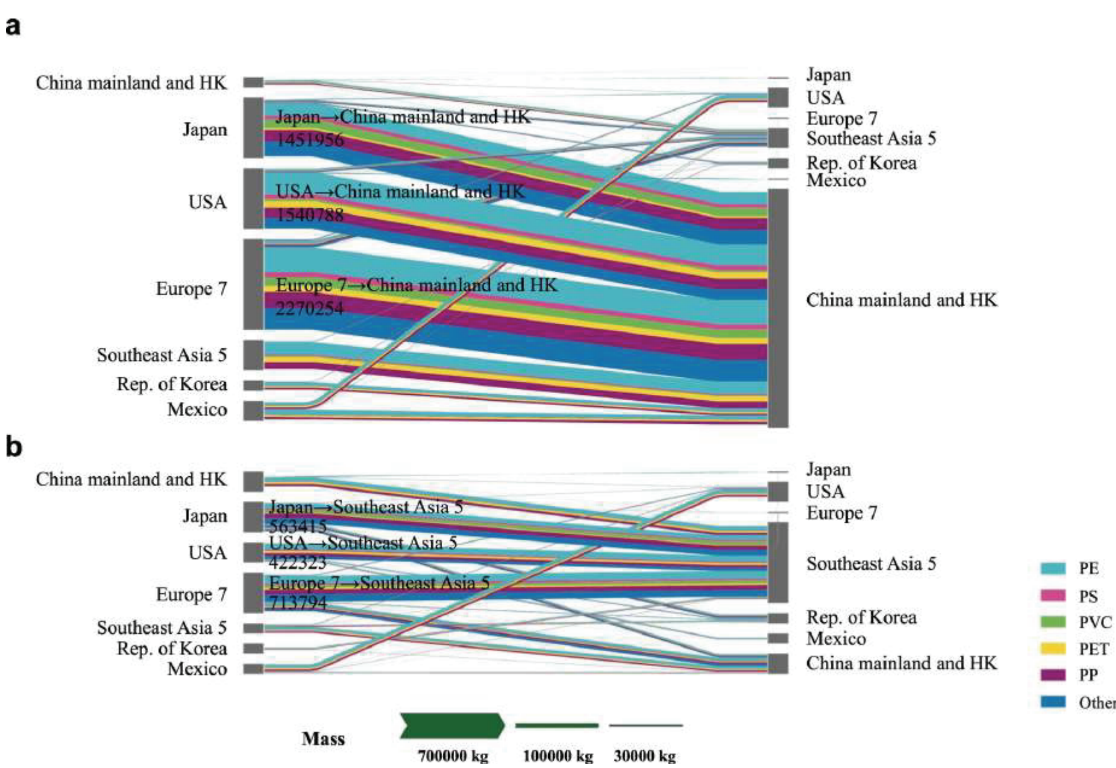
In recent years, some of studies proved that macroplastic waste often reaches the aquatic environment by natural driving forces such as wind and surface runoff, but most of plastic transport is blocked or retained by land surface friction (van Emmerik et al, 2022 and Meijer et al., 2021). In addition, relatively short travel distances of plastic waste in an aquatic environment, due to the above-mentioned retention mechanisms, was demonstrated (Weideman et al., 2020). Therefore, river system is more of a plastic waste reservoir than the source of marine plastic pollution. If river can be seen as a plastic reservoir, flood events must be considered as a plastic release mechanism (van Emmerik et al, 2022): extreme events can empty the plastic reservoir, flashing land-based plastic waste from the floodplain, excavating buried plastics from riverbed sediments, mobilising and transporting the retained plastic waste into the ocean.

A number of studies have been published to capture the global hotspots of plastic waste leakage. The focus of this report is on the leakage mechanism, and a detailed description of plastic current global hotspots can be found in a recent IIASA study*. In the following section, however, the global plastic waste exportation is presented as it is a root cause of high plastic leakage observed in China and East Asia.

1.3.1. Global plastic waste exportation and China's importation ban in 2018

China was by far the main importing country of global plastic waste since 1990s and the largest plastic producer in the world. It is estimated that nearly half of the planet's plastic waste export (e.g. single-use bottles, food wrappers, plastic bags, etc.) had been sent to China in the past two decades (Garcia et al., 2019). China imported 8.88 Mt of plastic waste per year of which up to 70.6% was buried or mismanaged, causing serious environmental deteriorations nationwide (Wen et al., 2021).

Figure 4: The trade flows of six types of plastic waste under two scenarios (Wen et al., 2021).
a: Global trade flows before the ban b: Global trade flows after the ban



As shown in Figure 4, a significant change is observed before and after 2018 in the global plastic waste traffic market since major exporters with high dependence on China were urged to internally treat their own plastic waste and/or to find other destinations. as depicted in Figure 4b. As a consequence, several South Asian countries that were heavily dependent on the export to China before the ban, have become the new global plastic waste destinations after the ban - even though most of these countries do not yet have the sufficient plastic waste management infrastructure for such demand.

*Gomez-Sanabria, A., Lindl, F. (2024). The crucial role of circular waste management systems in cutting waste leakage into aquatic environments. DOI: 10.1038/s41467-024-49555-9

In the global market, the plastic leakage is a deep-rooted global problem and global flows of plastic waste to countries with no proper infrastructure contribute to environmental challenges in these regions and undermine global efforts to circular economy and the effective management of plastics and its associated pollution.

1.4. Microplastic leakage to the environment

Basic microplastic waste composition is already presented in Figure 1. Microplastics represent 12% (or 2,64 Mt) of the total leaked plastic waste of which 4% are from transport related microplastics (mainly tire abrasion: 0.7 Mt, break wear: 0.1 Mt, and eroded road markings: 0.2 Mt), 3% are from microplastics dust (0.8 Mt from shoe sole abrasion, paint chips and textile dust), 3% are from wastewater sludge (mainly from loss of synthetic fibres during washing, micro-beads in personal care products), and 2% from other origins including accidental losses of pellets: 0.28 Mt and abrasion of artificial turf: 0.05 Mt (OECD, 2022). Therefore, most microplastic leakage sources are related to the daily activities of modern societies.

Microplastic leakage from industrial sources include pellets spills during transportation, pellet loss through mismanagement from plastic manufacturing value chain (virgin and recycled pellets), and the use of abrasive microplastic scrubbers in drilling liquids used for oil and gas exploration and as abrasive blasting media for rust and paint removal and cleaning, to name only a few (NEA, 2014). Among these industrial microplastic leakage sources, however, the pellet spills are the most important factor of industrial microplastic leakage to the environment with the estimated value of 280 000 tons/year. The following section provides an overview of pellet leakage to the environment and the threat to the marine environment due to the toxicity of these pellets.

1.4.1. Plastic pellet leakage to the environment

Plastic pellets are the building blocks of all plastic products from packaging materials to automobile parts. They are about the size of a lentil bean, and there are approximately 50 million pellets in a ton of raw plastic: 14 trillion pellets leak annually based on the estimate of 280 000 tons/year of pellet leakage. Plastic pellets are shipped through various means – in big bags, boxes, trucks, rail cars, barges – to companies that make products with these pellets.

Pellets can be lost during production processes regardless of the production volume due to careless handling, poor training and awareness of workers, and inappropriate packaging (FFI, 2022), but pellet production usually takes place in large petrochemical complexes so the leakage at production sites is easy to identify. Large quantity of pellets can be released during transport accidents or inappropriate handling particularly when pellets are poorly packaged (FFI, 2022). In addition, pellets can be lost further during conversion processes. Since there are numerous plastic converters globally, the leakage source is diffuse, and difficult to identify.

Plastic alone is of an environmental concern, but plastic pellet leakage poses an additional risk as they can carry a number of different chemicals intentionally added from the production level, and spilled pellets can unintentionally sorb environmental pollutants owning to the plastics' oleophilic characteristics. A study carried out by IPEN (Karlsson et al., 2021) found that all washed-off pellets from their 23 study locations had target PCBs (polychlorinated biphenyls, banned by the Stockholm convention) and BUVs (benzotriazole, UV stabilisers) with varying concentrations (Karlsson et al., 2021). Hence, plastic pellet leakage is of a particular pollution due to the marine exposure of hazardous chemicals absorbed by the oleophilic characteristics of plastic resins.

2. Plastic waste management as integrated part of MSW management strategies

Plastic waste is a part of municipal solid waste, and mismanaged municipal solid waste (MSW) is the main source of plastic leakage as was shown in Chapter 1. The MSW management strategies depend on the country's economic, social and environmental capabilities; hence, there is a large variation in the levels of MSW management infrastructure.

In this chapter, a basic MSW management strategies and approaches that characterise a country's waste infrastructure are briefly explained.

2.1. MSW generation pattern by income levels

Waste is a good indicator for the income level of a nation. In general, there is a strong correlation in the income level and per-capita generation of waste: as the average income level increases, so does the per capita generation of waste. The daily per capita waste generation by geographic region depicts that sub-Saharan Africa generates on average 0.46 kg while North America generates 2.21 kg (Kaza et al., 2018).

In addition to the waste quantity, waste composition also reflects the income level (classification provided in Table 1) as shown in Figure 5. Waste generation volume and waste composition are two most important parameters for selecting an appropriate MSW strategy along with financial and technical feasibilities (Kaza et al., 2018).

Figure 5: Waste composition by income level (Kaza et al., 2019)

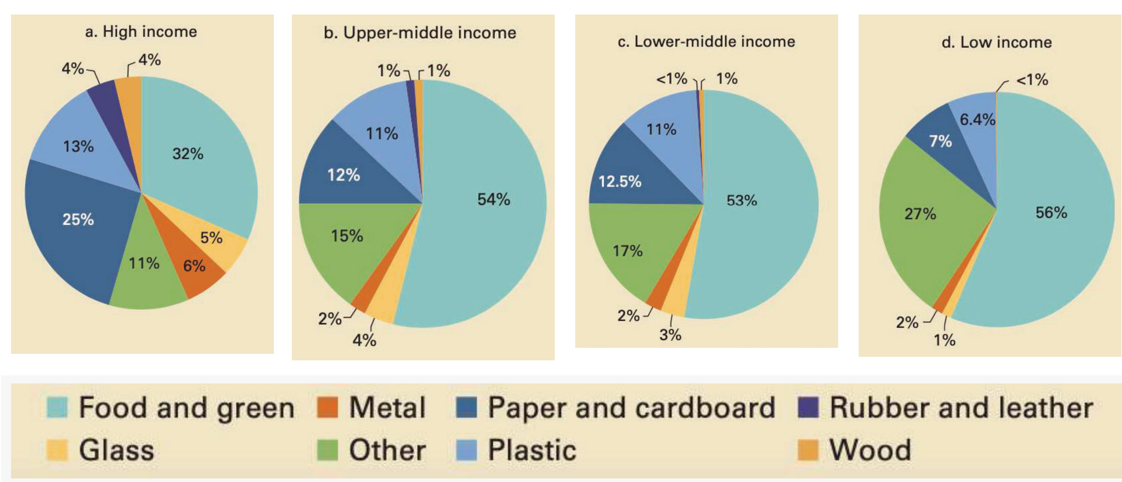


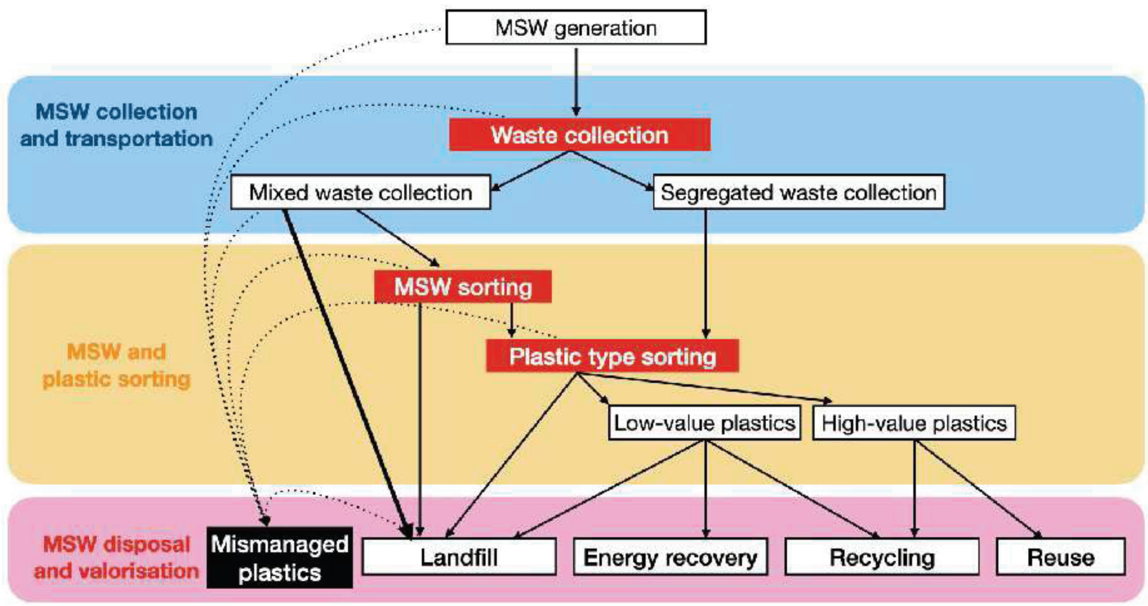
Figure 5 shows that wet waste (food and greens) dominates the MSW from low-income and lower-middle income regions whereas dry waste is predominant in high income regions. It is interesting to notice how plastics are prevalently present across all income levels at a relatively stable proportion to the total waste (6.4% for LIC, 11% for LMC and UMC and 13% for HIC).

In the following sections, general waste management flowchart and different waste management approaches are presented with examples to illustrate how different approaches fit better to a certain socio-economic context.

2.2. MSW management and the fate of plastic waste

MSW management has a universal process flow starting from the waste generation, waste collection, waste disposal and valorisation. For recyclable materials such as plastic waste, the material flow can involve reprocessing steps depending on the local capacities. Figure 6 presents a global MSW management flowchart showing the fate of plastic waste at the end of the process flow (in the pink box). Key processes requiring services (formal or informal) are shown in red boxes.

Figure 6: Fate of plastic waste through MSW management



World Bank report (Kaza et al., 2018) provides valuable financial information on waste management processes as shown in Table 1 which reports the range of waste management costs by income level. Waste management costs are disproportionally high for LIC compared to HIC with more than 10 times stronger national economy. Waste management indeed is one of the most costly public services, and many countries can simply not afford such costs as their priorities are placed in public health and education (Kaza et al., 2018). The wide-spread practice of open dumping of waste in developing countries is, therefore, a result of the lack of financial means, and it is of a global interest to financially support these countries to develop a sustainable and environmentally-sound MSW management infrastructure to avoid future plastic leakage arising from mismanaged MSW.

Table 1: Waste management costs by income level in USD/tonne of MSW (Kaza et al., 2018)

	LIC	LMIC	UMIC	HIC
GNI (gross national income) per capita range	< $1,035	$1,036 - $4,085	$4,086 - $12,615	> $12,616
Collection and transfer	20-50	30-75	50-100	90-200
Controlled landfill to sanitary landfill	10-20	15-40	20-65	40-100
Open dumping	2-8	3-10	-	-
Recycling	0-25	5-30	5-50	30-80
Composting	5-30	10-40	20-75	35-90

2.3. Centralised vs. decentralised waste management approaches

There are various waste management strategies but the first and the most determinant strategy is to choose between centralised and decentralised approaches, or the combination of the two.

Centralised waste management involves collecting waste from homes, businesses, and other sources and transporting it to a large-scale treatment facility. These facilities are often located in industrial areas or on the outskirts of cities.

Decentralised waste management involves collecting, sorting, and processing waste within a smaller geographic area, such as a neighbourhood or district. This approach, sometimes referred to as « community-based approach » is often more suitable for smaller communities or areas with lower waste generation rates.

In general, the centralised approach requires heavy and intensive infrastructure with more space and finance for transfer and management of a large quantity of MSW, and the decentralised approach requires considerably less infrastructures depending on the scale and the method of final disposal (Jayakumar Menon & Palackal, 2022). Both approaches have their advantages and disadvantages as described in Table 2 (compilation from Jayakumar Menon & Palackal, 2022, Pighi et al., 2013, Poerbo, 1991).

Table 2: Advantages and disadvantages of centralised and decentralised approaches

	Centralised approach	Decentralised approach
Advantages	• Economy of scale • Higher efficiency • Single monitoring point • Integration of high-end technology • Ease of pollution control • Efficient conversion to energy (in case of incineration)	• Short transport distance • Reduced storage of perishable waste • Local community engagement • Local livelihood • Increased public acceptability • Relatively low infrastructure costs
Disadvantages	• Longer transport distance • Less community engagement • High infrastructure costs • Socio-economic discrimation	• Labor intensive • Lower processing capacity • Pollution and contamination risks

It is widely accepted that decentralised approach is suitable, regardless of the income-level of a country, for the management of wet perishable waste (food and green waste) whereas centralised approach would be beneficial for special wastes such as hazardous and biomedical wastes as well as recycling and recovery of inorganic materials due to the economy of scale effect (Kaza et al., 2018).

It is of particular interest to cite the study reported from Indonesia (Poerbo, 1991) as it provides insightful observations during the rapid expansion of urban zones in Indonesia, and how large cities in Indonesia shifted from a conventional centralised waste management system to a larger number of waste management « modules », or decentralised approach, in collaboration with informal waste pickers. It reports that as a city grows, so do the distances between residential areas and the dumping sites, reflecting a sharp increase in transport costs, and new dumping sites were harder and more expensive to obtain due to the urban zone expansion. The cost increases were beyond the financial capacity of local municipalities, and the large cities decided to close centralised facilities to open smaller but a larger number of waste management « modules » serving between 25,000 and 30,000 inhabitants.

Indeed, decentralised approach is often more suitable for smaller communities or areas with lower waste generation rates. Most studies and reports recommend this waste collection model for the developing countries due to the lower costs associated with implementation and operation, its flexibility and scalability as well as its facility to integrate existing informal sector (Poerbo, 1991, UN Habitat 2010, Kaza et al., 2018, USEPA 2020, Jayakumar Menon & Palackal, 2022). In fact, the integration of the informal waste management sector is the key to achieving the successful waste collection in developing countries where more than 15 million people globally are involved (Medina 2010). The informal waste picking activities contribute significantly to prevent the plastic leakage although it is important to keep in mind that they collect only the high-value plastics such as PET bottles and hard plastics, leaving low-value plastics such as soft packaging plastics littered (Braaten et al., 2021). Therefore, an effective collection of low-value plastic waste needs to be implemented.

In the following sections, key waste management processes (shown in red boxes in Figure 10) are described in detail. Both centralised and decentralised approaches are presented for each key process.

2.4. MSW collection methods

The most critical and important step to prevent the plastic waste mismanagement is the waste collection although the collected plastic waste must be processed until its final fate as shown in Figure 6. It is generally the most costly operation throughout the entire process of waste management as shown in Table 1 (Kaza et al., 2018). Without efficient waste collection system, the plastic waste will continue to leak to the nature as people have no other way of disposing their waste.

Globally, municipalities are responsible for waste collection, and waste collection service is more available and complete in urban areas than rural areas (Table 3). In lower income countries, waste collection service can be infrequent and regularly disturbed due to the lack of finance and political instability. In middle- and high-income countries, large collection trucks are utilised while low-income countries often utilise more manual transportation systems that minimize investment costs such as buggies, handcarts, and donkeys (Kaza et al., 2018).

Table 3: Waste collection rates by income level (Kaza et al., 2018)

	Urban	Rural
High income countries	100 %	98 %
Upper-middle income countries	85 %	45 %
Mower-middle income countries	71 %	33 %
Low income countries	48 %	26 %

Studies in Indonesia identified that rural areas generate the largest quantities of mismanaged plastic waste due to the lack of waste collection services, and only 15% of plastic waste in these areas are collected by formal and informal services, or 85% of plastic waste is mismanaged and leaks into the environment (Braaten et al., 2021 and World Bank 2021). On the other hand, it is also reported that even with high waste collection rate, plastic mismanaged rate can still be high (Pucino et al., 2020), and the authors gave examples from Thailand and South Africa, as both countries have a plastic collection rate of 70% yet with over 50% of plastic mismanagement.

Similar examples are reported in detail from the Philippines where the national average collection rate is 85 %, reaching 90 % in the metropolitan Manila region though about 74% of plastics that leak into the ocean were initially collected but escaped from open landfills or during the waste transport (Braaten et al., 2021). In addition, waste pickers often sort on the waste collection vehicles, leaving low-value plastics behind (Braaten, 2021).

The effectiveness of waste collection to prevent plastic waste pollution depends strongly on the people's awareness evoked by education and successfully designed waste collection methods. Following documents describe in detail the implementation of MSW collection system in developing countries:

- Collection of Municipal Solid Waste in Developing Countries (UN Habitat, 2010)
- Solid Waste Management Toolkit for Developing Countries (USEPA, 2020)

2.5. Waste transfer stations as MSW waste sorting facility

A waste transfer station is an intermediate facility where municipal solid waste (MSW) is temporarily stored and consolidated before being transported to its final destination for processing, disposal, or recycling with a larger vehicle. Waste transfer stations play a crucial role in efficient waste management by reducing the number of trips required by waste collection vehicles and minimising traffic congestion; hence, they should be conveniently situated to transfer distances to reduce traveling distances so the collection vehicles can complete multiple round trips within a day (USEPA 2020).

In waste transfer stations, discharged waste undergoes a screening process to remove unacceptable products, such as batteries and metal containers containing toxic products, for the final disposal method (landfilling, incineration, etc). With the rise of recycling needs and interest in recent years, waste transfer stations have become centres for waste reuse and recycling where collected waste is sorted on-site. These stations have been renamed as MBTs (mechanical biological treatment) for a large-scale application and MRFs (materials recovery facility) for a smaller-scale application.

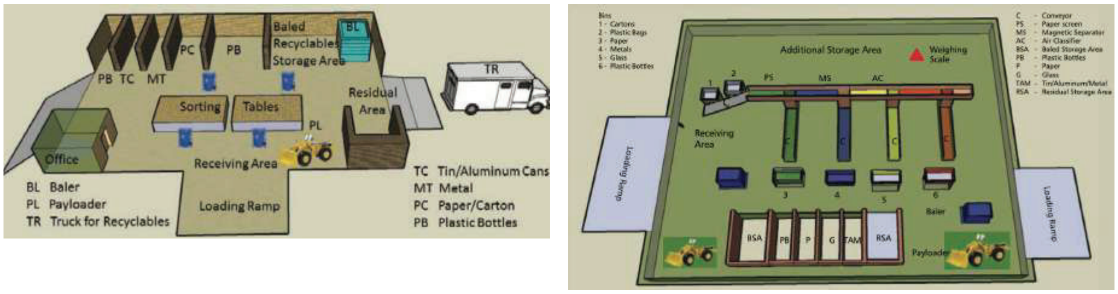
2.5.1. MBT facilities

MBT facilities handle waste that can't be recycled. It combines mechanical sorting with biological treatment (composting or anaerobic digestion) to break down organic matter. This can stabilise the waste and potentially produce a fuel source (Refuse-derived fuels, RDFs. See Section 3.3.3.2). MBT facility is a large facility consisting of covered waste reception halls, waste preparation and sorting process lines with specialised equipment, waste compacting system and a biological treatment system (Bourtsalas & Themelis, 2022).

2.5.2. MRFs

MRF focuses on recycling, on the contrary to MBT facilities. It uses mechanical sorting techniques such as conveyor belts, magnets to separate recyclables such as paper, plastic, glass, and metal from the MSW stream. These materials can then be transferred to local or international recycling facilities. MFRs usually use a mix of manual and automated separation processes to remove undesirable materials. Detailed design specifications for the construction of simple MFRs in the Philippines is provided from Asian Development Bank (2013) in which both manual and automated MFR designs are presented as shown in Figure 7.

Figure 7: Manual (left) and automated (right) MFR designs (ADB, 2013)



2.5.3. Cost of the construction and operation of MTB facilities and MRFs

The cost of constructing a waste transfer station depends significantly on the area and the equipment to be installed, but globally it consists of the following costs:

- Land acquisition cost
- Site preparation: installing utilities and road access
- Construction: open structure, roofed structure, or building
- Equipment: waste handling, sorting, compaction and consolidation

Basic transfer stations can cost about US$500,000 to construct, but when sorting and recycling capacities are integrated, the facility's construction cost climes by several times (Kaza et al., 2018). Financial aspects of MBT facilities and MRFs from the EU countries with sorting capacity are presented in Table 4[1].

Table 4: Capital and operational costs for MBT and MRF in the EU

Type of facility	Throughput (tonne/year)	Capital cost		Operational cost (€/tonne)	Location
		m€	€/tonne/year		
MBT (general)	25 000	12.2	488	24 - 81	
	60 000	13.5	225	24 - 81	
	100 000	56	560	NA	
	120 000	42	350	55	
	200 000	40.5	203	24 - 81	
MRF	12 000 - 15 000	2,37	158	NA	Karditsa, Greece
	12 000 - 15 000	2,35	157	NA	Alexandroupoli, Greece
	30 000	5,39	180	NA	Elefsina, Greece

2.6. Plastic waste separation methods and sorting technologies

Under the optics of a circular economy, waste has values. However, in order for waste to obtain its intrinsic economic value, a waste must be sorted and categorised so that the subsequent

[1] http://www.epem.gr/waste-c-control/database/default.htm

reuse and recycling processes can transform this valuable waste into a raw material to produce a new product: hence, separation and sorting of the waste is the key to achieve environmentally sound and sustainable waste management practices.

2.6.1. Plastic waste separation methods

Plastic waste separation enables plastic recycling by the removal of unwanted and contaminating materials. Different separation methods yield varying cleanness level of plastic waste.

- Source separation: It involves the plastic separation at the household level. It is the most cost-effective plastic waste separation, with the cleanest plastic waste. Public awareness must be raised and a plastic waste collection system (door-to-door collection by itinerant waste collectors, curb-side collection, drop-off collection stations, buy-back and/or deposit/return system) should be implemented by a local authority.
- Separation at a centralised facility: Plastic separation at sorting facilities such as MBT facility or MRF. Mixed plastic waste is often soiled by other residual waste, requiring a washing process for recycling. Or it will go to other fate paths such as landfill and energy recovery as shown in Figure 6.

It is widely known that source-separated plastic waste has a higher probability of being recycled compared to the mixed plastic waste (ECDGE, 2015 and Plastic Europe, 2022). Figure 8 presents the fate of mixed plastic waste from MSW and the source-separated plastic waste in Europe (Plastic Europe 2022)

Figure 8: Fate of plastics for mixed and separated waste collection in Europe (Plastics Europe 2022)

2.6.2. Plastic waste sorting technologies

There are a number of plastic sorting technologies available, and many of these technologies are explained in detail elsewhere (Ruj et al., 2015, Serranti and Bonifazi, 2019, Lubongo and

Alexandridis, 2022). Plastic sorting technologies can be categorised by the fundamental mechanisms such as size-based separation (trommel screen separator), gravity-based and density-based separation (air classifier, ballistic separator, sink-float separator, jig separator and hydrocyclone separator), electrostatic-based separation, magnetic-density-based separation, and sensor-based separation (UNEP, 2023a and Serranti and Bonifazi, 2019). These separators are often used in combination to increase the plastic separation accuracy and efficiency in modern MRFs and MBT facilities. A summary of technical information for sorting technologies is provided in Annex 1.

Costs for some separation equipment are published and summarised in Table 5 that presents the combined data from Tsilemous (2007), Caputo & Pelagegge (2001), and Āriņa et al. (2014).

Table 5: Published costs of separation equipment (Tsilemous (2007), Caputo & Pelagegge (2001), and Āriņa et al. (2014)

Separation equipment	Data source	Capacity (t/h)	Power (kW)	Cost (k€)	Operating cost (€/h)
Manual sorting capin	Arina et al.	10-80	NA	120-180	NA
Belt conveyor	Caputo & Pelagegge		6	15.49	0.43
Trommel screen	Caputo & Pelagegge	15	20	103,29	1.45
		25	30	154,93	2.17
	Tsilemou	15-191	NA	35.30-218,60	NA
	Arina et al.	10-80	NA	160-1,200	NA
Air classifier	Caputo & Pelagegge	5	12	41.31	0.87
Ballistic separator	Arina et al.	10-80	NA	220-750	NA
Eddy current separator	Caputo & Pelagegge	5	2.2	7.23	0.27
		10	2.2	11.87	0.45
		15	2.2	14.97	0.48
	Tsilemou	1.3-35	NA	29.3-108	NA
	Arina et al.	10-80	NA	120-240	
Magnetic separator	Caputo & Pelagegge	5	3.75	36.15	0.16
		10	6.25	41.83	0.16
		15	6.6	49.57	0.16
	Tsilemou	4.3-40	NA	7.3-54.3	NA
	Arina et al.	10-80	NA	60-200	NA

3. Plastic waste management strategies & technologies

Chapter 2 demonstrated that there is no universal one-fits-all waste management strategy because waste varies significantly on the social-economic situations and the availability of efficient waste infrastructure. Plastic waste management strategy follows the same argument as the presence of solid waste infrastructure described in Chapter 2 determines the sound management of plastic waste. In addition, household plastic waste a heterogeneous mixture that contains a wide variety of plastic types, each with unique physical and chemical properties. Furthermore the plastic waste composition depends significantly on socio-economic factors such as economic development level and consumer behaviour. Hence, an effective solution for developed countries may not be applicable for the developing countries that operate with different waste management practices and different types of plastic waste. It is important to develop an economically and environmentally viable plastic waste management strategy that fits to each context.

In this chapter, a basic scheme classifying different plastic waste management methods is first presented, taking into account the waste hierarchy concept Reduce, Reuse, Recycle. Indeed, plastic waste management strategies must give priorities to reduce, reuse and recycle in the order of preference as clarified by the UNEP's Environmentally Sound Management framework defines[2]. Then the reuse and recycling of plastic waste are presented with various reuse models and recycling technologies.

3.1. Classification of plastic waste management methods

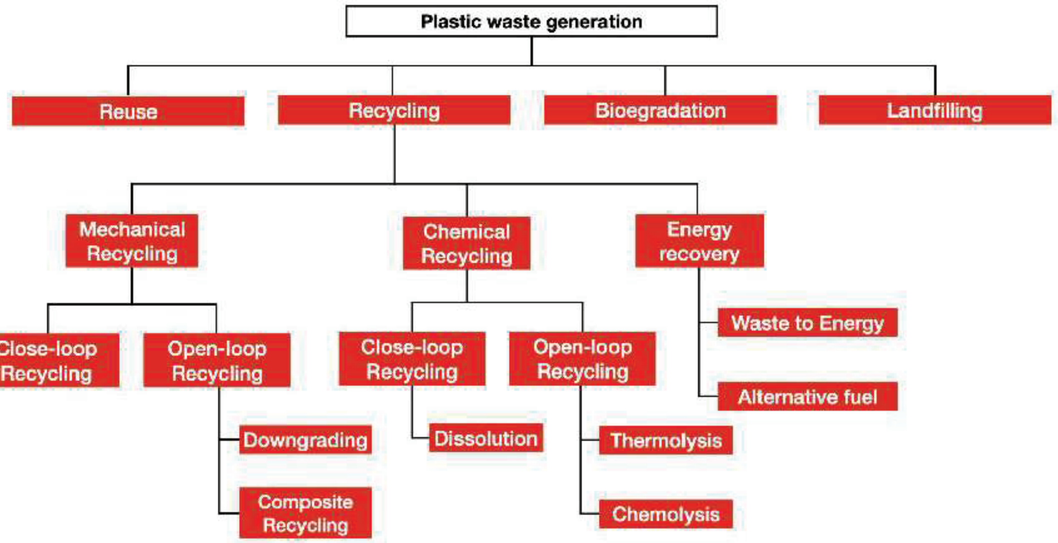
There are several categories and subcategories of plastic waste management methods, each with its own advantages and disadvantages. The holistic classification is shown in Figure 9. The classification was developed from the frameworks proposed by UNEP (2002, 2023), Zhang et al. (2021), and Kassab et al. (2023). The first classification involves the disposal method and the fate of plastic waste: reuse, recycling, biodegradation and landfilling. The circularity of plastics is strongly recommended as some common plastic products can easily be reused and plastics is the simplest and the most cost-effective materials to recycle (Werner et al., 2022).

There are three types of plastic recycling methods – Mechanical, Chemical and Energy Recovery as defined by ISO 15270:2008 – represent a range of various technology groups as shown in Figure 9. The selection of appropriate recycling technologies depends on various factors, including the type and characteristics of plastic waste, the desired product quality, economic and technical feasibility and viability, and environmental considerations, and this aspect will be explored more in Chapter 5.

The fate of plastic waste by regions is presented in the recent study conducted by Alliance to End Plastic Waste as shown in Figure 10. It reveals that globally landfilling is the most predominant disposal methods followed by the leakage and non-collection. Indeed, these two fates of plastic waste are not environmentally sound but comprise the majority of the plastic waste's fate regardless of geographical regions.

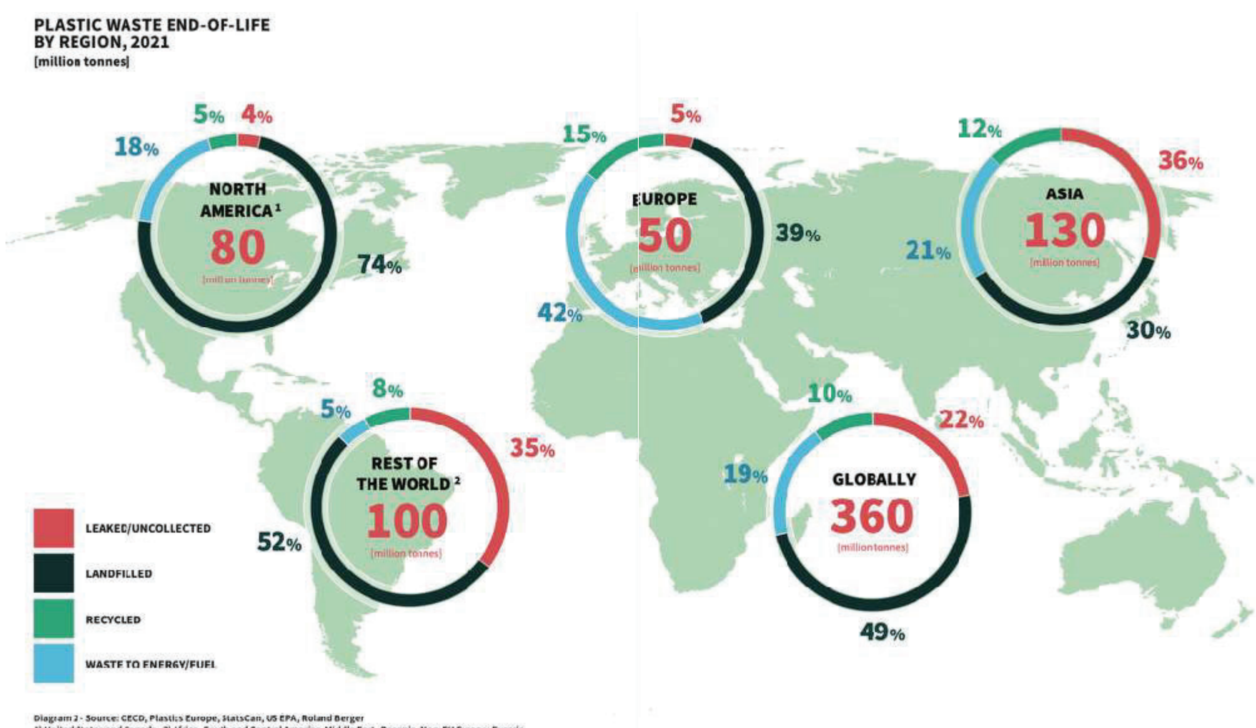
[2] https://www.basel.int/Implementation/CountryLedInitiative/EnvironmentallySoundManagement/ESMFramework/tabid/3616/Default.aspx

Figure 9: Classification of plastic waste management methods



In the following sections, each category and subcategory will be explored. However, the purpose of this report is not to provide detailed technical information of these technologies, but rather to provide basic but comparable technical information such as plastic waste compatibility, implementation and operation costs and scalability although the information from the published sources is limited to date.

Figure 10: Plastic waste fate by region, 2021 (Alliance to End Plastic Waste, 2023)



3.2. Reuse

Ellen MacArthur Foundation (2019) identified that reusing plastic packaging materials creates six benefits: cutting costs, adapting to individual needs, optimising operations, building brand loyalty, improving user experience, and gathering intelligence. The underlying concept of reuse is the refillability of plastic packaging materials (or containers) so that they can be used repeatedly. Four reuse models proposed include: Refilling at home, Returning from home (pick-up service), Refilling on the go (refilling at an in-store dispensing system) , Returning on the go (return at a store or drop-off point). All models involve business-to-consumer relationships differing in terms of packaging « ownership », and the economic benefit of shifting to reuse models is estimated at USD 10 billion (Ellen MacArther Foundation, 2019 and UNEP 2023b).

Industrially packaged products are sometimes collectively termed as « fast-moving consumer goods » which indicate products that are sold quickly and at a relatively low cost. These products include foods, beverages, toiletries, candies, cosmetics, over-the-counter drugs, and other consumables. These products are mostly packaged in plastic packagings. The reuse of packagings used for fast-moving consumer goods is of a great interest to reduce the global plastic waste quantity as the packaging plastics is by far the major source of plastic waste (refer to Chapter 1).

3.2.1. Refilling at home

Refilling at home model refers to the bulk purchase of a product (such as household cleaning products and personal care products) to refill a reusable packaging, the replaceable functional parts (razor or toothbrush with a reusable handle and replaceable water filter for home filtering jugs, reusable water and beverage bottles, and reusable and washable nappy for infants (Tassell and Aurisicchio, 2023). Refilling at home model also involves a bulk purchase by a consumer or a subscription to the periodic delivery of refill products.

3.2.2. Return from home

Return from home model often refers to reusable and returnable delivery packagings. It can be picked up from home (delivered point) or a prepaid postal return service. Dabbawala service (workers who deliver hot meal from homes and restaurants to people at work in India) and Demae service (restaurants delivering hot meals to home and offices in Japan) are traditional return-from-home models.

For e-commerce, RePack packaging[3] developed sustainable and reusable packaging services where they pack products from the partner companies in their innovative reusable packaging which folds into letter size and can be posted for return, once empty, without additional fee. The return-from-home model employed by RePack relies on the global postal network, and reduces the packaging materials related to global e-commerce.

3.2.3. Refilling on the go

Refilling on the go model refers to customers refilling their own reusable container on the point of distribution such as an in-store refill machine, a mobile location or a refillable vending machine.

[3] https://www.repack.com/

There are a number of cases in developing and developed countries where the refill-on-the-go model is employed to tackle the plastic waste problem.

Countries such as Indonesia have numerous game-changing reuse ventures that are redefining refill convenience through mobile apps such as KoinPack, Siklus and Qyos by Algramo and other initiatives (UNEP 2023c). In fact, the South Asia has a sachet culture in which a small portion of daily product is packaged into an individual packaging for its affordability. Such plastic packages (often coated with aluminium layer) are categorised as low-value plastics which are not collected by informal waste pickers; hence, remain littered and mismanaged. Refilling-on-the-go model can provide an economically and environmentally viable solution to end the sachet culture in the South Asia. Similar cases are observed also in Latin America in Chile where customers bring reusable containers to refill from machines named « Algramo » meaning « by the gram » in Spanish[4].

Another game-changing example is reported from Senegal where automatic water dispensers start to replace the sachet water[5]. Sachet water, drinking water heat-sealed in thin polyethylene bags, is a common product is African nations. In Nigeria alone, there are about 50-60 million used water sachets thrown on the streets daily[6] and even 140 million during the dry season (UNIDO 2021). The lack of drinking water source and the affordability of sachet water are the main reasons for its success, but with a negative environmental consequence. Improvement in drinking water supply and the water dispensers can help reduce the plastic use and waste leakage from sachet water in these countries.

Water refill app « Mymizu[7] », meaning « my water » in Japanese, is a Japanese social innovation that helps identify free water refill points. Mymizu contains 200 000 water refill points globally as of 2023.

3.2.4. Return on the go

Return on-the-go is an old system that has been brought back to life and attracted attention in recent years. It refers to a deposit system in which the container is owned by the product supplier. A spectacular decrease in consigned glass beverage bottles, beers and soft drinks, took place in the end of last century as shown in Table 6 (EU, 2022) .

Table 6: Change in consigned refillables' market share for beer and soft drinks in Europe (EU, 2022)

Country	Market Share refillables 1999	Market Share refillables 2019	% difference
Denmark	93%	13%	-80%
Finland	80%	4%	-76%
Romania	70%	13%	-57%
Bulgaria	74%	22%	-52%
Hungary	63%	11%	-52%
Slovak R.	69%	20%	-49%
Sweden	44%	4%	-40%
Germany	73%	54%	-19%
France	9%	3%	-6%

[5] https://www.unep.org/news-and-stories/story/rarely-told-story-widely-used-water-sachets

[6] https://www.unep.org/news-and-stories/story/rarely-told-story-widely-used-water-sachets

[7] https://www.mymizu.co/home-en

In general, the deposit-refund system has a very high container recovery rate of above 85%, and European case studies report the return rates at 96% for cans, 92% for PET bottles, and 88% for glass bottles (EU, 2021). Newly developed smart reverse vending machines have been implemented globally, and some machines shred the returned items (often PET bottles) on site to minimise the storage volume.

3.3. Recycling

As already presented in Figure 6, plastic waste can be categorised into high-value plastics and low-value plastics. High-value plastics are typically hard plastics used in bottles and containers (PET, HDPE and PP) whereas low-value plastics are soft and flexible plastics used for wrapping and packaging as films and bags (LDPE for most plastic films and LLDPE for shrink wrap).

There are over 7000 different types of plastics with over 13 000 additives (UNEP, 2023b), and each type has its own chemical makeup and properties. This chemical heterogeneity makes it difficult to recycle all plastics, as they need to be sorted into the correct categories before they can be processed. In addition, plastics are often used in combination with other materials, such as metal or paper. This makes it even more difficult to recycle plastic, as the other materials need to be separated from the plastic before it can be processed. The recycling technologies presented in this report are mostly limited to the simple and standardised plastic products such as bottles and other packaging materials.

3.3.1. Mechanical recycling

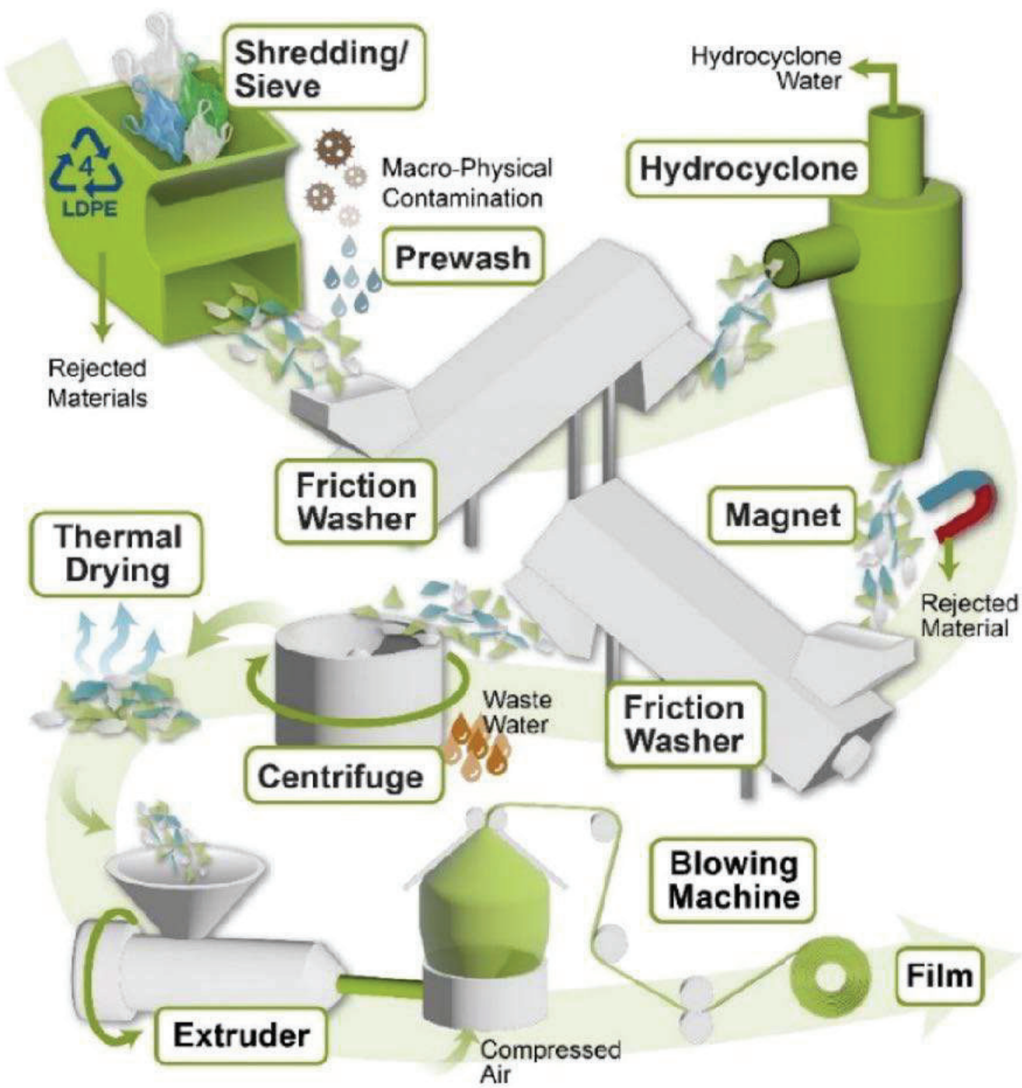
Mechanical recycling is the most common recycling method used today throughout the globe (Werner et al., 2022 and UNEP, 2023b). This method involves physically breaking down plastic waste into smaller pieces (often called flakes), cleaning it, and then melting and extruding it into new plastic products. Mechanical recycling is suitable for a wide range of plastics, including polyethylene terephthalate (PET), high-density polyethylene (HDPE), polypropylene (PP) and to a much lesser extent polystyrene (PS) and polyvinyl chloride (PVC) but not the thermosets such as unsaturated polyester and epoxy resin.

Figure 11 presents the basic processes of mechanical recycling: shredding, washing, drying, and extrusion into a product (Figure 18 shows a process to produce plastic films). The first mechanical equipment of importance is the shredder to prepare plastic flakes. Industrial-scale shredders vary significantly in capacity and price range, and the published information is summarised later in Table 7 in the cost section.

3.3.1.1. Closed-loop mechanical recycling

Closed-loop recycling, also known as primary recycling, involves a polymer-to-polymer recycling process. It reprocesses plastic waste into recycled granulates and pellets or products of the same quality as the original waste material. Since closed-loop mechanical recycling maintains the value of the plastic resource without downgrading, it is considered the most desirable form of plastic recycling. The most prevalent example is the bottle-to-bottle recycling scheme. Plastics must be collected in relatively clean state to maintain the plastic recyclate quality; hence, pre-consumer

Figure 11: Mechanical recycling steps of PE film at an industrial plant (Li et al., 2022)



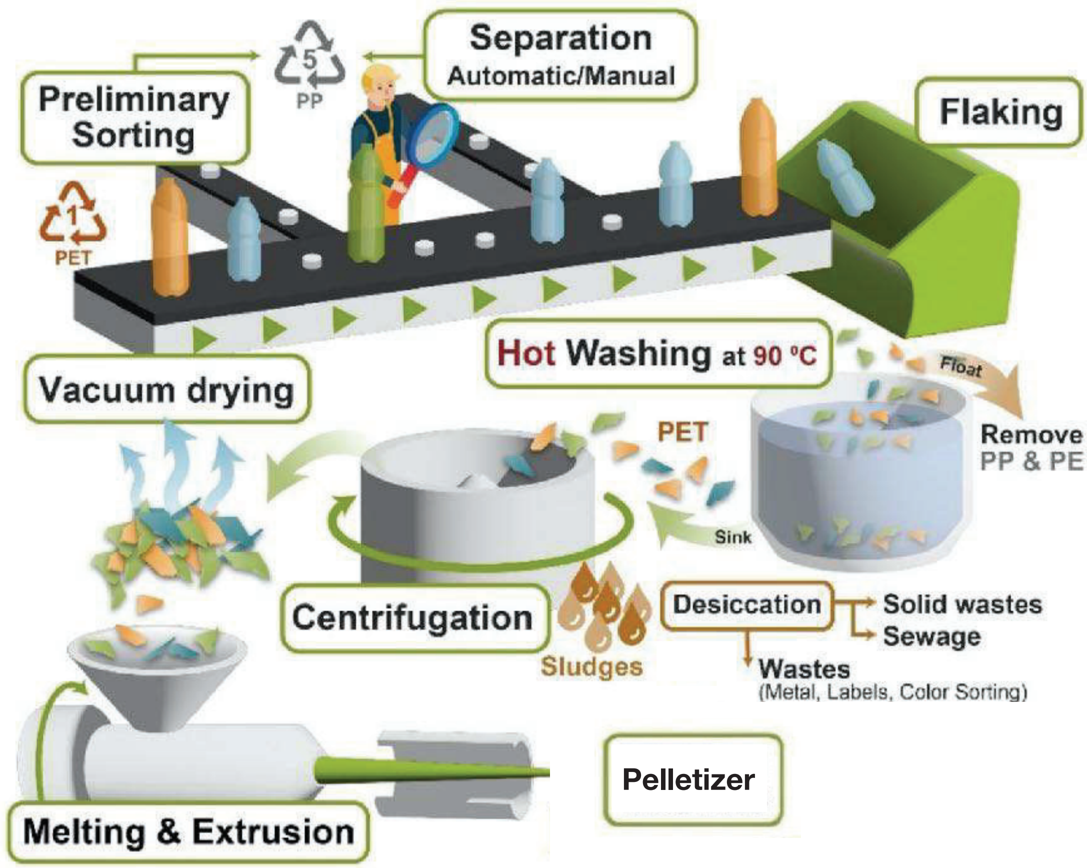
plastic waste from industrial production sites is particularly suitable. Post-consumer plastic waste can be washed or hot-washed, if necessary, to improve the recyclate quality in terms of the contamination level.

The basic processes of the closed-loop mechanical recycling are described by Li et al. (2022) as shown in Figure 12 which presents the processes of recycling used PET bottles into PET pellets (modified by the author). Most plastic recyclers do not perform the entire process: indeed, the recycling value chain involves many actors with intermediate traders. Most small-scale closed-loop plastic recycling actors produce washed flakes, sorted by materials and often by colours although hot-washed flakes can be sold at a higher rate.

3.3.1.2. Open-loop mechanical recycling

Open-loop recycling, also known as secondary recycling, involves processing plastic waste into products of lower quality or performance compared to the original material. This method typically involves sorting, cleaning, and processing plastic waste into flakes or pellets, which are then used to produce new plastic products with different applications. On the contrary to the closed-loop mechanical recycling, this method can reprocess more complex or contaminated plastics; hence, most small-scale plastic recycling activities fall into this category.

Figure 12: A generalised process flow diagram for a recycling of PET bottles (Li et al., 2022)



Advantage of this recycling scheme is its cost-effectiveness: relatively low initial investment is required and it can be easily scaled by increasing the production lines without having to purchase all the equipment as the same equipment (shredder, washer, and dryer) can be used for multiple extrusion line as shown in Figure 18.

Some companies such as Plasticpreneur[8] and Precious Plastic[9] produce equipment used in plastic recycling such as manual and electric plastic shredder, extruder, injector, compressor, sheet press, for small capacities. In addition, Plastic Odyssey provides turn-key micro-recycling factories for local and decentralised production of profile products (equipped with a shredder, an extruder and a barrel for the production of tubes, planks, poles, etc.), molded objects (equipped with a shredder, an extruder and a press for the production of bricks, pavers, tiles, etc.).

3.3.1.2.1. Downgrading mechanical recycling

Downgrading mechanical recycling, involves mechanically reprocessing plastic scrap to produce a product with altered properties. The resulting plastics are generally grey in colour and used in non-food-grade applications such as construction materials, garden furniture, or non-critical packaging. A certain level of contamination and plastic blending are possible within the limit of immiscibility and incompatibility which can cause poor and unstable plastic matrix.

PET bottles can be recycled into degraded products such as fibrefill for clothing or carpet manufacturing, and food-grade HDPE into drainage pipes, plastic lumber, and non-critical

[8] https://plasticpreneur.com/

[9] https://www.preciousplastic.com/

packaging materials. With the recent advancement with the 3D printing technology and the increased affordability of 3D printers, an increasing amount of plastic waste is reprocessed into 3D printing filaments.

3.3.1.2.2. Composite recycling

Composite plastics are the materials made by combining two or more materials, where one material (the matrix) binds the other materials (the reinforcement) together. Recycled plastic can be used as either the matrix or the reinforcement in plastic composites with non-plastic materials such as sand and gravels or plant-based materials such as straws and wood.

To be used as a matrix in plastic composites, recycled plastic must be melted and processed into a form that can bind the reinforcement materials together. This can be done using a variety of methods, such as extrusion, compression molding, or injection molding. To be used as a reinforcement in plastic composites, recycled plastic must be chopped into small pieces or fibres by grinding, milling, or cutting.

The type of recycled plastic that can be used to manufacture composite plastics depends on the desired properties of the composite. For example, recovered PET can be used to make composites that are strong and lightweight (ex: car bumper), while recovered PP can be recycled to make composites that are impact resistant such as construction materials (decking, lumber, etc.). This recycling technology is used often in the developing countries to produce eco-bricks and eco-pavers although recent studies warn the risk of micro-plastic generation over time due to the decaying of plastic binder due to UV exposure (Wei et al., 2021).

3.3.1.3. Costs of mechanical recycling equipment

There are different technologies of mechanical recycling of plastic waste, and they all have various economic models depending on the availability and the quality of plastic waste feedstocks, technical feasibility among other factors (see Chapter 5 for more information).

In terms of the economic investment, sorting and bailing the plastic waste (mostly PET bottles) is the least costly recycling operation although the operational output (plastic waste bails) still need to be reprocessed into a final product. The estimate for the equipment necessary for sorting and bailing amounts to 144 000 USD for approximately 19 million PET bottles per year: approximately 480 tons of PET/year. Although baled plastic bottles are traded at the lower rates than pelletised recycled PET resins, the IUCN study validated the economic feasibility of implementing a decentralised PET recycling plant in islands situations (Searious Business, 2021).

Costs of equipment for mechanical recycling of plastic waste vary depending on the process capacity and the product quality. Table 7 presents the costs of some equipment used in the mechanical recycling of plastics at the industrial scale from the published sources (Arina et al., 2014 and Caputo and Pelagagge, 2001).

In addition, there are small-scale plastic shredder, manual or electric, to support decentralised recycling activities. Three producers from Europe manufacture such shredders for the purpose of improving the plastic pollution situation by creating a local circular economy in developing countries. These manufacturers are

- Precious Plastic[10]: Electric shredder with 15-18 kg/h capacity for 2000 EUR

[10] https://bazar.preciousplastic.com/machines/shredder/shredder-fully-built/

- Sustainable Design Studio[11]: hand shredder with max. 5kg/h capacity for 550 GBP
- Plastic Odyssey[12]: Electric shredder with 50 - 100 kg/h capacity
- Plastic fantastic[13]: Machines and mobile micro recycling facility

Table 7: Published costs of equipment used in the mechanical recycling of plastics

Equipment	Data source	Capacity (t/h)	Power (kW)	Cost (k€)	Operating cost (€/h)
Shredder	Tsilemou	0.4-30	NA	11.7-103.6	NA
	Arina et al.	10-80	NA	270-950	NA
	Caputo & Pelagegge	6	25	56.81	1.81
		10	50	108.45	3.62
		15	50	129.11	3.62
		25	55	154.93	3.98
Press, Baler	Tsilemou	31	NA	74	NA
	Arina et al.	10-80	NA	150-350	NA
Dryer	Caputo & Pelagegge	6	140	309.87	10.12
Densifier	Caputo & Pelagegge	6	5	206.58	3.62
Pelletizer	Caputo & Pelagegge	4	50	206.58	3.62

As for the economic investment level of a large scale recycling plant, it is reported that a newly planned PET recycling plant in South Africa is expected to cost 60 million euros for recycling 60,000 tons of PET bottles per year to produce 35,000 tons of mechanically recycled rPET flakes and pellets (Global Recycling Magazine, 2023[14]). Considering the local PET resin price of 1.02 USD, it generates a minimum net revenue of 35 million USD.

3.3.2. Chemical recycling

Chemical recycling is the process of converting plastic waste and turning it back into substances that can be used as plastics or plastics' feedstocks. As shown in Figure 16, there are closed-loop and open-loop chemical recycling technologies, and the open-loop chemical recycling sometimes referred as feedstock recycling under which two sub-categories (chemolysis and thermolysis) that both have a number of newly developed technologies. Chemical recycling of plastics involves relatively developed technologies, and many technologies are still at the pilot-study level: hence, the technology readiness is lower than the mechanical recycling. However, chemical recycling attracts technical and economic interest from various stakeholders as promising technologies.

[11] https://www.sustainabledesign.studio/shreddermini

[12] https://technology.plasticodyssey.org/en/recycling-plastic-shredder/

[13] https://www.plasticfantastic.nu/en/contact

[14] https://global-recycling.info/archives/8706

3.3.2.1. Closed-loop chemical recycling by dissolution

Dissolution is a chemical process of recovering an intact polymer structure, so it is a polymer-to-polymer recycling scheme. Sorted plastic waste is dissolved in a solvent which dissolves only the polymer of interest, not the others nor any additives. Dissolved polymer is then purified and separated from the solvent, and finally pelletised. The process produces high-purity plastic resins, and allows a 100 % recovery rate. The dissolutive recycling of PS and ABS is commercialised[15] with a pilot plant in Quebec, Canada which treats 9000 tons of PS per year. Their pilot plant was constructed with the investment of 30 million Canadian dollars. The technology is mature and the economy of scale is estimated to be large, leading to lower recycling costs in near future. Another pilot plant for PC (polycarbonate) was constructed in the Netherland[16] but the information is not yet publicly available on this plant.

The advantage of dissolution recycling is its capacity to treat dirty and contaminated plastic waste as the contaminants will not be dissolved in the specific solvent, and Google'e report (Werner et al., 2022) identified the dissolution technology; they refer to « purification », as one of the most promising technology for the plastic recycling industry.

3.3.2.2. Open-loop chemical recycling

Open-loop chemical recycling is also know as feedstock recycling. This method involves breaking down plastic waste into its molecular components, including fuels, lubricants, and chemicals, using chemical processes, namely thermolysis and chemolysis (UNEP 2002, 2023a and b). The resulting monomers or oligomers of plastics can then be used to produce new plastic products. This method offers an alternative recycling option as it can utilise a wider range of plastic waste that cannot be effectively processed through mechanical recycling (Werner et al., 2022).

3.3.2.2.1. Thermolysis

Thermolysis is a thermal decomposition process in which plastic waste molecules are broken down into smaller molecules by the action of heat in the absence of oxygen. The resulting products are thermolysis oil and gas that can be used as feedstocks for fuel production and chemical synthesis. Thermolysis includes three distinctive technologies:

- Gasification: This method involves heating plastic waste in a controlled oxygen-deficient environment, converting it into a mixture of gases, primarily hydrogen and carbon monoxide. These gases can then be used to produce various chemicals or fuels.
- Pyrolysis: This method involves heating plastic waste in the absence of oxygen, breaking it down into a mixture of liquid and gaseous products. The liquid fraction, known as pyrolysis oil, can be further refined into fuels or chemicals.
- Hydrocracking: This method involves heating plastic waste under high pressure with hydrogen. The resulting products are hydrocracked oil and gases that can be used as high-quality liquid fuel.

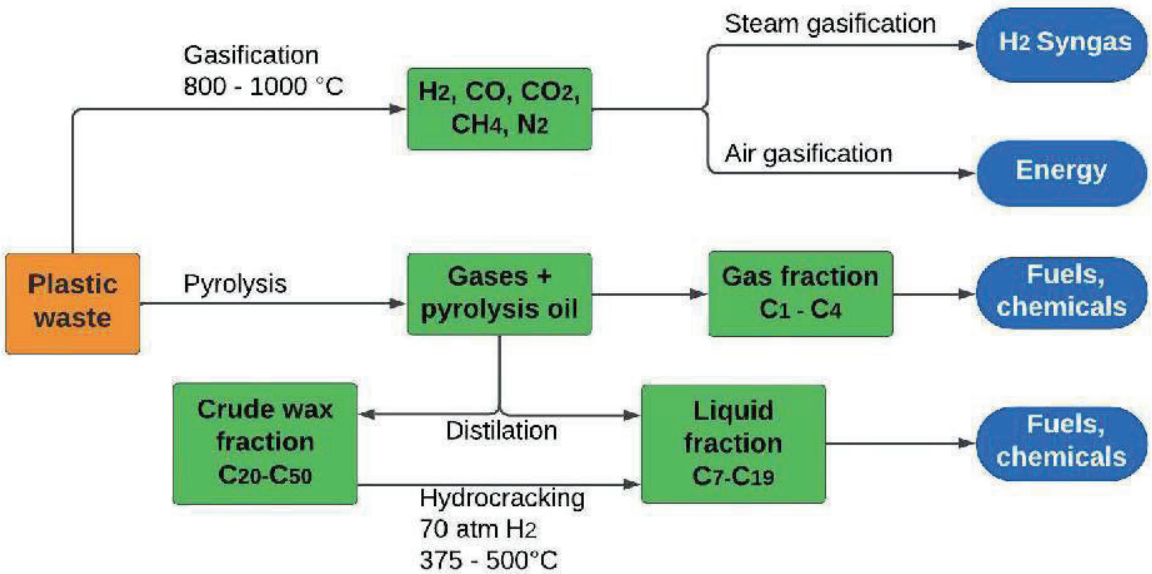
Overall processes and different operation conditions are described in Figure 13. These technologies can convert dirty, contaminated, and mixed plastic waste into chemical feedstocks. There are some large scale commercial plants globally. The first pilot plant is located in Portlaoise, Ireland with 3500 tonnes per year of chemical feedstock production (1.5 to 2 tons of plastic waste

[15] https://polystyvert.com/en/

[16] https://www.trinseo.com/

for the production of 1 ton of chemical feedstock). The plant costed a total of 12 million euros[17]. The largest pyrolysis plant in the world to date (as of December 2023) is located in Ashley Indiana, USA where the plastic waste is cleaned, chopped and pressed into small pellets before entering the pyrolysis chamber. The plant processes 100,000 tons of plastic waste per year and costed 260 million USD[18].

Figure 13: Overall processes for three thermolysis technologies (reproduced from Beghetto et al., 2021)



Thermolysis technologies are used for both energy production as described as Syngas, Energy, and Fuels in Figure 13, and feedstock production as described as chemicals in Figure 13. When thermolysis of plastic waste is used to produce liquid fuels, the technology is often termed « plastic-to-fuel ».

Small-scale and mid-range plastic-to-fuel plants are also commercially available, and provide a valuable option for mixed plastic waste treatment such as a turn-key solution proposed by Scarabtech[19]. In addition, small-scale plastic-to-fuel units have been developed by a number researchers (Patni et al. (2013), Joshi & Seay (2016), and Sharuddin et al. (2018)). Utilising this open-access knowledge, low-value plastics such as packaging films and other small plastic (only PE and PP plastic types which can be distinguished from other common plastics by floatation test) objects can be returned to diesel-like fuel (Joshi & Seay (2016), Sharuddin et al. (2018) and Joshi et al. (2019)). Such recycling technologies can provide economic value to low-value plastics which are diverted by informal waste pickers, and provide valuable fuel to the energy-deficient communities in the developing countries.

3.3.2.2.2. Chemolysis

Chymolysis[20] is a chemical process that converts a polymer into a molecular form known as a monomer by depolymerisation reactions. Monomers are the building blocks of plastics, and

[17] https://www.laoistoday.ie/2019/07/15/worlds-first-plastic-waste-to-wax-plant-opened-in-portlaoise/

[18] https://insideclimatenews.org/news/11092022/indiana-plant-pyrolysis-plastic-recycling/

[19] https://scarabtech.com/

[20] Interested readers are advised to read reviews by Zhang et al. (2020), Beghetto et al. (2021), and Li et al. (2022) for more information.

depolymerised monomers can be polymerised to form the same plastic. The advantage of this process is that it can form high-quality plastics without having limited recycling cycles. Current application of chemolysis; however, focuses on unsaturated polyesters and resins targeting the molecular bond cleavage at a specific bond such as C-O and C-N bonds (ex: polyamides, polyesters, nylons, PET, polyurethane, polycarbonate, and polylactide (Zhang et al., 2020).

There are several chemolysis processes used for the depolymerisation of plastic waste, and the following reaction mechanisms can be utilised for plastic recycling:

- Alcoholysis
- Hydrolysis
- Glycolysis
- Methanolysis
- Aminolysis
- Catalytic organo-catalysis
- Enzymatic hydrogenolysis

Plastic recycling by chemolysis has a high potential for literally closing the loop with the production of a high-quality plastic although the technology is still at the stage of pilot testing much like recycling by dissolution presented in section 7.1.3 (Werner et al., 2022). A pilot plant for PC (polycarbonate) recycling will be constructed in Leverkusen, Germany in the next few years[21] with « millions of euros » of investment (as of November 2023) as described by a manufacturer of high-performance PC plastics.

3.3.3. Energy recovery

Plastics are highly combustible materials with a high energy content: 40 to 50 mega-joules per kg (MJ/kg), in comparison to wood (15-20 MJ/Kg) and paper (8-15MJ/kg). Due to its high energy content, plastics are a potential source of energy fuel to generate electricity or heat. Energy recovery recycling scheme allows efficient use of plastic waste as energy source, particularly in urban settings where large quantities of waste are generated on a daily basis. There are two types of energy recovery recycling scheme: waste-to-energy and refuse-derived fuel production, and both technologies require an incinerator to combust the waste fuel to obtain energy. Incinerators attract particular attention in recent years due to the emission of greenhouse gas (GHG); consequently energy recovery from MSW and plastics waste remains an acceptable solution but no longer the preferred solution according to the official journal of the European Union (EU, 2018). The EU journal sustains that when waste cannot be prevented or recycled, recovering its energy content might be better than landfilling it (EU, 2018). In addition, it is reported that the incineration of plastic waste produces the most GHGs compared to paper, textile, and other MSW and industrial waste sources (Chen, 2018).

3.3.3.1. Waste-to-energy

Waste-to-energy (WtE) or energy-from-waste (EfW) is a process that generates energy, in the form of heat and electricity, from waste using an incinerator equipped with energy-recovery equipment such as heat exchangers, boiler and turbine. WtE facilities combust waste to generate steam, which can then be used to drive turbines to generate electricity or be used directly for heating purposes, and it is often utilised for mixed municipal waste. The incinerator; however, destroys the plastic resources and releases greenhouse gases, though the technology is widely used in

[21] https://www.covestro.com/press/chemical-recycling-of-polycarbonates-reaches-a-major-milestone/

developed countries as it can treat large quantities of mixed solid waste arising from urban areas on-site without further transportation requirement.

A new WtE plant is under construction for the Nairobi metropolitan area with a daily capacity of treating 3000 tons of solid waste and the electric output of 45 MW. The plant cost is estimated to be 197 million USD[22]. The world's largest WtE plant is under construction in Shenzhen, Guangdong Province, China for the capacity of 5000 tons per day and 165 MW electric output with the investment of 4 billion yuan ($580 million)[23]. As shown by these examples, a WtE plant is a costly investment with high O&M cost (up to 30 USD/ton) as shown in Table 8.

Table 8: Cost estimate comparison of WtE technologies for municipal solid waste treatment (GIZ, 2017)

WtE Technology	Incineration	Co-processing plant	Anaerobic digestion plant	Landfill gas capture collection	
Capacity	150'000 t/a	50,000 t/a, 20y operation	50,000 - 150,000 t/a, 20y operation	390,000 - 850,000 t/a, 21y operation	
Initial Investment	25 - 64 million $	4 – 21 million $ including preprocessing	10 – 17 million $	5 million $ (CDM-Brazil)	4.5 million $ (CDM-China)
Capital costs per ton of waste input	18-46 $/t	8 – 21 $/t	10 – 16 $/t	0.7 $/t	1,2 $/t
O&M costs per ton	17 - 30 $/t	8 – 17 $/t	8 – 13 $/t	0.7 $/t	0.25 $/t
Total cost per ton	35 - 76 $/t	17 – 38 $/t	18 – 29 $/t	1.3 $/t	1.4 $/t
Revenues from energy sales per ton	1.7 - 8.5 $/t (electricity)	0.8 – 4 $/t	6 – 13 $/t	2 $/t	2.8 $/t
Cost to be covered per ton waste input	34 - 15 $/t	16 – 34 $/t	12 – 15 $/t	0.7 $/t	1.4 $/t

It is important to note that the incineration inherently produces incineration by-products (bottom ash and fly ash) which require final disposal in landfills, for example. According to a UNEP report (2019) on the feasibility of waste-to-energy solution, it is necessary for the waste to have a relatively high energy content of at least 7 MJ/kg with less than 65% moisture content and more than 30% of volatile content, such as plastics. In addition, for the technology to be economically viable, of at least 100 000 tons per year must be fed to the incinerator over its lifetime, which may hamper efforts to reduce, reuse and recycle (UNEP, 2019).

3.3.3.2. Refuse-derived fuel production

Alternative solid fuel can be produced from the rejected portion (low-value paper and plastic waste) of MSW. Such fuel is often called refuse-derived fuel (RDF) that can be fed into incinerators, industrial boilers and cement kilns and co-processed with conventional fuels. RDF production often takes place in waste transfer stations such as MBT facilities where wet waste and recyclables are removed for composting and recycling. After sorting recyclables (bulk waste, cardboards, plastic containers, glass and metals), residual solid waste contains flat plastic pieces (film and small plastic objects), paper waste, and other residues. This « refuse » stream of municipal solid waste can be baled or shredded and pelletised as solid fuel because it contains a relatively high energy content (15 to 35 MJ/kg depending on the plastic content). RDF can be

[22] https://en.wikipedia.org/wiki/Dandora_Waste_To_Energy_Power_Station

[23] https://www.nsenergybusiness.com/projects/shenzhen-east-waste-energy-plant/

conditioned as bales or pellets depending on the destination as shown in Figure 14. RDF bales are conditioned in plastic wrapping or metal strips, and unpacked on the site and fed into the incineration.

Figures 14: RDF forms (wrapped bales, metal strapped bales and pellets)

RDFs can be sold to fuel municipal and private incinerators, coal power plants and cement kilns. RDFs sold to the cement industry should not contain above threshold level of PVC plastics as chlorine can damage their kilns (GIZ-Lafarge-Holcim, 2020). The investment cost resembles to the transfer station as the processes are similar. Caputo and Pelagagge (2001) provides RDF plant cost estimation based on the line design and equipment cost estimation as shown in Tables 7 and provided a methodology to arrange the process line to optimise the investment and RDF output.

3.3.4. Global plastic waste recycling effort

Plastic waste recycling attracts increasing attention globally, but the current recycling rate at the global scale remains at approximately 10% (OECD, 2022). Although developed countries have sufficient waste management infrastructure and economic capacities, plastic recycling rates remain relatively low, and the most utilised technology is the waste-to-energy which unfortunately does not provide a circular economic model of plastics. Statistics on the plastic recycling rates are scarce, but Alliance to End Plastic Waste published a white-paper reporting the data as shown in Figure 10 based on the data from OECD, Plastic Europe, StatsCan, US EPA. It shows that recycling is still a minor end-of-life fate for the plastic waste regardless of the geological regions, and high-income regions such as North America are not necessarily leading the circular economy despite the presence of highly efficient waste management infrastructure.

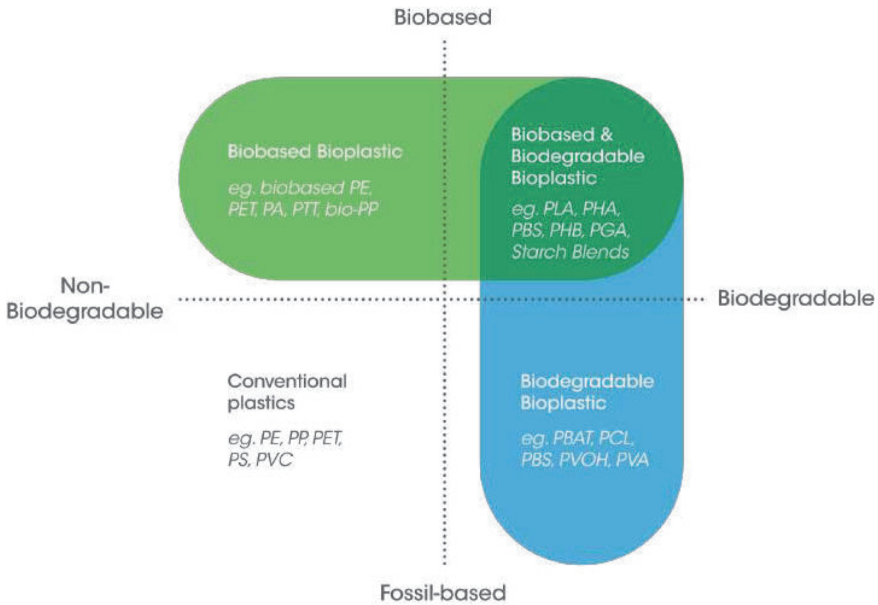
3.4. Biodegradation

Biodegradation can be a fate of plastic waste if the plastic is biodegradable. There are biodegradable plastics from petrochemical and biologically-sourced (bio-based) origins. Bio-based plastics are often termed « bio-plastics » but within the bio-plastics, two criteria can be identified: Bio-based plastics and Biodegradable plastics. Figure 15 presents the classification of all plastics based on the feedstock origin and the biodegradability. It is important to note that oxo-degradation of plastics is not considered as degradable nor biodegradation because it fragments into microplastics, and it is no longer considered as environmentally sound plastics in the EU (European Commission, 2016).

Bio-based plastics mainly reduce greenhouse gas emissions and the use of non-renewable and finite resources if sustainable feedstocks are used to produce bio-based plastics.

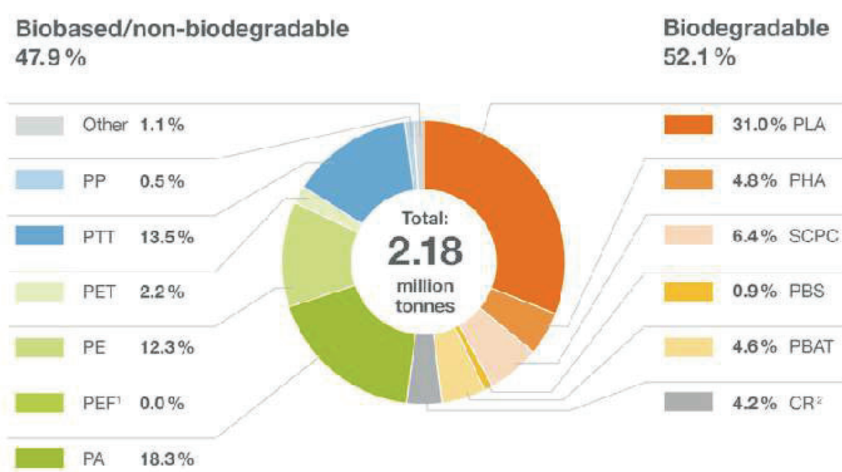
Biodegradable plastics mainly simplify the waste disposal process and reduce marine plastic litter if effective biodegradation takes place prior to reaching the marine environment.

Figure 15: Biodegradability of plastic types[23]



Regarding the bio-plastics, there are global debates raising questions of the life cycle reduction of greenhouse gases, the sustainability of biomass feedstocks, competing use of agricultural lands, and the true biodegradability of such plastics in the natural environments. To date, biodegradable bio-plastics make up about 0.2% of the total plastic production with the global production capacity of 0.86 Mt in 2022 with growth expectations up to 4.6 Mt by 2028 according to European Bioplastics Association[24]. Figure 16 shows the polymer-specific composition of the production capacity of the entire bioplastic industry.

Figure 16: Global production capacities of bioplastics in 2023 (European Bioplastics Association)



PP: polypropylene, PTT: Polytrimethylene terephthalate, PET: polyethylene terephthalate, PE: polyethylene, PEF: polyethylene furanoate, PA: polyamide (Nylon), PLA: poly lactate, PHA: polyhydroxyalkanoates, SCPC: starch-containing polymer compounds, PBS: polybutylene succinate, PBAT: poly(butylene adipate-co-terephtalate), CR: cellulose regenerates

---

[24] https://www.european-bioplastics.org/market/

Despite the global debate and questions, bio-plastics are expected to be a part of the solutions to mitigate the global plastic pollution due to the simplified waste treatment processes (biodegradation). A number of publications is available on the bio-plastics and the main advantages and disadvantages are summarised in Table 9 (extracted from Moshood et al., 2022).

Table 9: Identified advantages and disadvantages of bio-plastics

	Advantages	Disadvantages
Environmental aspects	• Biodegradability to reduce landfill accumulation and marine pollution • Reduced carbon footprint during production	• End-of-life management requiring adequate composting facilities • Contamination of recycling streams if not properly sorted
Social aspects	• Positive public perception and growing consumer awareness • Health and safety due to non-toxic and food-safe materials	• Misunderstanding and mislabeling leading to confusion among consumers • Access and affordability due to higher cost for lower-income consumers and countries
Economic aspects	• Market growth potential as eco-friendly alternatives and innovative business models • Energy savings from production processes	• Higher production costs due to the use of renewable resources and specialised production processes • Limited availability of composting infrastructure for waste management

As Table 9 indicates, there is a public misunderstanding that the biodegradation of bio-plastics can take place everywhere, and most biodegradable plastics require properly managed compositing conditions including the presence of aerobic microbial community, a certain range of humidity and appropriate temperature. None of the commercialised biodegradable bio-plastics can degrade in the aquatic environment although innovative bio-plastics have been developed in the industries.

Despite the disadvantages listed in Table 9, bioplastics can be used effectively in particular applications such as agricultural mulch alternative (FAO, 2021) and replacement materials of inevitable single-use plastics such as packaging materials as proposed by UNEP's zero draft Zero draft text of the international legally binding instrument on plastic pollution, including in the marine environment (UNEP 2023d). Agriculture, indeed, is one of the major source of plastic pollution other than mismanaged plastic waste from MSW streams (FAO, 2021, Li et al., 2023), and since mulching films are used directly on the soil where microbial action takes place, biodegradable plastic films can effectively replace the conventional non-biodegradable film to reduce the plastic pollution from agricultural activities. As for the single-use plastic packaging materials, it was shown in Chapter 1 that plastic waste from plastic packing is the most predominant portion of the plastic waste.

Overall, the biodegradable bio-plastic industry is not yet mature, but it can play an important role in reducing the plastic pollution problems once the cost-effective end-of-life management system is clearly defined.

3.5. Landfilling

Landfilling plastic waste is generally considered an environmentally unsound practice because plastics can leach into groundwater, and leak into the environment during heavy precipitation events. However, it has an advantage that it relatively few specialised materials and allows disposal of large quantity of plastic waste at once. If landfilling is the only viable option, there are certain measures that can be taken to minimize the environmental impact (US EPA,1998; Vaverková, 2019; WMW,2019).

1. Site Selection: Choose a landfill site with appropriate geological conditions to prevent the migration of contaminants into groundwater, and avoid a floodplain. This includes considering factors such as soil type, depth to groundwater, and surface water hydrology.
2. Liner Installation: Install a high-quality liner system at the base and sides of the landfill to prevent leachate from escaping into the surrounding environment. The liner should be made of durable, impermeable materials, such as compacted clay or synthetic liners.
3. Cover System: Install a cover system over the landfill to prevent rainwater infiltration and reduce the release of odours and dust. The cover system should be designed to withstand erosion and maintain its integrity over time.
4. Leachate Collection and Treatment: Install a leachate collection system to capture any leachate liquids from the landfill. The collected leachate should be treated to remove contaminants before being discharged to the environment.
5. Monitoring and Maintenance: Regularly monitor the landfill for any signs of leakage or environmental contamination. Implement a maintenance program to address any issues that arise and ensure the long-term effectiveness of the landfill's containment and control measures.
6. Gas Collection and Control: Install a gas collection system to capture and control methane gas generated from decomposing plastic waste. This will prevent methane emissions, which are a potent greenhouse gas.

The cost of constructing a sanitary landfill depends significantly on the region, and particularly on the land price, labor wage, and local regulations. World Bank report (Kaza et al., 2018) reported that landfill construction can cost roughly 10 million USD for a population of 1 million people although the largest cost of using a landfill as a final disposal method is associated with operational expenditures for labor, fuel and servicing equipment (Kaza et al., 2018).

4. Economic value of plastics and plastic waste

A study carried out by Beaumont et al. (2019) estimated the economic impact that the marine plastic pollution has on ecosystem services (benefits people obtain from nature such as fisheries, aquaculture, marine creatures, marine recreational activities, etc.) and reported a loss of 500 billion to 2.5 trillion USD per year based an estimated loss of 1-5% in marine ecosystem services as a direct result of plastic pollution. With the estimated 75 to 150 MT (million tonnes) of plastic debris in ocean, each tonne of marine plastic pollution has an annual cost in terms of reduced marine natural capital of between 3300 and 33,000 USD (Beaumont et al., 2019).

In Chapter 2, the general costs of plastic waste management was mentioned. Given the marine environmental cost loss due to marine plastic pollution and the plastic waste management cost, a new economic perspective can be withdrawn as summarised well in the WWF's report (2023):

« Despite what we've been told, plastic is not cheap. Its production and disposal - and the pollution it causes come with high social, environmental and economic costs, borne primarily by communities and governments. »

The WWF report reveals that the true lifetime cost of plastic is 10 times higher in low-income countries and 8 times higher in low- and middle-income countries than in high-income countries: or it is 10 times more expensive for low- and middle-income countries to manage plastic pollution than for high-income countries despite the fact that they consume on average 3 times less plastic per capita than high-income countries. Low- and middle-income countries are encountered by disproportionately large challenges in plastic waste management with limited technical and financial resources.

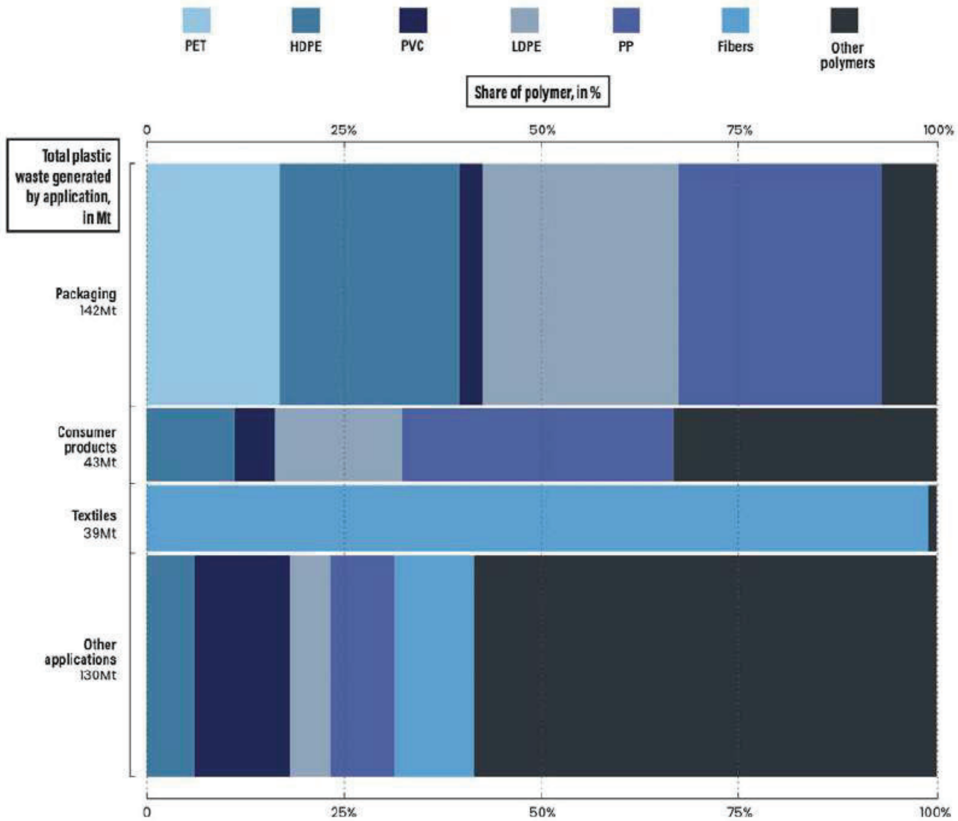
This chapter explores economic implications of plastics when it is lost as waste. The global plastic waste by polymer type, virgin plastics production costs, the market value of recycled plastics by polymer types and energetic values of mixed plastic waste are presented.

4.1. Global plastic waste by polymer types

About 40% of total primary plastic was used for plastic packaging in 2019: the packaging industry by far consumes the highest primary plastic compared to other industrial sectors. As a consequence of their short product lifetime and the production volume, plastic packaging is the most prevalent plastic waste globally. Figure 17 demonstrates the proportions of typical plastic polymers used for packaging materials, consumer products, textiles, and other products. The packaging industry uses mainly four polymers: PP (polypropylene), LDPE (light-density polyethylene), HDPE (high-density polyethylene) and PET (polyethylene terephthalate), in the order of increasing production volume.

IUCN study (Pucino et al., 2020) analysed the littered plastic waste in 8 study sites and reported the polymer type of all collected plastic waste as shown in Figure 18. IUCN data is valuable as it reveals that there is a regional characteristics. Plastic waste composed of LDPE predominates in the Southeast Asia, reflecting its sachet culture and other types of plastic packaging used for individual portion of food items. Sachets are small packets made of plastic and typically lined with aluminium, adhesives, and other types of plastics (Braaten et al., 2021) used to sell small amounts of different products such as shampoo, coffee or soy sauce.

Figure 17: Share of polymer types by product types (OECD, 2022)



Note:
PET= Polyethylene terephthalate;

HDPE= High-density polyethylene;

PVC=Poly-vinyl-chloride;

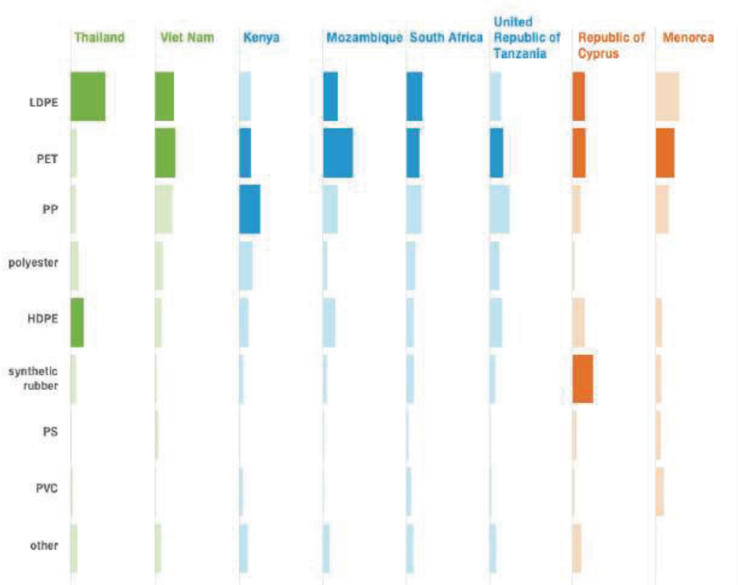
LDPE= Low-density polyethylene;

PP=Polypropylene.

Source: OECD Global Plastics Outlook Database, https://doi.org/10.1787/c0821f81-en

It is also important to note that LDPE, PET, PP, and HDPE are relatively simple-to-recycle plastics (PET and HDPE widely recycled, LDPE and PP moderately recycled) as already mentioned in Chapter 3. As a consequence, most plastics used for packaging materials can potentially be recycled or transformed into new products if all challenges such as efficient waste collection and sorting, economic and technical feasibilities are overcame.

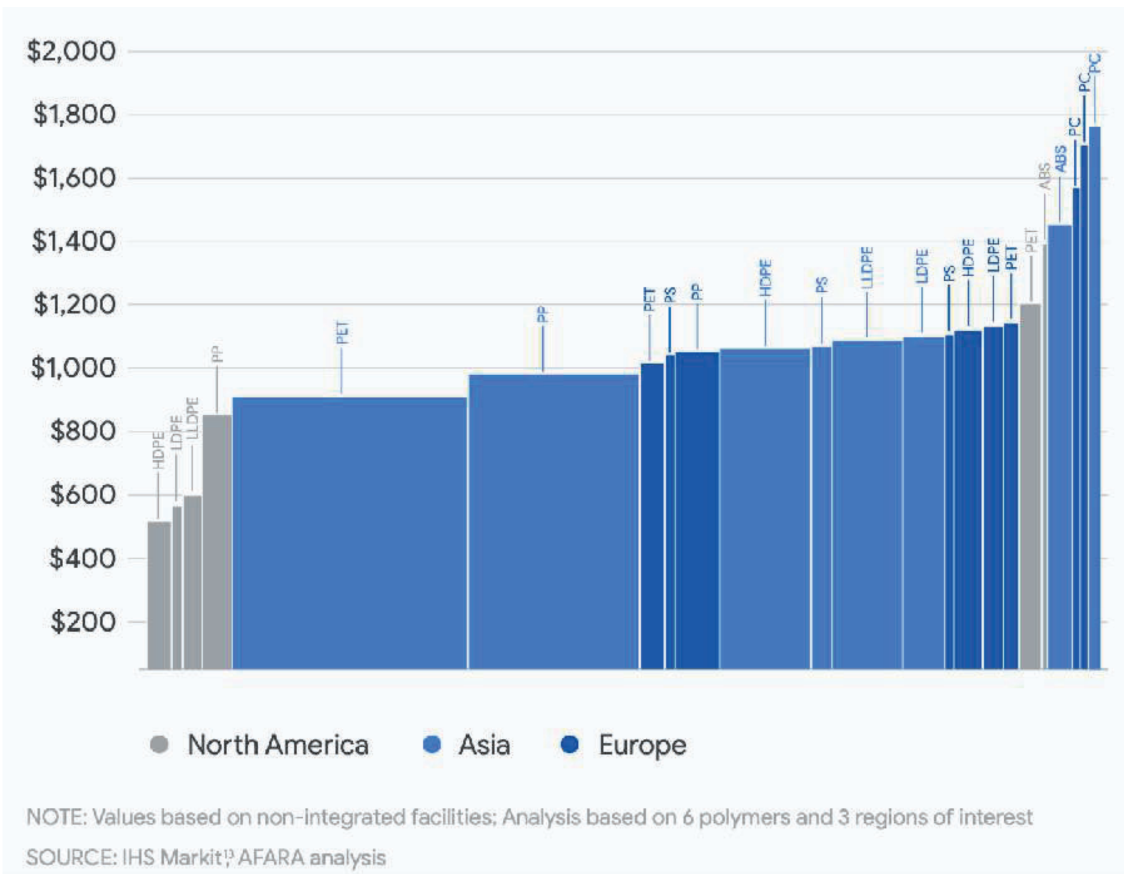
Figure 18: Mismanaged plastic waste analyses by polymer types by IUCN (2020)



4.2. Economic values of primary plastics

Google recently published a report that provides virgin resin production costs for Asia, Europe and North America (Werner et al., 2022). They report the cash cost[25] of primary plastic production by polymer and by region as shown in Figure 19 The cost is expressed in the unit of USD per metric tonne of production. The width (along x-axes) of each polymer bar in Figure 19 corresponds to the relative production volume.The same report also identified that the cost of chemical feedstocks (natural gas for North America, crude oil for Asia and Europe, and coal for China) is the predominant cost component to manufacturing plastic resins (Werner et al., 2022). North America has a lower production cost of plastic resins owing to the low cost of natural gas from the abundance of shale gas.

Figure 19: Cash Cost of Virgin Plastic Production by Polymer and Region in 2019 (Werner et al., 2022)



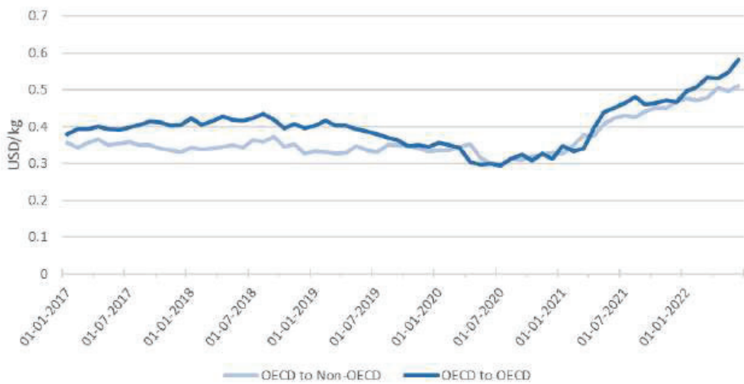
4.3. Economic values of plastic waste and scrap

Recyclable plastics are traded as a market-driven commodity. Plastic waste and scrap can be traded under the control of the Basel convention. Brown et al. (2023) reports the trading rate evolution of the plastic waste from OECD countries which export their plastic waste when in-country capacity of plastic recycling is not sufficient to recycle all of its collected plastic waste.

[25] **Cash Cost:** processing cost for a polymer that includes the cost of raw materials, utilities, and others such as labor, maintenance, and quality control. Cash cost excludes sales and distribution expenses, depreciation, return on investment, and income taxes.

Figure 20 shows that the plastic waste and scrap for recycling is traded between 0.5 to 0.6 USD/kg in recent years. The plastic waste exports are subject to strict regulations.

Figure 20: Trade value per weight of exports of plastic waste and scrap by OECD member countries (Brown et al, 2023)

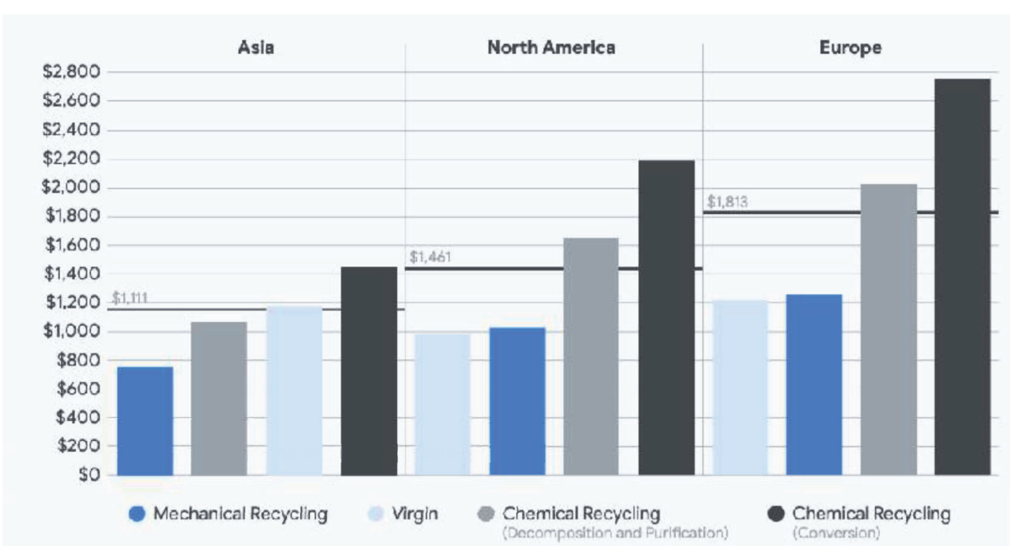


As mentioned in Chapter 3, plastic recycling requires four processes: plastic waste collection, sorting, washing, and reprocessing. The trade value of plastic waste depends significantly on the homogeneity, cleanness and state of the plastic waste and scrap. In addition, the reprocessed state also influence significantly: for example, we found a trade value difference of more than 15 Indian Rupee (approximately 18 US cents) per kg between PET bottle scrap and hot-washed PET flakes in a case in India[26], demonstrating how the plastic scrap can gain economic value when it is cleaned and prepared for recycling.

4.4. Economic values of recycled plastics

Recycled plastics are traded globally and the trade value depends significantly on the region as shown in Figure 21 (Werner et al., 2022). In Asia, mechanically and chemically (chemolysis) recycled plastics are cheaper than virgin plastics where as virgin plastics remain cheaper in North America and Europe. The plastic recycling cost depends significantly on the polymer types, labor costs and regions, but Figures 21 provide an insightful information on the technology-specific values of recycled plastics and regional characteristics.

Figures 21: Trade values of virgin and recycled plastics by region (Werner et al., 2022)



[26] https://scrapnews.recycleinme.com/newsdetails-611.aspx; https://scrapnews.recycleinme.com/newsdetails-803.aspx

Taking the most recycled PET plastics as an example, Table 10 shows the trade prices for virgin and recycled PET resins in the global market. It reflects the same observation as Figure 21 that recycled PET is more expensive than the virgin PET resins. This cost comparison is the major bottleneck for the development of plastic recycling global.

Table 10: PET price comparison by region (data as of 16/12/2023 from Business Analytiq)-1

Virgin PET	Recycled PET
North America:US$1.37/KG Europe:US$1.08/KG Africa:US$1.02/KG Northeast Asia:US$1.03/KG Southeast Asia:US$0.95/KG South America:US$1.02/KG India:US$0.91/KG	North America:US$1.79/KG Europe:US$1.35/KG Northeast Asia:US$1.29/KG

4.5. Economic impact of recycling plastics

Plastic recycling creates employment opportunities. USEPA reported that the country recycled 1.2 Mt (million tonnes) of plastic waste in 2012 which generated 28,521 employment opportunities with 1 273 million USD (M USD) wage and 170 M USD tax payment as shown in Table 11 (USEPA 2020). Table 11 demonstrates that plastics are the 3rd most profitable recycling material in the US after e-waste and nonferrous metals. It is reported that a plant producing about 50 Mt of recycled plastics annually will employ approximately 30 persons (d'Ambières, 2019) in developing countries.

Table 11: Summary of recycled volume and economic impacts in the US

	2012 (tonnes)	per 1000 tonnes recycled		
		Employment	Wage ($ 1000)	Tax ($ 1000)
Recycled ferrous metals	53 300 000	4.11	246.63	40.57
Recycled nonferrous metals (aluminum)	3 270 000	28.49	1489.06	265.24
Recycled glass	2 386 184	10.18	566.11	83.85
Recycled paper	27 213 728	1.69	99.43	14.22
Recycled plastics	**1215759**	**23.46**	**1047.41**	**139.76**
Recycled rubber crumb	992 007	11.86	579.45	75.81
Tire-derived fuel	1 294 580	11.86	579.45	75.81
Other recycled rubber	386 234	11.86	579.45	75.81
Recycled construction and demolition	372 913 275	0.47	26.78	2.62
Recycled electronics	299 371	33.00	2525.37	546.27

In Indonesia, Prevented Ocean Plastic ™ Southeast Asia opened a plastic collection centre with annual collection capacity of 1320 tonnes and created 30 jobs[28], and an aggregation centre (collection and recycling) with annual process capacity of 6000 tonnes created 40 jobs[29]. A PET

[28] https://www.preventedoceanplastic.com/25-by-2025-2-north-jakarta/

[29] https://www.preventedoceanplastic.com/25-by-2025-1-plastic-recycling-in-semarang/

bottle-to-bottle facility in the Philippines recycle 750 000 tonnes of PET bottles annually and created 200 local jobs[30]. These business cases clearly demonstrate how plastic recycling can be economically and socially profitable by reducing the environmental footprint related to the plastic waste.

4.6. Energetic values of plastic waste

Plastics are made of natural gas and petroleum co-products; hence, plastics themselves contain high energy value much like their feedstocks. The energy content of plastics varies depending on the type of plastic, but it is generally in the range of 18 to 42 mega-joules per kilogram (MJ/kg) as shown in Table 12. The range is similar to the energy content of coal and other fossil fuels. For the purpose of comparison, the calorific value of each polymer is also expressed in the volume equivalent of gasoline (energy density of 36.2MJ/L).

Table 12: Calorific values of plastics and fuel

	Calorific value (MJ/kg)	Equivalent energy in gasoline (L)
Polyethylene	43	1,26
Mixed plastics	30 - 40	1,17
Municipal solid waste	10	0,29
Methane	53	1,55
Gasoline	46	1,35
Fuel oil	43	1,26
Coal	30	0,88

Source: Panda et al. (2017). Thermolysis of waste plastics to liquid fuel A suitable method for plastic waste management and production of value added products - A world prospective. doi.org/10.1016/j.rser.2009.07.005

4.7. Financial instruments for implementing plastic waste management solutions

There are several established financial instruments to support the financial stability of plastic waste management for both developed and developing countries. Although it is not the main scope of this report, some of the important mechanisms are presented briefly to complement the financial analysis of this section. Interested readers are recommended to read the provided information sources.

- EPR (extended producer responsibility):

Extended Producer Responsibility is a concept where manufacturers and importers of products should bear a significant degree of responsibility for the environmental impacts of their products throughout the product life-cycle, including upstream impacts inherent in the selection of

[30] https://www.circularonline.co.uk/news/philippines-pet-recycling-plant-opens-in-partnership-with-coca-cola/

materials for the products, impacts from manufacturers' production process itself, and downstream impacts from the use and disposal of the products. Producers accept their responsibility when designing their products to minimise life-cycle environmental impacts, and when accepting legal, physical or socio-economic responsibility for environmental impacts that cannot be eliminated by design (OECD, 2016).

More information and initiatives around EPR:

- Basel Convention's ESM toolkit with a practical manual for EPR implementation
  https://www.basel.int/Implementation/CountryLedInitiative/EnvironmentallySoundManagement/ESMToolkit/Overview/tabid/5839/Default.aspx
- Global Action Partnership for EPR
  https://gap-epr.prevent-waste.net/

- Plastic bank: https://plasticbank.com/

Plastic bank was established in 2013 with an idea of transforming plastic waste into an economic value. It is a for-profit social enterprise baseline Vancouver, Canada, that facilitates the development of recycling ecosystems in under-developed communities with an objective to fight plastic pollution in ocean and high level of poverty in these communities. Collected plastics are recycled into PET, PP, HDPE and LDPE flakes or pellets that are used by global corporations as recycled resins. Plastic bank also issues Plastic Net-Zero certificate for individuals who wish to offset their plastic footprint.

- Plastic credits: https://verra.org/programs/plastic-waste-reduction-standard/

Verra is a nonprofit organisation based in Washington DC, USA, that operates standards in environmental and social markets. Verra launched a plastic credit program in 2022 to issue plastic credits to certified plastic waste collection and recycling projects. The program drives private-sector's finance and investment toward grass-root activities to tackle the global plastic pollution: or investment from upstream to downstream while collected and recycled plastics flow from downstream to upstream.

In addition to the above-mentioned financial mechanisms, there are some localised and international projects that issues credits to mitigate corporate plastic footprints. Although these financial mechanisms are available, not all waste management and recycling companies are eligible for them. In addition, several countries have a heavy importation tax on machineries (sometimes over 30% for the combined VAT, withholding fees and custom fees) which hampers the purchase of modern machineries from abroad (interviews with recyclers).

5. Comparison and evaluation of different plastic waste management technologies

Suitable plastic waste management approaches, solutions and technologies are highly context-specific and depend on the level of available waste management infrastructure which, in turn, reflects the country's income level and socio-economical situations. In terms of plastic pollution reduction, countries that make a step to move away from open dumping and implement a basic but effective plastic waste management strategy will contribute significantly to mitigate the global plastic pollution, and it is of a global interest to support these countries.

This chapter aims to provide an operational guidance for selecting a locally applicable and suitable plastic waste management solution. As already mentioned, environmentally-sound plastic waste management involves waste collection, sorting and the final disposal or reprocessing technology. However, it is important to keep in mind that technology is not a mighty solution to the problem of mismanaged plastic waste. Plastic management technology is not a panacea, but a vehicle to convert the problem into an opportunity to create a better environment and to transform the waste into a valuable resource.

In the following sections, a decision tree to facilitate the implementation of environmentally-sound plastic waste management solution is first presented. Then, a set of comparison and evaluation criteria for plastic waste management technologies are presented and used to evaluate, to the best of the author's experience and knowledge, all the technologies presented in Chapter 3.

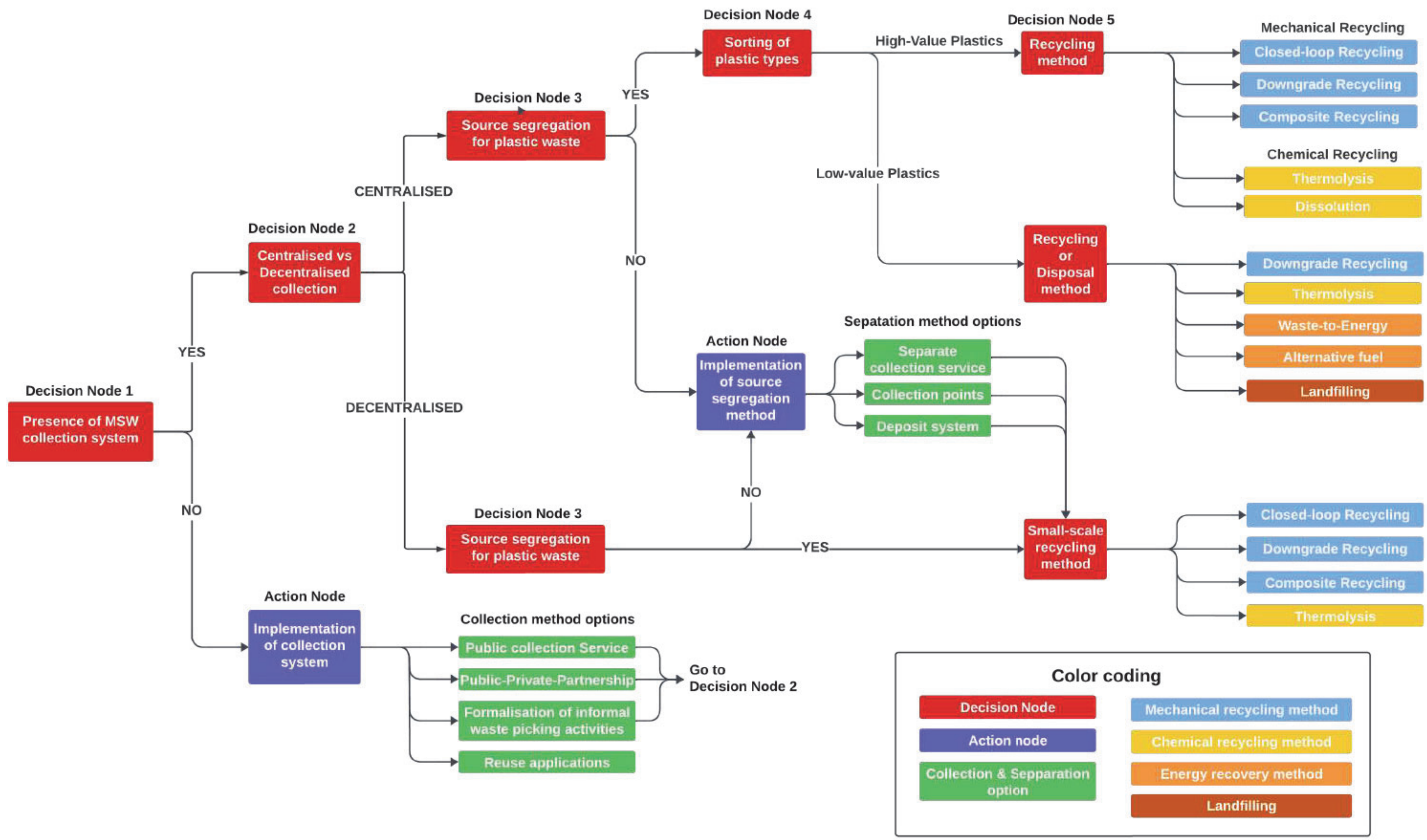
5.1. Selection of environmentally-sound plastic waste management

Plastic pollution is caused mainly by the mismanaged plastic waste as explained already in Chapter 1, and plastic waste is often a part of municipal solid waste (MSW) due to the lack of source-separation practices of plastics in many countries. In addition, Chapter 2 demonstrated that the waste infrastructure requires collection, sorting, and treatment (disposal and reprocessing). Indeed, effective plastic waste management depends strongly on the waste collection capacity, and successful plastic recycling requires efficient sorting of plastics. Hence, it is not possible to implement a plastic waste management strategy without these downstream operations.

Recognising these close linkage of downstream operations, Figure 22 proposes a decision tree to identify applicable plastic waste management technologies for different contexts. Different contexts are expressed by the presence or the lack of waste management operations (by formal or informal sectors) at each decision node in a red box. Each decision node brings to another decision node unless a necessary downstream operation is missing. In case of missing operations such as waste collection and waste separation, an action point proposes different implementation options as indicated in green boxes.

The development of efficient waste infrastructure requires a number of actors throughout the value chain, and it generally involves actors from the private-sector and the informal sector in developing countries. The involvement of cross-sectorial actors are particularly needed for the labor-intensive waste collection works. The details on different approaches of integrating multiple actors are out of the scope of this report, but interested readers can find extensive information on this topic from the following resources (the list is not exclusive):

Figure 22: An example decision tree for selecting a suitable plastic waste management solution set



Source: developed by the author

- WorldBank: Municipal Solid Waste PPPs
  https://ppp.worldbank.org/public-private-partnership/sector/solid-waste/FR
- UNEP: Topic Sheet Just Transition[31], ESM tool kit
  https://www.basel.int/Implementation/CountryLedInitiative/EnvironmentallySoundManagement/ESMToolkit/Overview/tabid/5839/Default.aspx
- WIEGO (Women in Informal Employment):Globalising and Organising
  https://www.wiego.org/waste-pickers
- IUCN: Waste pickers role in plastic pollution reduction: the ones we cannot leave behind
  https://www.iucn.org/news/environmental-law/202104/waste-pickers-role-plastic-pollution-reduction-ones-we-cannot-leave-behind

The technology boxes on the right end of Figure 22 are the potential plastic waste management technologies for each specific context defined by five decision nodes. It is widely recognised that the most environmentally-sound and sustainable disposal plastic waste management method is recycling (UNEP, 2022a). It is important to note that multiple solutions are proposed in Figure 28 as the implementation of multiple solutions would increase the effectiveness of plastic waste management strategy and accelerate the future plastic pollution prevention. There are numerous types of plastics with different physical and chemical properties, and it is practically impossible to treat all plastic waste by a single solution. Hence, last resort solutions such as landfilling and incineration via waste to energy may be needed to treat dirty low-value plastics in an environmentally sound manner while utilising the high-value plastics for recycling operations.

The following technologies might be particularly suitable for developing countries as they are scalable with relatively low technical, economic and environmental obligations:

- Closed-loop mechanical recycling (plastic bales, flakes and/or pellet production)
- Downgrading recycling
- Composite recycling
- Thermolysis

Successful case studies of these four recycling methods as well as small-scale mobile facilities for ambulant remediation application are presented in Annex 2.

Environmentally sound plastic waste management must privilege the waste hierarchy principal of reduce, reuse, and recycle. The options of incineration and landfilling should be considered as resort alternative methods when local context and situation do not allow the implementation of the reduce-reuse-recycle strategy. Developed countries with solid and efficient waste management infrastructure, for example, should lead the global plastic waste management practices by phasing out the incineration via energy recover and landfilling to accelerate the development of plastic circular economy.

5.2. Comparison and evaluation criteria for plastic waste management technologies

In order to identify the most suitable and feasible technology for a specific case, it is important to have a set of holistic criteria for the comparison and evaluation purposes. The proposed framework is structured by eight categories defined by a set of criteria as presented in Table 13. The definition of each criterion is provided in Annex 3.

[31] https://wedocs.unep.org/bitstream/handle/20.500.11822/42231/just_transition_sheet.pdf?sequence=3&isAllowed=y

Table 13: Comparison and evaluation criteria

Category	Criteria
Waste characteristics and compatibility	Plastic type and composition, Contamination level, Quantity, Presence of hazardous substances, Physical form
Land use	Land surface requirement, Land accessibility, Land availability
Cost effectiveness	Capital costs, Operation and Maintenance costs, Cost effectiveness in the long term, Life cycle cost analysis
Economic benefit	Job creation potential, Revenue generation potential, Product quality and marketability
Technical feasibility	Processing capacity, Scalability and adaptability, Technology compatibility and integrability, Operation and Maintenance requirements, Technology obsolescence
Positive environmental impact	GHG emission, Energy consumption, Water consumption, Water pollution potential, Air pollution potential, Soil pollution potential, Impact on ecosystem, End-waste generation and disposal
Social acceptability	Transparency, Consensual decision-making, Local community acceptance, Public health and safety considerations, Community impacts, Gender inclusiveness
Regulatory compliance	Local waste management regulations, Safety regulations

Source: developed by the author

These eight categories are equally important for a successful implementation of a plastic waste management technology although priorities may vary depending on the country's socioeconomic situations. Prioritising technologies that promise not only environmental sustainability but also economic development can lead to a situation where waste management strategies contribute holistically to the community's well-being, promoting sustainable development and resilience against economic challenges. The implications of the proposed criteria are explored in the following sections.

5.2.1. Waste characteristics and compatibility

This category of information is the feedstock specifications that determine the selection of applicable plastic waste management technologies. In particular, plastic type and composition, contamination level are important criteria for selecting a recycling technology. Due to the predominance of conventional plastics (i.e. HDPE, LDPE, PP, and PET) as shown in Figure 24, most recycling technologies have developed to recycle these four plastic types. However, advanced chemical recycling processes often target very high-value plastics such as PET and polycarbonate (PC) as chemical recycling (sometimes called molecular recycling) generates high purity recyclates.

Mechanical recycling is by far the most prevalent recycling technologies, but it is important to recover relatively clean plastic waste for mechanical recycling. When soiled plastics need to be recycled, it is necessary to « hot wash »these dirty plastic waste. Hot-washing is a labor and energy-intensive process, and small-scale to mid-scale recyclers in developing countries do not perform this washing method.

The quantity of plastic waste to be collected, sorted and reprocessed is a critical information to scale the recycling operation. All equipments must have the capacity to treat the desired volume of plastic waste. Hence, the quantity is the key in plant scaling. Once the plant capacity is determined, it will be difficult to upgrade the reprocessing capacity except by installing a second line of plastic reprocessing processes. Having multiple process lines has a great advantage of enabling the processing of different plastic types in parallel.

The presence of hazardous substances is common for the plastic waste originating from electronic devices (WEEE). For this reason, plastic recyclers tend to avoid WEEE plastics as some hazardous substances can not only harm the health and the environment, but also hinder some key processes of recycling such as polymerisation.

5.2.2. Land use

Land use plays an important role in the decision-making process which involves assessing how the implementation and operation of selected technologies can fit with the local land resources, ensuring technical feasibility including transportation considerations, and positive impacts on the community and environment. It's crucial that these facilities are strategically located to optimise accessibility and minimize transportation costs and emissions, thus enhancing the efficiency of waste collection and processing networks.

Additionally, underdeveloped infrastructure can make transporting large waste volumes expensive. Focusing on technologies with a smaller footprint and minimal transport requirements is key. Furthermore, land suitable for waste management facilities might also be needed for critical development projects, and balancing these needs is essential for the development of environmentally sound plastic waste management strategy.

5.2.3. Cost effectiveness

Cost-effectiveness is important for achieving environmentally sound plastic waste management especially in developing countries where resources are often limited. While environmental benefits are crucial, ensuring the chosen technology is financially sustainable is equally important. A comprehensive evaluation of cost-effectiveness ensures not only the initial affordability but also their sustainability and efficiency over the long term.

A long-term perspective is vital. The most cost-effective solution may not be the cheapest option initially, and conducting a life cycle cost analysis that considers all expenses over the technology's lifespan is the most important aspect of the feasibility study. Such a study ensures choosing a solution that delivers lasting value. By prioritising cost-effectiveness, it is possible to create a sustainable plastic waste management system that is financially viable for the long term.

5.2.4. Economic benefit

Considering the broader economic benefits is an important step to develop the framework of environmentally sound plastic waste management strategy as a part of development scenario. By integrating plastic waste management solutions that offer economic advantages, local communities can foster a more inclusive economic environment by transforming this challenge into an opportunity for economic development and catalysing the creation of new industries or support existing ones. The incentivised waste collection, sorting, and processing facilitate the development of a circular economy where plastic waste becomes a valuable resource.

Additionally, generating revenue from waste management, whether through processing fees or selling recycled materials, enables the creation of financial self-sufficiency. Selecting the technologies with positive environmental impacts can also enhance the marketability of recycled products, making them competitive in both local and global markets.

5.2.5. Technical feasibility

Processing capacity, scalability and adaptability are inherent in the facility design. Scalability is a key consideration from the conception of a project implementation especially for defining necessary space for the future operations. Plastic recycling requires a large surface for the storage of incoming plastic waste. Plastic recycling lines can be designed for future scale-up by installing some equipment with a higher processing capacity than the current need. In particular, a plastic shredder (crusher) is an expensive equipment, in terms of capital cost and O&M cost, so it is advised to purchase a higher-capacity machine which can operate sufficiently for the future scale-up of the recycling operations.

Technology compatibility and integrability depend on the existing waste management infrastructure; hence, newly developed facilities will not need to consider these criteria. Operation and maintenance requirements include the presence of technical staff to operate a facility; therefore, if no such human resources are available, on-site training will be required. In addition, machines require maintenance and repair; hence, the spare parts and replacement pieces must be secured from the contracting phase.

5.2.6. Positive environmental impact

The chosen solution and technologies should minimise its environmental footprint throughout its lifecycle, and must align with principles of the circular economy by minimising resource extraction and waste generation. It involves a comprehensive assessment of how these technologies contribute to environmental sustainability, aiming to minimise negative effects on natural resources and ecosystems.

Prioritising technologies that ensure a positive environmental impact reflects a commitment to long-term ecological resilience and public health: the foundation for a sustainable future. Such an approach not only addresses the immediate challenges of plastic waste but also contributes to the broader goals of sustainable development, enhancing the quality of life for current and future generations.

5.2.7. Social acceptability

Technologies with positive environmental benefits might face resistance if communities are not involved in the decision-making process. Transparency and open communication about proposed solutions are essential for building trust with the public. Plastic waste management requires the effort from all stakeholders including households; hence, fostering a collaborative decision-making process ensures that the chosen technology addresses community concerns and priorities.

In addition, it is crucial to consider potential community impacts, such as frequent transportation of waste, noise and odours. Additionally, promoting gender inclusivity in waste management practices empowers women and ensures all voices are heard.

5.2.8. Regulatory considerations

Compliance with local and international regulations safeguards that waste management practices meet established standards for safety, environmental protection, and public health. It provides a structured approach to managing plastic waste, emphasising adherence to laws that govern waste treatment, disposal, and recycling processes at the local and national levels.

Prioritising regulatory compliance means investing in technologies that are sustainable in the long-term and contributing to the broader environmental and public goals. By adhering to regulatory requirements, plastic waste management projects can avoid conflictual situations with local authorities, foster innovation within legal boundaries, and ultimately achieve more sustainable and socially responsible outcomes.

5.3. Evaluation of different plastic waste management technologies

Nine plastic waste management technologies presented in Chapter 3 are evaluated in this section. The evaluation of each technology is presented in a radar chart with the relative scaling criteria (between 1 and 3) as presented in Table 14. Two evaluation criteria (waste characteristic and compatibility and regulatory compliance) are region- and context-specific, so the information related to these criteria are provided as a description instead of a scaled evaluation.

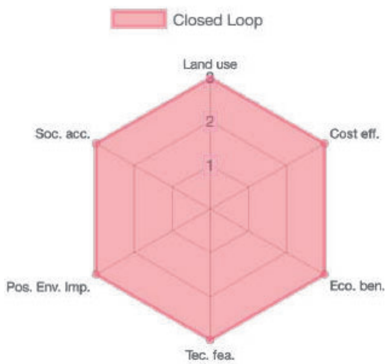
Table 14: Evaluation definition

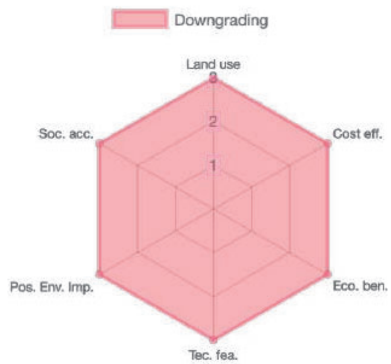
	Max (3)	Min (1)
Land use	most efficient	least efficient
Cost effectiveness	most effective	least effective
Economic benefit	most beneficial	least beneficial
Technical feasibility	most feasible	least feasible
Positive env. impact	high impact	low impact
Social acceptance	most accepted	least accepted

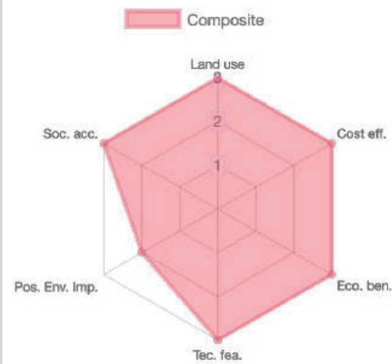
The results of the evaluation of the nine technologies are summarised in Table 15. The evaluation is based on the published information (Uekert et al., 2023) complemented by the author's professional professional expertise and discussion with industry insiders. Evaluation matrix provided in Table 15 refers to a comparative baseline proposed by Uekert et al (2023), which takes in consideration technical, economic and environmental aspects for closed-loop plastic recycling technologies; whereas open-loop technologies were evaluated by the author.

The presented evaluation of nine technologies intends to provide a tentative basis for selecting the suitable technology options indicated from the decision-tree presented in Figure 28 by integrating the proposed set of key criteria and sub-criteria presented in Table 13. Due to the limited information on the recycling technologies mentioned in this report, the economic estimates presented below considers a small-scale plant in alignment with the published cost information for a facility that treats 1 ton/day (Nikiema & Asiedu, 2022). Small scale plant is normally disadvantageous for chemical recycling and waste-to-energy plants as they are always designed to treat large volumes of waste.

Table 15: Comparative evaluation and pros and cons of various plastic waste management technologies

<table>
<tr><td colspan="3">Mechanical Recycling</td></tr>
<tr>
<td>


</td>
<td>


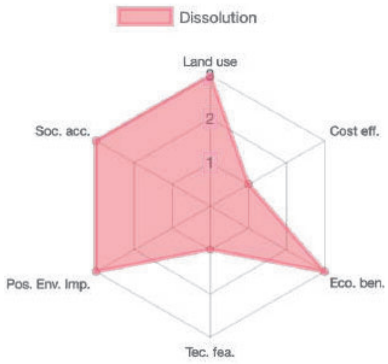
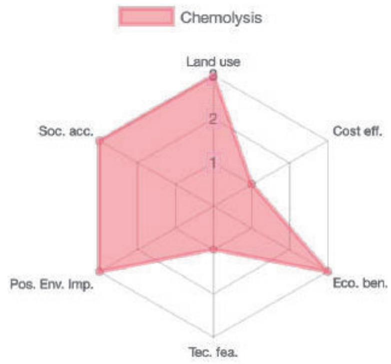
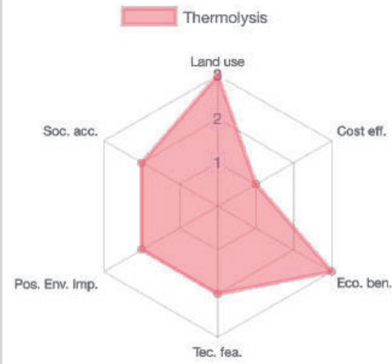
</td>
<td>


</td>
</tr>
<tr><td colspan="3">Capital cost: USD 2000 - 10,000 (for a smallo facility with 1 ton/d capacity, Nikiema & Asiedu, 2022)
O&M cost: USD 500 - 1500 (Nikiema & Asiedu, 2022)
Lifecycle cost of recycling (capital and O&M): EUR 204/ton (Nikiema & Asiedu, 2022)</td></tr>
<tr>
<td>• Applicable for hard plastics: HDPE, PP, PET with low contamination levels
• PS possible with very low contamination levels but lower quality recycled resins (Welle, 2023).
• PVC possible but with a risk of toxic gas generation (Inamdar, 2022)</td>
<td>• Applicable for hard plastics: HDPE, PP, PET with low contamination levels
• Co-processing of PP and HDPE to a certain level.</td>
<td>• Applicable for hard and soft plastics: HDPE, LDPE, PP, PET with low contamination levels.
• Possible to co-process different polymers (compatibility must be first analysed).</td>
</tr>
<tr>
<td>Pros:
• Robust process with wide applicability and scalability (Uekert et. al., 2023).
• High circularity with low material quality degradation (Uekert et. al., 2023).
• Simple technology to implement regardless of the socio-economic situations.
• Significantly lower capital and O&M costs (Uekert et. al., 2023).
• High potential for the development of local supply chain of plastic based products.
• High integrability of the informal waste management sector.

Cons:
• Degrading material quality after a certain number of recycling cycles.
• Lower tolerance for contamination (Uekert et al., 2023), and not applicable for dirty plastic recycling (remediation work of legacy plastic waste).
• Economic vailability highly dependent on market demand for lower-quality products (Uekert et al., 2023).</td>
<td>Pros:
• Simple technology to implement regardless of the socio-economic situations.
• Robust process with wide range of applicability and scalability.
• Certain contamination level is acceptable.
• Significantly lower capital and O&M costs.
• High potential for the development of local supply chain of plastic based products.
• High integrability of the informal waste management sector.

Cons:
• Lower quality for the recycled plastics.
• Co-processing highly dependent on the mixture and the quality of plastic waste, and must be tested on a case-by-case basis.
• Production of grey plastic products (impossible to change colours).</td>
<td>Pros:
• Wide range of matrix material acceptance to fit to the local availability (sand, sawdust, pulp waste, etc.).
• Possibility of using low-value plastics such as soft plastics as a binding material.
• Resulting composite materials can be used for various applications such as construction materials (e.g., lumber, paver, brick alternatives), reducing reliance on virgin resources like wood.

Cons:
• Optimal composition and processing techniques for different composite materials are not yet established, and case-by-case trial is necessary.
• Ensuring consistent quality and performance can be challenging.
• Generation of microplastic from the composite materials upon usage and UV exposure.</td>
</tr>
<tr><td colspan="3">Chemical Recycling</td></tr>
</table>

		
• Capital cost: 30 M CA$ for capacity of 9000 ton of PS/year (Polystyvert plant) • O&M cost: high expenses for solvent use and disposal.	Financial data not available	• Capital cost: US$ 385000 - 875000 1ton/d capacity plant, (Nikiema & Asiedu, 2022). • Maintenance cost: US$18100 (Nikiema & Asiedu, 2022).
• PS (ABS, GPPS, HIIP) and PC. Other plastic types possible at research level. • Acceptance of dirty plastic waste.	• PET and polyester. Other plastic types possible at research level. • Acceptance of dirty plastic waste.	• All but PVC and plastics containing hazardous chemicals • Acceptance of dirty plastic waste. • Profitability from large volumes: 50,000-10,000 tons (Nikiema & Asiedu, 2022).
Pros: • High-purity recyclate quality (Uekert et al., 2023) that can be accepted for food-grade packaging materials. • Potential for mutiple recycling cycles (Uekert et al., 2023). • Capacity to recycle mixed and contaminated plastics (Uekert et al., 2023). • Potential for high-value recyclate production (Uekert et.al., 2023). • Potential for reduced costs with technological advancements and scale-up (Uekert et al., 2023). • Low GHG emissions and energy use (Uekert et al., 2023). Cons: • Complexity in solvent recovery and purification processes (Uekert et al., 2023). • High operational costs due to solvent use (Uekert et al., 2023). • Collection of a large volume of high-value plastic may pose a logistic challenge.	Pros: • High-purity monomer production suitable for food-grade applications (Uekert et al., 2023). • Potential for mutiple recycling cycles (Uekert et al., 2023). • Potential for reduced costs with technological advancements and scale-up (Uekert et al., 2023). • Capacity to recycle mixed and contaminated plastics (Uekert et al., 2023). • Potential for high-value recyclate production (Uekert et.al., 2023). • Low GHG emissions and energy use (Uekert et al., 2023). Cons: • Catalyst and process conditions need optimisation for higher efficiency (Uekert et al., 2023). • Cost of reagent recovery and purification may impact overall economic feasibility (Uekert et al., 2023). • Lifecycle environmental impact due to the energy and chemical requirement varies significantly on the method (Uekert et al., 2023).	Pros: • Capacity to process a mixed and contaminated plastic waste. • No requirement for the plastic waste sorting and cleaning. • Diverse outputs (syngas, oils, waxes, and monomers) that can serve as feedstocks for new plastics or as fuels. • High compatibility with the existing chemical industry's infrastructure. Cons: • High energy requirement due to the thermal processes at high temperatures. • Significantly lower material-to-material recycling efficiency. • Complex and delicate processing requiring experienced technical staff. • High capital and O&M costs. • Potential production of hazardous by-products and emissions if managed improperly. • Inflexibility of the system scale-up once constructed. • Requirement of extensive supply chain and energy infrastructure for utilising all by-products.

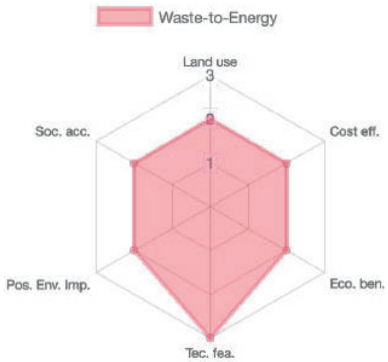
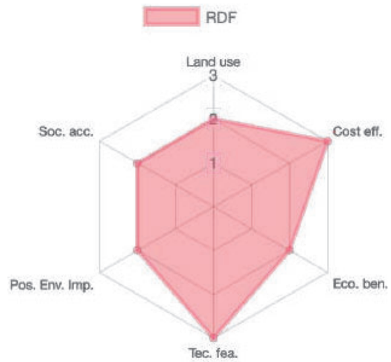
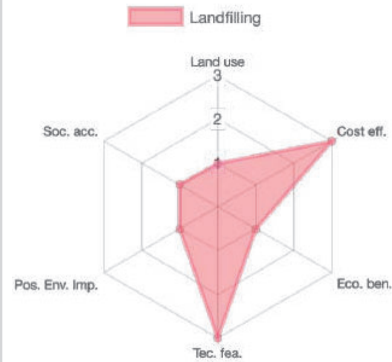
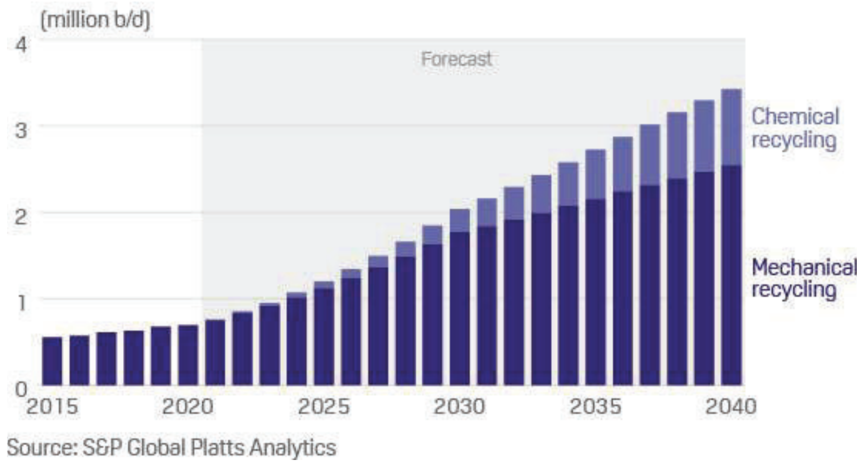
Waste-to-Energy	Refuse Derived Fuels (RDF)	Landfilling
		
• Capital cost: US$ 100,000-330,000 (in Myanmar), EUR 455,000-480,000 (in France) for 1 ton/day capacity (Nikiema & Asiedu, 2022). • O&M cost: US$ 10,800-14,000 (in Myanmar), EUR 40,000 (in France) for 1ton/day capacity (Nikiema & Asiedu, 2022). • Life cycle cost:EUR 120-130/ton (Nikiema & Asiedu, 2022).	• RDF production plant is relatively inexpensive and often integrated as a part of MSW sorting facilities.	Cost varies significantly.
• All plastics except hazardous plastics if the facility is modern.	• All but PVC and hazardous plastics.	• All except hazardous plastics.
Pros: • Energy recovery from plastic waste. • Provides an alternative plastic waste management solution for non-recyclable plastics and other waste streams. • Capacity to treat large amount simultaneously and continuously. Cons: • High capital and O&M costs. • Air pollution potential unless costly advanced emission control technologies are employed. • Energy intensive process, and heat use is crucial for profitability economic viability but heat requirement is often not satisfied due often to the lack of industries in the proximity, especially in hot regions. • Potential disincetivisation for recycling. • High CO2 emissions. • Elevated level of public opposition due to the health risks.	Pros: • RDF can be sold to commercial boiler facilities, cement kilns, and incinerators as solid fuel. • Alternative solution for non-recyclable plastics from MSW at a sorting facility. • Energetic recovery as alternative solid fuels for certain industries. Cons: • RDF bales are piled in the facility, requiring a large surface for storage. • Requirement of downstream industries to sell the RDF. • RDF transportation cost to the buyers may cancel the economic benefit in many cases.	Pros: • Simple and low-cost disposal method for plastic waste. • Disposal of wide range of plastic waste streams. • It can serve as an immediate solution for plastic waste management. Cons: • Variable and uncertain long-term environmental impact. • Resource loss and potential to discourage recycling. • Odour problems and visual impact for the local community. • Large land surface requirement. • Long-term maintenance and monitoring are required. • GHG emissions and microplastic generation.

Table 15 shows that the mechanical recycling of plastics is the most technically established and economically viable solution at the moment in agreement with the findings from Uekert et al. (2023), and this recycling sector is present globally and developing rapidly. Indeed, it is anticipated that the plastic recycling industry is expected to grow up to 400% by 2040 as shown in Figure 23[32]. Chemical recycling is expected to develop in the near future but mostly in developed countries, whereas mechanical recycling will continue to dominate the plastic recycling industry according to this industrial forecast.

[32] https://www.spglobal.com/commodityinsights/en/market-insights/blogs/chemicals/031121-recycled-plastics-global-market-commoditization-standards-pricing

Figure 23: Forecasted plastic recycling development



6. Conclusions and recommendations

This report explored the root causes of the global plastic pollution, and presented how the effective plastic waste management should be accompanied by efficient MSW management infrastructure. In fact, waste collection, sorting, disposal and reprocessing are all important components of the environmentally sound management of plastic waste.

<u>Important findings on the root causes of the global plastic pollution:</u>

- Mismanaged plastic waste consists of up to 82% of the global plastic leakage to the environment. The main reasons for the plastic waste mismanagement is the lack of proper waste management infrastructure in most of the developing countries. Studies show that up to 93% of the MSW is disposed of in open dumps in low-income countries.
- River system function as a plastic waste reservoir rather than the source of marine plastic pollution. Extreme weather events (heavy rain and flooding) functions, then, as a plastic releasing mechanism that empties the plastic reservoir, flashing land-based plastic waste from the floodplain. Therefore, global effort to end the marine plastic pollution must consider the importance of coastal regions and the regions along the rivers.
- Studies identify that plastic waste found in coastline consists mainly of packaging waste with the plastic films (LDPE and PP) and PET bottles as the most predominant source.
- Plastic waste can be categorised into 1) high-value plastic waste (hard plastics such as PET and HDPE bottles) and 2) low-value plastic waste (soft plastics such as packaging films, plastic package bags and sachets). High-value plastic waste can be recycled; hence has a certain market value whereas low-value plastic waste is difficult to recycle, and generally has no market value.
- Although waste collection is a gatekeeping component of the environmentally sound waste management, waste collection alone can not contribute to the significant reduction of plastic leakage from the developing countries as long as a proper disposal method is not

implemented. Plastics will be mobilised by natural forces such as winds and human activities to leak into the environment.

- Plastic waste export from high-income countries to lower-income countries have a significant impact on the global plastic pollution as many of the importing countries do not have proper waste management infrastructure, nor efficient value chain of plastic recycling.
- Microplastics consist of 12% of the global plastic pollution of which 10% from modern daily activities and 2% from other origins including accidental losses of plastic pellets. Plastic pellets leakage poses a particular environmental risk as they can carry a number of different chemicals intentionally added from the production level, releasing these chemicals in the sensitive environment such as aquatic ecosystems.

Recommendations for environmentally sound plastic waste management strategy:

- Global supply chain must work together to integrate the waste hierarchy concept (reduce, reuse, recycle) in the product design especially for the products commercialised in the developing countries.
- Decentralised waste management system or community-based system is more adapted for the developing countries as it requires less resources and it can be more scalable than the centralised waste management system.
- It is primordial to develop and implement a feasible plastic waste collection system to prevent the plastic leakage to the environment. The waste collection can be organised in close collaboration with the informal waste picking community in the developing countries.
- It is strongly recommended to develop a separate collection system for plastic waste. Source-separated plastic waste is cleaner and has a higher economic value for the plastic recycling industry. Source-separated collection system can be organised efficiently with the informal waste picking community in the developing countries.
- Low-value plastics are light, and it can travel by the natural forces to reach an aquatic environment once littered. Due to its valuelessness, the informal waste picking communities are not interested in this plastic waste type; hence, no collection for economic exchange. It is important to identify an economically viable solution to utilise this low-value plastics to divert it from open dumping or landfills.
- Different technologies to utilise this low-value plastics are discussed such as composite recycling and thermolysis (plastic-to-fuel). With the maturing of these technologies, small-scale applications are already present in the developing countries as presented in Annex 2.
- Plastic waste management is a complex chain of waste management processes that involve multiple stakeholders and actors. Effective collaboration among these actors are necessary to improve the effectiveness. Environmentally sound management of plastic waste; therefore, requires collaboration throughout the value chain: local authority, households, waste collectors and sorters, and waste processors.
- It is also important to combine multiple technologies to develop a robust and complimentary strategy as there are many different types of plastics that can not be treated together, and some plastics are not suitable for certain technologies.

- A decision tree is proposed in this report to facilitate the development of a roadmap (with decision-making steps and action points) to conceptualise a context-specific plastic waste management strategy by integrating the environmentally sound management principles.
- Recycling of plastic waste can be economically viable especially in the resource-poor countries (see Chapter 4). A number of technologies are available in various scales, and it is of the global interest to foster these technologies and support the developing countries to transform plastic waste into a valuable resource.

References

Āriņa, D., Kļavenieks, K., & Burlakovs, J. (2014). The cost-estimation of mechanical pre-treatment lines of municipal solid waste in Latvia. Proc. Latv. Univ. Agr, 32(327).

Asian Development Bank (2013). Materials Recovery Facility Tool Kit, https://www.adb.org/publications/materials-recovery-facility-tool-kit

Beaumont, N. J., Aanesen, M., Austen, M. C., Börger, T., Clark, J. R., Cole, M., ... & Wyles, K. J. (2019). Global ecological, social and economic impacts of marine plastic. Marine pollution bulletin, 142, 189-195.

Beghetto, V., Sole, R., Buranello, C., Al-Abkal, M., & Facchin, M. (2021). Recent advancements in plastic packaging recycling: a mini-review. Materials, 14(17), 4782.

Bourtsalas, A. T., & Themelis, N. J. (2022). Materials and energy recovery at six European MBT plants. Waste Management, 141, 79-91.

Boucher, J. and Friot D. (2017). Primary Microplastics in the Oceans: A Global Evaluation of Sources. Gland, Switzerland: IUCN.

Boucher, J., Billard, G., Simeone, E., & Sousa, J. (2020). The marine plastic footprint. IUCN, Gland, Switzerland.

Braaten, H. F. V., Karlsson, M., Nordbø, A. J., Hurley, R., O'Neill, C., Jaya, R. K., ... & Olsen, M. (2021). Plastic pollution in Indonesia and the Philippines: current status and upcoming knowledge needs. NIVA-rapport.

Brown, A., F. Laubinger et P. Börkey (2023), "Monitoring trade in plastic waste and scrap", OECD Environment Working Papers, n° 210, Éditions OCDE, Paris,

Chen, Y. C. (2018). Evaluating greenhouse gas emissions and energy recovery from municipal and industrial solid waste using waste-to-energy technology. Journal of Cleaner Production, 192, 262-269.

d'Ambrières, W. (2019). Plastics recycling worldwide: current overview and desirable changes. Field Actions Science Reports. The journal of field actions, (Special Issue 19), 12-21.

Ellen MacArthur Foundation (2019), Reuse – rethinking packaging.

European Commission, Directorate-General for Environment, Weißenbacher, J., Dollhofer, M., Herczeg, M. (2015). Assessment of separate collection schemes in the 28 capitals of the EU : final report, Publications Office. https://data.europa.eu/doi/10.2779/49194

European Commission, Directorate-General for Environment, Hogg, D., Gibbs, A., Ettlinger, S. et al., The impact of the use of "oxo-degradable" plastic on the environment – Final report, Publications Office, 2016, https://data.europa.eu/doi/10.2779/992559Geyer, R.,

European Union, (2018) Opinion of the European committee of the Regions - The role of waste-to-energy in the circular economy. Official Journal of the European Union (2018/C 164/12)

European Union, 2021. Deposit Refund Schemes

European Union, 2022. COMMISSION STAFF WORKING DOCUMENT IMPACT ASSESSMENT REPORT Accompanying the document Proposal for a Regulation of the European Parliament and the Council on packaging and packaging waste, amending Regulation (EU) 2019/1020, and repealing Directive 94/62/EC

FAO. 2021. Assessment of agricultural plastics and their sustainability. A call for action. Rome. https://doi.org/10.4060/cb7856en

Fauna & Flora International (FFI). (2022). Stemming the tide: putting an end to plastic pellet pollution.

GAIA (2021). Plastics Exposed: How Waste Assessments and Brand Audits are Helping Philippine Cities Fight Plastic Pollution.

Garcia, B., Fang, M. M., & Lin, J. (2019). Marine plastic pollution in Asia: All hands on deck!. Chinese Journal of Environmental Law, 3(1), 11-46.

Geyer, R., Jambeck, J. R., & Law, K. L. (2017). Production, use, and fate of all plastics ever made. Science advances, 3(7), e1700782.

GIZ (2017). Waste-to-Energy Options in Municipal Solid Waste Management.

GIZ-LafargeHolcim. (2020). Guidelines on Pre- and Co- processing of Waste in Cement Production – Use of waste as alternative fuel and raw material.

Global Recycling Magazine, 3/2023, Page 26. https://global-recycling.info/archives/8706 (retrieved on the 20th November 2023)

Hande, S. (2019). The informal waste sector: a solution to the recycling problem in developing countries. Field Actions Science Reports. The Journal of Field Actions, (Special Issue 19), 28-35.

Havstad, M. R. (2020). Biodegradable plastics. In Plastic waste and recycling (pp. 97-129). Academic Press.

Inamdar, I. (2022). Recycling of plastic wastes generated from COVID-19: A comprehensive illustration of type and properties of plastics with remedial options. Science of The Total Environment, 838, 155895.

Jang, Y.C., et al., 2015. Estimating the global inflow and stock of plastic marine debris using material flow analysis. Journal of the Korean Societyfor Marine Environment and Energy 18, 263–273.

Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., & Law, K. L. (2015). Plastic waste inputs from land into the ocean. Science, 347(6223), 768-771.

Jayakumar Menon, V., & Palackal, A. (2022). Centralized and decentralized approaches to solid waste management–a case study. The holistic approach to environment, 12(4), 155-164.

Joshi, C., Seay, J., & Banadda, N. (2019). A perspective on a locally managed decentralized circular economy for waste plastic in developing countries. Environmental Progress & Sustainable Energy, 38(1), 3-11.

Joshi, C. A., & Seay, J. R. (2016). An appropriate technology based solution to convert waste plastic into fuel oil in underdeveloped regions. J. Sustain. Dev, 9(4), 133.

Karlsson, T., Brosché, S., Alidoust, M. and Takada, H. (2021) Plastic pellets found on beaches all over the world contain toxic chemicals. International Pollutants Elimination Network (IPEN).

Kaza, S., Yao, L., Bhada-Tata, P., & Van Woerden, F. (2018). What a waste 2.0: a global snapshot of solid waste management to 2050. World Bank Publications.

Kassab, A., Al Nabhani, D., Mohanty, P., Pannier, C., & Ayoub, G. Y. (2023). Advancing Plastic Recycling: Challenges and Opportunities in the Integration of 3D Printing and Distributed Recycling for a Circular Economy. Polymers, 15(19), 3881.

Li, H., Aguirre-Villegas, H. A., Allen, R. D., Bai, X., Benson, C. H., Beckham, G. T., ... & Huber, G. W. (2022). Expanding plastics recycling technologies: chemical aspects, technology status and challenges. Green Chemistry, 24(23), 8899-9002.

Li, Y., Zhang, Q., Baartman, J., van Wijnen, J., Beriot, N., Kroeze, C., ... & Strokal, M. (2023). The Plastic Age: River Pollution in China from Crop Production and Urbanization. Environmental Science & Technology, 57(32), 12019-12032.

Lubongo, C., & Alexandridis, P. (2022). Assessment of performance and challenges in use of commercial automated sorting technology for plastic waste. Recycling, 7(2), 11.

Meijer, L. J., van Emmerik, T., van der Ent, R., Schmidt, C., and Lebreton, L. (2021). More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean. Sci. Adv.:10.1126

Medina, M. (2010). Solid wastes, poverty and the environment in developing country cities: Challenges and opportunities (No. 2010/23). WIDER Working Paper.

Mor, S., Ravindra, K., De Visscher, A., Dahiya, R. P., & Chandra, A. (2006). Municipal solid waste characterization and its assessment for potential methane generation: a case study. Science of the Total Environment, 371(1-3), 1-10.

Moshood, T. D., Nawanir, G., Mahmud, F., Mohamad, F., Ahmad, M. H., & AbdulGhani, A. (2022). Sustainability of biodegradable plastics: new problem or solution to solve the global plastic pollution?. Current Research in Green and Sustainable Chemistry, 5, 100273.

Nikiema, J., & Asiedu, Z. (2022). A review of the cost and effectiveness of solutions to address plastic pollution. Environmental Science and Pollution Research, 29(17), 24547-24573.

Norwegian Environmental Agency (NEA) (2014). Sources of microplastic-pullution to the marinne environment

OECD (2016), Extended Producer Responsibility: Updated Guidance for Efficient Waste Management, OECD Publishing, Paris.

OECD (2022): Global Plastic Outlook

Panda, A. K., Singh, R. K., & Mishra, D. K. (2010). Thermolysis of waste plastics to liquid fuel: A suitable method for plastic waste management and manufacture of value added products—A world prospective. Renewable and Sustainable Energy Reviews, 14(1), 233-248.

Patni, N., Shah, P., Agarwal, S., & Singhal, P. (2013). Alternate strategies for conversion of waste plastic to fuels. International Scholarly Research Notices, 2013.

Pires, A., Martinho, G., Rodrigues, S., & Gomes, M. I. (2019). Sustainable solid waste collection and management (pp. 45-59). Cham: Springer International Publishing.

Plastics Europe (2022): Plastics – the Facts 2022

Plastics Europe (2023): Plastics- the fast Facts 2023

Poerbo, H. (1991). Urban solid waste management in Bandung: towards an integrated resource recovery system. Environment and Urbanization, 3(1), 60-69.

Poulakis, J. G., & Papaspyrides, C. D. (1997). Recycling of polypropylene by the dissolution/reprecipitation technique: I. A model study. Resources, conservation and recycling, 20(1), 31-41.

Pucino, M., Boucher, J., Bouchet, A., Paruta, P., Zgola, M., (2020). Plastic Pollution Hotspotting and Shaping Action: Regional Results from Eastern and Southern Africa, the Mediterranean, and Southeast Asia. Switzerland: IUCN.

Ruj, B., Pandey, V., Jash, P., & Srivastava, V. K. (2015). Sorting of plastic waste for effective recycling. Int. J. Appl. Sci. Eng. Res, 4(4), 564-571.

Righi, S., Oliviero, L., Pedrini, M., Buscaroli, A., & Della Casa, C. (2013). Life cycle assessment of management systems for sewage sludge and food waste: centralized and decentralized approaches. Journal of Cleaner Production, 44, 8-17.

Searious Business, (2021). Report to IUCN Plastic Waste Free Islands, Bottle-to-Bottle Recycling Business Pan, Antigua and Barbuda, Gland, Switzerland, IUCN

Serranti, S., & Bonifazi, G. (2019). Techniques for separation of plastic wastes. In Use of recycled plastics in eco-efficient concrete (pp. 9-37). Woodhead Publishing.

Sharuddin, S. D. A., Abnisa, F., Daud, W. M. A. W., & Aroua, M. K. (2018, March). Pyrolysis of plastic waste for liquid fuel production as prospective energy resource. In IOP Conference Series: Materials Science and Engineering (Vol. 334, p. 012001). IOP Publishing.

Tassell, C., & Aurisicchio, M. (2023). Refill at home for fast-moving consumer goods: Uncovering compliant and divergent consumer behaviour. Sustainable Production and Consumption, 39, 63-78.

Tramoy, R., Gasperi, J., Colasse, L., Silvestre, M., Dubois, P., Noûs, C., et al. (2020a). Transfer dynamics of macroplastics in estuaries–new insights from the Seine estuary: part 2. Short-term dynamics based on GPS-trackers. Mar. Pollut. Bull. 160:111566.

Uekert, T., Singh, A., DesVeaux, J. S., Ghosh, T., Bhatt, A., Yadav, G., ... & Carpenter, A. C. (2023). Technical, economic, and environmental comparison of closed-loop recycling technologies for common plastics. ACS Sustainable chemistry & engineering, 11(3), 965-978.

UNEP (2002) Technical guidelines for the identification and environmentally sound management (ESM) of plastic wastes and for their disposal

UNEP (2015) Biodegradable Plastics and Marine Litter. Misconceptions, concerns and impacts on marine environments. United Nations Environment Programme (UNEP), Nairobi.

UNEP, (2023a). Technical guidelines on the environmentally sound management of plastic wastes : UNEP/CHW.16/6/Add.3/Rev.1

UNEP (2023b). Turning off the Tap. How the world can end plastic pollution and create a circular economy. Nairobi.

UNEP (2023c). Topic Sheet: Reuse Schemes. https://wedocs.unep.org/ 20.500.11822/42237.

UNEP (2023d). Zero draft text of the international legally binding instrument on plastic pollution, including in the marine environment

UN habitat (2010). Collection of Municipal Solid Waste in Developing Countries https://unhabitat.org/collection-of-municipal-solid-waste-in-developing-countries-2

Unido (2021).Study on Plastics Value-Chain in Nigeria

United States Environmental Protection Agency (USEPA, 2019). Advancing Sustainable Materials Management: Facts and Figures Report.

U.S. Environmental Protection Agency (EPA), (1998). MSW Landfill Criteria Technical Manual (EPA530/R-93-017)

United States Environmental Protection Agency and Office of Resource Conservation and Recovery. (2020a). Best practices for solid waste management: A guide for decision-makers in developing countries.

United States Environmental Protection Agency (USEPA, 2020b). Recycling Economic Information (REI) Report.

van Emmerik, T., Mellink, Y., Hauk, R., Waldschläger, K., & Schreyers, L. (2022). Rivers as plastic reservoirs. Frontiers in Water, 3, 212.

Vaverková, M. D. (2019). Landfill impacts on the environment. Geosciences, 9(10), 431.

Veolia (2019). Plastic recycling: a key link in the circular economy. Planet (october 2018).

Waste Management World (WMW): "Landfilling: Best Practices for Environmental Protection" (September 2019).

Watanabe, K., Adnan, K., & Haji Abdullah, M. R. (2014). Waste Management in Japan and Malaysia: Centralise or De-centralise?. ISIS Focus, 5-9.

Weideman, E. A., Perold, V., and Ryan, P. G. (2020). Limited long-distance transport of plastic pollution by the Orange-Vaal River system, South Africa. Sci. Total Environ. 727:138653. doi: 10.1016 j.scitotenv.2020.138653

Welle, F. (2023). Recycling of Post-Consumer Polystyrene Packaging Waste into New Food Packaging Applications—Part 2: Co-Extruded Functional Barriers. Recycling, 8(2), 39.

Werner, M., Narayannan, A., Rabenschlag, O., Nagarajan, P., Saboo, R., Banatao, R., Moedritzer, S., Zilnik, D., Wong, T., and Mez, M. (2022) Closing the Plastics Circularity Gap - full report. Google

Wen, Z., Xie, Y., Chen, M., & Dinga, C. D. (2021). China's plastic import ban increases prospects of environmental impact mitigation of plastic waste trade flow worldwide. Nature communications, 12(1), 425.

Wei, X. F., Nilsson, F., Yin, H., & Hedenqvist, M. S. (2021). Microplastics originating from polymer blends: an emerging threat?. Environmental Science & Technology, 55(8), 4190-4193.

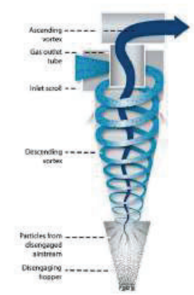
World Bank (2021). Plastic Waste Discharges from Rivers and Coastlines in Indonesia. Marine Plastics Series, East Asia and Pacific Region. Washington DC.

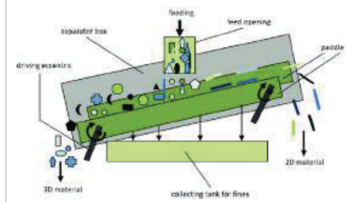
WWF (2021) Plastics: The cost to society, environment and the economy

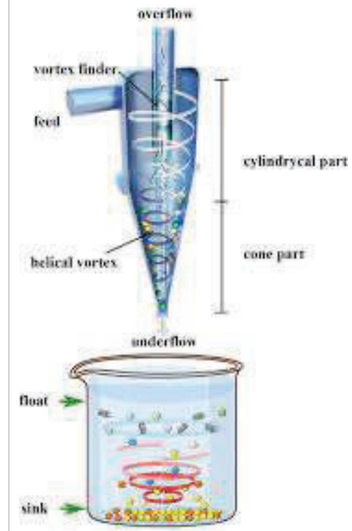
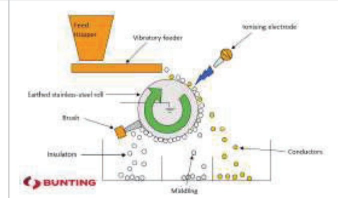
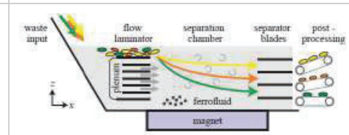
WWF (2023). Who Pays For Plastic Pollution?

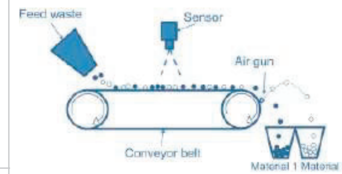
Annex 1

Waste Separation Equipment List

Mechanism	Equipment	How it works	Separation properties	Visual reparesentation
Manual sorting	Sorting cabine	Visual inspection and manual removal by inspectors.		
Gravity separators	Air classifier	Remove light contaminants (dust, small particles, paper, foils) from the main plastic waste stream.	particle density and morphology	

Mechanism	Equipment	How it works	Separation properties	Visual reparesentation
	Ballistic separator	Separate the flow of material into 3 fractions: heavy and rolling fraction (called 3D), flat and light fraction (called 2D) and the sieved fraction (or under-screen fine fraction).	Size, shape (2D or 3D) weight	
	Sink-float separator	Separate materials that float from those that sink.	Density Separate PET from PP/PE, and ABS from PS	
	Jig separator	Separate plastic waste from other materials, such as paper, glass, and metal.	Density	

Mechanism	Equipment	How it works	Separation properties	Visual reparesentation
	Hydrocyclone separator	Use centrifugal and centripetal forces and fluid resistance for separation. Lighter fractions moved to the upper part, the heavier ones to the bottom.	Density Separate PET from PVC	
Electrostatic separators	Applicable for clean plastics. Utilize the triboelectric effect to separate materials based on their differing surface electrical charges, and effective for separating various types of plastics because electrical charges vary as follows: (+) ABS - PP - PC - PET - PS - PE - PVC - PTFE (-)		Surface electrical charges	
Magnetic density separator	Use magnetized fluids to separate different types of plastic particles. Particles characterized by different densities are suspended in ferro-fluid at different heights.		Density PP from PE, or PET from PVC (similar density values)	

Mechanism	Equipment	How it works	Separation properties	Visual reparesentation
Sensor-based separation	Visible spectroscopy	uUtilize the interaction of light with materials to separate plastics based on their unique spectral properties.	Color, siwe, shape, surface texture	
	Near infrared spectroscopy	Most used non-contact sorting technology in plastic recycling. Utilize the interaction of near-infrared light with materials to separate plastics based on their unique absorption spectra.	absorption spectra (PP, PE, PVC, PET, PS, etc. can be separated)	
	Hyperspectral imaging	Identify and separate different materials, such as plastics, textiles, metals, glass, paper, and cardboard, based on their chemical structure.	Broad chemical properties	
	X-ray fluorescence	Primarily used to sort PVC from PET. It can detect and separate brominated plastics (used as flame-retardant in electronic products), and black and very dark polymers.	Emitted wavelengths upon x-ray irradiation	
	Laser-induced breakdown spectroscopy	Detect the elemental composition of the sample based on emission spectra	Atomic composition	

Annex 2: Case studies & available mobile technologies

Closed-loop & Downgrade Mechanical Recycling

There are numerous small-scale mechanical recycling facilities. A case study is provided by EcoBrixs from Uganda as follows:

EcoBrixs
Building Zero Waste Communities

Masaka, Uganda
Since 2017
https://www.ecobrixs.org/

- Removal of >190 tonnes of plastic water per month
- Recycling > 100 tonnes of plastic waste per month
- 32 full-time employees
- > 3000 income opportunities for RRAs (resource recovery agents, or waste pickers)

EcoBrixs recycles hard plastics (PET, HDPE, and PP) collected from local communities. They conducts closed-loop and downgrading mechanical recycling.

PET bottles: **Closed-loop mechanical recycling** into PET flake

Collection:

- Establishment of a independent recycling association composed of RRAs (waste pickers)
- Contracts between EcoBrixs and RRAs through the association
- Development of an interactive platform to indicate the collection sites and growth anticipation
- The collection of > 200 tonnes per month to be reached in 2024

Collection centres and transport:

- Transport capacity of 2 tonnes/outing
- Collection from 5 regions of Southern Uganda with 41 community collection hubs that are trained on sorting plastics
- 4 balers (40 tonnes per month capacity) are installed to improve the transport capacity

Processing

- Secondary manual sorting in the recycling facility
- Labels are removed by the label-remover
- Plastic bottles are shredded in a crusher (1 tonne per hour) with a water circulation system for cooling
- Sink-float separator (PET sinks, and labels float)
- Drum dryer for the centrifugal drying of shredded PET bottles (PET flakes)
- EcoBrixs' PET recycling line can process up to 1 ton/h of PET bottles, and the recycling line costed approximately 45,000 USD with some used equipment.

Final product: PET crush washed flakes
Financial mechanism:

- Sales contract of 100 tonns per month with a UK recycling company
- PET flake export trade value at 285 USD/tonne (high quality PET flakes at 550-650 USD/tonne)
- Plastic offset (100 tonnes/month)with a company
- Carbon credits and Plastic credits (Verra)

HDPE bottles: **Downgrade recycling**

Collection:
Same as above: Up to 50 tonnes per month of HDPE collection rate

Collection centres and transport:
Same as above

Processing
- Same as above
- Industrial injection mold & extruder machines turn plastic waste into marketable durable products

Final product::
- Eco paver
- Eco lamber

Mobile Mechanical Recycling Unit

There are a number of commercially available mobile units for mechanically recycling plastic waste.

EcoPlasticos
Bogata, Colombia
https://ecoplasticos.net/

Mobile plastic waste processing unit for shreddinig, washing and drying.
Process capacity of 500 kg per hour
Suitable for PET, HDPD, PP, PS, and PVC
EcoPlasticos provides a service of processing the collected plastic waste on-site. It can be mobilised on a product production facility or in a place requested.

Precious Plastic
https://www.preciousplastic.com/

Order-made mobile plastic recycling unit for India, utilising an electric vehicle.

Thees moobile GmbH
Dinklage, Germany
https://www.thees.com/en/mobile-recycling/

Specialised mobile unit for shredding crates, large containers, boxes and pallets
PET briquetting

Composite Recycling: Use of plastic waste in road construction

The types of plastic that can be used for construction of roads are Polystyrene (PS) (Hard packaging, cartons, plates, vending cups etc.); Polypropylene (PP) (ketchup bottles, yogurt cups etc.); Polyethylene (PE) (both high and low density) (plastic bags, water bottle, shampoo bottle etc.). Non-recyclable flexible plastic wastes can be utilised in the composite recycling. The method is widely recognised and recommended in India, and it is described in detail in the Government's document (2019). Plastics are melted and used to replace bitumen or asphalt, a viscous constituent of petroleum that binds aggregate particles for road construction. Basic steps are described below.

1. Collection and segregation of plastic waste (except PVCs)

2. Cleaning and sun drying of plastic waste

3. Shredding of plastic waste (2 to 4 MM size)

4.Heating of stone aggregate (160°C-170°C)

5. Adding of shredded plastic waste (5 to 10% w/w for 30 to 40 seconds)

6. Coated aggregate is mixed with hot bitumen (Temp 155°C to 163°C)

7. The mix-plastic aggregate bitumen mix (130°C- 140°C) The mix can be used for road laying

References:

- Ministry of Housing and Urban Affairs, Governement of India (2019): Plastic Waste Management. Issues, Solutions, & Case Studies. http://swachhbharaturban.gov.in/writereaddata/SBM Plastic Waste Book.pdf
- Shaikh, A., Khan, N., Shah, F., Kale, G., & Shukla, D. (2017). Use of plastic waste in road construction. *International Journal for Advance Research and Development*, *2*(5).

Thermolysis of plastic waste

Small-scale mobile pyrolysis unit

Plastics are made from feedstocks derived from crude oil refining and natural gas processing. It is possible to reverse the production pathway to degenerate plastics into feedstocks as described in the report. There are a number of commercial plants of « plastic-to-fuel » as well as small-scale commercial units. Mobile « plastic-to-fuel » units are of particular interest for the use in developing countries and remote areas. Mobile units can be deployed to clean up the legacy plastic pollution. Plastic Odyssey[1] has a unit of pyrolysis to convert the marine plastic debris collected into fuel used directly to run their vessel engine.

[1] A global project of sailing globally with a research vessel to collect and recycle plastics onboard, to foster a network of actors committed to end plastic pollution and to educate and raise awareness on the plastic pollution

Johannesburg, South Africa
Since 2021
https://scarabtech.com/our-why/

- Converts 100 kg of plastic waste into 90L of fuel
- Self-driving of the mobile unit requires 1L of produced plastic fuel to produce 9L of such fuel
- Plastic waste must be washed to avoid damaging the pyrolysis unit (particularly inorganic aggregates and salt must be removed)
- Washing, shredding and drying modules are not included in the Scarabtech's pyrolysis unit, but the preprocess unit can be integrated. The combination of the preprocess unit and the pyrolysis unit can fit in a 40 ft container.

- Output plastic fuel can be used directly in a petrol electric generator and a burner. For gasoline vehicle, it must be mixed with 50% of commercial gasoline.
- Hard plastics are easier to deal with than soft plastics in terms of feeding, but with the use of a densifier, soft plastics can be fed into the pyrolysis unit
- Output capacity of 30-40 kg/h for hard plastics for up to 16 hours/day.

- Unit price (as of December 2024) is set at 160,000 USD including one-year maintenance and technical training for assemblage and overhaul.
- Current units are manufactured by order, and the company is ready to scale up for mass production which will induce a cost reduction on the sales price in the future.

Scarabtech provided a pyrolysis unit to remediate the plastic pollution accumulated along Padma river in Bangladesh. The legacy plastic pollution has been collected by local waste pickers, and they are turned into liquid fuel for local use.

Annex 3 Comparison and Evaluation Criteria for plastic waste management technologies

Key criteria		Criteria Description
	Assessment points	
Waste characteristics & compatibility		
	Plastic type and composition	The type and composition of plastic waste affect the suitability of different technologies since different plastic types have different material properties and recycling potentials.
	Contamination level	The level of contamination in plastic waste varies significantly depending on the collection method, and it affects the feasibility and effectiveness of certain management technologies. High levels of impurities or mixed waste streams may limit recycling options or require additional sorting and cleaning processes.
	Quantity	The amount of plastic waste generated and collected can influence the selection of management technologies.
	Presence of hazardous substances	The presence of hazardous substances such as flame retardants, certain plasticizers, and other substances that can inhibit the chemical processes can impact the selection of a suitable technology.
	Physical form	The physical form of plastic waste, such as bulk solid, film etc., can determine the suitability of various technologies.
Land use		
	Land surface requirement	The land surface requirement refers to the extent of space that can be allocated for establishing and expanding of the implementation of a certain technology.
	Land accessibility	The land accessibility refers to the presence of roads for the waste and product transportation.
	Land availability	The land availability refers to the lack of computing land use demands such as residential areas and agricultural activities.
Cost effectiveness		
	Capital costs	The capital costs are initial investment required to implement a technology, including equipment, infrastructure, and site preparation costs.
	Operation and maintenance costs	The operation and maintenance costs are ongoing expenses associated with running and maintaining the technology such as labor, utilities, waste handling, maintenance and repair costs.
	Cost-effectiveness in the long-term	The overall cost-effectiveness of the technology, such as the net costs and benefits derived from the technology implementation must be assessed by comparing the total economic costs of the technology to the environmental, social and economic benefits achieved.
	Life cycle cost analysis	The assessment of the total costs incurred throughout the life cycle of a technology, from procurement, operation and maintenance costs, to end-of-life costs (closure of the facility) should be assessed. Comparing the life cycle costs of different technologies can provide insights into their economic feasibility.
Economic benefit		
	Job creation potential	Job creation potential refers to the capacity to generate employment opportunities, particularly in waste collection, sorting, and processing, contributing to economic growth, economic and social inclusion of informal workers.
	Revenue generation potential	The revenue generation potential can include revenue from energy production from waste-to-energy conversion, material recovery, production of valuable by-products, or participation in carbon and/or plastic credit markets.
	Product quality and marketability	The quality and marketability of the end product from technologies that produce recyclable or recovered plastic materials are important considerations related to the revenue generation and return on investment. The marketability of the recycled materials should be assessed to evaluate the economic viability of implementing a technology.

Key criteria		Criteria Description
	Assessment points	
Technical feasibility		
	Processing capacity	The processing capacity of the technology should match the volume and generation rate of the plastic waste stream to ensure efficient and timely waste management.
	Scalability and adaptability	The scalability and adaptability is the ability of the technology to adapt to changing waste streams and volumes to assure long-term sustainability. Scalable technologies can accommodate future growth or fluctuations in waste generation patterns while adaptable technologies can handle variations in waste composition, contamination levels, and/or feedstock quality.
	Technology compatibility and integrability	The compatibility of the technology with existing waste management infrastructure, such as the presence of waste collection systems (non-segregated vs. segregated), sorting facilities, and disposal sites, play an important role in successful technology integration and cost-effectiveness. The ability of the technology to be integrated in the existing waste management processes ensures seamless operation.
	Technological maturity and reliability	The technology maturity and reliability should be assessed by the technology readiness level and proven track records.
	Operation and maintenance requirements	The operation and maintenance requirements of the technology should be assessed for each context by evaluating the technical complexity, operational conditions and training requirement, maintenance needs, frequency and required expertise, the availability of technical staff locally for the operation and maintenance tasks.
	Technology obsolescence	The anticipated life cycle and longevity of the technology should be evaluated based on the current and forecasted regulations to avoid premature obsolescence and ensure effectiveness over time.
Positive environmental impact		
	GHG emission	The greenhouse gas emission (GHG) potentials must be assessed and minimised.
	Energy consumption	The energy consumption and efficiency of the technology impact both operational costs and environmental sustainability.
	Water consumption	The water consumption requirement must be assessed to assure the sound operation of a technology.
	Water pollution potential	The risk of water pollution directly resulting from the technology's operation should be assessed to avoid future pollution.
	Air pollution potential	The potential for air emissions of volatile organic compounds (VOCs) and particulate matter should be assessed.
	Soil pollution potential	The potential for soil contamination and degradation, particularly by microplastics, should be assessed.
	Impact on ecosystem	The potential impact of the technology on wildlife and ecosystems can be evaluated by considering habitat disruption, entanglement of wildlife, and ecosystem contamination.
	End-waste generation and disposal	The amount of end waste generated during the technology's operation and the disposal options for such residual waste should be evaluated.
Social acceptability		
	Local community acceptance	Engaging the public in discussions about waste management options, potential impacts, and concerns is essential for understanding local perspectives and building trust.
	Public health and safety considerations	Conducting a thorough health risk assessment to identify and mitigate potential health risks associated with the technology's operation or waste products. Development of the emergency preparedness and response plans to address potential accidents, spills, or malfunctions related to the technology is required.
	Community impacts	Assessing the potential impacts of the technology on vulnerable communities, such as exposure to pollutants or disruption of livelihoods, is crucial to avoid environmental injustice. Ensuring that the benefits of the technology, such as improved waste management or economic opportunities, are equitably distributed among all members of the community.
Regulatory compliance		
	Local waste management regulations	Adherence to local regulations is essential to ensure the safe and responsible handling of plastic waste.
	Safety regulations	Compliance to safety regulations must be assured